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Options for Renewable Hydrogen Supply to Urban Centres. A Modelling Approach

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ABSTRACT

Transportation is likely to be the greatest source of noise and local air pollution in urban centres and one of the major contributors to carbon dioxide emissions, which is the predominant greenhouse gas. A promising option for the decarbonisation of this sector, and for reducing local pollution, is the use of hydrogen as a transport fuel. In order to introduce hydrogen fuel in the transport sector the development of an infrastructure is an essential prerequisite. However, the design of a hydrogen delivery system is a complex venture that includes considerable uncertainties and numerous parameters that have to be considered in order to achieve its implementation.

This thesis examines the potential of supplying hydrogen fuel produced exclusively from renewable energy resources to urban centres. The issue of the least-cost hydrogen infrastructure design is addressed by developing an original model able to assess the performance of different hydrogen pathways in terms of both economic and technical criteria while taking into account the evolution of the infrastructure over time, meeting increasing demand, and the renewable resource potential of the geographical region under study in order to perform resource optimisation.

The model is designed by means of mixed integer linear programming and developed in MATLAB®. It is built in such a way so as to provide a generic framework for modelling several hydrogen fuel chains for establishing a hydrogen infrastructure that could be readily extended to different infrastructure patterns and geographical areas.

The model is applied to the case of London examining the potential for delivering hydrogen fuel to such a large urban centre. The case study investigates the possibilities of developing a renewable hydrogen infrastructure able to deliver sufficient hydrogen in order to cover London's road transport fuel demand within a 50-year time horizon. The results include the description of a cost-effective infrastructure development scenario along with its corresponding overall cost. The case study illustrates that the hydrogen infrastructure development modelling approach developed in this study assists the identification of least-cost renewable hydrogen supply chain options.

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LIST OF ACRONYMS

BP	British Petroleum
BWEA	British Wind Energy Association
CH_2	Compressed Gas Hydrogen
CO_2	Carbon Dioxide
DFS	Depth First Search
DfT	Department for Transport
DP	Dynamic Programming
DTI	Department of Trade and Industry
EC	European Commission
EJ	Exajoule; Metric Unit of Energy
EU	European Union
EWEA	European Wind Energy Association
FR	Forestry Residues
GAMS	General Algebraic Modelling System
GB	Great Britain
GEF	Global Environmental Facility
GHG	Greenhouse Gas
GIMP	GNU Image Manipulation Program
GUI	Graphical User Interface
H_2	Hydrogen
Ha	Hectare; Unit of Measurement
IEA	International Energy Association
IPHE	International Partnership for the Hydrogen Economy
kW	Kilowatt; Unit of Power
kWh	Kilowatt hour; Unit of Energy
LH_2	Liquid Hydrogen
LHP	London Hydrogen Partnership
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MSW	Municipal Solid Waste
NGO	Non-governmental Organization
NLP	Nonlinear Programming
Nm^3	Normal Cubic Meter; Unit of Volume
NO_x	Nitrogen Oxide
O&M	Operation and Maintenance
Odt	Oven Dry Tonnes; Unit of Weight

OECD	Organisation for Economic Co-operation and Development
PEM	Polymer Electrolyte Membrane
PJ	Petajoule; Metric Unit of Energy
PM_{10}	Particulate Matter of less than 10 millionths of a metre
PV	Photovoltaics
R&D	Research and Development
SO_2	Sulfur Dioxide
SRC	Short Rotation Coppice
TfL	Transport for London
TNUoS	Transmission Network Use of System
UI	User Interface
UK	United Kingdom
UKSHEC	UK Sustainable Hydrogen Energy Consortium
USA	United States of America
XML	Extensible Markup Language


To Nikos, Irene and Panayiotis
H_2

C H_2 A P T E R 1

Introduction

1.1 Background

Every paper, report or thesis that includes the words hydrogen fuel in their title commences by referring to issues such as energy security, air and noise pollution, carbon emission reductions, greenhouse effect, ozone layer depletion and acid rain. In the previous years, the consequences of the use of carbon-based fuels had been discussed and a number of scientists had foreseen the severe environmental damage that entails their use. What comprised a prediction in the past became a reality in the present and frustratingly it is almost impossible to exaggerate the danger of continuing using fossil fuels. Recognizing the necessity for alternative fuels is the first necessary step in order to change this situation. Determining possible solutions and implementing the most promising among them is the subsequent step. At present, society has made the first step and is struggling to make the second one.

However, the selection and use of clean fuels and energy sources can be prognosticated as one of the most intriguing challenges for the future of the environment and society. One of the main sectors that depends heavily, if not exclusively, on fossil fuels and thus is a major contributor of air pollution is the transport sector. Worldwide it is responsible for about 25-35% of CO_2 emissions (MacLean and Lave, 2003). This picture is getting worse as most of the future growth in energy is expected to take place in transportation (Dunn, 2002). Realizing the remarkable impact of the transport sector on the environment makes the decarbonisation of this sector an imperative need for the amelioration of the environmental quality.

New and environmentally benign alternative fuels to the use of petrol and diesel are necessary to be introduced in the transport sector. A number of alternatives have been studied such as methanol, ethanol, methane and synthetic liquids from coal and natural gas and hydrogen. Among these, hydrogen is of keen interest and perhaps the most promising option because it holds the promise of reducing the dependency on fossil fuels, delivering deep cuts in greenhouse gas emissions and other air pollutants and improving the energy security simultaneously.

Hydrogen is an efficient, versatile and clean-burning fuel. It can be used in both modified internal combustion engine and fuel cell vehicles without the emission of carbon dioxide, carbon monoxide, sulphur dioxide and particulates at point of use. It can be derived from a wide range of sources from fossil up to renewable energy sources by a number of different routes. The flexibility in its production may assist in the gradual switch of the transport sector from fossil fuels to renewable fuels. As hydrogen during combustion is almost free of polluting emittents, its environmental benefits strongly depend on the way of production. Thus, the energy used to obtain hydrogen is the factor that determines whether hydrogen is clean or dirty.

Realistically, in the short term due to economic and technical factors the predominant source of hydrogen may be fossil fuels. Although fossil fuel derived hydrogen may produce less harmful emissions than conventional fuels, it limits the extent to which these emissions can be reduced. Fossil fuels as a hydrogen source eliminate most of the benefits offered by hydrogen. In order for hydrogen to fulfil its promise as an abundant, available and sustainable fuel, hydrogen from fossil fuels shall not be considered as the ultimate alternative to the current fuels but as an interim step to a more sustainable transport fuel. The supreme sustainable fuel that has the potential to inhibit further environmental damage may be considered hydrogen generated from renewable energy sources. Renewable hydrogen may eventually replace fossil fuels and therefore free the transport system from carbon. Renewable hydrogen may be an ideal complement to electricity and together they may create an energy loop that is 100% renewable.

Without renewables, hydrogen may just be another fuel that can to some extent mitigate the environmental impacts of the transport sector but will not solve any problem satisfactorily. In a world that strongly requires the use of clean fuels it is disappointing to have a fuel like hydrogen and not to exploit the fact that its versatile production allows its derivation from renewable energy sources. It is meaningless to talk about hydrogen if it is not a part of an integrated sustainable energy scheme. Hydrogen and renewable energy sources shall be considered as closely interwoven ingredients for a successful sustainable transport recipe. Renewable energy sources without hydrogen cannot supply a significant share of the world's energy demand as most of them are intermittent and broaden their role in the supply of clean fuels for transportation. On the other hand, hydrogen without renewable energy sources cannot be regarded as a totally clean fuel and thus unfold its environmental benefits.

In order to introduce hydrogen fuel to the transportation sector the development of an appropriate fuel infrastructure is necessary. The required infrastructure involves fuel chains that consist of certain stages in order to deliver hydrogen to the point of use. The main stages of a fuel chain include the production, storage, transport and dispensing of the fuel. For each step in the chain there is a considerable variety of technologies, making the diversity of different possible fuel chains quite wide. The technology options available for each stage in the chains differ in technical, economic and environmental characteristics. Apart from these characteristics, they also vary in terms of current status and potential. Some technologies are mature and widely used, others are still at the development stage and others are in the transition from a proven technology to one in widespread use.

The focus of this study is on the exploration of the fundamental questions surrounding the development of a renewable hydrogen infrastructure such as, which and where are the available renewable energy resources that can be used as a primary energy feedstock. Or, is it more economical to start with large centralised production plants or small forecourt production facilities? Are storage and transport of hydrogen required, and if so, which technologies? In which form hydrogen is less costly to be delivered, in liquid form or as a compressed gas? How the infrastructure could be evolved to meet increasing demand?

1.2 Aim and Objectives

In recognition of the necessity for cleaner fuels and the potential of hydrogen as a candidate fuel that may assist in the amelioration of environmental quality this thesis addresses the potential for renewable hydrogen supply to urban centres in order to be used as a transport fuel and thus free the transport system from carbon based fuels and their ensuing repercussions.

The central aim of this study is the development of a methodology to examine various fuel chains options in order to determine the least-cost renewable hydrogen infrastructure development plan. Being more specific, the thesis aims to assess the performance of diverse pathways involving the primary energy feedstock production, the hydrogen production, storage, and distribution technologies in terms of both economic and technical criteria. Moreover, given that market conditions, such as hydrogen demand, energy prices, GHG mitigation legislation, are expected to change in the future it accommodates the evolution of the infrastructure development over time. Emphasis is placed on the generality of the developed methodology in order to constitute a generic framework for modelling the variety of possible fuel chains for establishing a hydrogen infrastructure that could be readily extended to different conditions and geographical areas.

The main objectives that deliver this aim can be summarised as follows:

- To assess the modelling approach of previous relevant studies aiming to identifying their strengths and weaknesses;
- To determine the renewable energy resources that are available and suitable for the production of hydrogen fuel;
- To examine the technical and economic characteristics of hydrogen production technologies;
- To develop various possible fuel chains for hydrogen fuel;
- To review the current status of technology for each component of the fuel chains;
- To take into account the evolution of the supply options in time, meeting hydrogen demand;
- To develop an algorithm able to model the development of a hydrogen fuel infrastructure;
- To apply the algorithm to the case of London, determining for its specific conditions the least-cost renewable hydrogen infrastructure development plan, demonstrating the merits of the approach.

1.3 Methodology, Scope and Limitations

The modelling approach of this study is a combination of different technological fields. The model has been designed using XML, image processing and Mixed Integer Linear Programming (MILP) and has been developed in MATLAB.

The issue of the infrastructure development is mathematically formulated as a MILP problem. A linear programming (LP) problem in which all the variables are constrained to take integer numbers is known as integer linear programming problem. In this study some variables were restricted to be integers and thus made the problem MILP problem. MILP models have the advantage of being more realistic than LP models. However, they have the disadvantage of being much harder to solve. As in MILP the variables can take the values 0 or 1, a MILP model may well support logical operations, such as decisions on the expansion or shut-down of production facilities. Because of this feature of MILP, the model is able to combine the different options. This combination is an essential ingredient for the building up of the infrastructure. In modelling the planning and designing of an infrastructure a number of fixed costs at certain stages of the process have to be taken into account. MILP can support the inclusion of start up or fixed costs, making this another reason that justifies MILP as the preferred method to deal with the present problem. Moreover, the application of MILP incorporates dynamic systems and thus is used in this problem which is of dynamic behaviour.

The assessment and comparison of different fuel chains is conducted using the Optimisation Toolbox from MATLAB. Presenting the results as they returned from MATLAB is unlikely to be understood other than being the developer of the model. For this reason, the creation of a graphical user interface (GUI) is necessary. Although various packages of software offer the possibility of creating GUIs, MATLAB is selected in order to avoid potential interconnectivity problem arising from developing the model and the GUI in different software. GUI is produced by using GUIDE, which is the MATLAB graphical user interface development environment.

The GUI is the chosen way of entering data into the model. It is the mode of interaction between the user and the model. It passes the input data to the model and after the simulation shows the results. The data of the desired renewable hydrogen infrastructure development under study that enter into the model involve the formation of the fuel chains, which includes the selection of technologies for all the stages in a fuel chain; the choice of the geographical region under study; the choice of demand centres and the setting of the technical and economic values of all the parameters.

The data entered into the GUI pass to the model through an XML file. More specifically, when the input data are imported, an XML file is produced and it passes the data into the model. XML, which stands for Extensible Markup Language, is a markup language that was designed to describe data and to concentrate on what data are. In other words, it can structure, store and send information. The XML technology has a wide range of uses, such as exchanging data between incompatible systems or using plain text files for sharing data, or creating new languages like WAP and WML (XML, 2005). In this study it is used for storing and carrying data.

The case study undertaken is intended to demonstrate the suitability of the modelling approach adopted. It comprises a large-scale problem in order to show the capability of the model to support a complex and large-scale problem. The choice of London as the urban centre under study is not arbitrary. London has shown particular interest in the use of hydrogen as a transportation fuel. The Mayor of London "strongly supports the development of hydrogen and fuel cell technologies in London as a means of providing low and zero-emission energy" (Joffe *et al.*, 2003). The UK capital is one of the cities that have taken early action in the uptake of hydrogen fuel and hydrogen powered vehicles (fuel cell vehicles). This interest is justified as London is one of the cities of the world where road transport considerably contributes to environmental pollution. The promotion of hydrogen as a clean fuel may well be benefited by the fact that its environmental attributes could reinforce the endeavour to tackle the increasing pollution problems. An endeavour that is inevitable considering the strict targets with regard to the reduction of greenhouse gases that the UK government has committed itself, namely 60% reduction of CO_2 emissions, with respect to 1990 emission levels, by 2050 (DTI, 2003b).

The model is also applied in a small-scale problem in order to show its correct and smooth operation. This small-scale case study is not intended to comprise a representative infrastructure development plan for the selected geographical region but to serve as a testing method that ensures the production of credible results.

It should be mentioned that the present study examines the issue of a hydrogen fuel infrastructure that includes the stages from the primary energy feedstock production point to the demand centre point. The demand centre is considered as a single point and thus the dispersion of refuelling stations within the market place is not examined. The geographical allocation of the refuelling stations is outside the scope of this thesis.

An extensive description and justification of the choice of the approaches taken in the research to achieve the objectives and aim of this thesis are presented in Chapters 3, 4 and 5.

1.4 Originality of Research

The majority of previous studies on the design of hydrogen supply chains are focused on routes for hydrogen production from non-renewable energy sources, such as steam reforming of natural gas or electrolysis using non-renewable electricity (Ogden, 1999; Schoenung, 2001; Thomas *et al.,* 1998). This general tendency is justified considering that in the near- to medium- term future hydrogen production may continue relying mainly on fossil fuels. Comparing various studies, differences among the main findings of each study can be observed. This discrepancy is mainly due to the different assumptions that have been considered in every study. Moreover, national strategies for the development of a hydrogen delivery system vary considerably from country to country because of different national constraints. There are many ways to develop a renewable hydrogen infrastructure and the best one depends on the key drivers and the location.

To date, studies of the construction of a hydrogen infrastructure include the simulation and comparison of individual pathways, which consists of the primary energy feedstocks, production, storage, distribution and dispensing of the fuel, with respect of economic, greenhouse gas emissions, and energy efficiency factors (Mann *et al.,* 1998; LBST, 2002; Simbeck and Chang, 2002; Oi and Wada, 2004). In the majority of the studies various assumptions have been made related to hydrogen demand, size of production units, distribution distance and prices of the feedstocks. Most of the projects carried out are limited in their general applicability and lay emphasis on individual pathway steady state simulation excluding the dynamics of the infrastructure over time.

Up to now, there have been limited mathematical models that describe and integrate all components of a hydrogen delivery system within a single framework. Moreover, the role of optimisation techniques in developing a hydrogen infrastructure has hardly been examined. The use of optimisation in this field would give indications of the optimal design of a renewable hydrogen infrastructure assisting in the decision making of national and international policies for the uptake of hydrogen fuel.

The hydrogen-related studies that have been reviewed constitute a useful starting point for the development of the present model. Their strengths, weaknesses, results and methodologies have been studied thoroughly in an attempt to determine the best possible approach to achieve an original and valuable contribution to the problem of the renewable hydrogen infrastructure development. The model is developed in such a way so that it can perform resource and economic optimisation, spatial and temporal distribution of resources and hydrogen facilities, and design and optimisation of a renewable hydrogen supply infrastructure, attributes that distinguish it from other studies and reinforce its original contribution.

1.5 Structure of the Thesis

This Chapter has briefly described the primary problems associated with the use of current petroleum-based fuels in the transport sector and the need for alternative fuels as they constitute the motivation of this research. The proposed alternative fuel has been introduced along with the requirement of the development a new fuel infrastructure. The aims and objectives have been presented and the methodology and its originality laid out.

The next Chapter describes hydrogen as a worthwhile-examined fuel option in an endeavour to mitigate the harmful emissions of the transport sector. The technical and economic characteristics of the components necessary to build a hydrogen transport infrastructure are discussed. Moreover, the evolving transport policy framework in the EU, the UK and London, mainly with respect to hydrogen, is reviewed. This Chapter also critically reviews various modelling works dealing with the same problem and assesses their results and approach.

Chapter three describes the development of a methodology in order to achieve the goal of the present study. The whole procedure that consists of multiple sequential steps is presented.

Chapter four describes the development of the algorithm that is used to address the options for supplying renewable hydrogen to urban centres. The structure of the algorithm is fully explained and the definition, usefulness and formation of every step of the algorithm are explicitly described. Moreover, the justification of every tool that is used to develop the algorithm is explained.

Chapter five presents the testing strategy that the hydrogen infrastructure development model is subjected to. A small-scale case study is also included as part of the testing strategy. The focus of this small-scale simulation is how the optimal decisions, the outputs, are produced from the input data, rather than on how the input data are gathered or estimated.

Chapter six marks the start of the main case study of this thesis. This Chapter begins with the selection of the urban centre under study. The description and justification of this choice are laid out. The Chapter continues with the presentation of all the specifications that are included in the simulation, such as the renewable energy resources of GB, or the hydrogen technologies, or the demand. This case study is a large-scale problem that studies the formation of a hydrogen delivery network for supplying hydrogen fuel to London.

Chapter seven includes the results of the modelling work. A sensitivity analysis is also carried out to investigate the influence of parametric variation on the outputs of the model. In addition, a policy discussion is followed indicating some of the main challenges that renewable hydrogen infrastructure developments face and how policy intervention may assist in overcoming these challenges. The modelling approach of this study is critically assessed and a number of alternative applications of the model are also discussed.

Chapter eight summarises the conclusions of this study with respect to the modelling approach, the hydrogen infrastructure development, the results of the case study and the policy considerations. Possible model refinements are discussed and areas for further work are presented.

1.6 Summary

Having introduced the main theme of this thesis and presented the motivation behind the current research, the issue that is aimed to be addressed and the methodology that has been selected in order to tackle this issue, the essential background has been formed in order to discuss the political EU and UK framework related to hydrogen, review the hydrogen and renewable electricity-generating technologies and assess a number of hydrogen fuel infrastructure modelling works in the subsequent Chapter.

CHAPTER 2

Policy Framework, Renewable Energy Sources and Hydrogen Technologies

2.1 Aims and Scope of Review

In this Chapter, the main theme of the thesis is introduced. Hydrogen is presented as a worthwhile-examined fuel option in an endeavour to mitigate the harmful emissions of the transport sector. The technical and economic characteristics of the components necessary to build a hydrogen transport infrastructure are discussed. The discussion includes a review of the different stages in the "life" of the fuel, that is the production, conversion, storage and transport. Moreover, the evolving transport policy framework in the EU, the UK and London, mainly with respect to hydrogen, is reviewed.

As this thesis focuses on the supply of a clean, zero-emission fuel, the review includes only renewable energy sources as feedstock material for the production of hydrogen. A range of renewable technologies is assessed, with focus on the cost, performance, current status, strengths and weaknesses. The technologies of all the stages of the fuel chain are explored, with particular attention given to the technologies that have passed the proof-of-technology stage and mature, although not yet in widespread use.

This Chapter also describes the modelling work that has been carried out addressing the issue of a hydrogen supply network. Various models are reviewed aimed at exploring the different approaches that have followed and the questions that have addressed. Moreover, the assessment of the results and conclusions and the extent of their agreement are discussed.

2.2 Hydrogen as a Transport Fuel

2.2.1 The Need for Cleaner Fuel

Modern societies depend on the use of large quantities of energy, most of it in the form of fossil fuels. After the two oil crises during the 1970-1980 decade, the price rises and the uncertainty of security of supply compelled the governments of many industrialised nations to reassess energy policy in order to reduce the reliance on oil from the Persian Gulf, one of the most politically volatile regions of the world (Bockris, 1999). Phenomena like the greenhouse effect, the ozone layer depletion and the acid rains indicate the immediate need for the use of cleaner fuels and end-use technologies. In 2003, the world's primary energy consumption increased with Asia Pacific being on the front line of this growth with 6.3%; while North America had the weakest increase that of 0.2% (BP, 2004). In a world of growing appetite for energy, the continuation of the reliance on fossil fuels will amplify the environmental, political and resource concerns of their use.

Almost 60% of oil consumption in OECD countries is used in the transport sector (IEA, 2004). In EU, this sector accounts for 31% of the total energy usage, while 98% of it uses petroleum-based fuel (Bellona, 2003). Transportation is the greatest source of noise and local air pollution and one of the major contributors to carbon dioxide, which is the predominant greenhouse gas. Worldwide it is responsible for about 25-35% of CO_2 emissions (MacLean and Lave, 2003). On environmental grounds, this picture is getting worse as most of the future growth in energy is expected to take place in transportation (Dunn, 2002). Realizing the remarkable impact of the transport sector on the environment makes the decarbonisation of this sector an imperative need for the amelioration of the environmental quality. For this reason, new and environmentally benign alternative fuels to the use of petrol and diesel are necessary to be introduced in the transport sector.

2.2.2 Hydrogen as a Candidate Fuel

A number of alternatives to current fuels have been studied such as methanol, ethanol, methane and synthetic liquids from coal and natural gas and hydrogen. Among these, hydrogen is of keen interest and perhaps the most promising option because it holds the promise of reducing the dependency on fossil fuels, delivering deep cuts in greenhouse gas emissions and other air pollutants and improving the energy security simultaneously.

The attractiveness of hydrogen is based on its unique properties. It can be produced from and converted into electricity at fairly high efficiencies. The raw material for its production is water, which is abundant. So, it is a renewable fuel as the product of its utilization is pure water or water vapor. It can be stored in gaseous form, liquid form or in the form of metal hydrides. It can be transported over large distances through pipelines or via tankers. It can be converted into other forms of energy more efficiently than any other fuel. Apart from flame combustion, it may be converted through electro-chemical conversion, catalytic combustion and hydriding. When fossil fuels are burned, they release significant quantities of carbon dioxide into the atmosphere with coal having the highest carbon content, then petroleum and lastly natural gas. On the contrary, hydrogen's production, storage, transportation and use do not produce any pollutants, greenhouse gases or any other harmful effects on the environment (expect from small amounts of NO_x when hydrogen is burned with air at high temperatures) (Veziroglu and Barbir, 1998).

Moreover, it can be used in both modified internal combustion engine and fuel cell vehicles without the emission of carbon dioxide, carbon monoxide, sulphur dioxide and particulates (Veziroglu, 1995). It can be derived from a wide range of sources from fossil up to renewable energy sources by a number of different routes. The flexibility in its production may assist in the gradual switch of the transport sector from fossil fuels to renewable fuels. As hydrogen during combustion is almost free of polluting emittents, its environmental benefits strongly depend on the way of production. Thus, the energy used to obtain hydrogen is the factor that determines whether hydrogen is clean or dirty.

As hydrogen produced from fossil fuels eliminates most of the benefits offered by hydrogen, the candidate fuel that may be considered as the most attractive option is hydrogen produced from renewable energy sources. Renewable hydrogen is not only a fuel that does not emit anything when used in fuel cell vehicles but also an alternative that offers an emission free production process and can alleviate the overdependence on geographically restricted energy sources. This promising candidate transport fuel is the fuel under study in this thesis that determines the least cost plan for the supply of this attractive alternative.

2.2.3 Hydrogen Properties

Hydrogen is the simplest, lightest and most abundant element in the universe. Due to its high reactivity it is very rare to find elemental hydrogen in nature. Hydrogen gas usually exists only in the molecular state, H_2. However, most of it is in the form of chemical compounds with other elements. It can be found in combination with oxygen in water (H_2O), with carbon in various hydrocarbon fuels (C_XH_Y), plants, animals and other forms of life. It is an odourless, tasteless and colourless gas. It has the highest energy to weight ratio of all fuels, namely its specific energy is around 33 kWh/kg, almost three times higher than gasoline and twice than natural gas (EURO-ISLAS, 2002). Some important properties of hydrogen are shown in table 2.1.

Property	Value	Unit
Molecular Weight	2.016	
Density	0.0838	kg/m^3
Higher Heating Value	141.90 11.89	MJ/kg MJ/m^3
Lower Heating Value	119.90 10.05	MJ/kg MJ/m^3
Boiling Temperature	20.3	K
Density as Liquid	70.8	kg/m^3
Critical Point Temperature Pressure Density	 32.94 12.84 31.40	 K bar kg/m^3
Self - Ignition Temperature	858	K
Ignition Limits in Air	4-75	(vol. %)
Stoichiometric Mixture in Air	29.53	(vol. %)
Flame Temperature in Air	2,318	K
Diffusion Coefficient	0.61	cm^2/s
Specific Heat (cp)	14.89	kJ/(kgK)

Table 2.1: Properties of hydrogen

As hydrogen cannot be found freely in nature, it must be produced. Since a considerable energy is consumed in the extraction process, the energy released when it is used is the energy that was invested in its original manufacture (minus any losses). Thus, hydrogen should properly be considered as an energy carrier – secondary form of energy- and not as an energy source. When it is extracted, it becomes a valuable feedstock to several industrial activities and in the near future a widespread fuel adequate to energize all aspects of society, from homes to electric utilities to business and industry to transportation.

Today, hydrogen is used worldwide mainly as a chemical commodity in industrial processes and rarely as a fuel for stationary or transport applications. However, as a fuel it has principally been used to propel spacecrafts and supply on-board power during space missions.

Energy carriers like electricity and hydrogen increasingly dominate the final-energy mix. The latter due to the efficient end-use technologies increases its share considerably, accounting for almost 49% of the global final consumption by the end of the 21st century, becoming the main final energy carrier (Barreto *et al.*, 2002). This speculation can become reality with intensive R&D programmes and deployment strategies aiming for further cost reductions on hydrogen technologies resulting in their wider diffusion.

2.3 Policy Framework

Throughout the world there has been a huge growth of interest in the potential for hydrogen to become an important alternative energy carrier. At present, the transition from current fuels to hydrogen fuel is hindered by a number of techno-economic barriers that make the introduction of a new fuel to the transport sector a matter of several decades.

In previous years changes in transport fuels have been driven by the fact that they provided private benefits, such as greater mobility, so that investment in them proved worthwhile to private firms and individuals. Because hydrogen has a few private benefits compared to current fuels, widespread use will require either radically different market conditions or new policies.

As the introduction of hydrogen is probably a dramatic change to the current energy system, Governments should play a catalytic role in its uptake especially at the beginning. Governments should provide policies to support its development by ensuring the simulation of hydrogen fuel cell vehicle market and the development of hydrogen refuelling infrastructure simultaneously. This section describes policy measures and initiatives that, directly or indirectly, could favour the adoption of hydrogen.

2.3.1 Policies and Initiatives to Favour the Move to Hydrogen as a Transport Fuel

Hydrogen is not a new concept. It has been developed significantly in the world for more than thirty years (Veziroglu, 2000; Momirlan and Veziroglu, 2002). In the USA, the "Strategic Plan for Hydrogen Program" was launched in 1979, aiming at promoting hydrogen as a cost-effective energy carrier for transportation, buildings and utilities (Chen *et al.*, 2005). More recently, the Department of Energy's Office of Fossil Energy develops the "Vision 21 Program", which is a concept that envisions a virtually pollution-free power plant. The aim of this program is the development of a wide range of technologies that can be interconnected and produce products that have near-zero emissions by 2015. Hydrogen fuel is among the multiple products (US DOE, 2006). In 2002, the Department of Energy in USA presented the "National Vision of America's Transition to a Hydrogen Economy", which described where and how the transition to the hydrogen economy will be achieved by the year 2030 and beyond (US DOE, 2006a). In 2003, President Bush announced a $1.2 billion initiative to develop the hydrogen production and delivery technologies and fuel cell vehicles in order to provide a reduced or near-zero emission transportation and energy system (US DOE, 2006b). Combined with the FreedomCAR (Cooperative Automotive Research) initiative, President Bush is proposing a total of $1.7 billion over the next five years to develop hydrogen-powered fuel cells, hydrogen infrastructure and advanced automotive technologies (FreedomCar Partnership Plan, 2002).

Apart from the USA, another country that has a leading role in the hydrogen and fuel cell research is Japan. Japan has vigorously conducted research and development on various kinds of new energies. In 1993, the New Energy and Industrial Technology Development Organisation established a joint industry-government-academia effort, the WE-NET project, to research and develop hydrogen energy technologies aiming at achieving a hydrogen economy by the year 2030. The WE-NET project is divided into three stages up to the year 2020 with a total funding of $11 billion (WE-NET, 2005). Japan, which has a target of 50,000 fuel-cell vehicles on Japanese roads in 2010, aims to raise the number of such vehicles in use to 5 million by 2020 (Jama, 2003). The Japanese Government has adopted a comprehensive strategy including R&D, demonstration programmes and market support guided by long-term strategic plans. In 2002, the Ministry of Economy, Trade and Industry organized the Japan Hydrogen &Fuel Cell Demonstration Project that involves a wide range of activities related to the use of fuel cell vehicles (JHFC, 2002).

In 2003, the International Partnership for the Hydrogen Economy was launched aiming to provide an international institution to accelerate the arrival of hydrogen economy. The Partnership has 17 members and offers a significant programme focusing on international research, development and demonstration projects of hydrogen and fuel cell technologies (IPHE, 2003). On an international level, an interesting programme for hydrogen development throughout the world was the Euro-Quebec Hydro-Hydrogen Project that promoted the transport of large quantities of liquid hydrogen by sea. Due to the huge estimated cost for this venture (around 800 Mio Euro) both the European Commission and the Government of Quebec did not agree on funding the investment. However, it was decided to continue the project aiming to offer a platform for demonstrations of hydrogen applications (EQHHPP, 1994).

A worth mentioning organization that funds demonstration projects in developing countries that protect the environment is the Global Environment Facility (GEF). GEF grants projects in six focal areas: biodiversity, climate change, international waters, ozone depletion, land degradation and persistent organic pollutants. The GEF climate change projects are divided into four areas, one of which is the support of the development of sustainable transport. Under this area, GEF funds programs on fuel cell buses and related infrastructure in Sao Paulo, Mexico City, Beijing and Shanghai, Cairo and New Delhi. The total fund of these programs is $59.6 million, of which $36 million have already been approved. Currently, the demonstration activities have started in Sao Paolo, Mexico City, Beijing and Shanghai (GEF, 2004).

On European level, research on hydrogen is still under-funded and lagging behind the programs of the USA and Japan. Characteristically, at the 2nd European Hydrogen Energy Conference in 2005, representatives of Japan, USA and EU presented their policy framework and the former was first concerning the funding on research on hydrogen with $3 billions, the latter was last with $1.8 billions, while the USA was in the middle with $2.7 billions (EHEC, 2005). As London is the city that has been selected for the case study of this thesis the policy framework of the UK and London is described in more detailed in the following sections. However, since the European Union is increasingly driving the policies of the Member States in a wide range of sectors it is worth briefly mentioning the European policy as well.

2.3.2 Policy in EU

Energy security, air quality, greenhouse gas emissions and economic competitiveness are key drivers for Europe's energy research. The European Commission aiming to bring industry, the research community and government together in order to provide a sustainable energy system to its citizens, has developed several strategies, policies and proposals (EC, 1997; EC, 2000; EC, 2001; EC, 2001a). Hydrogen has been considered as an energy carrier that has the potential to simultaneously address all major energy and environmental challenges. For this reason, the European Commission launched in 2002 the High Level Group for Hydrogen and Fuel Cells Technologies aiming at accelerating the development of these technologies and their contribution to a sustainable European future energy system. To reinforce its commitment to hydrogen, Europe established in 2004 the European Hydrogen and Fuel Cell Technology Platform in order to "assist in the stimulation and efficient coordination of European, national, regional and local research, development and deployment programmes and initiatives, to ensure a balanced and active participation of the major stakeholders and to promote awareness and understanding of fuel cells and hydrogen market opportunities and foster deeper co-operation, both within the EU and at global scale" (EC, 2002).

In order for Europe to reap the benefits of hydrogen, it has realized the necessary existence of a consistent political framework between the European Union and the national governments of member states (EC, 2002). The European impetus to hydrogen includes the coordination of strong policy measures in support of the technology, research and development such as fiscal, financial and regulatory support for projects, review and removal of regulatory barriers to commercialisation, international coordination of policy development and deployment strategies and review and development of codes and standards to support commercial development (Chen *et al.*, 2005).

The European scientific effort focuses on addressing non-technical and socioeconomic issues and solving the remaining technical obstacles to the uptake of hydrogen. More specifically, the attention is given on overcoming the technical challenges of the processes included in the fuel chain and decreasing the costs of all these processes. Moreover, on the techno-economic, environmental and socio-economic analyses of different transition pathways and the continuous improvement of a European hydrogen roadmap based on targets and criteria derived from the ongoing research results (Chen *et al.*, 2005).

The introduction of hydrogen and the development of a new refuelling infrastructure is a venture that requires large capital investments. Funding is necessary for research, technological development and demonstrations. The main European funding mechanism is the Framework Programme (FP) which is principally implemented through calls for proposals (EC, 2002). The EU support to hydrogen and fuel cell initiated in 1986 within the 2nd Framework Programme (1986-1990) and since then the Framework Programmes have played a lead role in hydrogen and fuel cell research and cooperative activities in Europe. From 1986 to 2007 a lot of progress has been made and most importantly the European Commission has gradually reinforced its commitment to hydrogen. This is evident first of all from the continuously increasing budget that EC allocates for such programmes. The EC contribution on hydrogen and fuel cells research from €8 million in the 2nd Framework Programme has increased to €53.2 billion within the latest Framework Programme. The latter is the 7th Framework Programme that spans over seven years (2007-2013) and has the largest budget so far (EC, 2006; EC, 2007).

The 7th Framework Programme has started this year and is the natural successor to the 6th Framework Programme. The latter was intended to be used for a set of new instruments designed to focus, integrate research and create a true "European Research Area" resulting in an internal market for knowledge and new technologies (EC, 2002). This Programme has funded several projects on various aspects of hydrogen such as production, storage, safety, regulations, codes and standards, pathways and end-use (Hyways, Hysafe, NaturalHy, Solar-H, StorHy). The outcome of years of research and technological development of earlier Framework Programmes constitutes the backbone of the 7th Framework

Programme. The latter aims to support the collaboration of trans-national projects, to introduce longer term public private partnerships reinforcing industrial technological development, to strengthen the European research and to achieve the integration of a European research at local, regional, national and international level (EC, 2007).

The main differences of the 7th Framework Programme to earlier programmes, apart from the apparent and aforementioned budget difference, include the European Research Council, an agency that intends to finance more high-risk projects, a new Risk-sharing finance, a facility mainly aiming to improve backing for private investors in projects, the Joint Technology Initiatives, a novel concept that aims to provide an alternative approach for goals that cannot be achieved through the "Call for Proposals" method (EC, 2007).

2.3.3 Policy in UK

As in most developed countries around the world, in the UK hydrogen has been seen as good long term fuel option to substitute diesel and petrol in the transport sector. The UK even though is not considered as a leader in the hydrogen area, has identified hydrogen in many of its strategies as the future transportation fuel in the long term (EST, 2002; PFV, 2002). There are a growing number of UK companies and research institutions focusing on different aspects of hydrogen area.

However, due to rising concerns over the environmental repercussions of transport, several possibilities for future vehicles like electric and hybrid, and low carbon fuels such as liquefied petroleum gas and biofuels, have been examined. These possibilities may play a major role in the transition from today's fuels to hydrogen fuel. More specifically, the Government's effort to reduce UK emissions, as highlighted in the Energy White Paper "Our energy future – creating a low carbon economy", aims at a target of 60% reduction of carbon emissions, with respect to 1990 emission levels, by 2050 (DTI, 2003b). As about 25% of those emissions are at the moment generated by road transport, it is clear that in order to meet the target a shift towards low-carbon transport is needed as well.

The measures to achieve such shift are set out by the Powering Future Vehicles strategy, where hydrogen fuelled vehicles are regarded as one of the main options. The main objectives of this strategy are the promotion of the development and deployment of new vehicle technologies and fuels and the encouragement of involvement of the UK automotive industry in the new technologies. Two very important commitments within this strategy are the target of achieving the 10% of the new car sales to be low-carbon vehicles in the next decade and to increase the number of low carbon buses. Beyond 2010, the focus will be on the implementation of the shift towards technologies such as hydrogen fuel cells (PFV, 2002). An important development originating from this strategy is the setting up of the UK Low Carbon Vehicle Partnership in 2003. This is an action and advisory group that brings together the vehicle and fuel industries, to encourage their engagement in the shift to low carbon transport (Low CVP, 2003).

In 2003, the UK-SHEC is established as part of the EPSRC SUPERGEN programme involving eight leading UK universities and research centres and the Greater London Authority (McDowall and Eames, 2004). The goals of this initiative were the knowledge and understanding of hydrogen systems and to guide and inform the use and integration of sustainable hydrogen energy systems. In July 2007, this four-year initiative was renewed until 2011 forming a proposal that is divided into two parts, the CORE and the PLUS. The priorities of this proposal involve storage technologies, sustainable methods of hydrogen generation and the feasibility and acceptability of sustainable hydrogen energy through a range of key socio-economic projects (EPSRC, 2007).

The UK Department of Trade and Industry has developed its Hydrogen energy strategy since 2003. In 2004, it published a report which intended to form a strategic framework for hydrogen energy in the UK (DTI, 2004). The main outcome of this report is that the use of hydrogen as a transport fuel offers a cost-competitive option that may assist in reaching the CO_2 emission reduction target. The report examined six different pathways for hydrogen supply and found them adequate to meet UK's target. However, this requires significant changes to the energy system (DTI, 2004).

In 2005, the UK Government issued a response to the strategic framework showing its intentions for the future of hydrogen in UK. The Government supports the idea of establishing a Hydrogen Co-ordination Unit necessary for hydrogen activities and a Hydrogen Energy Industry Association in UK. It realizes the importance of R&D, demonstration, commercialisation and demand simulation and aims to support them mainly through research councils, the DTI Technology Programme and appropriate policy measures. It is committed with a budget of around £15 million over 4 years for demonstrations of hydrogen and fuel cell technologies (DTI, 2004).

2.3.4 Policy in London

London has shown particular interest in the use of hydrogen as a transportation fuel. This interest is justified as London is one of the cities of the world where road transport considerably contributes to environmental pollution. The promotion of hydrogen as a clean fuel may well be benefited by the fact that its environmental attributes could reinforce the endeavour to tackle the increasing pollution problems. The Mayor of London "strongly supports the development of hydrogen and fuel cell technologies in London as a means of providing low and zero-emission energy" (Joffe *et al.*, 2004). For this reason, Research Councils have funded a number of projects aiming to assist the progression of hydrogen technologies and evolution of hydrogen refuelling infrastructure.

The UK capital is one of the cities that have taken early action in the uptake of hydrogen fuel and hydrogen powered vehicles. London along with eight other European cities has taken part in the EU-funded Clean Urban Transport for Europe (CUTE) project by testing the zero-emission hydrogen fuel cell buses. The project aimed to demonstrate the feasibility of an innovative, high energy efficient, clean urban public transport system. This public transport system intended to reduce overall CO2 emissions, thus contribute to the Kyoto commitments of the EU Member States, as well as eliminate local NOx, SO2 and PM10 emissions, with the result of improving health and living conditions in urban areas (Jones, 2002).

After the successful completion of this project the partners decided to join forces with Canada and buy environmentally friendly hydrogen-powered buses. Europe supports this alliance and sees it as a means of making the hydrogen fuel cell bus a commercially viable technology. London is one of the cities that have signed a Memorandum of Understanding in Brussels along with Amsterdam, Barcelona, Berlin, British Columbia Province and Hamburg (Fuel Cell Works, 2006).

Besides that, the Mayor's Draft Energy Strategy clearly indicates the Mayor's will to implement a hydrogen economy in London, with the construction of a hydrogen energy infrastructure and widespread use of hydrogen fuel cells both for transport and for stationary applications (GLA, 2003). In order to achieve this, the London Hydrogen Partnership has been set up in April 2002, which aims to unify the powers of industry, academia, national and local Government and NGOs to facilitate the use of hydrogen as a clean fuel in London. The Partnership is working on a London Hydrogen Action Plan, which is currently in its second draft, and aims to deliver the hydrogen economy (GLA, 2002).

Based on the deployment of fuel cell buses, London had taken part in the Public Acceptance of Hydrogen Transport Technologies project (ACCEPTH$_2$) (ACCEPTH$_2$, 2005). This project had been considered as a means of contributing towards the objectives of introducing hydrogen and fuel cell vehicles into the market. The aim of the project was to assess the economic preferences towards the potential use of hydrogen fuel cell buses by conducting an economic evaluation studies within five cities (Altmann *et al.*, 2004). According to the results of this study, people are generally positive towards fuel cell buses and feel safe with the technology while newspapers and bus stops are where most people get information about the buses. The drivers are generally positive to the fuel cell bus project whereas passengers above the age of 40 desire more information about the new technologies. However, although the environment is rated as an important factor, 64% of the bus passengers were not willing to pay a higher fee if more fuel cell buses were to be used (Altmann *et al.*, 2004; Haraldsson *et al.*, 2005).

In February 2006, London's Mayor reinforced its commitment to hydrogen by announcing his aim of introducing 70 new hydrogen vehicles to London by 2010 (LHP 2006). This initiative aims to deploy up to 70 hydrogen cars, vans, motorbikes, buses and other vehicle types both of internal combustion engine and fuel cell technologies from a range of suppliers. The vehicles will be operated by public sector fleets and a hydrogen refuelling infrastructures will be established within the city (LHP, 2006).

2.4 Renewable Energy Sources

In this study, renewable energy sources are considered the primary energy feedstock for the production of hydrogen fuel. This section presents a brief description of the resource, economics and technical maturity of the electricity-generating (or hydrogen-generating in the case of biomass) technologies for each renewable energy source. The technical and economic data of this section have been used to understand the range of technologies and issues with them to be able to design a model to capture their characteristics.

Energy sources that rely on the natural flows in the environment like the wind, the sunlight, the waves and the tides have the benefit of renewability. The amount of solar energy incident on the earth and the resultant natural energy flows are an infinite resource with the solar radiation input alone being around 90,000 TW (Elliott, 1998). The magnitude of such a number can more likely be realized considering that the earth receives yearly an amount of solar energy that is approximately equal to 15,000 times the annual energy consumption of the world (Kruse *et al.*, 2002). These figures indicate that theoretically the renewable energy resource has an enormous potential.

In practice not all of this resource can be effectively captured and used. Most of it is diffuse, some is intermittent and the location of the source has to be taken into consideration. However, the issue is not of the availability of the resource, but of the efficiency of converting it to forms suitable for human use. A number of studies have been carried out evaluating the total amount of renewable energy available for extraction (Boyle, 2000; DTI, 1998; Sorensen *et al.*, 2004). This is the maximum theoretical potential that may be orders of magnitude greater than the practicable potential which is the amount of the resource that is technically possible to be used taking into account various technical and physical constraints such as geography, intermittency, electricity grid. Other limiting factors that amplify the difference between the theoretical and the practicable potential are planning, social and economic constraints. The economic viability of the resource depends on the state of the renewable energy technologies and the relative costs of alternative energy sources. Many constraints may change over time with the advancement of technologies. As costs decrease in line with accumulation of experience, the technological progress in conjunction with the political support especially to new areas of technology, may accelerate the rate of the development and deployment of renewable energy technologies (Chapman and Gross, 2003).

Technologies that generate electricity from renewable energy sources differ widely in costs, environmental impacts and resource availability. Some of the renewable technologies are widely used and technologically mature, while others are at development stage. The costs of renewable hydrogen production depend on the costs of electricity generated from renewable energy sources that are determined by the state of the technologies and the market trends and thus change in the course of time.

2.4.1 Wind Energy

Wind energy is the fastest growing energy source. By the end of December 2006, its worldwide installed capacity has been increased to over 73GW (WWEA, 2007). As wind power has boomed significantly, likewise its technology has been greatly developed. There has been a gradual growth in the size of the wind turbines. Current turbines' size ranges between 660kW and 3MW (Vestas, 2004), while larger turbines of up to 5MW are being tested. Generally, technical improvements have facilitated the integration of the wind turbines with the power transmission grid that is important for a higher penetration (Komor, 2004).

The world's wind resources are huge and distributed over almost all regions and countries. The global wind resources are estimated to be 53,000TWh/year, while its electricity consumption growth is forecasted to be around 25,578TWh/year by 2020. Several studies have shown that the European onshore wind resource could provide 5 to 10% of Europe's electricity consumption (EWEA, 2003). Argentina's Patagonia district has such a large wind energy resource that can produce enough hydrogen to replace all oil production in the world (Kruse *et al.*, 2002). In North

America, USA have states with excellent wind resources and if included the sites with average wind resource then forty five out of fifty states can be considered appropriate to support wind turbines. China is another country with enormous wind resource especially in the northern and western regions and along the coast (Vestas, 2004a).

Generally, the sites that are considered appropriate for the construction of wind parks are these with average wind speeds around 8-10m/s. However, as the power in the wind is proportional to the cube of the wind speed, sites with fairly good average wind speeds (5-6.5m/s) can also be used for wind parks. Although this wind speed range increases the wind resource, there are practical and economic constraints that reduce the total resource. The constraints of this renewable energy source include high population areas, forests, difficult terrain, inaccessible mountain areas or far from the transmission lines, visual and noise impacts (WEA, 2001).

Putting the turbines offshore eliminates some of these constraints and also has the advantage that offshore wind speeds are higher than on land. Resources offshore are much larger than those onshore, but have to be close to electric infrastructure in order to be attractive. Several locations worldwide are well endowed with offshore wind energy resources like Europe where especially its Northern part, has a remarkable offshore resource.

The economics of wind energy rely on the costs of wind technology and of alternative options. Current wind turbine's cost is estimated to be US$650-&700 per kW. The cost of electricity generated by wind power is to some extent site and project dependent. For a good wind speed onshore site the cost of electricity amounts to 4-5 US cents per kWh, making it the cheapest of all generating technologies.

Electricity from onshore wind parks is still cheaper than from offshore installations. Energy from offshore wind farms is more expensive due to the extra costs of civil engineering for substructure, higher transmission cables costs, expensive materials to resist the corrosive marine environment and harder access for service and maintenance (Komor, 2004).

Wind energy has a promising future as it combines electricity production at relatively low costs and environmentally benign and mature technologies. The wind resource both onshore and offshore is enormous and even though it is limited by various constraints such as difficult terrain, inaccessible mountain areas or far from the transmission lines, visual and noise impacts, the lack of the resource is unlikely going to be a barrier to the exploitation of wind power.

As wind energy is now commercial, realistic and even a profitable electricity generation option, it is rational to expect that in the near future the electricity required for the production of hydrogen will be mainly wind based electricity. In the short term, wind energy due to its sufficient capacity could assist the uptake of hydrogen fuel by providing an amount of the total electricity produced to the production of hydrogen. At present, many of the other renewable energy sources do not have sufficient capacities and have already contracts in place for the sale of the electricity they generate. Consequently, wind energy is an important renewable energy source because it may well support hydrogen fuel at the very outset of its introduction.

2.4.2 Solar Energy

Solar energy can be converted directly into electricity in solid-state devices known as photovoltaics (PVs). PVs have many attractive features as they are quiet, have no moving parts, no waste products, are flexible in size and can be installed quite quickly. There are two main types of PV modules, the crystalline silicon and the thin film. At present, the conversion efficiency of a PV power system is around 12-14% for silicon modules and 7-10% for thin film technology (Komor, 2004). Taking into consideration these efficiencies and today's energy consumption that means that large areas are needed to trap and convert considerable amount of solar irradiance to meet energy needs.

PVs can be used to produce electricity as grid-connected systems (usually in densely populated countries) stand alone systems (in rural regions) and when they are integrated into building materials. Another way to generate electricity from solar energy is solar thermal systems. These systems can be utilized to produce electricity by first producing solar heat to drive a heat engine, which then provides mechanical work to drive an electrical generator. There are various solar thermal electricity technologies like power towers, solar ponds, solar chimney available, each with distinct characteristics and at different technological stage. Among them, the parabolic through concentrator system are the one that rivals the best commercially available PV systems (WEA, 2001).

Solar resource is huge and is available at any location on the surface of the Earth. The amount of solar irradiance at a certain place depends on the daily and seasonal variations. Solar insolation also depends on latitude. Places near the equator receive more solar radiation than subpolar regions. The variation of solar energy depending on the geographic location is quite noteworthy. In northern Scandinavia and Canada the annual solar power density is approximately 800kWh/m^2, while in some dry desert areas near the equator can be 2,500kWh/m^2 (WEA, 2001).

Currently, there are numerous solar panel systems installed worldwide. Many countries have set targets and programs for the development and deployment of PVs. In the European Union, the aim for PVs is to install a 3GW capacity until 2010. The Million Roofs program intends to install 500,000 grid-connected PV systems on roofs and facades and to export 500,000 village systems for decentralised electrification in developing countries (EC, 1999).

The cost of generating electricity through a PV system varies widely. This variation results from its dependence on a number of factors. The most important of them is the cost of the PV-based electricity system. The cost of a complete electricity generating PV system includes not only the cost of the PV module but the cost of all the system components like inverters and transformers, the electrical installations costs and costs associated with building integration, site preparation. Although the initial costs of PV systems are high, the operating costs should be quite moderate in comparison with other renewable or non-renewable energy systems. The size and the type of the components also affect the economics of the system. From country to country the electricity price differs. Generally, the higher the solar insolation level, the lower the per-kilowatt-hour cost. Nowadays, a representative PV-sourced electricity cost is around 20-40 US cents per kWh (Komor, 2004).

Despite the high costs of PV systems, world's PV production continues to grow. Improvements in the technologies of the PV modules and all the components included in a PV based electricity systems will allow a more efficient operation of the system. Increased production coupled with technical progress will enable reductions in costs. At the moment and for the next decade, the cost of PV electricity cannot compete with the fossil fuel electricity cost.

Considering the large world's solar resource, it is apparent that the share of solar energy to global energy supplies scheme will not be restricted by resource availability. Of all the renewable energy forms, PVs have the advantage of being the least resource-constrained. PVs can operate anywhere the sun shines. The extent to which solar energy will be used in the long term is determined by the availability of efficient and cost-competitive sun-to-electricity conversion technologies.

The cost of PV electricity is now well above that of conventional electricity and this is unlikely to change in the next decade. It is uncertain whether and when the PVs will compete with the fossil fuels on a large scale but the costs are dropping and this trend is likely to continue as technologies advance.

2.4.3 Wave Energy

Compared with wind and solar energy, wave power is still in its infancy, with only a few prototype systems actually working. Wave energy devices that can convert the energy from waves into electricity can be categorized as shoreline devices, near shoreline devices and offshore or deep water devices. There are numerous suggestions for the exploitation of wave energy, but the question of which is the best wave energy conversion device still remains open. At present, the most popular is the oscillating water column that can be sited at the shoreline. The wave-based electricity depends on the size of the waves and thus on the distance of the conversion device's location from the shoreline (WEA, 2001).

The worldwide wave energy resource is huge. Apart from being large, it is also quite dependable. While solar and wind energy availability is around 20-30%, wave energy's availability can be up to 90% (Fujita and Pelc, 2002). Studies assessing this resource have estimated that the global resource is around 8,000-80,000 TWh/year (BWEA, 2005). The greatest areas for the exploitation of wave power are at the temperature latitudes between 40^0 and 60^0 north and south on the eastern boundaries of oceans, where strong winds occur. UK is one of the countries with remarkable wave climate, particularly the north part of Scotland. In Europe, apart from the UK, Ireland, Norway, Portugal and Spain have also energetic wave climates. In the USA, the Pacific northwest coast may offer a satisfactory resource of wave energy. Globally, wave power has the potential to supply around 2TW of electricity (Fujita and Pelc, 2002).

Like many other renewable energy technologies, wave energy's capital costs are high. Although the amount of electricity from shoreline systems is relatively small, the costs are lower than those for offshore systems. The electricity from wave energy plants is not yet competitive with fossil fuel based electricity. Further technological developments are required to sink the costs in order to enable wave power to fulfil its promise. Currently, costs are projected for less than 10 US cents/kWh and optimistic companies aim to drop this to 5 US cents/kWh. If this is the case, then wave-sourced electricity may be able to compete with the electricity from fossil fuel plants (Fujita and Pelc, 2002).

Wave energy resource not only is large, but has the advantage of being more dependable than most renewable energy resources. Currently, wave power remains at an experimental stage, with only few demonstration systems operating. In order wave energy to contribute significantly to the energy requirements in the long term, it has to move further offshore into deeper water where the energy densities are higher due to larger waves. For this to become a reality, extensive refinements of the existing prototype systems and development of offshore structures are necessary.

2.4.4 Tidal Energy

Power plants that use tidal energy depend on the diurnal flow of tidal currents. Unlike wind, solar and wave power, tidal energy can provide a highly predictable output. The basic technology for electricity generation for tidal power is well developed. The rise and fall of the tides is usually exploited with the use of barrages across suitable estuaries. As there are only two tides every day a tidal barrage will not operate continuously. Instead of using expensive barrages, it is possible to harness the energy of the tides in tidal streams at suitable sites using wind turbine-like rotors (Elliott, 1998). However, this idea is far from being commercially viable with only few prototypes having been tested.

As tidal power is included in the family of renewable energy sources, shares the benefits of being an environmentally benign technology. However, tidal plants located at the mouths of estuaries cause a few environmental impacts on local marine ecosystems.

The overall world tidal resource available is estimated at 3000GW, though less than 3% is sited at regions suitable for tidal exploitation (BWEA, 2005). Clearly, tidal power availability is very site-specific. Europe has a substantial tidal energy resource that is of the order of 300TWh/year. There are numerous major sites around the world, in Canada, the UK, Russia, the USA, Argentina, China, Korea, France, India and Australia with an estimated total potential around 300TWh/year (Boyle, 2000).

Currently, there is a number of successfully operating large tidal plants like La Rance in the Brittany coast of northern France, Kislaya in Russia, Jiangxia in China and Annapolis in Canada (Fujita and Pelc, 2002). Although the major potential for tidal energy is expected form large scale plants, there are many potentially suitable sites for small and medium plants.

The economics of tidal barrages depend on their initial capital costs and their operational performance. The capital costs of barrages are significant at around £1300 per kilowatt of installed capacity (Boyle, 2000). The main factors that determine the cost-effectiveness of a tidal power site are the size (length and height) of the barrage needed and the difference in height between high and low tide. The average power output from a tidal energy plant is approximately proportional to the square of the tidal range. Naturally, even small variations in the tidal range can cause significant difference to the viability and economics of a plant. The manufacturers of most tidal energy technologies hold that the cost of electricity from tidal energy is projected around 10-14 US cents per kWh. This cost is expected to decrease to 6 US cents per kWh with the accumulation of experience and maturity of technology (Boyle, 2000).

Tidal energy has the potential to produce considerable amounts of electricity at certain sites around the world. The technology required for electricity generation from the tides is well established and increasing attention has been given to the innovative idea of the tidal stream turbine systems. Currently, the latter technology is at the prototype stage, with only small experimental devices in operation around the world. Under present conditions, tidal energy appears to be a relatively unattractive commercial investment option. However, the predictability of the tides coupled with the sizeable resource are the incentives for further development of the tidal power technologies. These factors along with expected cost reductions will establish the future role of tidal energy in the power sector scheme.

2.4.5 Hydro Energy

Unlike most of the other renewable energy forms, hydro power is already a major contributor to world energy supplies. In some countries it is the principle source of electricity. In Brazil, for example, hydroelectricity amounts to 96% of the total electricity. Hydropower is a controversial form of renewable energy sources due to the negative effects that can have to the environment, such as ecosystem changes, fish passage difficulties and damage to the shoreline of the rivers that support numerous plants and animals. Hydroelectricity is a mature technology that has been generating power at competitive prices for around a century (Boyle, 2000). As a result further improvements in the performance of the technologies are going to be modest. However, modern construction of dams seeks techniques that may minimize the ecological impacts.

Hydro energy, which depends on the natural evaporation of water by solar energy, contributes about a third of its potential to the electricity supply (WEA, 2001). Hydro practicable resource is not evenly accessible and depends on the topography and rainfall patterns of the location (Boyle, 2000). The global theoretical hydro resource is estimated around 36,000-44,000TWh/year.

However, the world's economic potential ranges from 6,000 to 9,000 TWh/year (WEA, 2001).

The initial costs for the construction of large hydropower plants (with average size of 31MW) is between US$1,900 to $2,600 per kW of installed capacity. Although the initial costs are high, the operating costs are very low. The electricity production cost of large hydroelectricity plants is around 4 US cents per kWh. This cost is lower than some fossil fuel based plants and all the renewable technologies. For small hydroelectricity plants the cost is higher but is expected to come down in the long term (Komor, 2004).

The potential for new electricity generation from hydropower is significant. However, this potential is restricted by environmental concerns and resource limitations. In many developed countries, most of the attractive sites appropriate for large hydropower plants have been exploited. In such countries, the installation of new hydropower facilities has been inhibited due to environmental issues. However, small and medium scale new projects are under construction and planned in industrialized countries. In less developed regions such as parts of South America, Asia and Africa, large hydroelectricity developments have recently completed or are under consideration (Boyle, 2000).

2.4.6 Geothermal Energy

An ideal energy source is cost-effective and its utilisation causes no harm to the environment. Nowadays, cost-effective (a characteristic of fossil fuels) and environmentally friendly electricity generating technologies (a characteristic of renewable energy sources) usually do not go together. Nevertheless, geothermal energy is one of the renewable energy sources that combines these characteristics in a pretty good extent. It has the staggering advantage of operating at high capacity factor, namely 90%, and so can supply baseload electricity (Komor, 2004). Locations with hot water or steam close to the surface are usually considered worthwhile regions of geothermal energy exploitation for electricity generation. As locations with these requirements are quite limited, geothermal power has a geographically restricted resource.

The geothermal electricity generating technologies are reliable and environmentally clean. Most of the existing geothermal plants are either dry steam power or binary cycle power plants. A new method, the hot dry rock technology, has been the subject of much recent research but still needs refinements in order to be commercially available.

Although the global geothermal resource for electricity production is estimated at 12,000TWh per year, only a few countries have exploited their geothermal resource to generate electricity (WEA, 2001). The USA has the largest installed geothermal electricity generating capacity, that of 2,228MW, while Philippines is following with 1,909MW. Italy, Mexico, Indonesia, Japan are also countries with more than 500MW of installed capacity. With the development of the hot dry rock technology a vast amount of the resource that currently cannot be exploited might be tapped as access can be gained to hot rocks deep underground (Komor, 2004).

The initial costs of geothermal power plants vary considerably depending on the nature of the geothermal resource. A rough estimation of the capital costs of a large geothermal power plant, including the plant and the resource infrastructure, is between US$1,500 and $2,000 per kW. Geothermal plants generate electricity at costs of around 5-6 US cents per kWh. In the case of an ideal resource, which means very hot water or stream close to the surface, few contaminants, small distance between the power plant and the well, this cost may fall. In northern California, the Geysers plant, which is one of the largest geothermal power plants, sells its electricity at the price of 3 to 3.5 US cents per kWh (Komor, 2004). The fact that the geothermal energy has a mature electricity generating technology leaves no space for significant cost reductions in the future.

Geothermal energy is a significant and dependable source of electricity. A geothermal power plant due to its high capacity factor can supply power close to its maximum output most of the time. Although the geothermal resource is quite substantial, the actual locations in the world that can support electricity generation are relatively rare. The cost of generated electricity can compete with the cost of electricity from some fossil fuel plants, especially at good geothermal sites. As geothermal energy has a well established technology, this cost is unlikely to fall due to technological developments.

2.4.7 Biomass

Biomass is another source of renewable energy that has a great potential and could be a significant near-term source of hydrogen. Unlike other renewable energy forms, biomass can produce hydrogen directly. Biomass is a complex source of energy that can be utilized in many ways producing a range of products. Biomass resources are any organic matter available on a renewable basis including sustainably grown energy crops, agricultural residues and wastes such as municipal solid waste, landfill gas and industrial and commercial wastes (Boyle, 2000).

Currently, biomass contributes considerably to the world's energy needs, especially in many developing countries that is the primary energy source. In the USA, among the renewable energy forms it is the second energy source (43%) just behind hydropower (51%) (Chum and Overend, 2001). Aiming to a carbon constrained world, the USA government endeavours to increase the deployment of biomass energy and biomass fuels (biofuels). Increasing attention to biomass has also been given by the EU. In 2003, the EU brought into force the Biofuels Directive in order to promote the use of biofuels and other renewable fuels as alternatives to current fuels in the transport sector. Hydrogen from biomass could be benefited from this directive as the term biofuels includes the biohydrogen fuel, namely hydrogen produced from biomass (EC, 2003; EC, 2000a).

2.4.7.1 Energy Crops

Energy crops are those grown exclusively as energy sources. These energy dedicated crops are an environmentally benign method of producing fuels. While the harvested crops generate carbon dioxide during their combustion or gasification, they absorb carbon dioxide during their growth. Thus, carbon dioxide follows a loop that as long as this loop remains closed the net emission of carbon dioxide is zero. Provided that the replenished rate of the crops matches the rate of their utilization, this loop will always stay closed, making the overall process of energy crop growing and processing environmentally friendly. Energy crops have the advantages over other renewable energy sources that they are not intermittent and unpredictable as they can be produced whenever and wherever are required and if it is necessary can be stored.

Energy crops can be categorized either by the plant species or the replanting rate. In the first case they are divided into herbaceous (switchgrass, miscanthus, bamboo), woody (hybrid poplar, hybrid willow, sweetgum), agricultural (vegetable oils) and aquatic crops (algae, seaweed, marine microflora) (EERE, 2003). In the second case they fall into two categories; perennial crops like miscanthus and switchgrass. Hydrogen is a biofuel with a quite versatile production as there are numerous plant species that can be used as feedstock for its creation. Among them some are currently widely used, while others are likely to become the most popular option in the future.

Perennial crops have recently captured increasing attention by both the EU and the USA due to their advantages over the annual crops. Some of their attributes that justify this attention are their high potential hydrogen yield, low replanting rate, requirement of less maintenance and fewer fertilizer inputs than (Lewandowski *et al.*, 2003). There are various perennial crops candidates, which differ in the potential productivity, properties of their biomass and crop management requirements, available for the production of hydrogen. The most promising ones are switchgrass, miscanthus, sugarbeet, sugarcane, short-rotation plantations of hybrid poplar and willow, reed canary grass, eucalyptus, kenaf, giant reed and wheat grass. Extensive research programs evaluate, test and evolve continuously these candidates in order to improve their utilization as feedstocks for the production of hydrogen.

The use of land with the purpose of fulfilling human needs has radically been increased over the years. This increase can be witnessed by the rising land prices and increasing land-use efficiency and intensity, especially in densely populated countries. In this context, the introduction of energy crops as a new land-use category is not quite simple. Of all the competing uses of land, food production is the most important. Thus, the use of energy crops for the production of hydrogen is suitable in regions those are not needed or poorly suited for food crops. However, hydrogen has not got to compete only with food. The biomass resource that is exclusively used for fuel production cannot be wholly dedicated to hydrogen as hydrogen is not the only biofuel. Thus, in order to estimate the biomass available resources for hydrogen production, it is noteworthy to take into consideration that the unsuitable food production areas are shared among all biofuels (Nonhebel, 2005).

The multiple purposes of land use make the efficient use of land an unquestionable necessity. This can be achieved by the multiple land use, namely the production of more than one type of product or service on the same tract of land, if possible (Londo *et al.*, 2004). Some energy crops, like cellulose crops, can be produced more efficiently in terms of land use than others and thus be more suitable for hydrogen production (Graham *et al.*, 1995). Energy crops are geographically dispersed and because they grow in different soil and weather conditions may have variations in quality and productivity.

The global biomass energy potential is around 100EJ/a, which is approximately 30% of the current total world energy consumption. From the total worldwide biomass resources, the amount of 40EJ/a has been exploited for energy purposes of which Asia impressively uses 60% (Parikka, 2004). Asia, though, is an exception as in the majority of the countries in the world the current biomass use is considerably below the available resources. So, if biomass is to become a major feedstock for hydrogen production an increased biomass use is indispensable worldwide (Czernik *et al.*, 2004).

Currently, biomass energy feedstock supply costs range between £25 and £55 per delivered oven dry tonne (Lewandowski *et al.*, 2003). The costs are highly variable as they depend on several factors such as demand, supply, site of the plantation, biomass yield, production costs, final specifications of the fuel like moisture content and particle size. As a result, the cost of producing hydrogen from biomass differs from country to country and is mostly affected by the specific local harvested yields. Production costs are also important and are normally broken down into establishment, cultivation, harvest, storage, drying, transport and chipping costs (Venturi *et al., 1999*). In general, high production costs are caused by farm labour, machine use, land costs, conservation and transport.

Adequate plantations available in relatively high concentrations may assist in making energy crops an economically viable option of hydrogen production as they minimize the cost of harvest. From a techno-economic perspective, the main problems that energy crops are currently facing are related to the production costs and difficulties in harvesting and storing the harvested material, especially in the case of annual energy crops. The relatively costly transportation costs have made the local or regional biomass production a favourable option. Generally, as the harvest yields have a great effect on the production costs, the more the yield per hectare increases the more the costs of production decrease (Venturi *et al., 1999*).

The extremely diverse biomass feedstocks make biomass one of the most versatile renewable energy sources. There are an impressive number of different types of energy crops that each one is appropriate for different ecological and climate conditions. This diversity makes the deployment of energy crops feasible in almost every country of the world. In the hydrogen production context, energy crops have many specifications to be a valuable renewable energy source. Energy crops' merit of flexibility may well service hydrogen, especially if hydrogen is to become a major worldwide fuel. For being such a fuel, hydrogen production needs the support of such a highly adaptable renewable energy source.

In order for energy crops to considerably contribute to the production of hydrogen, they need to surmount a few barriers. The main obstacle in the growth of energy crops is the high production costs. These costs could be decreased by the development of new and the improvements of the already existing agricultural practices.

2.4.7.2 Agricultural Residues

Agricultural residues are another biomass resource that can be used as a source of hydrogen fuel. Agricultural activities generate large volumes of residues, which can be divided into crop, forestry and livestock residues. Crop residues are the materials remain after harvesting crops for their primary purpose. There is a wide range of the remaining materials in terms of their size, shape, form and density. The most common crop residues are straws, stalks, sticks, leaves, haulms, fibrous materials, roots, twigs, husk, and dust. Operations like thinning and logging of plantations and trimming of felled trees provide large amounts of forestry residues, which include leaves, branches, lops, tops, damaged or unwanted stem wood (Boyle, 2000). At present the majority of these residues are left to rot on site or to be burnt. This results in important environmental problems such as soil acidification and harmful air emissions. The production of hydrogen from residual wood provides a possible solution to these problems, while creating a new market for the forestry residues (Nunez-Regueira *et al.*, 2003; Boyle, 2000).

Another case that the production of hydrogen in line with the reduction of fossil fuel based CO_2 emissions has the potential to solve the waste disposal problems is the use of livestock residues as a fuel source. Livestock facilities like dairy farms, hog farms and chicken houses produce large quantities of wet manure, which have a high potential of water and air pollution (Sweeten *et al.*, 2003; Dagnall *et al.*, 2000). Another kind of animal wastes is the dry manure that is generated by feedlots and livestock corrals but is collected and removed only once or twice a year (He *et al.*, 1998).

An important issue with agricultural residues as a source of hydrogen fuel that has to be taken into consideration is their variation in harvest volumes. Agricultural residues are not available throughout the year. Large amount of residues is generated after harvests but during the rest of the year they are minimal. The quantity of residues produced varies depending on many factors such as the type of the crop, the season, the soil type, the irrigation conditions, the tillage practices (Tripathi *et al.*, 1998). The yield of the residues is also different for the same crop types as it depends on the type of cultivation and the location of the plantation (Di Blasi *et al.*, 1997).

Generally, the potential for agricultural residues is high in countries with enormous agricultural areas and low in countries with small land resources. Worldwide large quantities of crop residues are produced every year that are greatly underutilized. As the crop production depends on the climatic conditions, all residues are not available in all parts of the world. The global potential of the most common crop residues, namely bagasse, rice husk, olive flesh and cane trash, has been estimated around 3433Mt/yr. In energy terms that is equivalent with 62×10^{12}MJ/yr (Natarajan *et al.*, 1998).

Wood residues have also significant resource potential especially in countries where forests cover a substantial part of the whole land area. The worldwide area of forests is estimated to be 3870(10_6)ha of which large amounts are found in countries like Sweden, Finland, Austria, in the eastern European states, North America, Southeast Asian and Australia (Parikka, 2004). In the EU the energy potential of forest residues is estimated around 649PJ/yr (Nikolaou *et al.*, 2003).

In rural areas, especially arid and semi-arid regions where there are wood shortages, animal wastes could be a significant option as a fuel source. Manure from cattle, chickens and pigs are the most common wet animal wastes in Europe, particularly in the Netherlands and Denmark (Boyle, 2000). In the EU the total resource potential of livestock manure amounts to 646PJ/yr (Nikolaou *et al.*, 2003).

The quantity of agricultural residues that could be used for hydrogen production depends on the demand, the economics and the technology. There are a number of factors like available equipment, harvesting methods, pre-treatment processes, location of the residue sites, amount of residues per site, soil maintenance that limits the available resources of residues (Junginger *et al.*, 2001). The production of hydrogen has to compete with several applications in which agricultural residues could be used. These applications include fuels for cooking, water and process heating, fodder for animals, feedstocks for fertilizers, materials for roof construction, fibre. Technically, apart from the fodder and fertilizer residues, all other agricultural residues with low moisture content can be used as feedstocks for the biomass-to-gas conversion technology, gasification (Tripathi *et al.*, 1998).

The cost of agricultural residues, like their quantity, fluctuates strongly, mostly depending on harvests, increased use by competitors, season and location (Junginger *et al.*, 2001). The final delivery cost of residues includes the costs of production, harvesting, transportation and storage. For crop residues, the costs of collecting, chopping and baling contribute towards the harvest cost. The location of the plantations significantly determines whether an agricultural estate is economically viable to be used as a source of hydrogen production (Nurmi, 1999). Transportation costs depend on the amount of residues those have to be transported, the availability of the farm's own trucks or the use of local hauliers and the distance between the farm and the hydrogen production plant. Apart from the quantity, the density and water content of the residues have to be taken into account as the low values of the former and the high value of the latter make difficult to transport them efficiently and thus restrict the feasibility of transportation. Generally, due to the low energy densities only for distances less than 50miles between the plantation and the hydrogen conversion plant transportation is considered economic (R.W.BECK, 2003).

The production of hydrogen from agricultural residues could be more economical when coupled with the production of additional products like activated carbon (Kumar *et al.*, 2002). In the EU the cost of crop residues was estimated to be from 1.4€/GJ in Spain to 6.45€/GJ in Ireland. Differences in the costs are not only observed between the states but even within a country. For instance, in Greece the difference in residues cost is ±1.9€/GJ (Nikolaou *et al.*, 2003). The operating expenses, namely the costs for mowing, raking, baling, gathering and stacking, range between \$11.26 to \$14.01Mg^{-1} depending upon biomass yield (Thorsell *et al.*, 2004). At present, some of the lowest cost residues are rice straw and wheat straw.

The cost of forestry residues is higher than that of crop residues. The total cost includes the costs of skidding, yarding, loading, chipping and transporting. In the USA the cost of wood residues starts at £30 per bone-dry ton and can increase to almost three times that much (R.W.BECK, 2003). In Europe, forestry residues cost varies between 1.4€/GJ in Spain and 7.7€/GJ in Slovenia (Nikolaou *et al.*, 2003).

As far as livestock manure is concerned, the delivery cost varies from farm to farm depending on the storage and handling system and the transport distance. The type and cost of storage depends on the kind of manure. The cost of storage is roughly estimated about \$50/cubic metre (Nurmi, 1999). The transportation cost of manure, like the corresponding cost of crop residues, is determined by the quantity, the moisture content and the distance it has to be transported.

Conclusively, agricultural activities produce significant amounts of crop, forestry and livestock residues. Every year worldwide large volumes of agricultural residues are generated. Due to the different climatologic conditions among the countries, the resources of the residues widely vary from country to country. Thus, what is the best residue option for the production of hydrogen in one country may be the least favourable option for another country. However, there are some residues that are generally considered quite good choices for hydrogen generation. One of these is the sugarcane residue, bagasse. Bagasse may have a great potential as a source of hydrogen fuel due to its wide distribution and abundance in many countries. Like other renewable energy sources, it is not the available resources that create a bottleneck in the use of agricultural residues as a hydrogen source, is the costs associated with the handling, storage and transportation of the residues.

2.4.7.3 Wastes

Another form of biomass that constitutes a large proportion of the biomass resource is wastes. Although the term 'wastes' encompasses a wide range of leftovers, there is an ongoing debate about what should be included as a biomass waste. Technically, some wastes are not biomass fuels as a significant fraction of them is not biological in origin. Their organic part, though, is considered a biomass fuel but it is impossible to completely sort and filter wastes to obtain only the biodegradable fraction of them (R.W.BECK, 2003). Apart from the disagreements over the definition of biomass wastes, there is also confusion about wastes categories due to the numerous different ways in which they can be classified.

In this study wastes are divided into municipal solid, industrial and commercial wastes. Much of the industrial and commercial wastes are unsuitable for combining with domestic wastes because of safety or for minimizing disposal costs (Boyle, 2000). Municipal solid waste originates mainly from households, sewage sludge, demolition, and construction debris, public areas, institutions and services (Nikolaou *et al.*, 2003; Buenrostro *et al.*, 2001). The wastes generated in dwellings include paper, containers, tin cans, aluminium cans, plastic, food scraps, cardboard, wood wastes, leather, and yard wastes. Building sites produce wastes from activities like construction, renovation, demolition, land excavation and road works. Public areas like parks and gardens can also create wastes such as cut grass and tree prunnings. Institutional and service wastes include sources like governmental and private offices, education centres, museums, recreation centres, department stores, restaurants and marketplaces, among others (Buenrostro *et al.*, 2001; Demirbas, 2004).

A significant portion of municipal solid waste ends up in landfill sites. Due to the increase of these wastes existing landfills are being exhausted and harmful emissions are increasing at alarming rate. The use of wastes to produce hydrogen has the dual beneficial effect of the decrease of greenhouse gases emissions and the reduction of the amount of disposed wastes.

Industrial waste is generated in processes like extraction, benefit, transformation and production of goods (Buenrostro *et al.*, 2001). The main sources of industrial waste are food, timber and tanning industry. Some of the food industries that may provide considerable amounts of wastes for the production of hydrogen are dairy, slaughter and cereal industry (GEB, 2003). A promising candidate biomass feedstock for the production of hydrogen from food industry is nutshells. Nutshells originate from nut processing and can be found in large quantities around the world (Lau *et al.*, 2002).

Forest industry is a further source of industrial waste. Wood manufacturing processes such as paper mill, saw mill, manufacturing of plywood, lumber and furniture generate wastes in the form of sawdust, bark, needles, wood chips, black liquor, paper pulp and scrap lumber (Fung *et al.* 2002). Tanning/leather industry disposes large quantities of wastes, including fleshings, shavings and sludges. The quantity of wastes depends on the type of leather, the produced by-products and the techniques applied (GEB, 2003).

Commercial waste is generated in areas like scientific research, health, industrial and automobile maintenance shops, human and veterinarian drugstores, hospitals and airports. This type of waste needs special controlling techniques and requires pre-treatment before disposal either because is hazardous due to its chemical content or because environmental regulations demand it (Buenrostro *et al.*, 2001).

The world produces million of tonnes of municipal solid waste each year and a similar amount of industrial and commercial wastes. The increase of municipal solid waste in both developed and developing countries every year, justifies the consideration of municipal solid waste more as an energy resource than a waste matter. It is estimated that in industrialised countries 0.9-1.9kgs/capita of municipal solid waste are generated every day (WEA, 2001). From the 210 million tons of municipal solid waste that the USA produces every year only a small fraction is used for energy purposes the rest (70%) ends up on landfill sites (Wallman *et al.*, 1998). In EU the total energy potential of wastes is estimated around 846PJ/year. In particular, the energy potential of sewage sludge is 94,06PJ/year, landfill gas 207,3PJ/year, municipal waste for incineration 291,7PJ/year and demolition wood 254,04PJ/year (Nikolaou *et al.*, 2003).

The energy potential of industrial waste for Europe was found to be around 1107PJ/year. This amount refers to industrial wastes in the form of dry wastes, industrial sludges and black liquor. Dry wastes and black liquor represent a large fraction of this amount with energy potential equal to 594PJ/year and 454PJ/year respectively and industrial sludges are the remaining 119PJ/year. The largest European producer of dry industrial waste that can be used as a biomass resource for energy purposes, with hydrogen production one of them, is wood industry. The amount of wastes from the latter is expected to increase 1% a year from 1990 to 2020 (Nikolaou *et al.*, 2003). The Nordic countries of the Union use almost all the available bark and black liquor for energy production (EFI, 2000). In the USA the wood industry consumes 85% of the available waste utilized for energy production (Burden, 2003). On the contrary, the wastes of food industry are predominately used for animal feeding. The conversion of food industry waste into hydrogen fuel is the next low-value option of utilization (GEB, 2003).

The annually increased amount of municipal solid waste ends up in landfill sites intensifying the concerns about the environmental repercussions of landfills and the lack of new sites available for landfilling. Typically, the costs of landfilling vary between $20 and $50 per tonne. In some locations, though, these costs are very high and may be as expensive as $150 per tonne (Warren and El-Halwagi, 1996). While this makes landfilling an expensive and unattractive option of waste disposal, it reinforces the attractiveness of the use of wastes for hydrogen production.

The total municipal solid waste management cost includes the cost of collection, transfer and disposal (Dogan and Suleyman, 2003). An economical advantage of industrial wood waste over municipal solid waste is that the in-forest collection and chipping of the former are already included as part of the commercial industry operations. This is the reason why wastes from forest industries are a more economically desirable biomass feedstock than forestry residues (R.W.BECK, 2003).

In Europe the cost of solid industrial waste ranges between 0.8€/GJ in Latvia and Lithuania and 6.9€/GJ in Slovenia. Differences in this cost are also observed within a country. For instance, in Germany the average cost is 3.3€/GJ but differences within the country are ±2.3€/GJ (Nikolaou *et al.*, 2003).

Apart from wastes as a biomass feedstock for hydrogen generation, hydrogen can also be obtained using electricity generated by landfill gas. The price of electricity from municipal solid waste is highly variable and affected by a number of factors. The cost of landfill gas electricity is mainly determined by the gas productivity, the availability of municipal financing and the size of the landfill gas-to-electricity conversion facility (Komor, 2004). A typical cost of landfill gas based electricity ranges between $6 and $9cents/kWh (Komor, 2004).

Unlike other renewable energy sources, wastes can be detrimental to the environment if they are not used as a renewable energy source. Wastes are not only a source that is replenished; they are also a source that its available resource is increased every year. Worldwide, especially in densely populated areas, disposal sites are gradually more constrained and the municipal fees are quite high that make the conversion of wastes to hydrogen a possibly profitable option. The reduction in the number of future landfills followed by the decrease in the associated air and water environmental repercussions and the generation of an environmentally benign fuel like hydrogen emphasize the importance of the utilization of wastes as a hydrogen fuel source. This importance may well constitute incentive for the technical and economic development of the production of hydrogen from wastes.

Table 2.2 summarizes a number of characteristics of each renewable energy resource. It shows the worldwide potential and the resource available in the UK, which is used for the case study of this project. The former comprises the maximum theoretical potential that may be orders of magnitude greater than the technical potential which is the amount of the resource that is practically possible to be used taking into account various technical and physical constraints. There is a considerable difference among various studies in the estimated technical potential (Hart, 2002; ETSU, 1994; ETSU, 1999; WEC, 1994; NREL, 2006; REvision 2020, 2005; Garrad Hassan and Partners, 2001; Boyle, 2002; Komor, 2004; Sustainable Development Commission, 2006). The reason for this variation is the numerous diverse constraints such as geography, intermittency, electricity grid, planning social or economic. Each study estimates the technical potential according to different constraints or combination of constraints from others. The UK resource potential in Table 2.2 corresponds to the technical potential. Like in the worldwide theoretical potential case, the estimations vary from study to study. Every estimate is presented along with its reference.

Renewable Energy Resource	Global Potential (TWh/year)	UK Technical Potential (TWh/year)	Maturity	Electricity Cost	Hydrogen Route	Advantages	Disadvantages
Wind Energy	1,666,666	262 (Boyle, 2000)	-Onshore Wind: technologically mature -Offshore Wind: reaches maturity over the next 10 years	-Onshore Wind: ~ 3 p/kWh -Offshore Wind: ~ 5 p/kWh	Electrolysis	-Mature technology -Relatively inexpensive -Scalable	-Sitting -Intermittent
Solar Energy	13,843,611	266 (ETSU, 1999)	~ Proven Technology	~ 40 p/kWh	Electrolysis	-Ubiquitous resource -Wide range of application -Noiseless	-Very expensive
Wave Energy	18,055	237 (Boyle, 2000)	Experimental stage	~ 4 p/kWh	Electrolysis	-Fairly predictable -Large UK resource	-Lack of mature technology
Tidal Energy	21,944	53 (Boyle, 2000)	-Well-established -Tidal Streams: development stage	~ 5 p/kWh	Electrolysis	-Dispatchable -Large UK resource	-Relatively expensive
Hydro Energy	40,833	4.9 (ETSU, 1999)	Technologically mature	~ 2-7 p/kWh	Electrolysis	-Dispatchable -Can be inexpensive	-Restricted resource due to land, water and ecological impacts
Geothermal Energy	3.8E10	210 (Hot Dry Rocks) (IEE, 2002)	-Technologically mature -Hot Dry Rock: new approach at development stage	~ 3.5 p/kWh	Electrolysis	-Dispatchable -Can be inexpensive	-Limited resource
Biomass	805,555	84 (IEE, 2002)	~Well-established technology	~ 3-8 p/kWh	-Electrolysis -Photosynthetic Processes -Fermentation -Gasification -Pyrolysis	-Dispatchable -Large UK resource	-Can be expensive -Produces emissions

Table 2.2: Characteristics of renewable energy resources

2.5 Hydrogen Technologies

In order hydrogen to be successfully used as a transportation fuel, there is a pathway that needs to be followed. This pathway is a chain that consists of certain stages. The main stages of a fuel chain are the production, conversion, storage, transport and dispensing of the fuel. For each step in the chain there is a considerable variety of technologies, making the diversity of different possible fuel chains quite wide. The technology options available for each stage in the chains differ in technical, economic and environmental characteristics. Apart from these characteristics, they also vary in terms of current status and potential. Some technologies are mature and widely used, others are still at the development stage and others are in the transition from a proven technology to one in widespread use. Figure 2.1 shows the structure of the fuel chain. In this study, "fuel chain" includes all the necessary stages in order to produce and deliver hydrogen at the point of use.

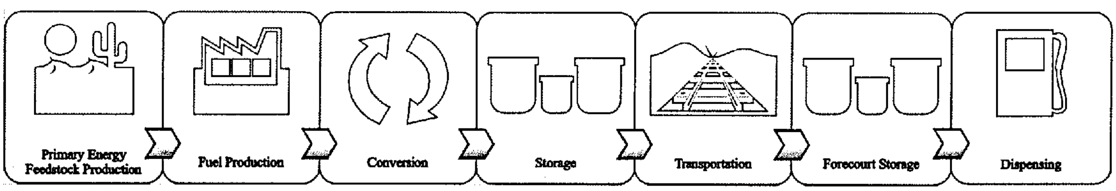

Figure 2.1: Schematic of a fuel chain

2.5.1 Hydrogen Production

There are several technologies able to produce hydrogen that are in different points in the path they have to follow in order to become commercially used techniques from innovative concepts. Hydrogen production processes vary widely in terms of costs and technical performance. The suitability of a technology is determined by a number of factors such as the availability of the feedstock or the resource, the quantity of hydrogen required and the required purity of the produced gas.

Renewable hydrogen can be produced mainly from water and biomass. Water can be broken up and give hydrogen in several ways, such as directly with high temperatures, with the help of chemicals, with both chemicals and heat, by the use of microorganisms and by an electrical current running through water in electrolysis (Hoffmann, 2002). Of these water-based processes, some are well established, though expensive and some are still far from been commercially available.

The attractiveness of methods using biomass as a feedstock for hydrogen generation is the direct hydrogen production without the need of electrolysis. The elimination of this need results in higher system efficiency (Zittel and Wurster, 1996). The successful use of biomass technologies is mainly determined by the optimum match of feedstock and conversion technology. The suitability of the process for a specific feedstock depends on the feedstock qualities such as cost, distribution, mass, and physical and chemical characteristics. These qualities, which also affect the efficiency of the overall process, must be carefully considered before matching the feedstock with the technology (Milne *et al.*, 2001).

Thermal decomposition of water (Thermolysis)

It is feasible to decompose water thermally at very high temperatures above 2000 K. The degree of dissociation is a function of temperature and the product is a mixture of gases. The main difficulties of this method are the materials needed for high temperatures and the separation of hydrogen from the mixture. Moreover, due to the high temperatures required, it is yet impractical outside the laboratory.

Thermochemical water decomposition

Water can be split with high temperatures and some catalysts, through a series of cyclical chemical reactions that release hydrogen. This process has the advantage over the direct thermal decomposition method of employing in lower temperatures owning to the presence of the chemical reactions that reduce the required temperature. The efficiency of this technique relies on the temperatures and can be around 40-50% (Veziroglu and Barbir, 1998).

Electrolysis

Electrolysis is regarded as the only water-based process developed to date that can be used for large-scale hydrogen manufacture in a post-fossil fuel era. It is a mature technology based on a plain and clean process, it is very efficient and does not include moving parts. Electrolysis is accomplished by passing an electrical current through water to split water molecule into its constituent hydrogen and oxygen (Ivy, 2004).

Electricity is applied to two electrodes immersed in an electrolyte to force the dissociation of water. Water is induced in the negatively charged electrode (anode), where it is decomposed to oxygen, protons (H^+) and electrons (e^-). The oxygen is released in a gaseous form at the surface of the electrode. The protons pass the membrane of the electrolyte to the positively charged electrode (cathode) and the electrons move through the external circuit. Hydrogen is formed at the cathode, where the protons combine with the electrons (McAuliffe, 1980).

An electrolyser is a device that can store electrical energy in the form of fuel. There are three main advanced electrolyser technologies that have been developed for electrolytic water splitting. The first is the liquid alkaline electrolyte, usually potassium hydroxide, that uses a diaphragm to separate the cathode and the anode parts. This separation prevents the mixing of the gas. Moreover, employs new materials for membranes and electrodes that allow advances in efficiency, up to 90%. The second is the polymer electrolyte membrane (PEM) employs a proton-conducting ion exchange membrane as electrolyte and as a membrane that separates hydrogen and oxygen. This electrolyser can operate at very high current densities. In addition, dissolved electrolyte is not necessary to increase its conductivity for the dissociation of the water, which is added only to the anode side (Veziroglu and Barbir, 1998).

The third type is the high temperature steam electrolysis that uses oxygen ion-conducting ceramics as electrolyte and operates at temperatures between 700 and 1000 °C. Heat is supplied for the dissociation of water, reducing the total energy requirement for this process. The water in the form of steam enters the anode and generates a steam-hydrogen mixture during the process, while oxygen is discharged as a gas at the surface of the electrode (Veziroglu and Barbir, 1998).

At present, the electrolysers most commonly used are the alkaline and the PEM that both employ at high efficiencies, up to 90%-94%. Alkaline systems are preferred because the corrosion is more easily controlled and the construction is cheaper. Especially, for larger systems they are favoured due to the easier scale–up and thermal management resulting from the circulating alkaline electrolyte. However, PEM electrolysis can generate hydrogen cost-effectively at high pressure without the existence of an extra compressor and with high purity. Moreover, they take rapid increases or decreases in electrical input without creating any complications in the system (Hoffmann, 2002; Kreuter and Hoffmann, 1998; Ivy, 2004).

Currently, commercially large-scale alkaline electrolysers costs are in the range \$500-700/kW and the scale production is still small. However, the growing interest of hydrogen economy may motivate the manufacturer to raise the production to match the future demand of alkaline electrolyser and thus drive down the cost to the level of \$250/kW. Small-scale alkaline and PEM electrolysers' costs are higher as a result of the early development stage and in the range \$1,000-1,500/kW. Potential costs of PEM electrolysers are estimated to decrease to about \$300/kW (Thomas and Kuhn, 1995).

Photoelectrolysis

In photoelectrochemical water splitting, light illuminates a semiconductor material and causes the movement of electrons and thus provides the electricity needed to decompose water. This process has the advantage of the elimination of the need of an electrolyser. Theoretically, the maximum efficiency can be more than 35% but at present demonstrations in the laboratories have achieved up to 13% (Dincer, 2002). Photoelectrochemical process is still under experimental stage and needs further development in order to become a stable and cost effective technique of hydrogen production.

Biological processes

Biological processes are mostly operated at an ambient temperature (30-40°C) and normal pressure. For this reason they are considered more environmentally benign and less energy intensive than thermochemical and electrochemical processes. They can be divided into two major categories, photosynthetic processes and fermentation processes. Until today, the latter have received little attention, while the former have been studied extensively.

Photosynthetic hydrogen production uses organisms like green and blue green algae and photosynthetic bacteria under light conditions to split water or other organic compounds to form hydrogen (DTI, 2003). Theoretically, the maximum efficiency of hydrogen production from algae is equal to 25%. The most important limitations of this method are the production of oxygen along with hydrogen during the process and the low rates of hydrogen evolution (Bellona, 2003). Research in the field of algal hydrogen production attempts to overcome these problems.

Unlike green and blue green algae, photosynthetic bacteria do not have the difficulty of the oxidation of water. These bacteria generate hydrogen from organic acids. Utilizing organic substrates for starting compounds they need less light energy to produce hydrogen (Miyake *et al.*, 1999). Photosynthetic hydrogen production holds great promise due to the relatively high conversion yields of organic compounds into hydrogen (the highest conversion yield among all the microorganisms that can produce hydrogen), the use of a wide range of the spectrum of light and the flexibility of the sources that can be used as starting materials (Eroglu *et al.*, 2004). In recent years, the stability and the yield of hydrogen production are the main areas that photosynthetic process research has been focused to.

Fermentation processes utilize anaerobic (or fermentative) bacteria to ferment organic material like wastes, under dark anaerobic conditions, to produce hydrogen. This process is technically simpler and gives higher hydrogen production rates than the photosynthetic process (Chang and Lin, 2004). However, it has lower yields of hydrogen. Despite this disadvantage, the high rate of hydrogen evolution, the fact that it does not rely on the availability of light and the wide range of sources that can be used as substrates make it a promising hydrogen production method (Nath and Das, 2004). The application of anaerobic processing is currently an established technology for treating high moisture content biomass (Morimoto *et al.*, 2004). Although the fermentation technique of biomass is commercially available, the coupling of this technique with hydrogen production is not yet economic and technically viable. In order fermentation to be an important hydrogen production method in the future, further investigation is necessary upon the physiological and physico-chemical conditions under which the microorganisms provide high hydrogen yields (Hawkes *et al.*, 2002).

Gasification

Biomass, usually in its solid form, can produce hydrogen thermochemically through the gasification method. The term gasification includes a range of processes in which solid fuels are reacted with hot steam and air or oxygen to generate gaseous products (Boyle, 2000). Most of the process equipments, such as reforming, shift reaction, recovery equipment, are commercially available and widely used for industrial hydrogen production. However, the gasifier and the gas cleaning equipment are still at a pre-commercial stage (DTI, 2003). There is a broad range of types of gasifiers with operating temperatures varying from a few hundred to over a thousand degrees Celsius and pressures from near atmospheric to as much as 30 atmospheres (Boyle, 2000). The choice of the gasifier type is determined by the availability and the physical characteristics of the feedstock and the temperature and pressure required obtaining the optimal hydrogen yields (Lau *et al.*, 2002). Current demonstrations of biomass gasifiers have achieved thermal efficiencies of 55-65% (Williams *et al.*, 1995).

Apart from air and steam gasification, an innovative gasification method that is currently under development, is that of supercritical water gasification. The purpose of developing this method is the existence of a gasification process that can directly utilize the wet biomass, like sewage sludge, without drying, converting it with high efficiency into hydrogen of high purity. At present, the research challenges of supercritical water gasification are the feedstock preparation, the supercritical water process development and the product upgrading (EC, 2001b).

Pyrolysis

Pyrolysis is another thermochemical process that can produce hydrogen from biomass. Pyrolysis converts biomass into a liquid product, called bio-oil, that can form hydrogen through catalytic steam reforming and shift conversion (Abedi *et* *al.*, 2001). This method is currently at development and demonstration stage. Biomass conversion to hydrogen through pyrolysis has lower overall efficiencies than gasification because it involves multiple stages (DTI, 2003). However, there are quite a few advantages of this process over the gasification technology, which constitute incentives for further research. Unlike solid biomass, bio-oil can be easily transported and therefore, can be transferred at various locations at which hydrogen is needed. In this way, pyrolysis and reforming can be carried out in different places, with the latter being able to take place at sites where infrastructure for hydrogen use or distribution exists. The product of pyrolysis contains several oxygenated components that can be transformed into several products, including hydrogen. Co-products opportunity is an important advantage as the production of high value products in conjunction with hydrogen may considerably influence the economics of this technology (Abedi *et al.*, 2001). The cost of hydrogen from pyrolysis with by-products approach is in the range of \$6-\$8US/GJ, which is quite encouraging for short-term application (Nath and Das, 2004).

There are several comparative studies that have been carried out investigating the economics of different hydrogen production methods. Some analyses concluded that biomass gasification is the most economic renewable hydrogen production method, whereas other assessments showed that pyrolysis combined with the sale of co-products is the most economically favourable renewable process and cost-competitive even with some fossil fuel hydrogen production technologies. Hydrogen derived from pyrolysis can compete with hydrogen from natural gas at large plants. Going one step further and considering the places where there is no natural gas infrastructure, makes hydrogen from pyrolysis possibly cheaper than natural gas-derived hydrogen (Bellona, 2002).

Table 2.3 summarizes the different production technologies that can be used to produce hydrogen and their corresponding technical maturity and economic status.

Production Technology	Technical Maturity	Technical Barriers	Cost	Attractiveness
Thermal Decomposition of Water (Thermolysis)	- Impractical outside the laboratory - Efficiency: < 30%	- High temperatures - Separation of Hydrogen from the mixture. -Low efficiency levels	One of the most expensive technologies among new technologies	- No need of catalysts - Environmentally safe process
Thermochemical Water Decomposition	- Developing technology - Efficiency up to ~50%	- Increase of lifetime of cells - Design of gas separation equipment - Improvement of efficiency	Projected to be a cost-effective method	- High Efficiency
Electrolysis	- Mature Technology - Efficiency: 70-95%, depending on temperature	- Elimination of exotic material on the electrodes - Production of electrodes with electrochemical stability	One of the less expensive methods from renewable energy sources	- Proven Technology - No moving parts -Plain and clean ptocess
Photoelectrolysis	- Experimental Stage - Theoretical efficiency: > 35% - Current achieved efficiency: 13%	- Identification of the suitable semiconductor material - Performance stability - Conversion efficiency of photoelectrochemical cells	Currently, not cost-effective, but offers great potential for cost-reduction of electrolytically produced hydrogen	- No need for electrolyser - High Efficiency
Photosynthetic Processes using green and bleu green Algae	- Developing Technology - Efficiency: 25%	- Oxidation of water - Low rates of hydrogen evolution	Moderate	- More environmentally benign and less energy intensive than thermochemical and electrochemical processes
Photosynthetic Processes using Photosynthetic Bacteria	- R&D Stage - Efficiency: >10%	- Stability of production rate - Increase efficiency	Potentially cost-effective	- Use of a wide range of the spectrum of light - Flexibility of the primary feedstocks
Fermentation Processes	- Not yet technically viable for biomass-to-hydrogen conversion - Efficiency: 15-33%	Low production yield	Not yet economically viable	- High production rates - Wide range of substrates
Thermal Gasification	- Most of the process equipments are commercially available - Gasifier and gas cleaning equipment at pre-commercial stage - Efficiency: 55-65%	Gasifier Reactor	Relatively cost-effective	- Established technology - Economically viable
Supercritical Water Gasification	- R&D stage - Efficiency: >60%	- Feedstock preparation - Product Upgrading	Potentially cost-effective	- Directly utilizes wet biomass - High purity produced hydrogen - Gas available at high pressure
Pyrolysis	- Development and demonstration stage - Efficiency: > 50%	- Improvement of interim products' physical properties such as viscosity, longer storage life, lower solids content	Not expensive	- Bio-oil, which generates the hydrogen, can be easily transported - Opportunity for co-products exploitation

Table 2.3: Characteristics of hydrogen production technologies

2.5.2 Hydrogen Storage

Contrary to oil and natural gas, hydrogen is difficult to be stored because of its extremely light and low calorific value characteristics. Hydrogen storage methods can be divided into physical and chemical. In the former category hydrogen is stored by changing its state conditions (temperature, pressure), while in the latter category compounds are used to absorb or bound hydrogen through a chemical interaction (H-SAPS, 2001). Even though each storage technique has attractive attributes, at present there is no method that satisfies all the efficiency, cost and safety requirements for stationary applications. Research in storage technologies is underway with some methods capturing more attention than others. From the aforementioned methods, compressed hydrogen gas, liquid hydrogen and metal hydrides are the state-of-the-art techniques normally used in stationary applications.

Each of the numerous possible fuel chain options encompasses hydrogen storage at varying scales and stages of the chain. The difference in scale makes possible the use of different kind of storage method to store the fuel after its production and different method to store it at the point of use (forecourt storage). The choice of the best hydrogen storage technology for a certain application is based on a number of factors. These factors are the quantity that needs to be stored, storage time, required energy density, end use, handling safety, distance between production point and point of use, availability of energy forms and capital costs (Amos, 1998). At present, the storage methods in which the scientific research in this field has been mainly focused on and thus are the most technologically developed are compressed hydrogen gas storage, liquid hydrogen storage and metal hydrides.

Compressed Gas

Currently, the compression of hydrogen in gaseous form at very high pressure is the most commonly used storage method. Compressed hydrogen can be stored either underground or aboveground. Aboveground storage is the simplest storage option as it only requires a compressor and a vessel. The technology of the former is well established but still relatively expensive (Bellona, 2002). In aboveground storage systems, hydrogen is compressed and stored in large cylinders, spherical containers and long tubes. The main difficulty that this storage method faces is the low storage density that depends on the storage pressure. The overall storage cost is mainly dependent on the storage time and pressure. Typically, the capital cost for a short and long term aboveground storage system is estimated around \$2,088 and \$32,428/MWh of storage capacity, respectively (Padro and Putsche, 1999). This storage method is preferred for small to medium scale storage applications where underground storage is technically unfeasible (Padro and Putsche, 1999). In the case of large scale applications, it becomes an economically unfavourable option.

Contrary to aboveground storage, storage of hydrogen underground on large scale is not expensive. Underground reservoirs such as salt or mined caverns, aquifers, depleted gas wells are used for storing large quantities of gas (up to a billion Nm^3). The ability to store hydrogen underground depends on the nature of the rock layers (McAuliffe, 1980). In geological suitable places, this type of storage may be more economic than any other storage technology for large quantities of hydrogen. This type of storage is more appropriate for long term or seasonal storage of hydrogen. However, it is not favourable for gradual development. The type of storage used affects the capital cost of an underground storage system, which ranges between \$5.5 and \$288/ MWh of storage capacity. In the case the storage space exists like depleted gas or oil fields, natural caverns or rock formations, this cost can be considerably reduced to \$7-\$80/MWh of storage capacity (Padro and Putsche, 1999).

Liquid Hydrogen

Hydrogen can be liquefied and stored in insulated cryogenic containers. Due to the higher energy density of liquid hydrogen than that of compressed hydrogen, the amount of liquid hydrogen that a truck can store is equal to the amount of compressed hydrogen 20 trucks can store. However, liquefaction is an energy-intensive process that requires 30-40% of the energy content in the hydrogen, making this method the one with the lowest efficiency among the other technologies (H-SAPS, 2001). Although the high capital costs of liquefaction and storing equipment impede the application of this method, liquid hydrogen storage is advisable for long term storage and thus suitable for the transportation of hydrogen over great distances (Amos, 1998).

The capital costs for liquid hydrogen storage facilities depend on the quantity of hydrogen that needs to be stored and varied between \$25,600/kg/hr and \$118,000/kg/hr (Amos, 1998). Due to the higher energy density of liquid hydrogen than that of compressed hydrogen, the amount of liquid hydrogen that a truck can store is equal to the amount of compressed hydrogen 20 trucks can store. Moreover, the boil-off losses decrease with the increase of the size of the vessel. For large quantities the boil-off losses decrease (with the use of big vessels) and the cost of the alternative pressure vessel increase more rapidly than the liquefaction costs, making liquid hydrogen storage method competitive. Like underground storage, liquid hydrogen storage method is advisable for long term storage, making this method suitable for the transportation of hydrogen over great distances (Amos, 1998).

Metal Hydrides

Metal hydrides can absorb hydrogen at varying temperatures and pressures depending on the alloy. Metal hydride storage systems can operate at ambient and at high temperatures (> 200 °C) (Dutton, 2002). The former category is possible to be used for compression. When a hydride absorbs hydrogen at low pressure and is then heated up, it releases hydrogen at a higher pressure. Theoretically, metal hydrides can attain high densities and thus are very efficient. Specifically, the volumetric energy density is three to four times higher than that of a compressed vessel (Conte *et al.*, 2001). However, experimental results to date show that the storage densities are relatively low at about 3%wt (Veziroglu and Barbir, 1998). This technology is considered one of the safest hydrogen storage methods, mainly because the charging and discharging of hydrogen may occur at ambient pressure and temperature conditions (H-SAPS, 2001). The high energy densities, efficiency and safety of this method constitute incentives for further improvement.

The costs of metal hydride storage systems encompass the storage material, the pressure vessel, the heat exchanger and compressors, if they are necessary. For relatively small metal hydride storage system the cost is estimated between$820/kg of hydrogen and $60,000/kg (Amos, 1998). From the overall cost of this storage method, the cost of the hydride material is the main capital cost. This leaves no room for economy of scales. Thus, as the quantity of hydrogen required being stored increases, the metal hydrides cost increases as well making this method fairly expensive. Thus, metal hydride storage systems may be considered the suitable choice of storing small quantities of hydrogen.

Table 2.4 below summarizes the characteristics of the main hydrogen storage technologies.

Storage Method	Storage Technology	Technical Maturity	Technical Barriers	Cost	Suitability
Compressed Gas - Aboveground	- Large cylinders - Spherical containers - Long tubes	- Established Technology - Efficiency: 97-99%	Low storage density	-Relatively inexpensive for short-, medium- term and scale applications -Expensive for long- term and scale applications	Short- to medium- term and scale applications
Compressed Gas - Underground	- Salt, mined caverns - Aquifers - Depleted gas wells	- Established Technology - Efficiency: 97-99%	Applied only on suitable geographical regions	-Inexpensive for long- term and scale applications -Very expensive for small-, medium- scale and term applications	Long-term and seasonal applications
Liquid Hydrogen	Insulated cryogenic containers	-Proven Technology but not yet in widespread use - Efficiency: 45-80%	-Low efficiency -Energy consumption of liquefaction -Boil-off losses during storage and handling	-Inexpensive for long- term and scale applications -Very expensive for small-, medium- scale and term applications	Long-term and scale applications
Metal Hydrides	-Metals (lanthanum, titanium, magnesium) - Alloys	- Developing technology - Efficiency: 70-85%	-Relatively low storage density according to experimental results up to date	Fairly expensive	-Small scale applications -Applications where safety is the highest concern

Table 2.4: Characteristics of hydrogen storage technologies

Other than the aforementioned storage technologies, there are various methods possible to store hydrogen that are still far from commercialization but each one has certain advantages that justify the research attention of industry and research institutions. These include:

1. Carbon nanostructures

Hydrogen can be stored in carbon materials such as carbon nanotubes, carbon nanofibres, fullerenes, carbon onions and activated carbon. Carbon nanostructure storage method has been contemplated as an innovative hydrogen storage solution with the outlook of improving the volumetric and gravimetric energy density of storage systems. Two methods, in particular, have captured the attention of the research community, carbon nanotubes and carbon nanofibres (Conte *et al.*, 2001). Theoretically, carbon nanostructures are able to absorb considerable amounts of hydrogen but up to date experiments have not yet verified the theoretical predictions. Apart from the discrepancy between the theory and the experiments, there is an impressive variation in the experimental results of different research teams. In order for carbon nanostructures to be a viable hydrogen storage method, further research is necessary to decrease the deviation between theory and practice and to investigate their volumetric capacity and the adsorption/desorption mechanism (Atkinson *et al.*, 2001).

2. Sponge Iron

This method utilizes sponge iron (iron oxide) that reacts with hydrogen to form iron and water. The hydrogen can be recovered with the reaction of the iron with steam. The outcome of experimental results to date indicates that this method may have high energy density and low storage cost. However, it is still at research and development stage with demonstrations only on a laboratory scale (Amos, 1998).

3. Zeolites

Zeolites as a hydrogen storage method have not been yet greatly investigated. Hydrogen can be encapsulated in microporous media and reversibly retrieved from zeolites. The storage capacity of these materials mainly depends on the pore architecture and the composition of the zeolite used. Although zeolites have the potential of further improvement as a storage method by applying the modern techniques of zeolite synthesis and modification, it is unclear whether they will play a major role in hydrogen storage in the future (Weitkamp *et al.*, 1995).

4. Liquid Hydrides

Another developing method of storing hydrogen is the use of liquid storage in the form of liquid hydrides. Hydrogen can react with benzene to form cyclohexane. Then, hydrogen can be obtained by the use of a catalyzed reaction with membrane separation. Although this method allows hydrogen to be transported as a stable liquid, it has the disadvantages of involving toxic chemical and requiring complex recovery equipment (Amos, 1998).

5. Glass Microspheres

Hydrogen can be contained at very high pressures in small permeable glass microspheres and can be recovered by heating the microshperes. Although microspheres are permeable to hydrogen at high temperatures, they can store it at ambient temperatures (Amos, 1998).

6. Ammonia

Hydrogen can be reacted to form ammonia and it can be retrieved along with nitrogen using an iron oxide catalyst. This method has the advantage of high storage density. On the other hand, it has the disadvantages of using electricity to dissociate ammonia and being hazardous to handle (Amos, 1998).

2.5.3 Hydrogen Transport

Hydrogen can be transported using various methods such as truck, rail, ship and pipeline. The most favourable method for a specific application depends on the distance transported, volume transported, production method, cost and use

(Padro and Putsche, 1999). Currently, the most commonly used methods of transportation utilize compressed or liquid hydrogen.

Compressed Gas

Compressed hydrogen may be transported by high pressure cylinders, tube trailers, ship, rail and through pipeline. Utilizing high pressure cylinders has the benefit of higher energy density and the drawback of expensive vessels. Tube trailers could also transport hydrogen in lower pressures and are more suitable for small market demand (Amos, 1998). Apart from their use as a transport means, they can also be utilized as on-site storage. As tube trailers are suitable for small quantities, it could be favourable to use this transport method for the initial small scale production of hydrogen at the early stage of hydrogen's introduction in the transport system (Simbeck and Chang, 2002). Transporting compressed hydrogen by ship is technically viable but not economically beneficial due to the increase of stored hydrogen cost with the increase of storage time (Padro and Putsche, 1999).

Another possible way of transporting compressed hydrogen is through pipelines. Pipelines may either be dedicated hydrogen structures or modified existing natural gas pipelines. Piping systems are frequently several miles long. Due to their large length and thus high volume, changes in the system's operating pressure result in large change in the quantity of hydrogen contained in the system, making pipelines work as storage. With this method storage at the generation site or the delivery site may not be necessary (Amos, 1998). The capital costs of pipeline, which includes the pipeline itself and the installation, is determined by length of the system and the energy delivery rate. Although pipeline capital costs, compared with other methods, are high, they are most effective for transporting large amounts of hydrogen. This, in combination with the fact that once they are installed is fairly difficult to change their routes or capacities leads to the conclusion that this type of transportation is advisable when hydrogen would be widely used and it would be easier to determine the capacity and the location of a pipeline system, taking into account the possibility of future expansion (Simbeck and Chang, 2002).

Liquid Hydrogen

Liquid hydrogen transport methods mainly include cryogenic vessels and tankers, both of which have to be heavily insulated to reduce boil-off losses. The capacity of tankers ranges between 360 and 4,300kg of liquid hydrogen (Howes, 2002). The cost of liquid hydrogen transport is affected by the distance and the amount of transported hydrogen. In contrast with compressed hydrogen transport, liquid hydrogen transport is more attractive in the case of large quantities of hydrogen. Liquid hydrogen may also be transported by rail and ship. With both means, this method is more beneficial than compressed gas from an economic viewpoint (Padro and Putsche, 1999). Liquid hydrogen is also possible to be transported through pipelines that require high insulation, pumping and recooling. However, the feasibility of this method as a liquid hydrogen transport alternative is questionable (Zittel and Wurster, 1996).

The characteristics of the major hydrogen transport technologies are summarised in Table 2.5.

Transport Method	Technical Maturity	Technical Barriers	Cost	Suitability
Compressed Gas by Road	-Established technology -Efficiency: 90-95%	-Small deliveries per truck	-Relatively inexpensive for small quantities of gas and distances -Expensive for large quantities and long distances	Small quantities over short distances
Compressed Gas by Pipeline	-Established technology especially for modified natural gas pipelines -Efficiency: 99%	-Inflexible; routes and capacities cannot be easily changed	-Capital intensive -Needs large volumes of hydrogen to justify pipeline costs -Low operation cost	Large quantities or long distances
Liquid Hydrogen by Road	-Established technology -Efficiency:99% for transport and 50-75% for liquefaction	-Expense and inefficiency of the liquefaction process -Boil off losses	-Expensive for small volumes -Economic for large amounts of hydrogen	Large quantities over long distances

Table 2.5: Characteristics of hydrogen transport technologies

2.6 Review of Previous Hydrogen Infrastructure Studies

The potential and promise of hydrogen as a fuel have been universally acknowledged and constitute two of the main priorities of the scientific community of the energy arena. This is evident from numerous projects around the world that examine the viability and challenges towards switching from a carbon-based to a hydrogen-based transport system. In the USA, the EU and Japan billions of dollars have been invested into hydrogen initiatives planning to improve hydrogen technologies and propel them to the market. Automobile and energy companies grant even more billions to build the hydrogen fleets and refuelling stations.

The majority of previous studies on the design of hydrogen supply chains from well-to-wheel is focused on routes for hydrogen production from non-renewable energy sources, such as steam reforming of natural gas or electrolysis using non-renewable electricity. This general tendency is justified considering that in the near- to medium- term future hydrogen production will continue to rely mainly on fossil fuels. Comparing various studies, differences among the main findings of each study can be observed. This discrepancy is mainly due to the different assumptions that have been considered in every study. Moreover, national strategies for the development of a hydrogen delivery system vary considerably from country to country because of different national constraints.

Most of the hydrogen projects are examining one particular technology of the fuel chain such as the production conversion, storage and delivery of hydrogen instead of looking at the fuel chain as whole. Yang and Ogden (2007) have developed models to examine costs, emissions and energy use for different types of hydrogen transmission and distribution technologies. The aim of their work was to identify the factors that mainly determine the hydrogen delivery cost. Their results reinforce the idea that factors such as the demand and the delivery distance mainly affect the cost of the distribution system. Specifically, for very low demand the ideal transport technology is compressed gas truck while for long distances and moderate demand liquid transport is more appropriate. Moreover, for dense areas and large demand the preferred choice is pipeline delivery. This study is currently being extended to include production options in order to compare overall pathways.

An analysis with similar goals to the Yang and Ogden study is the work that has been carried out within the European Commission's Joint Research Centre by the Institute for Energy in the Netherlands (Castello *et al.*, 2005). This work is a techno-economic assessment of hydrogen transmission and distribution systems in Europe in the medium and long term. Its goal is to calculate the evolution and size of a hydrogen delivery system and the necessary investment in order to build it by 2050. The calculations are based on three scenarios that differ in the degree of development of the hydrogen market. In the case of the most optimistic scenario, which assumes a penetration of hydrogen of 70% in 2050, the preferred option for delivering hydrogen is the pipeline delivery or with trucks as a liquid. The latter option is becoming more dominant in the case of the other two more conservative scenarios.

There are many other studies that examine different components of the fuel chain (Hawkins, 2006; Altmann *et al.*, 2004; Ivy, 2004; Koroneos *et al.*, 2004; Friedland and Speranza, 2001; Adamson, 2004; Farrell *et al.*, 2003; Dutton, 2002) though it is worthwhile to mention two of them as they constitute the backbone for many studies on hydrogen technologies. Firstly, the study of Amos (1998) that estimates the hydrogen storage and transportation costs. In terms of storage this study compares the capital and operating costs over a range of production rates and storage times for compressed gas, liquid hydrogen, metal hydride and underground storage. According to the results, underground storage was the cheapest option and liquid hydrogen has some benefits over compressed gas for longer storage times. In the case of transportation, the methods that are considered are truck and rail compressed gas, metal hydride, liquid hydrogen and pipeline delivery. The costs are calculated for a range of production rates and delivery distances. Generally, for high production rates pipeline is the preferred option, while for lower rates liquid hydrogen is more attractive. This study is very useful as a reference point in terms of storage and transportation technologies because it includes in satisfactory depth the technical and economic characteristics of these technologies. However, it misses the hydrogen production cost in order to determine the total pathway cost or the delivered cost of hydrogen.

Secondly, Padro and Putsche (1999) carried out a survey on the economics of hydrogen production, storage, transport and end-use technologies. This study provides a good reference for every component of the fuel chain, though it does not include novel technologies. Although a considerable amount of technical information was taken from these two surveys, their economic contribution was fairly restricted due to the existence of more recent studies. However, sometimes this was led to a vicious cycle as many recent studies are based on the findings of these two surveys.

A considerable body of literature focuses on the study and comparison of fuel chains as a whole. Various studies have analysed the technical status and cost of hydrogen pathways (Tzimas *et al.*, 2004; E4tech, 2005; Chen *et al.*, 2005; Hyways, 2004; Eyre *et al.,* 2002; Myers *et al.*, 2003). To examine the regional hydrogen infrastructure development a static approach, which includes steady state pathway simulation that assumes a fixed hydrogen demand is usually adopted. Although this approach, with or without optimisation, is straightforward it does not consider the dynamics of the infrastructure over time and how transitions from one pathway to another should take place as market conditions change.

Considerable work on hydrogen activities has been carried out in the USA. Ogden (1999) examined five hydrogen supply options for fuelling passenger vehicles in Southern California. These options included hydrogen production from natural gas in a centralized plant with truck delivery as a liquid or small scale gas pipeline delivery to the refuelling station, chemical industry sources as a by-product, small scale reforming of natural gas or small scale electrolysis both at the refuelling station. The cheapest method was found to be the delivery of liquid hydrogen produced at a centralized plant at $20-30/GJ. Schoenung (2001) has conducted a similar study, but also included partial oxidation at the refuelling station and compressed gas delivery by road. The most cost-effective route was found to be the delivery of liquid hydrogen produced at a centralised facility, at just under $20/GJ. Another work of interest is the cost analysis of Thomas and co-workers (1998). In this study a comparison of hydrogen delivery cost was performed for various manufacturing and distribution options. Moreover, the potential for cost reductions through the economies of scale was examined by varying the hydrogen demand and the size of the production units. According to this study, the difficulties developing a hydrogen infrastructure could be surmounted by incrementally adding small scale electrolysers and reformers to meet the increase in fuel cell vehicle sales.

Fewer studies consider large-scale systems for supply of hydrogen from renewable sources. Mann *et al.* (1998) conducted a techno-economic analysis of hydrogen production from wind energy, solar energy and biomass. The analysis of hydrogen from solar energy consisted of direct photoelectrochemical conversion of sunlight and photovoltaic technologies. In the case of wind energy, wind-based electricity was used to produce hydrogen through electrolysis. The study examined the economic viability of these technologies by exploring four different scenarios. The factor that determined the cost-effectiveness of each technology was whether the renewable system was coupled to the electric grid. The results concluded that the photoelectrochemical conversion of sunlight had the potential to be economically more attractive than the PV and wind systems, if the latter were not connected to the utility grid. In the case they were connected to the grid, then along with hydrogen electricity could be produced as a co-product and could be sold at peak prices to customers. This scenario improved the economic feasibility of the PV and wind systems. The analysis of biomass-derived hydrogen included low pressure gasification, high pressure gasification and pyrolysis. According to the results, the first system had the greater economic potential. The other two systems required negative-priced feedstocks to be within the range of market values.

GM (LBST, 2002) has carried out an extensive well-to-wheel study, comparing 32 different fuel chains, both renewable and non-renewable, along with 56 alternative options with respect to their greenhouse gas emissions and energy efficiency. The results showed that the combination of hydrogen produced from renewable sources with fuel cell powertrains could considerably reduce greenhouse gas emissions while improving fuel supply diversity. Simbeck and Chang (2002) analysed the economics of 19 different fuel chains; 15 of them included large-scale central production facilities utilizing various feedstocks, such as natural gas, coal, biomass, petroleum coke and electricity, with both liquid and compressed gas hydrogen distribution technologies being considered in their options. The other 4 used small-scale reformers and electrolysers at the refuelling station. The central large-scale production from natural gas with liquid truck distribution was found to be the option with the lowest delivery cost. This study included steady state simulations and thus excluded the dynamics of the infrastructure over time. Myers *et al.* (2003) have conducted a project that was focused on the development of a technically feasible pathway to supply 10 quads per year of hydrogen produced from renewable energy sources for transportation uses in the years 2030 to 2050 in the USA. According to the results of this study, such a pathway was achievable and leaded to a national average hydrogen delivery cost of $3.98/kg. From the renewable energy sources spectrum, wind and biomass were the most important resources that would play a significant role in the production of hydrogen.

Apart from the USA, research interest in hydrogen infrastructure issues is growing around the world. Mercuri *et al.* (2002) have carried out an Italian study developing a fuel cell vehicles penetration scenario based on a penetration of 2 million cars by 2015 and 60% of the parc could be fuel cell vehicles by 2030. The study included large-scale steam reforming, on-site reforming and electrolysis with both liquid and compressed gas hydrogen options considered. All the fuel chains were found to have future market potential. In the short-term, large-scale steam methane reforming could supply a considerable part of the fuel demand, while on-site steam methane reforming appeared to be the most attractive option to supply a fuel cell vehicle mass market. Electrolysis could become an attractive option if it could use renewable electricity at relatively low cost. Sorensen *et al.* (2003) has examined possible scenarios for a transition to a hydrogen society based on renewable energy sources for Denmark. As far as transportation is concerned, the general conclusion of the analysis was that it is possible to meet the entire transport demand by renewable hydrogen and methanol. By 2030, slightly less than 80% of the transport energy could be converted to hydrogen and methanol (with three-quarters of the former), while the remainder would be covered by gasoline and diesel fuels. The predominant renewable resources that would be used for the production of the fuels would be wind energy and biomass.

Ewan and Allen (2005) analysed and compared 14 hydrogen pathways including fossil fuel, nuclear energy and renewable sources routes based on criteria such as carbon dioxide emissions, resource availability, land use implications and production costs. The study emphasized the implications of each pathway, the limitations and strengths of certain technologies and the areas in which technological advances are mostly needed. A Japanese study has examined the technical and economic feasibility and the reduction of carbon dioxide emissions by developing a hydrogen infrastructure using off-peak power in the existing electrical power. The infrastructure cost was found to be 0.12 trillion yen/year (around 1.008 billion US $/year) in 2020. In terms of carbon dioxide emissions, fuel cell vehicles using hydrogen that has been produced from electrolysis utilizing off-peak electricity could achieve 37% reduction in carbon dioxide emissions compared with the internal combustion engine private cars running on gasoline (Oi and Wada, 2004).

The Energy Research Centre of the Netherlands has developed a model for examining the development of a hydrogen pipeline infrastructure for the Netherlands. The model divides Netherlands into 40 regions aiming to calculate for each one the development of hydrogen demand for automotive and stationary applications and to examine per region the economic feasibility to construct a hydrogen infrastructure between the year 2010 and 2030. The calculations, based on the assumption of fuel cell cost of 180 €/kW in 2030 and representative assumption on hydrogen and infrastructure cost, showed that the infrastructure could expand to around half (18 of the 40) regions by the year 2030 (Smit *et al.*, 2005). Greene *et al.* (2005) has developed a model capable of simulating the market transition to hydrogen aiming to produce possible scenarios for the transition. The project focuses more on vehicle choice rather than on infrastructure issues relative to technical options and infrastructure design.

Hugo *et al.* (2005) have used mixed integer linear programming to build a model in order to determine the optimal design of a hydrogen supply chain network in terms of both economic and environmental criteria. The features and capabilities of their model are illustrated in a case study, which includes an idealised network of 6 demand centres and 6 central production sites that include existing refineries, chemical complexes and natural gas compression stations. This limits the type of technologies that are allowed to be installed there. Moreover, the model does not explore the resource potential for the production of hydrogen and gives small attention to the spatial details. As this case study is a plain and simplified infrastructure design problem, it may not be argued that the model could support more complicated problems. More specifically, this model may be considered as an equation template that can be applied to cases similar to the case study for something more advanced or completely different from this case study either these equations are not applicable or not enough. For example, in the case it is desired to develop a hydrogen infrastructure in order to supply hydrogen to a geographical region like Venice in Italy that contains water channels instead of roads this model in not applicable.

A similar approach with Hugo *et al.* is followed by Almansoori and Shah (2006). This study examines the design of a hydrogen supply chain network using mixed-integer linear programming. The difference between that work and the work of the present study is fourfold. Firstly, Almansoori and Shah study does not include resource optimisation that constitutes a feature of the present study. Secondly, their supply chain network is presented as a steady state 'snapshot'. Thirdly, Almansoori and Shah carried out the generation of the hydrogen network using mixed-integer linear programming while the present study includes a number of different technological fields such as XML, image processing, MILP and MATLAB. Lastly, there is a difference in the way the geographical region under study is divided. The segmentation method is described in detail in Chapter 4.

A lot of different scenarios have been proposed and are under discussion for a possible future hydrogen production and distribution infrastructure. Eames and McDowall (2005) have produced 6 different scenarios for the development of hydrogen energy systems in the UK. These scenarios differ in the end-uses of hydrogen, the production and storage technologies and the degree of centralisation/decentralisation of hydrogen production and supply. The scenarios were created based on extensive review of literature, a UKSHEC hydrogen visions stakeholder workshop and a series of interviews with experts on hydrogen area. Watson *et al.*, (2004) have carried out a similar work with a fairly different approach. This work includes the elaboration of various possibilities for a hydrogen economy in the UK that range for a scenario in which there are no explicit drivers for hydrogen to a scenario in which hydrogen plays the major role in the energy system. These scenarios are used to model different fuel chains in order to achieve a hydrogen energy system for 2050. These studies are intended for a national perspective without as much attention to spatial details such as a geographical representation of a hydrogen transport infrastructure including location and distribution of demand centres or production sites and related transport distances.

An interesting analysis of the integration of hydrogen into energy systems is a German study focused on the comparison and evaluation of different hydrogen pathways in terms of both economic and environmental criteria and their integration into the German energy system (Ball *et al.*, 2007). Their method includes the development of a linear programming model aiming to determine the cost-optimal way to build up a hydrogen supply infrastructure within Germany until 2030. Their model has been developed based on the BALMOREL model, which supports analyses of the energy sector in the Baltic Sea region. This is an ongoing study and its results have not yet been published. It is worth mentioning that their approach includes the application of a Geographical Information System for estimating average transport distances between and within the area of the model for pipeline and trailer hydrogen delivery. With this approach, they tried to incorporate a feature that is generally excluded from relative studies, that is an appropriate geographical representation of a hydrogen infrastructure such as the location of demand centres or transport distances, modes and costs.

According to a considerable amount of literature, the issue of the development of a hydrogen infrastructure is addressed by means of linear programming. Dynamic programming has also captured the attention but is still an on-going effort to improve its applicability to large scale problems such is the design of an infrastructure (Secomandi, 2001; Godfrey and Powell, 2002; Powell *et al.*, 2000; Powell and van Roy, 2004; Powell *et al.*, 2004). Lin *et al.* (2006) have developed a model, the Hydrogen Infrastructure Transition (HIT) model, and applied it to the case study of Beijing. HIT is a dynamic programming model that determines the cost-effective way to develop a hydrogen infrastructure in terms of costs, carbon externalities and refuelling travel time. The main aim of their report is the presentation and capabilities of HIT model in addressing the infrastructure development problem. However, the selected case study is a rather simple infrastructure problem judging not only from the limited number of pathways under examination, that are five, but also from the fact that the focus is more on the last step of the fuel chain which is the distribution of the fuel in the city than on the other stages of the fuel chain. Considering though the difficulty and complication of solving a large scale problem with dynamic programming justifies the size of this case study. Thus, in terms of the distribution of the fuel within a city this approach succeeds in capturing the dynamics of the fuel dispersion system within a city-specific context.

From the nature of the hydrogen infrastructure development problem and the vast amount of relative literature it may be concluded that modelling is essential to understand how hydrogen infrastructure can be efficiently developed and deployed. Modelling the design of a renewable hydrogen infrastructure offers the necessary decision framework in order to make the successful transition of infrastructure development from conceptual idea to reality. The necessity of modelling stems from the benefits it offers some of which are:

- Replacement of real systems;
- Accessibility;
- Appropriateness for experiments;
- Appropriateness for observation (eg long time horizon);
- Intensive dynamics (eg sensitivity analysis);
- Full control;
- Virtual environment;
- Virtual time.

The use of an optimisation approach may provide a springboard for the development of a hydrogen infrastructure. Especially at the moment that the transition to new environmentally benign fuels is at a crucial point making its first steps, modelling may be used as a tool for exploring the optimal way forward and trade-offs between different routes and thus be of vital importance for policy makers before deciding their strategy concerning the introduction of hydrogen fuel.

2.7 Conclusions

Hydrogen is not a new concept. It has been suggested as a solution to the depletion of fossil fuels and the environmental effects of the burning of these fuels more than thirty years ago. Recently, it has captured increasing attention as the irreversible damage of the environment caused by the use of fossil fuels in conjunction with the security of energy supply force towards a more sustainable energy system.

Hydrogen constitutes an attractive alternative to current fuels in transportation as it holds the promise of freeing the transport sector from carbon. As hydrogen during combustion is almost free of polluting emittents, its environmental benefits strongly depend on the way of production. Although fossil fuel derived hydrogen produces less harmful emissions than conventional fuels, it limits the extent to which these emissions can be reduced. Fossil fuels as a hydrogen source eliminate most of the benefits offered by hydrogen. In order hydrogen to fulfil its promise as an abundant, available and sustainable fuel, hydrogen from fossil fuels shall not be considered as the ultimate alternative to the current fuels but as an interim step to a more sustainable transport fuel, that of renewable hydrogen.

The introduction of a new transportation fuel requires the development of a refuelling infrastructure. However, the development of a new infrastructure is a challenging, uncertain, and slow process, largely due to the difficulties associated with major changes in the social and economic systems. For this reason, Governments should play a catalytic role in hydrogen's uptake by providing policies to support and promote its infrastructure development and fuel cell vehicle market simultaneously. Certainly, some countries are more advanced in the hydrogen activities and their Governments are more supportive than in other countries. However, generally it can be concluded that hydrogen is gradually climbing the energy priority agendas worldwide and this is evident by the increasing commitment to it by the Governments. From nearly mentioned at previous policy frameworks, hydrogen has started asserting its own section.

Considerable amounts of funding are granted worldwide to research and development of hydrogen activities. These activities include both the infrastructure components, that are necessary to deliver the fuel, and the vehicle powertrain, that use the fuel. There is a considerable variety of technologies that can be used for developing a hydrogen delivery system. The technology options available for each stage of different fuel chains differ in technical, economic and environmental characteristics. Apart from these characteristics, they also vary in terms of current status and potential. Some technologies are mature and widely used, others are still at the development stage and others are in the transition from a proven technology to one in widespread use.

Apart from the development of hydrogen technologies, substantial attention has been given to study the most effective way to develop a hydrogen infrastructure. Most of the approaches include the creation of models or the improvement of already existing ones in order to compare different pathways mainly in terms of costs but also in terms of technical maturity and CO_2 emissions. Generally, probably it is more constructive to compare their methods than their results, as the latter are more difficult to be compared as every study has its own specifications and assumptions. By comparing their results, it may be concluded that there are many ways to develop a hydrogen infrastructure and the most effective one depends on the national strategy and the location. Naturally, there are some results and conclusions that may be considered general but these are mainly relevant with the comparison of individual components of the fuel chain, for example the fact that liquid hydrogen delivery is more economical for large volumes of hydrogen and long distances than compressed gas delivery, which becomes more attractive for shorter distances. By comparing their approaches, it could be deduced that there are some general tendencies that seem to be followed to address the infrastructure development problem but what overall determines the methodology is the key questions desired to be answered and the degree of in-depth analysis.

These studies were reviewed and used as a starting point, an inspiration and a way towards originality. By examining them the approach that was selected for addressing the infrastructure problem of this thesis was formed. This approach is described in Chapter 4.

CHAPTER 3

Methodology

3.1 Introduction

In order to achieve the goal of the present study a procedure consisting of multiple sequential steps was necessary to be followed. This Chapter provides an overview of the steps of this procedure. Every step comprises a task that has been carried out in this study. Figure 3.1 illustrates the main stages of the approach.

3.2 Problem Articulation

The first and probably the most important step in the problem's resolution process is the definition of the problem. The problem of this study was addressed by means of modelling techniques. The clarity of the question intended to be addressed is fundamental for the usefulness of the model. A successful model is a comprehensive and simplified but meaningful representation of reality. The literature review that was described in the previous Chapter comprised the basis of forming the research question and developing a suitable method to answer the research question. The research question has been stated in Chapter 1 and comprises the problem of determining which is the least-cost way to develop a renewable hydrogen fuel infrastructure.

3.3 Conceptual Model Development

Once the problem is clearly posed, the next step is to identify the key variables or parameters necessary for answering the question and to set the time horizon. This step produces the conceptual model. For the present problem, a long time horizon was chosen. The selected time framework was 50 years. This choice was emanated from the nature of the problem. Switching from conventional fuels to hydrogen fuel and building an infrastructure to accommodate this transition is clearly a problem that extends to the next few decades.

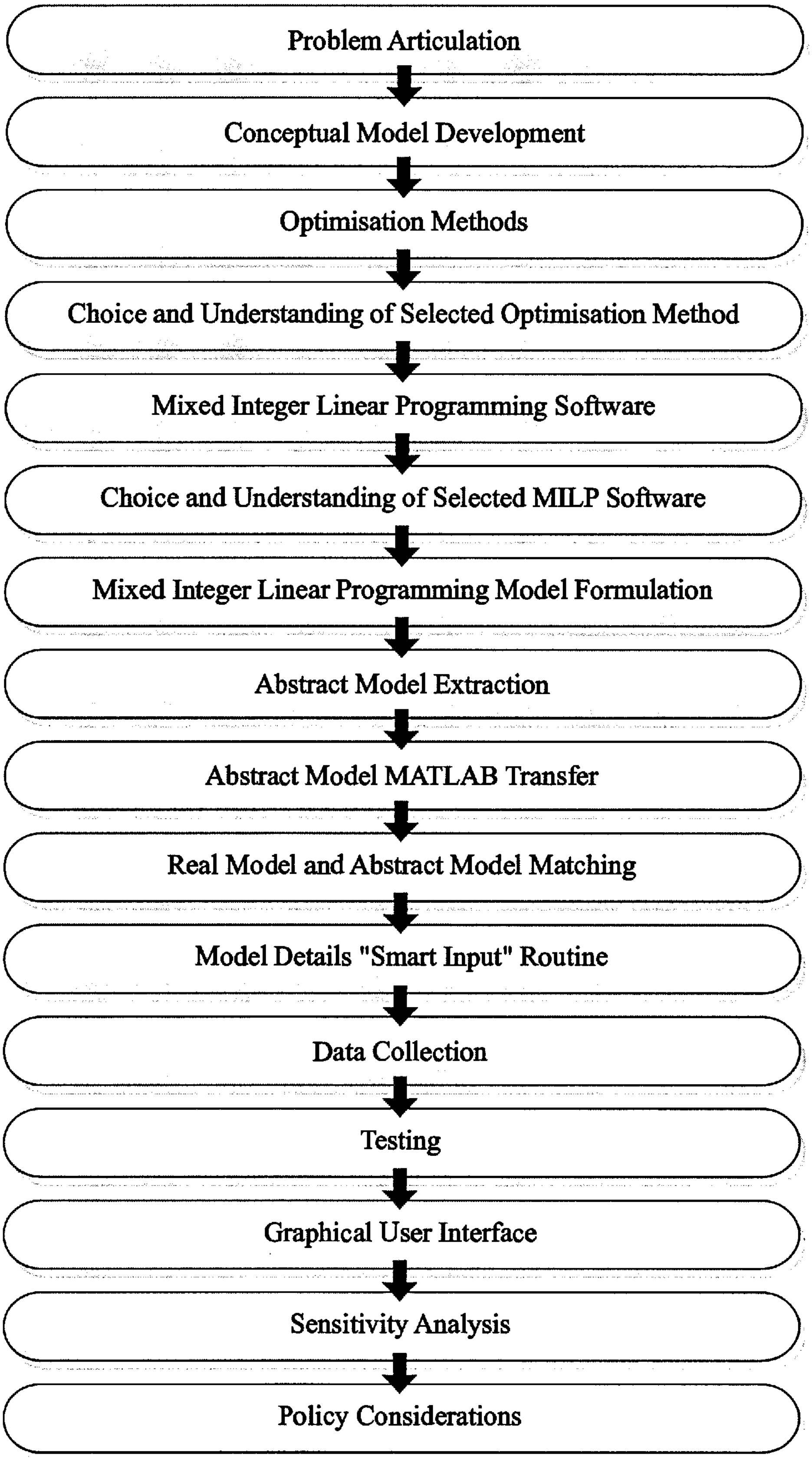

Figure 3.1: Methodology

3.4 Optimisation Methods

The assessment and comparison of different fuel chains are conducted considering the cost as the decisive factor. Thus, the issue of the development of a least-cost renewable hydrogen infrastructure is addressed by means of optimisation techniques. More specifically, the identification of the most cost-effective infrastructure development plan is treated as a cost minimisation problem. In this optimisation problem the aim is to minimize the cost function, objective function, by systematically choosing the values of real or integer variables from within an allowed set.

Optimisation problems usually involve three constituents; An objective function which is desired either to be minimized or maximized, a set of unknowns or variables that affect the value of the objective function and a set of constraints that let the unknowns to take on certain values but excludes others. The solution of the problem is to find the values of the variables that minimize or maximize the objective function while satisfying the constraints (NEOS Guide, 1996). As shown in Figure 3.2 optimisation is divided in various subfields.

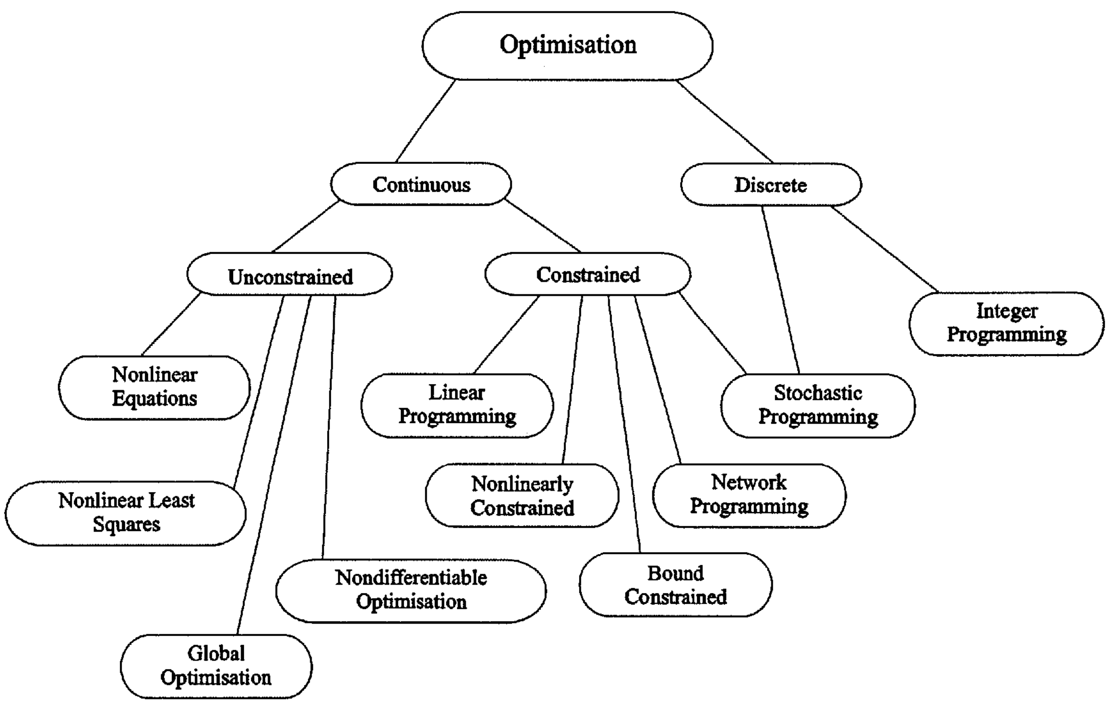

Figure 3.2: Optimisation Tree (NEOS Guide, 1996)

The suitability of an optimisation method is determined by both the algorithm and the model size. The chosen optimisation method for the present problem is described and justified in Chapter 4.

3.5 Optimisation Software

Thanks to the advances in computing of the past decade, there is no shortage of software available for solving optimisation problems. Modern optimisation software is divided in two packages: the algorithmic codes and the modelling systems. Algorithmic codes are designed to find optimum solutions to particular programs. A code is formed in such a way so as to take as input a compact listing of the constraint coefficients and to return as output a similarly compact listing of optimal solution values and related information. Algorithmic codes can either be free or commercial products. Large-scale codes depend on general-structure sparse matrix techniques and several other sophistications through years of experience that makes them fast and reliable but simultaneously expensive. On the other hand, free codes may be an economic option but are usually less robust (Optimisation Technology Centre, 2005).

Modelling systems assist in formulating optimisation problems and evaluating their solutions. Generic algorithms are already provided in modelling systems. For this reason, the input and output of modelling systems are in a comprehensive and convenient form. The majority of modelling systems support several algorithmic codes, while only the most popular codes can be used with many different modelling systems. Modelling systems are commercial products and reasonably expensive and can vary greatly in design and capabilities (Optimisation Technology Center, 2005). From the different software tools that have been developed for optimisation problems, the selected software along with the reasons for this choice are described in Chapter 4.

3.6 Modelling

Having decided the suitable approach for dealing with the problem in terms of the modelling technique and software the next step is the actual modelling process. This process begins with formation of the mathematical model. It involves the transition of the problem from a conceptual idea into a complete mathematical model with equations for decision rules and behavioural relationships, parameters and constraints. This is achieved by aggregating all the necessary variables and parameters and finding all the possible fuel chain options. By completing this step, the general form of the equations of the model is obtained, namely the objective function and the constraints to which it is subject to. Formulating the model is itself a very useful source of insight, as it assists in recognising vague concepts that might remain unnoticed throughout the conceptual phase.

The next stage involves the construction of the abstract model. This principally means the formation of the superstructure, which is the basis of the model. The superstructure has to be built in such a way so as to be able to support all the possible fuel chain options. For this reason, the most complicated fuel chain option is used in order to form the superstructure. The superstructure serves in accomplishing two objects. Firstly, it minimizes the required code and thus saves time. Secondly, and most importantly, it gives to the model the possibility of being generic. The advantage of generality is valuable as it offers the ability not only to be expanded but also to support numerous different scenarios. This broadens the applicability and use of the model making it suitable not only for London but for geographic locations with different characteristics. This leads to the effectuation of a general framework that may be used to solve relevant problems for different urban centres, which is the central objective of this study.

After formulating the superstructure, the abstract model has to be transferred into the selected optimisation software. This transfer has to be done in such a way so as with the minimum possible number of substitutions the superstructure to be able to take the form of any fuel chain. Every feasible fuel chain is crucial to be able to be described by the superstructure. At this stage, the construction of a "clever" way is necessary in order to feed into the selected software the structural details of the system such as the different types of renewable energy sources for the primary energy feedstock stage.

3.7 Data Collection

The collection of the information and data that feed into the model has been achieved mainly by means of literature and commercial information review. This collection was essential to be frequently updated because in the course of three years many changes may be occurred. This was particular true in the case of relatively new technologies that constantly change characteristics and costs. Considering the theme of this problem, revised data were imperative as the majority of the technologies are relatively or completely new. With respect to obtaining data, the collection of data concerning the economics of the technologies was quite difficult. This difficulty was mainly to due the reluctance of the companies and organizations to reveal the costs of their technologies. The complexity of this problem was reinforced by the existence of certain technologies that are quite novel and their cost data were unobtainable. To deal with this problem at certain points ranges of values were used as input variables.

3.8 Testing

In order to check the consistent behaviour, the credibility and the robustness of the model, testing is necessary. Testing is a critical tool to discover whether they are any flaws in the model and set the stage for improved understanding. There are two kinds of testing applied in this case; one for the model building process and the other for the obtained results. Chapter 5 describes in detail the testing process that was used to check the model.

3.9 Graphical User Interface

The hydrogen infrastructure model has been developed with emphasis on its ability to be applied to any urban centre. Hence, the import of input data and the export of output data were created in such a way so as to be used and understood by any user and not just the developer of the model. For this reason, the creation of a graphical user interface (GUI) is necessary. The GUI is the mode of interaction between the user and the model. The setting of the parameters of the model and the presentation of the results are implemented in GUI. The explicit description of the construction and use of the GUI is presented in Chapter 4.

3.10 Sensitivity Analysis

In some situations the values of the model data are not known with absolute certainty. In order to deal with the uncertainties in the input data, which is translated into uncertainties in the output of the model, the analysis known as sensitivity analysis of the effects of data changes on the optimal solution is necessary. Sensitivity analysis offers the benefits of measuring the impact on the model outcomes of changing parameters about which there is uncertainty. Such an analysis is carried out after the complete construction of the model and can be divided into parametric and structural sensitivity. The former deals with changes in the parameters of the system and will be carried out systematically for all input parameters. The latter involves several different structural options for the construction of the model. This type of analysis has been performed qualitatively during the stage of the model design. The model has been built in such a way to allow the variation of parameters and the comparison of the costs of hydrogen and capital investment required for each fuel chain option. Therefore, the results would be able to show the effect of uncertainty in projecting future components costs on future hydrogen costs. The uncertainties in projected costs of many hydrogen technologies may well be significant considering their early stage of development and commercialisation. Moreover, the results would demonstrate which of the component costs have the greatest effect on the economics of hydrogen.

3.11 Policy Considerations

The development of a fuel infrastructure is a complex and large capital investment venture. In the case of hydrogen this venture becomes more difficult as the few private benefits of hydrogen fuel make its widespread use almost impossible without drastically different market conditions and new policies.

The creation of an infrastructure for a new transport fuel is bedevilled by a classic 'chicken and egg' problem. On one hand, vehicle manufacturers are reluctant to invest in hydrogen vehicle production facilities unless there are adequate refuelling stations. On the other hand, fuel supply companies are unwilling to invest in a completely new fuel infrastructure unless there are a sufficient number of vehicles on the road for utilizing it. Government intervention would play a catalytic role in assisting in resolving this problem. This intervention should include co-ordinating policies to simultaneously stimulate the hydrogen vehicle market and develop a hydrogen infrastructure.

The hydrogen infrastructure model is used in the case of London examining the least cost renewable hydrogen infrastructure development plan. The results of this simulation form the basis for a policy discussion mainly focusing on how the Government may assist the introduction of hydrogen fuel and what are the key barriers to the establishment of a hydrogen infrastructure. Moreover, the policy discussion includes the suggestion of policy options that may influence and promote the uptake of hydrogen fuel making a renewable hydrogen infrastructure a more attractive and thus viable option.

3.12 Conclusions

This Chapter described the methodology that has been selected in order to solve the problem of the renewable hydrogen infrastructure development. All the stages that constitute the chosen approach are described and explained in detail in the subsequent Chapters.

The next Chapter presents the first stage of the methodology, the literature review. It establishes the necessary background with the purpose of developing an understanding of the issues pertinent to hydrogen infrastructure development.

CHAPTER 4

Model Development

4.1 Introduction

This Chapter describes the development of an algorithm to address specifically the options for supplying renewable hydrogen to urban centres. The structure of the algorithm is fully explained and the definition, usefulness and formation of every step of the algorithm are explicitly described. The first part of the Chapter presents the scope of the model and the tools that have been selected to create the algorithm along with the justification of their suitability. The Chapter continues by adding further detail to the features, inputs and outputs of the model. The equations and assumptions that lie behind the conceptual model are explained. As an understanding of the maths should not be essential for the user of a policy modelling tool, an understanding of the choices and assumptions made in the model design is fundamental for the appreciation of the results[1].

[1]The developed model has been written and presented as a paper, entitled: *Modelling the design of a renewable hydrogen fuel infrastructure for urban centres.* The paper was presented at the European Modelling Symposium (Parissis, 2006) describing the new modelling tool mainly focusing on the original and valuable contribution it may provide to the field of simulation while also showing its usefulness to the infrastructure development subject.

4.2 Scope of the Model

The question aimed to be explored within the modelling context is which is the most economical way of developing a renewable hydrogen infrastructure in order to substitute a certain percentage of automotive fuel by hydrogen. As it has been concluded from the review of other hydrogen infrastructure development modelling works, there is not a single answer to the infrastructure development question. The best way to build up a new fuel infrastructure varies considerably from country to country due to different national constraints and strategies. These factors determine to a great extent the modelling approach.

Apart from these factors, another factor that affects the modelling approach is the extent of in-depth analysis they desired to carry out. The design of a fuel infrastructure is a difficult and complicated venture that includes a lot of uncertainties and several parameters that need to be taken into account. A model is by definition a simplification of a possible reality. Thus, the more parameters a modelling study includes the more valuable results may achieve, as the model may be considered closer to reality. However, it is almost impossible for a model to incorporate all the parameters that may be included in the development of an infrastructure in reality, some studies include more parameters than others or focus on different parameters than others.

The model of this study tries to address the infrastructure development problem by evaluating various hydrogen supply pathways in terms of both economic and technical criteria while allowing the timing of the investment to account for changes in the market conditions, in order to identify the least-cost renewable hydrogen infrastructure development plan. To produce this plan, the model establishes and investigates a number of operational, spatial and temporal decisions that include:

- the required renewable energy resources;
- the location and number of all the necessary facilities (renewable energy sources and hydrogen production plants);
- the most suitable technologies for all the stages of the fuel chains;
- the expansion and/or "shut down" of the fuel chains;

- the switch from one fuel chain to another;
- the growth of the infrastructure over time in order to meet increasing levels of demand;
- the overall cost for the least-cost plan.

These decisions are taken considering the cost as the decisive factor and thus lead to the creation of a cost-optimal hydrogen supply network scenario. The model that supports the design of a renewable hydrogen delivery system is developed with particular attention to three points. Firstly, its *originality* both in terms of the design and the way it addresses the infrastructure development issue. This attribute is described and explained in detail in the subsequent sections. Secondly, its *generality* as it provides a general tool with applicability to a wide range of different geographical areas that is not based on a fixed structure of inputs but the structure can be tailored to suit the conditions and the data available in each area. Thirdly, its *potential* to include a large number of parameters depending on how much in-depth a simulation is desired.

4.3 Structure of the Algorithm

It is important at this point to clarify the sense of two words that are greatly used throughout this thesis in order to avoid any misunderstanding. These words are the algorithm and the model. The former is used to describe the whole procedure that has been followed in order to answer the research question, that is which is the least cost way to develop an infrastructure in order to supply hydrogen fuel to urban centres. The latter is the mathematical model, which includes the equations, and is implemented in the software that has been created in MATLAB. So, the one is the procedure and the other the equations. The model is part of the algorithm. This can be seen in Figure 4.1. Figure 4.1 illustrates the algorithm that has been developed in this study to address the infrastructure development issue.

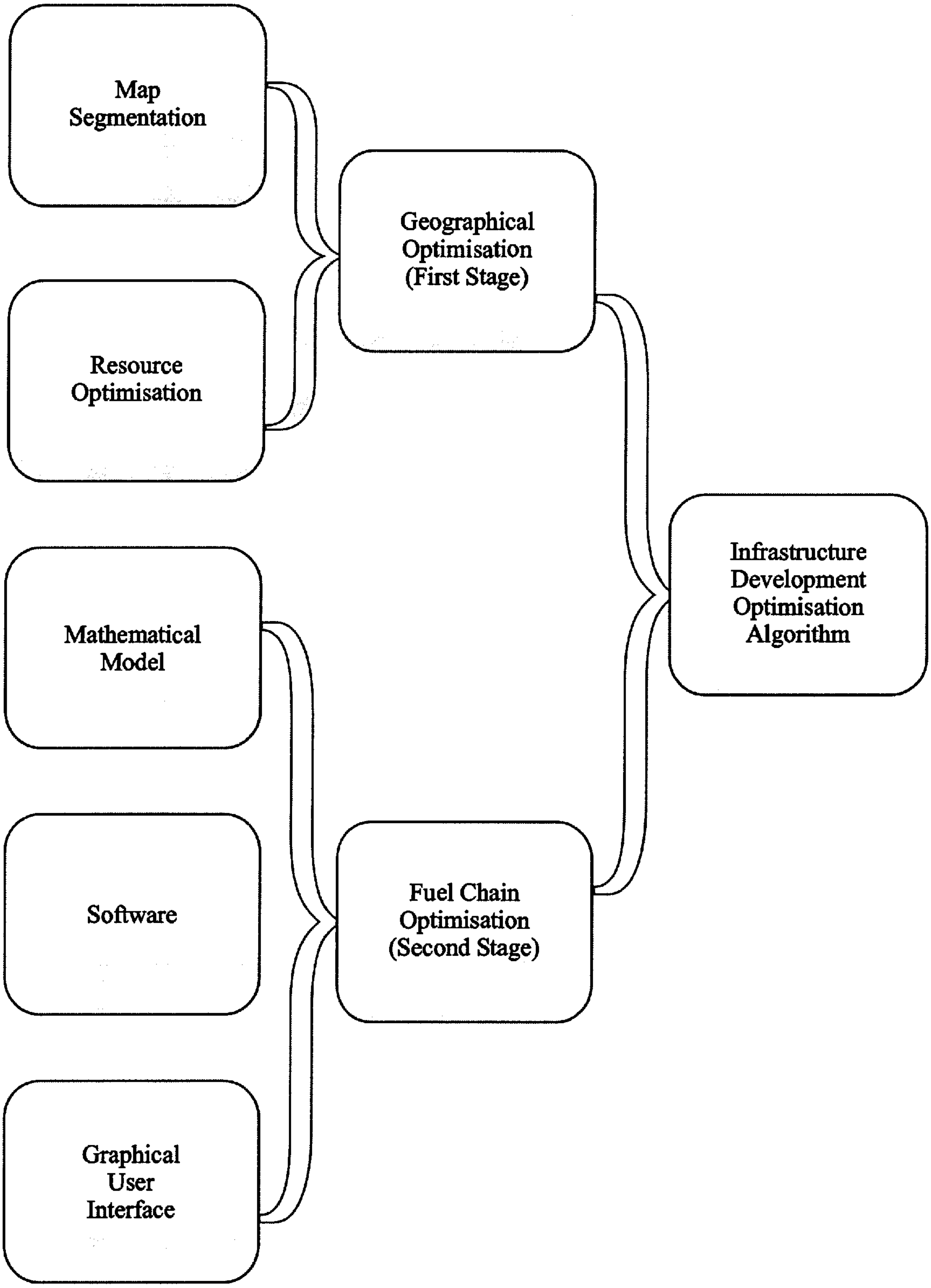

Figure 4.1: Algorithm addressing infrastructure development problem

As it can be witnessed from Figure 4.1 the problem has been treated as a two-stage linear programming problem. In multi-stage linear programming a problem is broken into subproblems that each one is solved in sequence and thus the results of each subproblem are used for the subsequent one. The two-stage linear programming problem of this study includes the geographical optimisation stage and the fuel chain optimisation stage. The combination of these stages constitutes the infrastructure optimisation algorithm.

The geographical optimisation stage, which is firstly executed, includes the map segmentation and the resource optimisation. The former as its name denotes is the step in which the map of the region under study is divided into areas. This division is not abstract; it is based on the renewable resource potential of the region, for example in the case of wind energy it is based on the wind speed of every point of the region, and it separates the region into a number of equal (in terms of renewable resource potential) parts. This segmentation method of dividing the region into areas that have the same renewable resource potential has the advantage of creating areas of equal renewable energy exploitation capabilities.

The next step is the resource optimisation. The aim of this step is to determine the optimal sites that may be used for the establishment of renewable energy plants. As the region is segmented in a number of areas, every area has a set of values, for instance in the case of wind energy every area has a range of wind speed values and thus has good and bad possible wind energy sites. Naturally, if the region is segmented into numerous areas and thus every area is very small the area will have only one value. For all other cases, the best value is determined, the site with the higher wind speed in the wind energy example. In case one area has the same value in more than one points the optimal site is determined by another factor that is the proximity of the site to the demand centre. The site closer to the market prevails over the others.

The second stage comprises the mathematical model, the structure of the software that implements the model and the GUI. These steps are described in detail in subsequent sections. This stage aims to determine the optimal delivery pathways. Thus, as the first stage determines the optimal starting points of the fuel chain, that is the primary energy feedstock production, and the second stage determines the optimal pathways their marriage produces the optimal infrastructure development plan.

This two-stage linear programming problem has been implemented both in an online and dynamic fashion. Online algorithms are algorithms that treat a problem as a sequence of static problems. They are basically myopic models that do not take into account any anticipation for the future. In the myopic approach the objective function used for the optimisation is sequentially carried out on a year-by-year basis for the whole region each year. Thus, the problem is divided into static subproblems and considering a linear representation the subproblems are solved for the whole time horizon.

The first stage of the problem is static by choice without this choice restricting its results as the geographical optimisation does not require a dynamic approach. The second stage is static for every subproblem and thus does not include a dynamic programming model. However, the model is a time-variant model or a dynamic model or even better a linear programming model with dynamic elements.

4.4 Selection of Tools

4.4.1 Selection of Optimisation Method

The need for a model to investigate the integration of hydrogen into energy systems has been identified from a critical review of the previous modelling works. The specification of the model of this study ensued in part from the results of this review. The modelling approach is selected firstly because a computer model can simulate an abstract model of a particular system and gain insight into the operation of this system and secondly for some problems, such as the design of a new fuel infrastructure, the only way of obtaining possible solutions is by designing a program to imitate a system. Usually, the modelling of a system includes a mathematical model that aims to find solutions to the problem and thus enables the prediction of the behaviour of the system from a set of parameters and initial conditions. Computer simulations build on and are a valuable addition to purely mathematical models.

Up to now, there have been limited mathematical models that describe and integrate all the components of a hydrogen infrastructure within a single framework. Moreover, a generalised framework to infrastructure modelling applicable to different situations has been hardly investigated. In this study, the issue of the infrastructure development has been addressed by using a mathematical model formulated as a linear programming problem. The reason for choosing linear programming is manifold. The justification of this selection is presented by describing the advantages of this method, its suitability and its prevalence over alternative methods.

LP is greatly used in logistics, transportation, finance, management and many other applications. It is the most used program in many areas, despite it has a number of arguments against, something that is true for every method, there are some solid reasons which lead to select this solving method owing to the complexity of the problems that can be handled. As it can be witnessed from the review, the overwhelming majority of studies modelling hydrogen pathways have used LP. It is not coincidence that dynamic models and programming have not been applied to study the creation of fuel delivery systems.

A sole exception (Lin *et al.*, 2006) that has applied dynamic programming is a study that has developed a dynamic programming model to understand the dynamics of hydrogen infrastructure transitions. Generally, the word "dynamic" is somehow misunderstood or misused. Some studies use it in order to describe a model that incorporates the time factor, where in this case the correct term is time-variant and not dynamic and others to express the behaviour of the system over time, where in these cases the models are indeed dynamic. Realistically, a dynamic model by definition could not be used in the case of a fuel infrastructure design problem, as it is unknown in the future what will happen but only scenarios can be made. So, the Lin *et al.* (2006) study has not developed a dynamic model but a mathematical model by means of dynamic programming.

Dynamic programming is method of solving problems exhibiting the properties of overlapping subproblems and optimal substructure. The former breaks down the problem into subproblems that are reused several times and the latter means that optimal solutions of subproblems can be used to find the optimal solutions to the overall problem (Powell and van Roy, 2004). The Lin *et al.* (2006) study uses dynamic programming to solve the problem by breaking it into stages and finding the best solution to the stages one after another. However, this is applicable in this study where the problem is not a large scale problem. Solving a large scale problem with numerous parameters makes the problem a lot more complicated and increasing its complication to a great extent may make its solution extremely difficult if possible. Thus, considering the size of the problem of this study, which does not examine individual hydrogen pathways or part of the infrastructure development but includes the design of a whole supply network and thus is a large scale problem with several parameters this method has not been considered the appropriate approach.

LP has been considered the most suited approach due to its generality, flexibility and ability to handle large scale complex problems with thousands of variables and constraints. LP models are flexible enough to adequately describe any realistic problems of modern industry and make use of the significant expertise on computational linear algebra that has been developed during the last few years. The wide applicability of LP in conjunction with the existence of good general-purpose techniques for finding optimal solutions make LP an important tool of Mathematical Programming (Optimisation Technology Centre, 2005). Moreover, LP analysis can assist both in determining whether the solution of the infrastructure development problem is feasible and in unbounded cases where the value of the solution is infinitely large, without violating any of the constraints, warning that the problem is improperly formulated. Another advantage of LP is that allows to check easily how the results vary when the values of the parameters are changed. This is the sensitivity analysis that determines how changes affect the optimal solution to the original LP problem.

Although LP is considered the optimal approach aiming to further improve the quality of the results and to be distinguished from all other LP models studying the infrastructure development problem, the model has been reinforced with the inclusion of dynamic programming elements. Specifically, the model has the originality that although is a LP model includes the characteristics of dynamic programming, such as the memoization and recursion. Memoization is an optimisation method used mainly to accelerate computer programs by storing the results of function calls for later reuse, rather than recomputing them at each invocation of the function. A recursive algorithm is one that calls itself repeatedly until a certain condition matches. It is a common method to functional programming (Andersen and Andersen, 1995; Nash and Sofer, 1996; Chvatal, 1983). Recursion and memoization were combined together to form the top-down approach that was implemented. The top-down approach is one of the two approaches DP takes and it breaks down the problem into subproblems, the solutions of these are remembered in case they need to be solved again. The other DP approach is the bottom-up, where all subproblems that might be needed are solved in advance and then used to build up solutions to larger problems. This approach is sometimes not intuitive to figure out all the subproblems needed for solving the given problem (Rein, 2000; Stuart, 1977). Section 4.11 describes explicitly the top-down approach.

In some applications, the solution of an LP optimisation problem makes sense only if certain of the unknowns are integers. The problem of this study is one of these applications. Integer LP models are ones whose variables are constrained to take integer or whole number values. In this problem some variables are restricted to be integers and some are not and thus make the problem a mixed integer linear programming (MILP) problem. MILP models have the advantage of being more realistic than LP models. However, they have the disadvantage of being much harder to solve. As in MILP the variables can take the values 0 or 1, a MILP model may well support logical operations, such as decisions on the expansion or shut-down of production facilities. Because of this feature of MILP, the model is able to combine the different options. This combination is an essential ingredient for the building up of the infrastructure. In modelling the planning and designing of an infrastructure a number of fixed costs at certain stages of the process have to be taken into account. MILP can support the inclusion of start up or fixed costs, making this another reason that justifies MILP as the preferred method to deal with the present problem. Lastly, the application of MILP incorporates dynamic systems and thus can be used in this problem which is of dynamic behaviour.

MILP problems have the general form (Nemhauser and Laurence, 1988):

$$\text{Minimize } cx + dy$$

$$\text{Subject to } Ax + By \geq b$$

$$L \leq x \leq U$$
$$y = \{0, 1, 2, \ldots\}$$

where $cx + dy$ is the objective function;

x is a vector of variables that are continuous real numbers;

y is a vector in variables that can only take integer values;

$Ax + By \geq b$ represents the set of constraints;

L is a vector of lower bounds on the continuous variables;

U is a vector of upper bounds on the continuous variables; and

$y = \{0, 1, 2, \ldots\}$ is the integrality requirement on the integer variables y.

Concluding the section of the selection of the optimisation technique it is worthwhile to mention a rational question that may have been raised, that is why linear and not nonlinear programming (NLP). NLP is the process of solving a system of equalities and inequalities over a set of unknown real variables along with an objective function to maximized or minimized. So, the majority of NLP problems have the same structure with LP with the only difference being that in NLP some of the constraints or the objective function is nonlinear.

It is well-known that NLP is a difficult field with very complex mathematics and for this reason researchers have identified special cases for study. One of these cases is LP. Generally, the attractiveness of LP over NLP emanates from its direct applicability to many problems, the availability of good, general-purpose algorithms and the fact that in various real-world situations the inexactness in the model or the data means that the use of a more sophisticated nonlinear model is not warranted. Moreover, linear programs do not have multiple local minima, as it is sometimes the case with nonlinear problems, which means that any local solution of a linear program also achieves the global minimum of the objective function over the whole feasible region (Andersen and Andersen, 1995; Nash and Sofer, 1996; Chvatal, 1983).

However, the use of a nonlinear model may be essential in some applications, when a linear or quadratic model may be too simplistic and therefore produce useless results. Nevertheless, even in these cases the use of nonlinear models entails certain problems, such as the fact that most algorithms cannot guarantee convergence to the global minima that is the value of x that minimizes the objective function over the entire feasible region. This problem is very difficult to be solved and although there are a number of algorithmic approaches for global minimization available, because their implementation strongly exploits the special properties of the main application, there is a fair chance that they will generate useful results in a reasonable amount of computing time. Another disadvantage of NLP over LP is that general software is to some extent less efficient because the nonlinear models include a variety of problems with a considerable number of potential pathologies and eccentricities (Byrd *et al.*, 1996; Bertsekas, 1995).

Conclusively, it could be deduced that it is not recommended to use NLP in cases where useful and meaningful results may be obtained by using LP models. Apart from the cases where there is a strong non-linearity in a problem, LP may produce valuable results. For this reason, the model of this study is sensibly treated as a LP problem as it is slightly non-linear. The degree of non-linearity of the current problem stems from the fact that all the equations that describe the problem appear large linear coefficients and small non-linear coefficients. Thus, there is a trade off between the ability to include non-linear behaviours and to support large-scale problems. For the former NLP is the preferred method and for the latter LP. In this problem as the non-linearity is small, more attributes are sacrificed if NLP is selected. Thus, in order to build a model aiming to address the issue of the infrastructure development in the aforementioned way LP is a good method of producing valuable results sacrificing the least-desired attributes.

Of course, every approach has its benefits and its drawbacks and the intention of this study is to select an approach that suits the problem best providing valuable results and being original.

4.4.2 Selection of Optimisation Software

Optimisation technology is traditionally made available to users by means of codes or packages for specific classes of problems. Nowadays, modelling languages have become an appealing way to interface to packages, as they allow the user to define the model and data in a way that makes intuitive sense in terms of the application problem. For general optimisation problems, various high-level modelling languages have become available that allow problems to be specified in intuitive terms, using data structures, naming schemes, and algebraic relational expressions that are dictated by the application and model rather than by the input requirements of the optimisation code.

A useful source of information for LP software is the Optimisation Software Guide by Jorge More and Stephen Wright. This Guide includes references to around 75 software packages for LP and other programming methods (Optimisation Technology Center, 2005). An additional valuable source of software packages is the Linear Programming Software Survey compiled by OR/MS Today. This survey contains feature summaries and contact information. Moreover, the OR/MS Today website has the largest selection of advertisements for optimisation software (OR/MS, 2005). Moreover, the NEOS guide (NEOS guide, 1996) contains basic information on modelling and algorithmic issues, information for most of the available codes in the two areas, and pointers to texts for readers who need background information.

One of the most widely used software for solving MILP problems is the General Algebraic Modelling System (GAMS). GAMS is a modelling system for mathematical programming and optimisation. It is designed for complex, large-scale modelling applications and provides stable integrated high-performance solvers. GAMS supports various model types with a wide range of solvers for each one. For MILP there are around 11 kinds of suitable solvers such as CPLEX 9.1, BARON 7.4, COIN, MOSEK 3.2, XPRESS 15.30 among others (GAMS, 2005).

From the different software tools that have been developed for MILP, MATLAB is the software that was chosen for solving the MILP model of this study. The reasons for this choice are manifold. MATLAB is a high-performance language for technical computing that has been undergone numerous refinements through years of experience. In academic environments, it is the standard instructional tool for mathematics, engineering and science. In industry, it is the preferred tool for high-productivity research, development and analysis. Its burgeoning evolution in conjunction with its powerful features make it a widely used language. Its application extends to several areas, such as (Mathworks, 2005):

- Algorithm development;
- Math and computation;
- Data acquisition;
- Modelling, simulation and prototyping;
- Data analysis, exploration and visualization;
- Scientific and engineering graphics;
- Application development, including graphical user interface building.

Its attractiveness as a modelling language, which leads to its widespread use, reinforces the applicability and usefulness of the model of this project. A model based on such a language may well be comprehended and thus utilized by other users. Hence, it would serve as a valuable reference point or as a starting point for future users that may desire to add in some features and expand it. In other words, MATLAB enhances the value of this model over time.

A valuable advantage of MATLAB is that is a fast language. This characterisation is referred to two of its features. Firstly, modelling in MATLAB allows for the completion of the problem in a relatively short period of time and secondly can quickly provide the results after running the code. The former is based on the fact that MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows to solve several technical computing problems, in particular those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or Fortran (Mathworks, 2005). In comparison with GAMS, MATLAB is more attractive as its capabilities for data manipulation and visualization are better. MATLAB offers a wide variety of plots and imaging capabilities that could be used to view the optimisation results.

Another important attribute of MATLAB is the easiness of its use. As a high-level language it integrates computation, visualization and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. MATLAB has also the great advantage of displaying the results in a very comprehensive, compact and aesthetically beautiful way. Moreover, this choice has been made with the purpose of providing an original contribution. It is believed that no MILP models using MATLAB have been developed so far for the problem of the development of a hydrogen infrastructure. Thus, the selected approach reinforces the originality of this project.

MATLAB includes a family of add-on application-specific solutions called toolboxes. Toolboxes are comprehensive collections of MATLAB functions that expand the MATLAB environment to solve specific classes of problems. They are available for a number of areas such as signal processing, control systems, neural networks, fuzzy logic, simulations and many others. Toolboxes are very valuable as they allow learning and applying specialized technology. The toolbox of MATLAB that is used in this model is the Optimisation Toolbox. This toolbox includes routines for several types of optimisation like (Mathworks, 2005):

- Unconstrained nonlinear minimization;
- Constrained nonlinear minimization, including goal attainment problems, minimax problems, and semi-infinite minimization problems;
- Quadratic and linear programming;
- Nonlinear least squares and curve-fitting;
- Nonlinear system of equation solving;
- Constrained linear least squares;
- Sparse and structured large-scale minimization;
- Binary integer programming.

It can be witnessed from the list above that the Optimisation Toolbox does not directly support MILP problems. For this reason, the model is solved using the linprog function, which is used to solve LP problems, that has been modified appropriately in order to satisfy the constraints of the MILP problem of the study.

The MATLAB system consists of five main components:

- the development environment;
- the MATLAB mathematical function library;
- the MATLAB language;
- the graphics;
- the MATLAB application program interface (API).

The development environment is the set of tools and facilities, with which the MATLAB functions and files can be used. It contains the MATLAB desktop, the command window, the command history, an editor and debugger and browsers for help, files, workspace and the search path. The MATLAB mathematical function library is a collection of computational algorithms containing from elementary functions, like sum, sine, complex arithmetic, to more sophisticated functions, like matrix inverse, matrix eigenvalues, fast Fourier transforms. The MATLAB language is a high-level matrix/array language with control flow statements, functions, data structures, input/output and object-oriented programming features. MATLAB has a wide range of facilities for displaying vectors and matrixes as graphs. It contains high-level functions for two- and three-dimensional data visualization, image processing, animation and presentation graphics. Moreover, it allows to customize the appearance of graphics and to build graphical user interface on MATLAB applications. The MATLAB application program interface is a library that enables programs written in C and Fortran language to interact with MATLAB (Mathworks, 2005).

4.4.3 Selection of Image Processing

One of the attributes of this model that greatly distinguished it from all other infrastructure development models is its capability of performing resource optimisation. Resource optimisation is implemented based on maps that show the resource potential of every renewable energy source of the desired region under study. Moreover, the model includes what the majority of other models exclude, that is a geographical representation of a hydrogen infrastructure, such as the location of demand centres, production plants and transport distances, modes and costs. In order to take these "real world" costs into account, the model needs to consider the topological characteristics of the examined region. These kinds of data were selected to enter into the model through maps.

The reasons for choosing to import a number of data in the model in the form of maps are the following:

- Simplicity and time-efficiency. It is less time-consuming to import data in the form of maps, where is possible, than in any other way. This can be realized considering for example the import of data regarding the renewable energy resource of a country, such as the wind energy resource. It is substantially more efficient to enter a map showing all the wind speeds in every region of this country than to enter manually all the data. Considering that the model can run a simulation with all kinds of renewable energy resources makes the importance of employing an efficient way of entering the day quite important. Moreover, there are other types of data that are imported in the model as maps, such as the geophysical map of the region under study and maps relative to the transportation stage of the hydrogen supply chain. The latter map category includes the data for simulations that desire to include the road, rail, electrical grid or pipeline network of a region or any other form of fuel transport;
- Extension. The model can easily be extended to include more data. The easiness of the extension is referring to the work that needs to be done in order the model to include more data. In this model, this work is trivial as it only involves the addition of more maps and not any change in the mathematical model. The mathematical equations and the data are independent and so changes, additions or removals, in data do not mean changes in the mathematical model. This feature is very important as it reinforces the model's ability to support any kind of simulation and thus provides results for any type of hydrogen infrastructure desired to be planned in any region;
- Originality. This is an important feature that when is aspired with the intention to produce valuable and not just original results usually leads to constructive products. The idea of importing maps into the model has not been used in any other hydrogen infrastructure development model;
- Proof of concept. As this approach is original but promising it has been considered worthwhile to examine whether is feasible and thus make this model the proof of the practicability and merits of this concept;
- Compact method. This method is very compact as it includes a lot of data in a simple figure.

In order to enter the maps into the model they need to undergo a certain process. This process is necessary because firstly the model has to be able to "read" the data on the maps and secondly all the maps have to be the same dimensions. This process is described in detail in Section 4.7. The image processing was carried out using the GIMP software. GIMP is the GNU Image Manipulation Program that can be used for photo retouching, image composition and image authoring (GIMP, 2005). GIMP along with Photoshop are the two most popular image editors. The capabilities of both of them satisfy the requirements of the present study. Photoshop is usually preferred in commercial arts, which is not the case in this study. GIMP is a free software replacement for Photoshop and can be installed, shared, or redistributed on any number of computer systems with zero licensing costs. Actually, this study includes the use of GIMP Portable that is a repackaged version of GIMP for Windows, which can be run directly from electronic media without installation. The word "portable" is used because this version is intended to be carried on portable storage devices such as USB flash drive or digital audio player (GIMP, 2005).

4.4.4 Selection of Graphical User Interface

Presenting the results as they returned from MATLAB is unlikely to be understood other than being the developer of the model. For this reason, the creation of a graphical user interface (GUI) is necessary. Moreover, as this model provides a general model-tool that can be applied everywhere without the need to alter the code, the GUI makes the use of the model possible even by people that do not acquire the knowledge of programming. There are various packages of software that offer the possibility of creating GUIs, such as the Qt software that is a program development environment in the C++ language. The software that has been selected is MATLAB. The reason for this choice was to avoid possible interconnectivity problem arising from developing the model and the GUI in different software. Apart from presenting the results, the GUI is used to enter the data into the model. Thus, the GUI is used in the beginning when the user imports the data of the desired simulation and at the end when the model passes the results to it. That is the reason why the interconnectivity issue is of great importance and MATLAB has been preferred over Qt software.

The GUI was produced by using GUIDE, which is the MATLAB graphical user interface development environment. GUIDE provides a set of tools that simplify the procedure of designing and building GUIs. It offers the possibility to lay out a GUI by using the GUIDE Layout Editor and selecting the appropriate components like panels, button, text fields, menus and so on into the layout area and program a GUI by automatically producing an M-file that controls how the GUI operates. The M-file activates the GUI and encloses a framework for the complete GUI commands (Mathworks, 2005).

For this study, a GUI has been created that sets the parameters of the model, run the simulation and presents the results in the form of a map demonstrating the optimal, according to the model, infrastructure development plan. A thorough description of the GUI is presented in Section 4.12.

4.4.5 Selection of Data Transfer Method

When the data are entered into the GUI it is necessary to pass them to the model. The chosen way to pass the details to the model is through an XML file. XML, which stands for Extensible Markup Language, is a markup language that was designed to describe data and to concentrate on what data are. In other words, it can structure, store and send information. A markup language is a mechanism to identify structures in a document. The XML technology has a wide range of uses, such as exchanging data between incompatible systems or using plain text files for sharing data, or creating new languages like WAP and WML. It is a relatively new tool that has been rapidly developed and quickly adopted by a large and constantly growing number of software vendors in the last years. It is considered that possibly will be as significant to the future of the Internet as important HTML has been to the establishment of the Internet and is anticipated to be the most common tool for all data manipulation and transmission (XML, 2005).

The reason for choosing the XML technology is the attributes it offers. The XML is (XML, 2005):

- Platform independent. It is recognized in any software, such as Windows, LINUX, Solaris;

- Free technology. It can be used without licence or restrictions;
- Immune to changes in technology. This feature makes possible to create an XML file in certain software and use it in any version of this software;
- Human and machine-readable simultaneously. This characteristic contributes to ease of parsing and error detection;
- Able to support Unicode encoding. This ability allows the software to be used in any human language;
- Suitable for hierarchical structural information. Structured information contains both content, like words and pictures, and some indication of what role that content plays. Typically, it can represent the most general computer science data structures that include records, lists and trees.

In this study, the XML is used for storing and carrying and structuring data. When the data are entered into the GUI, an XML file is produced and it passes the data into the model. Moreover, when it is desired to run again the same simulation it is not necessary to enter again the data into the GUI because the XML file can store the specifications of every simulation.

4.5 Features of the Model

The renewable hydrogen infrastructure model may be considered as a generic framework for modelling numerous possible fuel chains for establishing a renewable hydrogen delivery system for different scenarios and geographical regions. The model is able to perform economic and resource optimisation and spatial and temporal distribution of the renewable resources and hydrogen facilities. It supports the design of a renewable hydrogen supply network by accommodating a number of specific features. The main features of the model involve:

- A long-term timescale;
- Multiple primary energy feedstock sources;
- Various hydrogen production technologies, both mature and novel methods;
- Possibility of choice between large-scale centralized production plants and on-site production;

- A variety of different distribution and storage technologies;
- Economies of scale of production and distribution technologies;
- Geographical site allocation;
- Delivery of both liquid and gaseous hydrogen;
- Transition from one pathway structure to another;
- Evolution of the infrastructure over time, meeting increasing hydrogen demand;
- Possibility of expansion in order to include more resources such as non-renewable sources and technology options;
- Making the least possible assumptions at all the stages of the modelling process allowing for a more realistic optimisation that leads to more valuable and credible results.

One of the main characteristics of this modelling approach that distinguished it from all other relative modelling studies is that it constitutes an infrastructure pattern template and not an equation template. The term template is used to describe a generalised framework that can be used in several simulations without the need of modifications. More specifically, it does not provide a template of equations that are applicable to a limited set of simulations but a template that is restricted only in the structure of the fuel chain, namely the sequence of the stages in a fuel chain like the production or storage step. Therefore, there is no restriction in the geographical region under study, the distances, the renewable energy resources, the hydrogen technologies, the demand and any other parameter. This feature makes the model able to be applied not only in a number of different simulations but in any kind of simulation and thus be truly general.

4.6 Inputs and Outputs of the Model

The model is defined by its structure, its implementation and the parameters. The first and the second are described in the subsequent sections. The input parameters greatly affect the modelling results in two ways. Firstly, the calibration of the parameters determines how much realistic and valuable are the results. Unsurprisingly, the inputs of the model play a major role in the credibility of the outputs. Even if a model is perfectly developed inaccurate inputs most likely will produce incorrect or meaningless results. The calibration is based on up-to-date and reliable references, judgement and statistical estimation.

Secondly, the amount of input parameters determines how much detailed and close to reality is a simulation. This model is able to run simulations with different numbers of input parameters. According to the aim of every case study and the results that are desired to be achieved the inputs parameters and data may differ from simulation to simulation. For example, in the case of the transmission of electricity through the electrical grid network a simulation may include the cost of transmission in the already existing grid network and another simulation may include both the cost of transmission but also the cost of building new grid cables.

Figure 4.2 shows the required inputs and the outputs that the modelling is able to produce. The top box represents the inputs that need to be fed into the model, the pyramid corresponds to the modelling method and the bottom box shows the outputs. The pyramid is like a black-box into which when the information is entered preprogrammed logic is utilized in order to return the outputs. A black-box model contains formulas and calculations that the user does not see nor need to know to use the model.

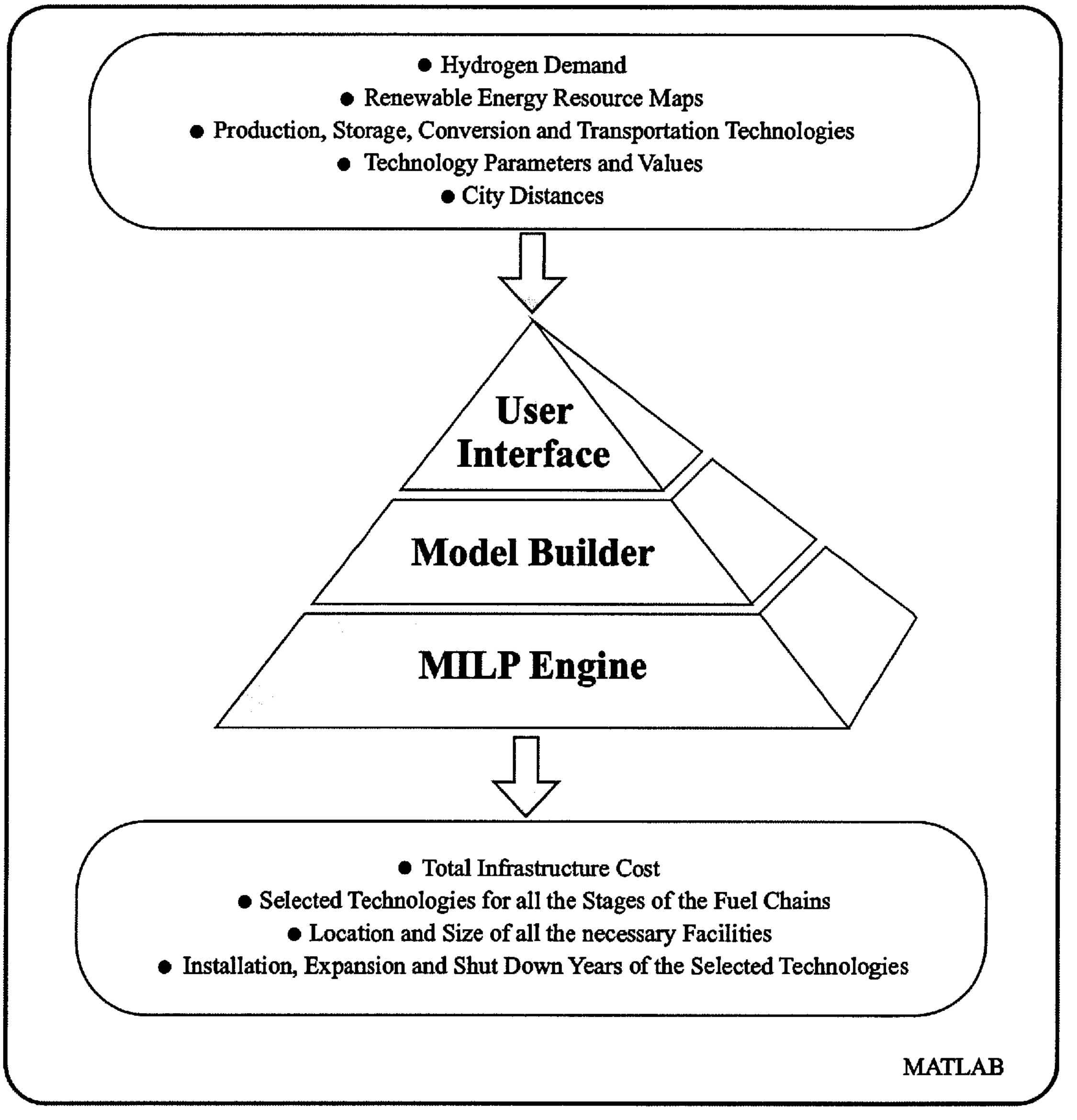

Figure 4.2: Inputs and outputs of the model

The inputs of the model include:

- A geophysical map of the area under study, which could be a country or a city or any geographical area ;
- The city distances (geographical coordinates) of the selected demand centres within the selected area. The demand centre, which could be one or many, constitutes the market that is the final stage of the fuel chain, that is the hydrogen supply destination;
- The hydrogen fuel demand needed to power the desired number of fuel cell vehicles in the examined region. The model has the great advantage

of being able to run simulations with constant, linearly increased and non-linearly increased demand;

- The renewable energy resource maps that illustrate the renewable resource potential of the selected region and they comprise the primary energy feedstock for the production of hydrogen;
- The technologies that form the desired fuel chains under examination. These technologies include both hydrogen facilities and renewable energy plants, for example wind energy for electricity production, electrolysis for hydrogen production, compressor for conversion, compressed gas in a vessel for storage, rail for transportation and compressed gas in a vessel for on-site storage;
- The values of all the parameters, for example the efficiency or the capital costs of the technologies;
- The infrastructure development specifications. This refers to a number of options that are offered by the model relative to logistics factors, such as the timescale or the number of regions the area under study is segmented.

Importing the required inputs and running the model produce the following outputs:

- The optimum (least-cost) renewable hydrogen infrastructure development plan that mainly includes:
  - The renewable resource requirements for hydrogen production;
  - The production plant sizes, locations and lifetimes;
  - The production plant expansion or shut down and at which years;
  - All the chosen primary energy feedstocks and hydrogen technologies infrastructure components that comprise the optimum development scenario;
- The overall cost of the optimal infrastructure development plan.

4.7 Map Segmentation

Studying the design of a fuel infrastructure in any geographical region involves the discretisation of this region into smaller areas that are compared with each other and examined for their suitability of including parts of the infrastructure, such as a renewable energy plant or a hydrogen production facility. Usually, in other studies this discretisation is carried out by segmenting the region under study in a somehow abstract method, for example dividing the region into areas of the same dimensions. In this algorithm a region is segmented into areas that do not have the same dimensions but have the same renewable resource potential and thus the same renewable energy exploitation capabilities. This is very useful particularly in the case of the expansion of the infrastructure.

This discretisation of the spatial domain is based on renewable energy resource potential data. These data are provided in the form of maps that show the renewable resource potential in the whole region under consideration. An example of such map can be seen in Figure 4.3. The example includes the resource potential of wind energy and Great Britain as the region under study.

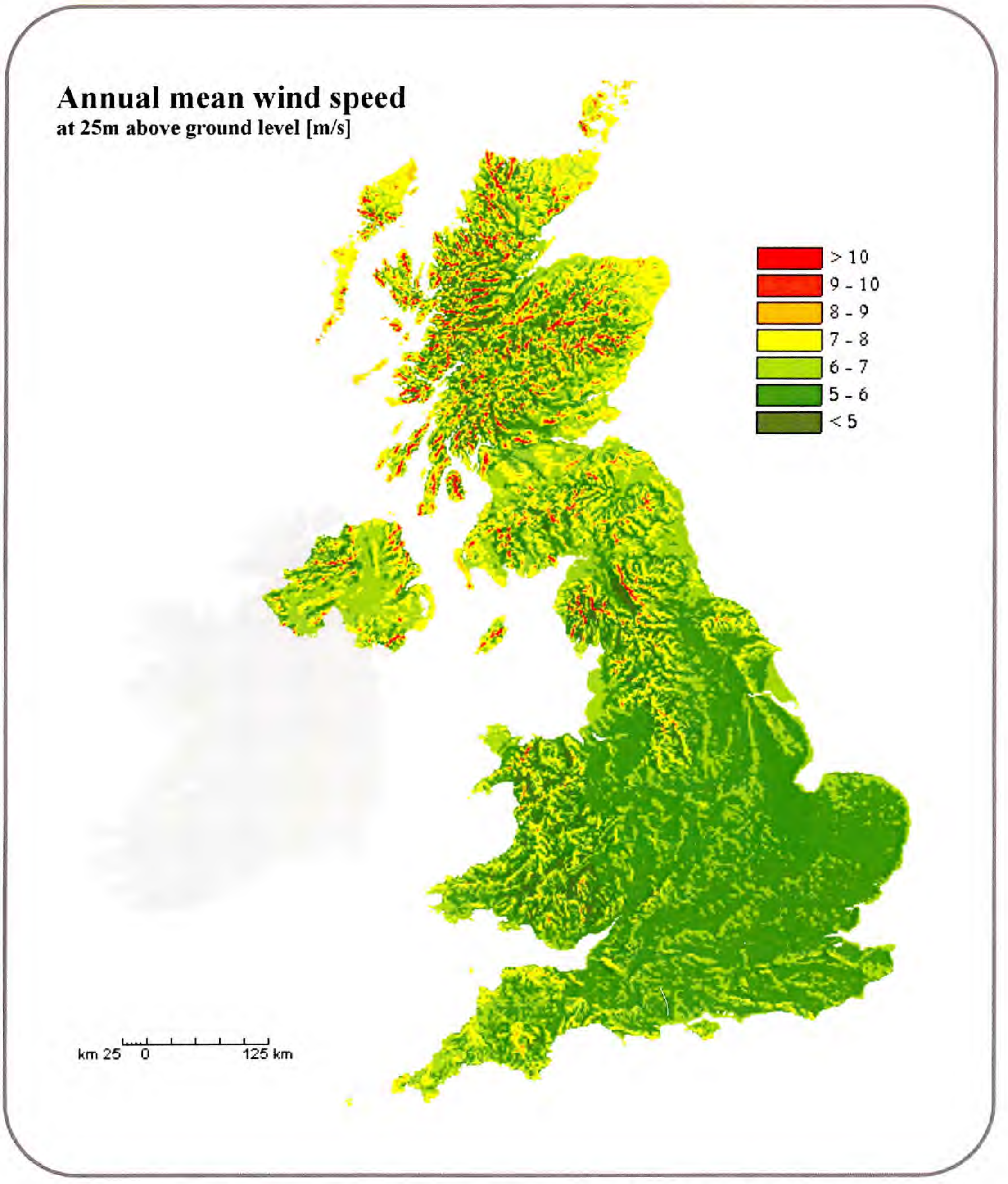

Figure 4.3: Onshore wind energy resource in the UK (Source: ETSU, 1999a)

In order to implement the discretisation the maps that constitute the input data for the segmentation need to undergo processing. The processing of the image data is necessary in order firstly to correct geometric distortions, secondly to eliminate unwanted areas and thirdly to normalise data from different images to physical units of reflectance rather than the arbitrary engineering units of the raw data and was carried out using the GIMP software. These reasons are obvious in the example in Figure 4.3.

Figure 4.3 is the onshore wind energy resource potential in Great Britain and shows the annual mean wind speed at 25m above ground level. Every colour of the map corresponds to a different wind speed. The range of wind speeds varies from less than 5m/s (dark green colour) to more than 10m/s (red colour). Naturally, the model does not "understand" the significance of these values and thus cannot distinguish between a good and a bad wind energy site. For this reason, it is necessary to normalize these values in order to be "comprehended" by the model. The normalization method converts these values into efficiencies from 0 to 1. The normalization was carried out for all input maps because apart from the fact that it is necessary the maps to be read by the model, all the maps should be in the same "units", which means that they should undergo the same normalization process and be the same size. Of course, as it was impossible to find all the required maps in the same size, without distortions and normalized they underwent processing.

Within the GIMP environment a map is converted from a 24 bit RGB into 8 bit grey scale. In the 8 bit grey scale form the map includes only a number of colours from the range of 255 colours. The number of colours that every map involves depends on the map resolution, that is, the number of colours that indicate the values of the resource, for example in Figure 4.3 the map includes 7 colours that correspond to 7 wind speed values as it can be seen from the table in the figure. The colour of the lowest value is replaced with a dark grey colour and as the values increase the percentage of white of the colours increases. So, the map after processing has dark grey colour in the areas of the lowest value and light grey in the areas of the highest value. The values in between are replaced with shades of colours between dark and light grey. So, the map of Figure 4.3 becomes the map of Figure 4.4.

Figure 4.4: Onshore wind energy map in Great Britain after processing

The map resolution also determines the normalization factor. The latter is used in order to transform all the values of a map into efficiencies between 0 and 1. This is done by multiplying this factor with the values of each map. As every map has different number of values the normalization factor is different among maps. The normalization factor for every map is given by:

$$\frac{1}{\textit{Quantity of different resource values}}$$

In the example of onshore wind energy the map has 7 wind speed values and thus the normalization factor is 0.14. Apart from the colours, Figure 4.4 differs from Figure 4.3 as the former shows only the resource of the selected region under study, which is Great Britain. All other areas have been eliminated. Moreover, the black colour in the map of Figure 4.4 represents the sea, which was considered as an area of zero potential and thus was necessary to take a colour, like black, that is darker than dark grey, which is the colour of the lowest value. Like the example of wind energy, the same processing was carried out for all the maps that are used as input data. When all the maps were processed they were converted in the same size and inclination.

Importing the processed maps into the model the region under consideration is segmented into R_s that is equal to:

$$R_s = 2^{S_i} \qquad R_S \in \mathbb{Z}$$

where R_s is the map segments after map segmentation is performed and S_i are the map segmentation iterations. As S_i is defined by the user, the number of segmented regions (R_s) is also determined by the user. The dimensions of every region are given by the following real time calculated variables:

$R_{x_{min_{l,i}}}$ is the lower boundary of width axis of segment l in map i, where $l=1..R_S$, $i=1..D_p$, $R_{x_{min_{l,i}}} \in \mathbb{Z}$

D_p is the number of primary energy feedstocks.

$R_{x_{max_{l,i}}}$ is the higher boundary of width axis of segment l in map i, where $l=1..R_S$, $i=1..D_p$, $R_{x_{max_{l,i}}} \in \mathbb{Z}$

$R_{y_{min_{l,i}}}$ is the lower boundary of height axis of segment l in map i, where $l=1..R_S$, $i=1..D_p$, $R_{y_{min_{l,i}}} \in \mathbb{Z}$

$R_{y_{max_{l,i}}}$ is the higher boundary of height axis of segment l in map i, where $l=1..R_S$, $i=1..D_p$, $R_{y_{max_{l,i}}} \in \mathbb{Z}$

The aggregation of map data that are the resource potential values, like wind speed, of all the points in every segment for a map is given by the equation:

$$F_{A_{i,l}} = \sum_{x=R_{x_{min_{i,l}}}}^{R_{x_{max_{i,l}}}} \sum_{y=R_{y_{min_{i,l}}}}^{R_{y_{max_{i,l}}}} D_{m_{i,x,y}}$$

where $l = 1..R_S$
$i = 1..D_p$
$F_{A_{i,l}} \in \mathbb{Z}$

Accumulating $F_{A_{i,l}}$ for all map segments gives the total number of map data in map i F_{A_i}, which is equal to:

$$F_{A_i} = \sum_{x=1}^{S_w} \sum_{y=1}^{S_h} D_{m_{i,x,y}}$$

where $i = 1..D_p$
$F_{A_i} \in \mathbb{Z}$

In order to ensure that all segments l in map i have the same renewable resource potential F_{A_i} is equal to:

$$F_{A_{i,l}} = F_{A_{i,l+1}} = F_{A_i} / R_s$$

where $l = 1..R_S - 1$
$i = 1..D_p$

The algorithm that implements the aforementioned equations is displayed in Figure 4.5. The green box in the top left hand corner is the starting point of the algorithm. Next to this box there are two side parallelograms that represent the data. The left one is the input data and the right one the output data. The light grey arrows represent the data flow and the dark grey arrows show the procedure flow.

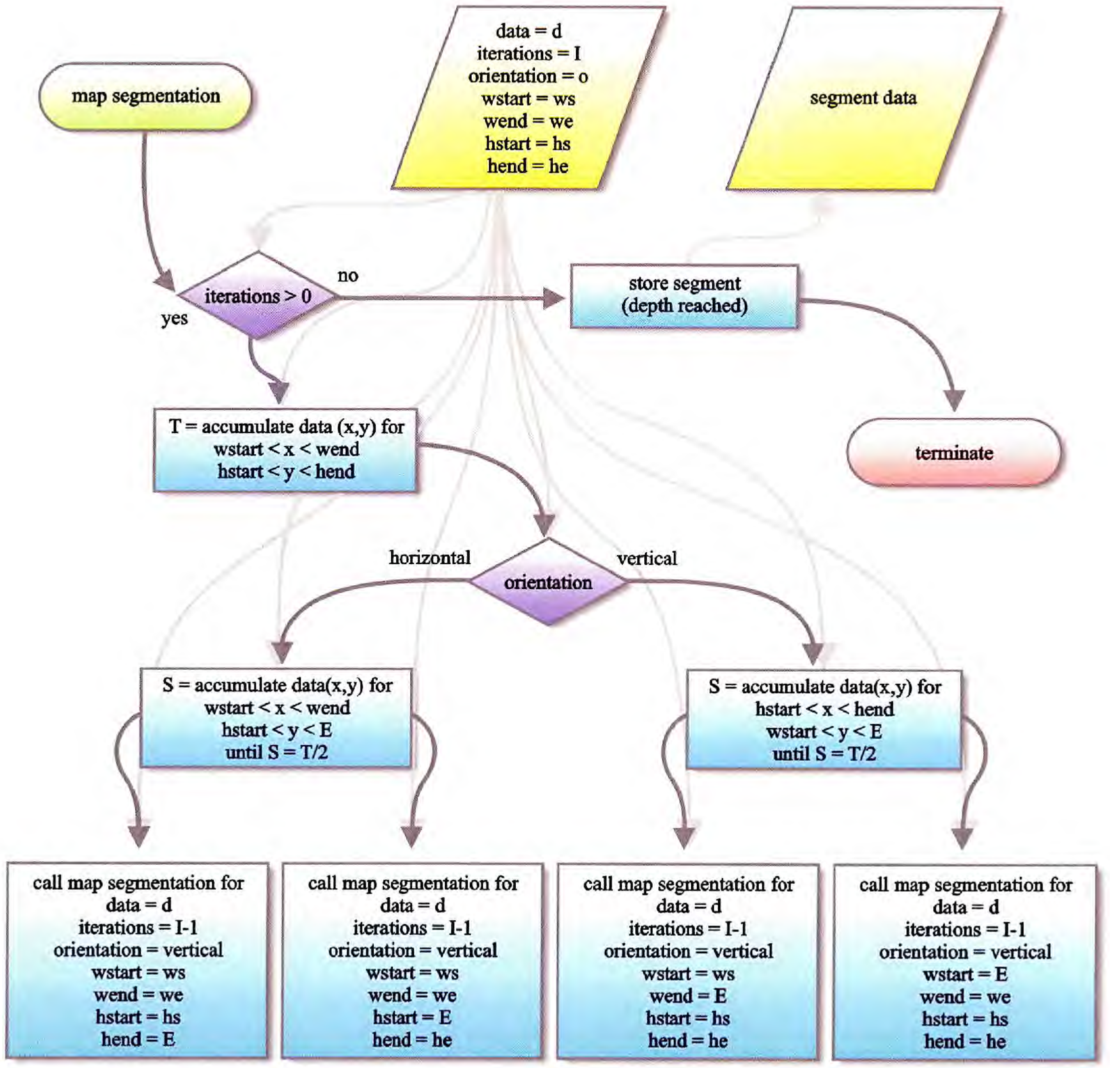

Figure 4.5: Map segmentation algorithm

When the map segmentation function is called two options are considered related to the number of desired iterations. If the iterations are non-zero, all the resource values of a map are added up (T) and then there is the orientation control that determines whether the segmentation is going to be horizontal or vertical. Actually, the first orientation is horizontal and when one type of orientation is selected the next one will be the opposite type in order to ensure that the segments will be cuboids. When the orientation is selected, for example in the case of a horizontal orientation, the resource values are added up and produce the sum S where x is between the first (*wstart*) and the last (*wend*) point of the map while y is between the first point (*hstart*) and the point E. The latter is the point where the sum S is half the total resource T ($S = T/2$). So, at this point the map is divided in two segments with equal resource potential.

After this point, the map segmentation function is called again for the same map (data = *d*), one iteration less (iterations = *i*-1) and opposite orientation. For every orientation there are two possible steps as it can be seen in Figure 4.5 and are represented by the squares at the bottom of the figure. So, for example if the horizontal orientation is selected and the map is divided into two segments, the map segmentation function is called again in order to further divide the segments. As the procedure flow shows, the first square from the left divides the top segment vertically and the second square divides the bottom segment vertically. The same procedure is followed if the initial orientation is vertical.

When the number of iterations is zero, the segmentation is terminated and the results of previous iterations, if any, are stored. The results include the coordinates of all the segments in which the map has been divided into.

4.8 Resource Optimisation

In this thesis, the issue of establishing a fuel infrastructure involves the very first step of the fuel chain that is the production of the primary energy feedstock that is used for the production of hydrogen fuel. Thus, it is considered that either electricity or biomass feedstock is not provided from already existing facilities. For this reason, the design of new renewable energy plants is necessary as they constitute the feedstocks. Of course, the model is able to support simulations that include already existing facilities. So, in order to develop a hydrogen infrastructure development plan as effective and economic as possible it was necessary to examine the renewable resource of the region under study and discover the optimal places in terms of resource potential for the establishment of renewable energy plants. This is accomplished by the resource optimisation.

Naturally, the resource optimisation is based on the renewable energy resource potential of the region under consideration. It is performed after the map segmentation aiming to determine the optimal sites that may be used for the creation of renewable energy plants and thus geographically allocate the beginning of the fuel chains. This allocation is carried out taking into consideration two factors. Firstly, the resource potential of the candidate site and secondly its proximity to the demand centre. As the discretisation of the map produces segments with equal total resource potential, the resource optimisation distinguishes the sites in every segments with the higher resource potential and in the case there are more than one promising sites it eliminates the sites that are distant from the supply centre favouring the sites closer to the market.

The distance between the candidate site and the market is calculated by evaluating the corresponding Manhattan Distance, which is equal to:

$$F_{TC_{x_d,y_d,x_o,y_o}} = WeightedManhattanDistance\ (x_d, y_d, x_o, y_o)$$

where $F_{TC_{x_d,y_d,x_o,y_o}}$ is the transportation cost from the origin point x_o, y_o to destination point x_d, y_d,

$x = 1 \ldots S_w$, where S_w is the map width in pixels
$y = 1 \ldots S_h$, where S_h is the map height in pixels
$F_{TC_{x_d,y_d,x_o,y_o}} \in \mathbb{Z}$

All transportation costs are calculated using the $F_{TC_{x_d,y_d,x_o,y_o}}$ function.

In order to ensure that the point of the site is within the boundaries of the segment, the following constraints are imposed on its coordinates:

The origin point of fuel chain in width axis, $R_{O_{x_{l,i}}}$, starts from segment *l* in map *i* for which map data are maxima for that segment and the cost of transportation to the next chain point is minimum:

$$R_{x_{min_{l,i}}} \leqslant R_{O_{x_{l,i}}} \leqslant R_{x_{max_{l,i}}}$$

where $l = 1..R_S$
$i = 1..D_p$
$R_{O_{x_{l,i}}} \in \mathbb{Z}$

The origin point of fuel chain in height axis, $R_{O_{y_{l,i}}}$, starts from segment *l* in map *i* for which map data are maxima for that segment and the cost of transportation to the next chain point is minimum:

$$R_{y_{min_{l,i}}} \leqslant R_{O_{y_{l,i}}} \leqslant R_{y_{max_{l,i}}}$$

where $l = 1..R_S$
$i = 1..D_p$
$R_{O_{y_{l,i}}} \in \mathbb{Z}$

The algorithm that implements the resource optimisation is displayed in Figure 4.6. As in the case of the map segmentation algorithm Figure, the green box is the starting point, the pink box the end, the side parallelograms are the input and output data and the light grey arrows represent the data flow while the dark grey arrows show the procedure flow.

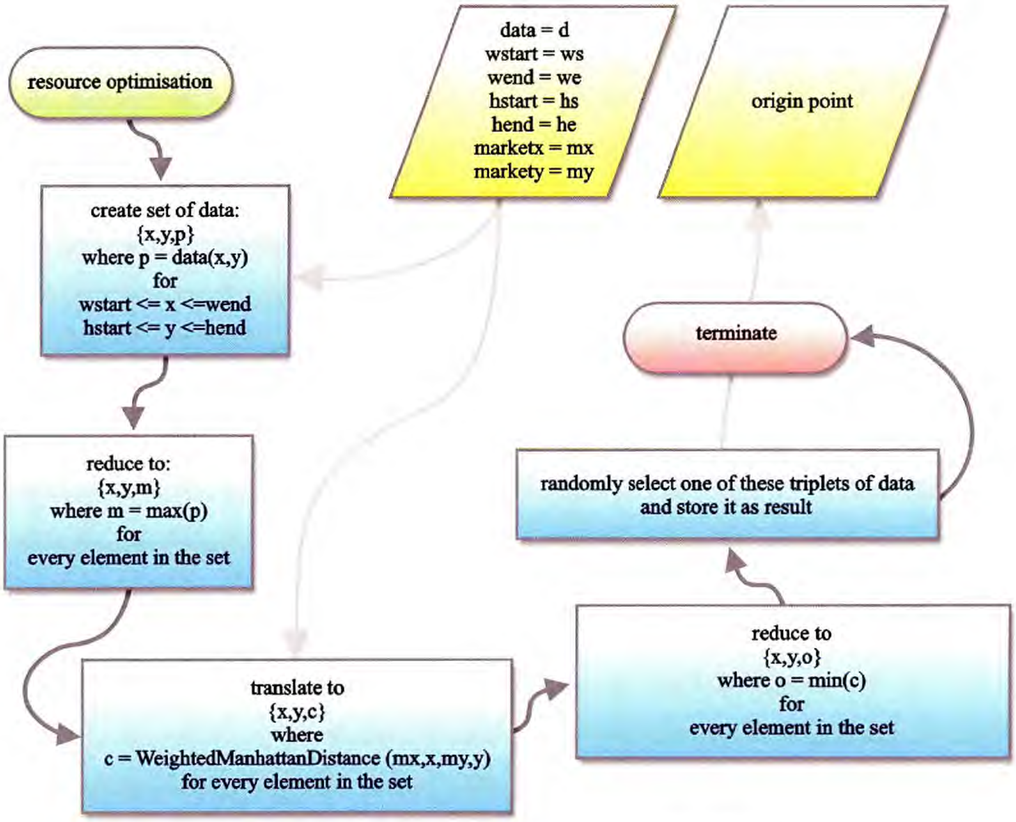

Figure 4.6: Resource optimisation algorithm

In the beginning of the algorithm, sets of data are formed that include three variables, the *xy* coordinates and the variable *p*, which is the value of the resource in a map in the *xy* coordinates. After creating these sets, the number of sets for the entire map is reduced as the sets that include the maximum resource value *p* are selected and all the others are eliminated. For all the remaining sites, the corresponding Manhattan Distance is calculated and the proximity to the market for every set is examined. Then, all the sets in all segments with the higher value of resource (*x*, *y*, *max(p)*) are further reduced and from these sets the ones that are far away for the market are discarded. Thus, the remaining sets are those that fulfil the criteria of having the maximum resource and of being close to the market. In case there are more than one sets in a segment that meet those criteria, the selection is random. However, this latter case is very rare.

When the most suitable sites have been selected the resource optimisation algorithm is terminated and its results are stored. These results include the points in the map that the fuel chains may begin and thus the model is then ready to perform the fuel chain optimisation for these points.

4.9 Equations of the Model

This section describes the first step of the fuel chain optimisation, which is the second stage of the infrastructure optimisation algorithm. This step consists of the equations that comprise the infrastructure development model. For reasons of completeness and comprehension the equations of this section include some of the map segmentation and resource optimisation equations.

The design of a hydrogen infrastructure is formulated as a MILP problem that its solution consists of a least cost infrastructure development plan, the cost of which is given by the following equation:

$$F_{CIT}=\sum_{i=1}^{D_p}\sum_{l=1}^{R_S}\sum_{v=1}^{D_{v_i}}\left(F_{CC_{i,l,v}}\cdot C_{i,l,v,x}+\sum_{p=x+1}^{S_p}F_{CE_{i,l,v}}\cdot C_{i,l,v,p}+\sum_{p=x}^{S_p}F_{CO_{i,l,v}}\cdot C_{i,l,v,p}\right)$$

This equation is the total infrastructure cost and comprises the objective function that needs to be minimized. The development of the model and the formulation of the objective function are described in detail with reference to the notation presented in Table 4.1.

Model Settings		
S_p	Number of simulation periods	$S_p \in \mathbf{Z}$
S_d	Period duration in years	$S_d \in \mathbf{R}$
S_i	Map segmentation iterations	$S_i \in \mathbf{Z}$
S_w	Map width in pixels	$S_w \in \mathbf{Z}$
S_h	Map height in pixels	$S_h \in \mathbf{Z}$
Model Input Data		
D_p	Number of primary energy feedstocks in the model	$D_p \in \mathbf{Z}$
$D_{m_{i,x,y}}$	Map i data in point x,y when i is a primary energy feedstock map or a transportation map	$i=1..D_p$ $x=1..S_w$ $y=1..S_h$ $D_{m_{i,x,y}} \in \mathbf{Z}$
D_{M_x}	Market x axis position value	$D_{M_x} \in \mathbf{Z}$
D_{M_y}	Market y axis position value	$D_{M_y} \in \mathbf{Z}$
D_{v_i}	Variations of chains using primary energy feedstock of map i	$i=1..D_p$ $D_{v_i} \in \mathbf{Z}$
$D_{S_{i,v}}$	Steps of chain using primary energy feedstock of map i using variation v	$v=1..D_{v_i}$ $i=1..D_p$ $D_{S_{i,v}} \in \mathbf{Z}$
$D_{CC_{i,v,s}}$	Capital cost of chain using primary energy feedstock of map i using variation v in steps s	$v=1..D_{v_i}$ $i=1..D_p$ $s=1..D_{S_{i,v}}$ $D_{CC_{i,v,s}} \in \mathbf{R}$
$D_{CE_{i,v,s}}$	Expansion cost of chain using primary energy feedstock of map i using variation v in step s	$v=1..D_{v_i}$ $i=1..D_p$ $s=1..D_{S_{i,v}}$ $D_{CE_{i,v,s}} \in \mathbf{R}$
$D_{CO_{i,v,s}}$	Operation and maintenance cost of chain using primary energy feedstock of map i using variation v in step s	$v=1..D_{v_i}$ $i=1..D_p$ $s=1..D_{S_{i,v}}$ $D_{CO_{i,v,s}} \in \mathbf{R}$
$D_{EF_{i,v,s}}$	Efficiency of chain using primary energy feedstock of map i using variation v in step s	$v=1..D_{v_i}$ $i=1..D_p$ $s=1..D_{S_{i,v}}$ $D_{EF_{i,v,s}} \in \mathbf{R}$

D_{DM_T}	$a_n \cdot T^n + a_{n-1} \cdot T^{n-1} + ... + a_1 \cdot T + a_0$ Market demand function	$a_n \in \mathbf{R}$ $T \in \mathbf{R}$ $D_{DM_T} \in \mathbf{R}$
D_{T_l}	Market demand tolerance lower limit	$D_{T_l} \in \mathbf{R}$
D_{T_u}	Market demand tolerance upper limit	$D_{T_u} \in \mathbf{R}$

Table 4.1: Notation of the hydrogen infrastructure model

The index v, variation, represents the possible different options that may be considered for every step of a fuel chain starting for a specific primary energy feedstock. For example, if the primary energy feedstock, which constitutes the first step of a fuel chain, is biomass the subsequent step which is the production of hydrogen may be one of the various options such as gasification or pyrolysis or fermentation. For each one of these options there are again a number of options for the next step of the fuel chain.

As it can be witnessed from Table 4.1, the demand is entered into the model in a form of a polynomial function. The advantage of this method is that the demand can be different for any simulation. The difference does not only lay in the quantity but also in the behaviour. Thus, the model is able to run simulations with constant or linearly varied or non-linearly varied demand.

To economically optimize the construction of a renewable hydrogen delivery system, it is necessary to select the most cost-effective fuel chains among the various possible fuel chain options. The chosen pathways form the optimal renewable hydrogen infrastructure development plan. The optimisation begins with the map segmentation, which is carried out according to the S_i parameter, and produces segments equal to:

$$R_S = 2^{Si}$$

For the highest resource points of every segment the distance between them and the market is calculated:

$$F_{TC_{x_d,y_d,x_o,y_o}} = WeightedManhattanDistance\ (x_d, y_d, x_o, y_o)$$

and the promising sites in the geographical region under study for the production of the primary energy feedstocks are determined. Thus, the promising points for the beginning of the fuel chains are determined. For every candidate point the model aims to find the optimal pathways. It selects the optimal fuel chains by 'activating' them and simultaneously 'deactivating' the others. To facilitate this decision-making process, it is necessary to introduce a binary variable $E_{i,l,v}$:

$E_{i,l,v}$: enable variable of chain originating from a primary energy feedstock using map i, in segment l with chain variation v,

$$\text{where} \quad \begin{aligned} v &= 1..D_{v_i} \\ l &= 1..R_S \\ i &= 1..D_p \end{aligned}$$

The variable $E_{i,l,v}$ can only take value 0 or 1:

$$0 \leqslant E_{i,l,v} \leqslant 1$$

The numerical value of the $E_{i,l,v}$ variable is controlled using the integer constraint, which allows this variable to take only integers values:

$$E_{i,l,v} \in \mathbb{Z}$$

The variable $E_{i,l,v}$ is a global variable. The variables that form the equations of the model are divided into local and global variables. The former are variables that refer to particular points in the lifetime of a fuel chains. These points could be the activation, expansion, reduction or deactivation of a fuel chain. Thus, they are the points at which a fuel chain experiences changes throughout the planning horizon. The latter are variables that refer to a fuel chain from its starting point to its end.

When a fuel chain is selected (active), its capacity, which is the amount of produced hydrogen, is determined by the $C_{i,l,v,p}$ variable:

$C_{i,l,v,p}$: capacity of chain originating from a primary energy feedstock using map i, in segment l with chain variation v in time period p,

$$\text{where} \quad \begin{aligned} v &= 1..D_{v_i} \\ l &= 1..R_S \\ i &= 1..D_p \\ p &= 1..S_p \end{aligned}$$

The $C_{i,l,v,p}$ variable is a local variable that represents the capacity percentage at which a fuel chain of map i, segment l, variation v, operates at a period p in the selected time horizon:

$$C_{i,l,v,p} \in \mathbf{R}$$

Once a fuel chain is chosen, the variable $E_{i,l,v}$ is set as the high limit of the $C_{i,l,v,p}$ variable, otherwise $E_{i,l,v}$ is set to zero and so is the $C_{i,l,v,p}$ variable:

$$\begin{gathered} \text{if } E_{i,l,v} = 1 \\ \text{then } 0 \leqslant C_{i,l,v,p} \leqslant E_{i,l,v}, \\ \text{else if } E_{i,l,v} = 0 \\ \text{then } C_{i,l,v,p} = 0 \end{gathered}$$

Every fuel chain may have a set of different $C_{i,l,v,p}$ values, the number of which is determined by the demand. Moreover, the upper limit of this number is controlled by the number of periods, which is one of the model settings, that the time horizon is divided. Setting as upper limit of $C_{i,l,v,p}$ the $E_{i,l,v}$ variable connects the maximum allowed capacity of the fuel chain at a certain point with its activation and thus ensures that this capacity takes value only if the fuel chain is selected for activation, otherwise its value is zero.

If a technology is chosen to be expanded, its capacity is expanded within certain limits. When a fuel chain is activated and chosen at a period to operate at its maximum capacity:

$$\begin{gathered} E_{i,l,v} = 1 \\ \text{and } C_{i,l,v,p} = 1 \end{gathered}$$

On the other hand, if a technology is selected to be shut down, its capacity is set to zero and it can not be expanded again in the future. All technologies can only be shut down once during the planning horizon.

Some pathways may never be selected to operate at the maximum allowed capacity. However, every pathway has it own maximum during the planning horizon. The maximum capacity that a fuel chain has experienced during its lifetime is represented by the global variable:

$MC_{i,l,v}$ maximum capacity of chain originating from a primary energy feedstock using map *i*, in segment *l* with chain variation *v*,

where $v=1..D_{v_i}$
$l=1..R_S$
$i=1..D_p$

$$MC_{i,l,v} \in \mathrm{R}$$

This variable takes the value:

$$0 \leqslant MC_{i,l,v} \leqslant 1$$

Moreover, the maximum capacity percentage of a fuel chain is greater or equal to each capacity percentage at all periods in the planning horizon:

$$MC_{i,l,v} \geqslant C_{i,l,v,p}$$

When a fuel chain is activated its total capital cost is represented by the $F_{CC_{i,l,v}}$ variable:

$F_{CC_{i,l,v}}$: total capital cost of chain originating from map *i*, segment *l* using variation *v*,

where $v=1..D_{v_i}$
$l=1..R_S$
$i=1..D_p$
$F_{CC_{i,l,v}} \in \mathrm{R}$

The $F_{CC_{i,l,v}}$ variable represents the capital cost of the whole chain, which is the capital cost of the primary energy feedstock, hydrogen production, conversion, storage and transportation technologies and is equal to:

$$F_{CC_{i,t,v}} = \sum_{s=1}^{D_{s,v}} D_{CC_{i,v,s}}$$

The reason why the variable $F_{CC_{i,t,v}}$ includes all the capital of all the stages of a fuel chain is the minimization of the simulation time of the model. A different approach was initially considered where the capital cost of each stage were not incorporated into one variable resulting in a large number of variables which in turn leads to a considerably long simulation time. According to that approach, the model gradually formed the cost equations of each stage of the fuel chain and then combined these equations to form the overall cost equation of the fuel chain. Although this approach could work for a limited number of fuel chain options, it is problematic when conducting a study with numerous pathway options. For this reason, this approach was abandoned. The new approach was carefully selected so as to simultaneously minimize the simulation time without restricting the number of fuel chain options that the model can support and thus preserve its generality.

The variable $F_{CC_{i,t,v}}$ is the total capital cost of a chain assuming that is operating at the maximum allowed capacity. It can be witnessed from the equations that the $MC_{i,t,v}$ variable is not connected with the $E_{i,t,v}$ variable. Once a fuel chain is chosen ($E_{i,t,v} = 1$) the chain capacity can take values between zero and 1 ($0 \leqslant C_{i,t,v,p} \leqslant 1$) and the $MC_{i,t,v}$ is the maximum value of the $C_{i,t,v,p}$ variable. The capital cost of the chain is connected with the $MC_{i,t,v}$ variable so because this variable is equal to the maximum value of the $C_{i,t,v,p}$ variable if the $C_{i,t,v,p}$ variable is zero, the $MC_{i,t,v}$ will automatically be zero as well. So, if a chain is not activated the $MC_{i,t,v}$ is zero. This is a result of the minimization.

The total cost of a chain depends on the capital cost, the operation and maintenance (O&M) costs and how these grow with the expansion of the chain.

The expansion is represented by the variable:

$F_{CE_{i,l,v}}$: total expansion cost for a chain originating from map i, segment l using variation v,

$$\text{where} \quad v=1..D_{v_i}, \quad l=1..R_S, \quad i=1..D_p, \quad F_{CE_{i,l,v}} \in \mathbb{R}$$

and is equal to:

$$F_{CE_{i,l,v}} = \sum_{s=1}^{D_{s_{i,v}}} D_{CE_{i,v,s}}$$

The $F_{CE_{i,l,v}}$ variable includes the expansion costs for all the steps of the fuel chain assuming the maximum allowed expansion.

The same reasoning is applied to the O&M costs of a chain:

$F_{CO_{i,l,v}}$: total O&M cost of a chain originating from map i, segment l using variation v,

$$\text{where} \quad v=1..D_{v_i}, \quad l=1..R_S, \quad i=1..D_p, \quad F_{CO_{i,l,v}} \in \mathbb{R}$$

The total O&M cost is given by the equation:

$$F_{CO_{i,l,v}} = \sum_{s=1}^{D_{s_{i,v}}} D_{CO_{i,v,s}} + F_{TC_{x_{e_{s+1}}, y_{e_{s+1}}, x_{e_s}, x_{e_t}}}$$

The overall cost of a fuel chain, $F_{CTC_{i,l,v}}$, is given by the sum of the capital cost, the expansion cost and the O&M cost:

$$F_{CTC_{i,l,v}} = F_{CC_{i,l,v}} + F_{CE_{i,l,v}} + F_{CO_{i,l,v}}$$

$$F_{CTC_{i,l,v}} = \sum_{s=1}^{D_{s_{i,v}}} D_{CC_{i,v,s}} + \sum_{s=1}^{D_{s_{i,v}}} D_{CE_{i,v,s}} + \sum_{s=1}^{D_{s_{i,v}}} D_{CO_{i,v,s}} + F_{TC_{x_{e_{s+1}}, y_{e_{s+1}}, x_{e_s}, x_{e_t}}}$$

$$\text{where} \quad v=1..D_{v_i}, \quad l=1..R_S, \quad i=1..D_p, \quad F_{CTC_{i,l,v}} \in \mathbb{R}$$

Adding up the $F_{CTC_{i,l,v}}$ of all the pathways that have been selected for activation gives the overall cost of the infrastructure, which is the objective function of the problem:

$$F_{CIT}=\sum_{i=1}^{D_p}\sum_{l=1}^{R_S}\sum_{v=1}^{D_{v_i}}(F_{CC_{i,l,v}}\cdot C_{i,l,v,x}+\sum_{p=x+1}^{S_p}F_{CE_{i,l,v}}\cdot C_{i,l,v,p}+\sum_{p=x}^{S_p}F_{CO_{i,l,v}}\cdot C_{i,l,v,p})$$

As it can be witnessed from the objective function, the total infrastructure cost is the summation of the capital, expansion and O&M costs of every fuel chain multiplied by the $C_{i,l,v,p}$ variable. This multiplication is the reason why all the costs are determined assuming the chains operating at maximum capacity or undergoing a maximum expansion. When the maximum costs are calculated the optimal capacities are determined and thereafter the multiplication of these capacity percentages with the maximum costs results to the formation of the optimal costs and thus gives the overall cost of the optimal infrastructure cost. This trick was used as it was considered the only method to solve the infrastructure problem using linear programming and having to deal with real time variables. This is possible because the problem under study is formulated as a linear programming problem and thus the model will initially form the necessary pathways for the planning horizon and afterwards select the optimal method. So, when it puts values into the variables already knows their maximum expanded capacity.

One of the main issues in designing an infrastructure that delivers renewable hydrogen is to ensure that the amount of delivered hydrogen meets the demand of the supply centre. The model satisfies the demand both in terms of energy (kWh) and power (kW). This is achieved by the formation of the following equations. The amount of hydrogen that is delivered through every fuel chain is affected but the efficiency of each fuel chain. All the technologies in every step of a fuel chain have their corresponding efficiencies.

For every pathway there is the variable $F_{EF_{i,l,v}}$:

$F_{EF_{i,l,v}}$: total efficiency for chain originating from map i, segment l using variation v, where $v=1..D_{v_i}$

$l=1..R_S$

$i=1..D_p$

$F_{EF_{i,l,v}}\in\mathbb{R}$

The total efficiency is equal to:

$$F_{EF_{i,l,v}} = \prod_{s=1}^{D_{s_{i,v}}} D_{EF_{i,v,s}}$$

The amount of hydrogen produced (in kW) in a period from a fuel chain is equal to:

$$F_{PC_{i,l,v,p}} = F_{EF_{i,l,v}} \cdot C_{i,l,v,p}$$

where $v = 1..D_{v_i}$
$l = 1..R_S$
$i = 1..D_p$
$p = 1..S_p$
$F_{PC_{i,l,v,p}} \in \mathbb{R}$

Adding up all the $F_{PC_{i,l,v,p}}$ of the fuel chains gives the total amount of hydrogen that is generated by the infrastructure in a period:

F_{P_p} : total infrastructure production for time period p,

where $p = 1..S_p$
$F_{P_p} \in \mathbb{R}$

The total infrastructure production for period p is equal to:

$$F_{P_p} = \sum_{i=1}^{D_p} \sum_{l=1}^{R_S} \sum_{v=1}^{D_{v_i}} (F_{EF_{i,l,v}} \cdot C_{i,l,v,p})$$

This equation includes all the fuel chains that are under comparison but the ones that are not selected have the $C_{i,l,v,p}$ variable equal to zero and thus are automatically eliminated.

The total production has to satisfy the demand at any time period of the planning horizon:

$$\int_{T=S_d \cdot p}^{S_d \cdot (p+1)} D_{DM_T} - \frac{D_{T_l}}{S_p} dt \leqslant F_{P_p} \leqslant \int_{T=S_d \cdot p}^{S_d \cdot (p+1)} D_{DM_T} + \frac{D_{T_u}}{S_p} dt$$

The $\int_{T=S_d \cdot p}^{S_d \cdot (p+1)} D_{DM_T} - \frac{D_{T_l}}{S_p} dt$ term is the demand from the beginning of a period until the end of the period minus a small amount ($\frac{D_{T_l}}{S_p}$) . The $\int_{T=S_d \cdot p}^{S_d \cdot (p+1)} D_{DM_T} + \frac{D_{T_u}}{S_p} dt$ term is the demand from the beginning of a period until the end of the period plus a small amount ($\frac{D_{T_u}}{S_p}$) . This double inequality eliminates possible errors in the formation of the infrastructure. For example, if the required demand is 100 GW throughout the planning horizon the model could activate a number of fuel chains that supply this amount in the beginning of the horizon and then shut down the chains. However, the inclusion of this inequality rules out that action and ensures the demand satisfaction of every period in the time horizon.

The total amount of hydrogen energy (kWh) that is produced has to be within certain limits. A single inequality constraint can be used where the produced hydrogen energy should be greater or equal to demand. Instead of this inequality, the total amount of hydrogen that is produced throughout the planning horizon is restricted within certain limits:

$$\int_{T=0}^{S_d \cdot S_p} D_{DM_T} - D_{T_l} dt \leqslant F_{PT} \leqslant \int_{T=0}^{S_d \cdot S_p} D_{DM_T} + D_{T_u} dt$$

The F_{PT} variable is the total infrastructure production that must be generally fulfilled over the whole planning horizon and is equal to:

$$F_{PT} = \sum_{p=1}^{S_p} F_{P_p} \qquad F_{PT} \in \mathbf{R}$$

The lower limit of the double inequality $\int_{T=0}^{S_d \cdot S_p} D_{DM_T} - D_{T_l} dt$ is the required demand lowered by a small amount (D_{T_l}). The upper limit $\int_{T=0}^{S_d \cdot S_p} D_{DM_T} + D_{T_u} dt$ is the required demand increased by the same amount (D_{T_u}). As it can be witnessed, both constraints involve the inclusion of a small amount the role of which is to increase the flexibility of the model and to confine the results. This amount is the "tolerance" of the model if the infrastructure produces a little less or more hydrogen energy than it is required. Practically, the upper limit is insignificant because the algorithm performs a minimization so it will not produce more than the required hydrogen energy. However, mathematically the double inequality is more accurate as it bounds the problem.

The model is designed in such a way so as the value of the tolerance can be changed and is determined by the user. The suitable value depends on the specifications of the simulation and is determined through experimental procedure, testing. Generally, if the value is too small the demand is tried to be covered from the fuel chains at any point and thus a lot of periods are necessary. If the value is too large the large number of periods is not necessary but the problem is less bounded and thus the results slightly less accurate. If it is desired to produce the exact amount of hydrogen energy, the user has simply to set tolerance to zero (Dtl = Dtu = 0).

It is important to mention that when a simulation is very complicated, namely includes a lot of pathways and/or a high level of demand and/or a large number of periods usually requires advanced computation systems. However, one of the advantages of this model is that even if it is necessary to run in a not so advanced computer by setting the appropriate settings, for example small number of periods or large value of tolerance, this is feasible.

Summarizing the aforementioned, the model for the development of a renewable hydrogen infrastructure could be outlined as follows:

The objective function that is desired to be optimized is a cost function that needs to be minimized in order to deliver the least cost option for the design of a hydrogen delivery system. This function is minimized taken into account:

1) technology constraints (for example the efficiency of the technologies);
2) production constraints due to renewable energy resource availability (the locations of the renewable energy plants that act as the primary energy feedstocks for the hydrogen production are determined by the resource potential of each energy source);
3) expansion and infrastructure constraints (for example the maximum allowed capacity of the renewable energy plants);
4) hydrogen demand satisfaction;
5) hydrogen demand satisfaction at any point throughout the planning horizon;

6) energy losses in all the stages of a fuel chain (for example electric grid loss);
7) costs of all the technologies that are included in the design of an infrastructure;
8) zoning constraints (for example the prohibition of installing a plant at certain location such as a city centre);
9) logical constraints (internalization of the costs in one variable wherever is possible).

4.10 The Superstructure of the Model

The superstructure (Figure 4.7) is the basis of the hydrogen infrastructure model. The flowchart begins with the set of the primary energy sources, which can be used as feedstocks for producing hydrogen. The model includes a wide range of primary energy feedstocks that can be divided into renewable electricity and biomass feedstocks. The first category consists of all the known renewable energy sources and the second category involves agricultural residues, energy crops and wastes. Agricultural residues comprise residues produced from agricultural activities and include crop, forestry and livestock residues. Energy crops are crops grown exclusively as energy sources and include herbaceous (switchgrass, miscanthus, bamboo), woody (hybrid poplar, hybrid willow, sweetgum), agricultural (vegetable oils) and aquatic crops (algae, seaweed, marine microflora). The third group comprise the biodegradable fraction of municipal solid, industrial and commercial waste.

The primary energy feedstocks can be used to generate hydrogen onsite using any of the production technology options, such as electrolysis, gasification, pyrolysis. The produced hydrogen can be stored as a compressed gas, liquid, in metal hydrides or in any of the novel methods. For delivering hydrogen to the point-of-use, the model considers four transportation mode options: road, rail, ship and pipelines. Rail and ship options have not captured high attention as hydrogen transportation methods but because they are technically viable options (Amos, 1998) they are included in the model. Once hydrogen is delivered at the refuelling station hydrogen is stored in the appropriate small-scale forecourt storage technologies.

The model is also able to support fuel chain configurations that include the production of hydrogen at a regional and forecourt level. In these cases, the primary energy feedstocks produce electricity that is transported through the electricity grid either to a regional hydrogen production plant or a refuelling station. In the former case, hydrogen is generated through large-scale electrolysis and then is stored and transported using the aforementioned options. In the latter case, electricity is converted to hydrogen through small-scale electrolysis at the forecourt and the produced hydrogen is stored in small-scale forecourt storage technologies.

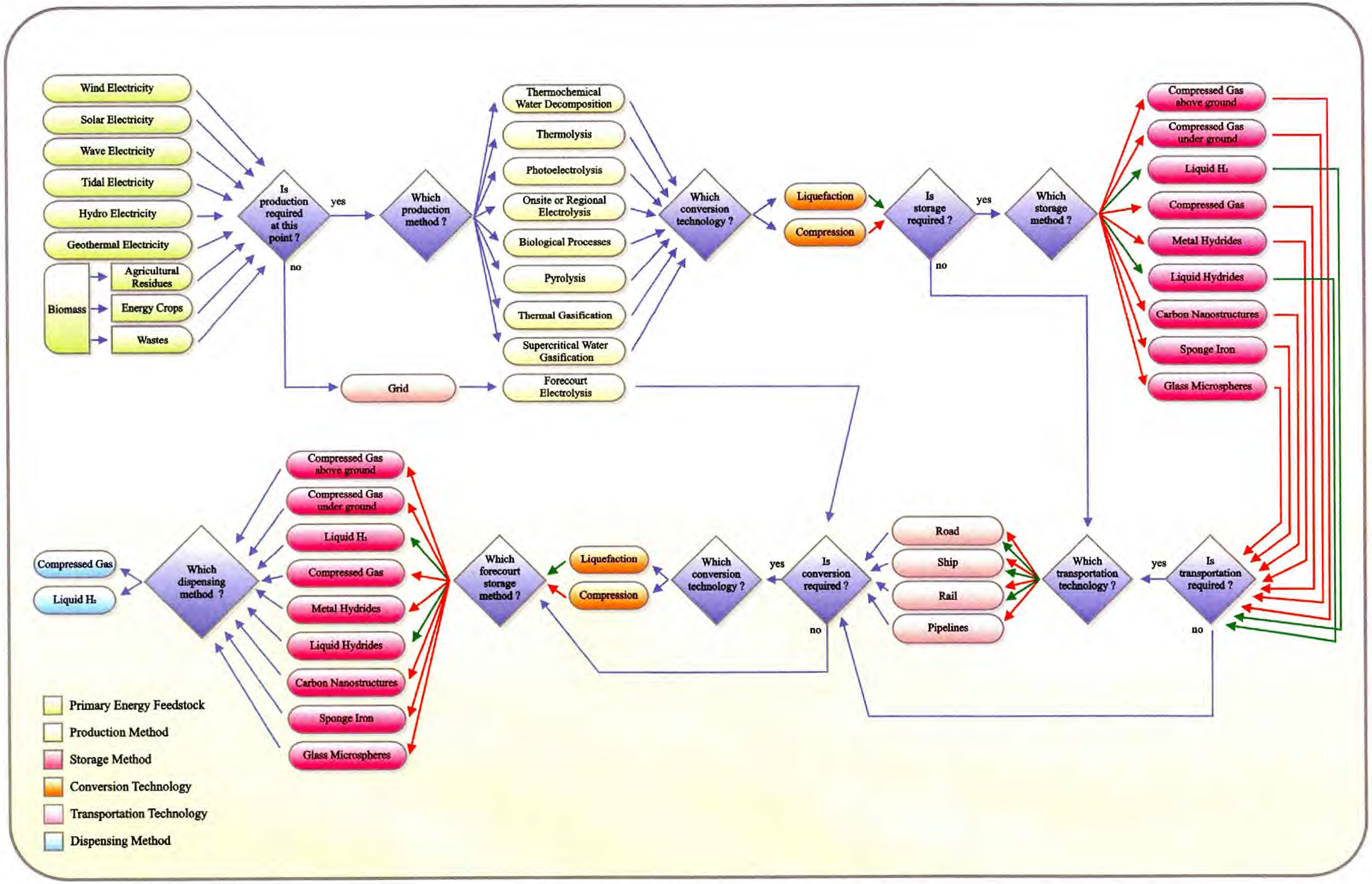

Figure 4.7: The superstructure of the model

Although a number of technologies in some of the stages of a fuel chain are quite novel as the design of a fuel infrastructure is a venture with a long-term time horizon, it is possible during this horizon a novel technology to become a technically and economically viable option and for this reason, the model is able to support the inclusion of all the known technologies irrespective of their maturity.

As it can be witnessed from Figure 4.7, the flowchart presents the life of the fuel from the point of the production of its feedstock until the point it is delivered in the demand centre. So, the superstructure does not include the dispensing stage at the refuelling station it ends with the storage stage at the forecourt. This is the case since the interest of this study, as the title indicates, is the supply of hydrogen to the demand centre, namely the development of a hydrogen network that aims to produce and deliver hydrogen fuel to urban centres. However, as the model is considered a general framework for hydrogen pathways simulations it is able to include the dispensing stage, if necessary.

4.11 The Structure of the Software

The second step of the fuel chain optimisation stage is the development of the software that implements the mathematical model. The software was chosen to be developed in the programming environment of MATLAB. Two approaches were examined in order to develop the necessary software to solve the problem. The first approach involves the construction of only one M-file that contains the complete necessary code for identifying the optimal solution and the second is based on the concept of object-oriented programming and is the one that was followed. The prevalence of the second method was mainly based on the fact that the first approach results in the production of one vast and chaotic file that would be incomprehensible to anyone else than the developer of the code.

The idea behind object-oriented programming is that a computer program consists of a collection of individual units, known as objects, and is not a list of instructions to the computer as is the case in procedural programming. An object is a software bundle of related variable and methods. Software objects interact and communicate with each other using messages. One of the main attractive attributes of object-oriented programming technique is the ability to create modules that do not need to be altered once a new type of object is added. A new object can inherit many of its features from an existing one. This makes object-oriented programs quite flexible and easy to be modified (Sun Microsystems, 2005). The reason why the present problem was not solved by performing object-oriented programming but by using the concept of object-oriented programming technique was just because the object-oriented programming library of MATLAB does not include a wide range of functions. In order to perform object-oriented programming an object-oriented language is necessary, such as Java, C++ and Smalltalk.

Following the chosen approach, a structured piece of software was built, which has the form of interconnected subsystems. Figure 4.8 presents the software like a pyramid that shows the path that the data have to follow in order the results to be produced. The pyramid consists of three subsystems that involve the User Interface (UI), the Model Builder and the MILP Solver subsystem.

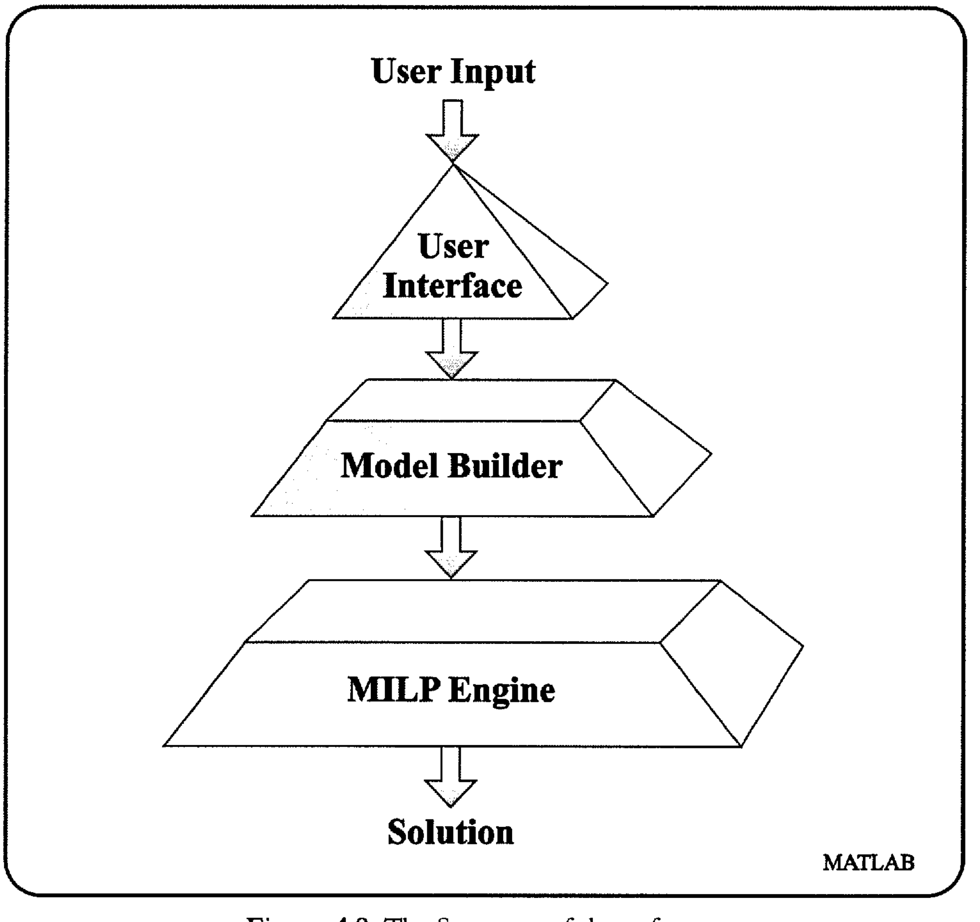

Figure 4.8: The Structure of the software

4.11.1 The User Interface Subsystem

The first component of the developed software is the UI subsystem. The purpose of this subsystem is to transform the input data into matrix structure. This transformation is necessary because the chosen software, MATLAB, reads data only in the form of matrices.

When the input data are imported, an XML file is produced and it passes the data into the UI subsystem. This subsystem is responsible to read the XML file (or input file) and to export the data in the form of matrices. The structure of the XML file is shown in Figure 4.9. After the comments, the text in the <!-->, the root element of the file is written. This element is the <infrastructure>. The root element has a number of child elements, such as the primary energy feedstock or the production technology. Every stage of the fuel chain constitutes a child element of the root element <infrastructure>. Likewise, every child element has its own branches that represent the necessary data of the child element. An example can be seen in Figure 4.9 that shows part of the XML file.

```
<?xml version="1.0" encoding="ISO-8859-1"?>

<!-- Imperial College-->
<!-- Centre for Environmental Policy-->
<!-- Olga S Parissis-->

<infrastructure>
        <primary_energy_feedtsock>
                <name>WindElectricity</name>
                <map>c:\maps\wind.png</map>
                <capital_cost>function of t</capital_cost>
                <operation_cost>function of t</operation_cost>
                <expansion_cost>function of t</expansion_cost>
                <capacity_factor>function of t or static value</capacity_factor>
                .
                .  more parameters here
                .
                <followed_by>Electrolysis</followed_by>
        </primary_energy_feedstock>

        <production_technology>
                <name>Electrolysis</name>
                <capital_cost>function of t</capital_cost>
                <operation_cost>function of t</operation_cost>
                <expansion_cost>function of t</expansion_cost>
                <efficiency>function of t or static value</efficiency >
                .
                .  more parameters here
                .
                <followed_by>Liquefaction</followed_by>
                <followed_by>Compression</followed_by>
        </production_technology>

        <conversion_technology>
                <name>Compression</name>
                <capital_cost>function of t</capital_cost>
                <operation_cost>function of t</operation_cost>
                <expansion_cost>function of t</expansion_cost>
                <efficiency>function of t or static value</efficiency>
                .
                .  more parameters here
                .
                <followed_by>MetalHydrides</followed_by>
                <followed_by>CompressedGas</followed_by>
        </conversion_technology>
        .
        . complete list of technologies for every stage follows here
        .
</infrastructure>
```

Figure 4.9: XML file structure

The UI subsystem consists of four main steps. The first step opens the input file. In this step a number of diagnostic routines are executed in order to inform the user in the case of an error. For example, if the input data does not contain any primary energy feedstock, the model will return a message stating this omission. Then, the UI reads the input file by applying top-down functional decomposition. The top-down technique is a systematic approach aiming to divide a problem into subproblems, the solutions of which produce the overall solution (CS, 1998).

In the next step, the UI reads the produced hierarchical structure and transforms it into a tree-like structure that is suitable to be read by MATLAB. This is achieved by performing depth first search (DFS). DFS is an algorithm for traversing or searching a tree structure or a graph. In this study, DFS searches the hierarchical structure and produces a MATLAB-readable tree. DFS has a recursive implementation. It begins selecting a node as the root and explores all the links of this node. When it finds no other link for this node, it backtracks to the preceding node and explores all other links that leave that node. For example, Figure 4.10 presents the creation of a tree based on the data from the XML file (Figure 4.9).

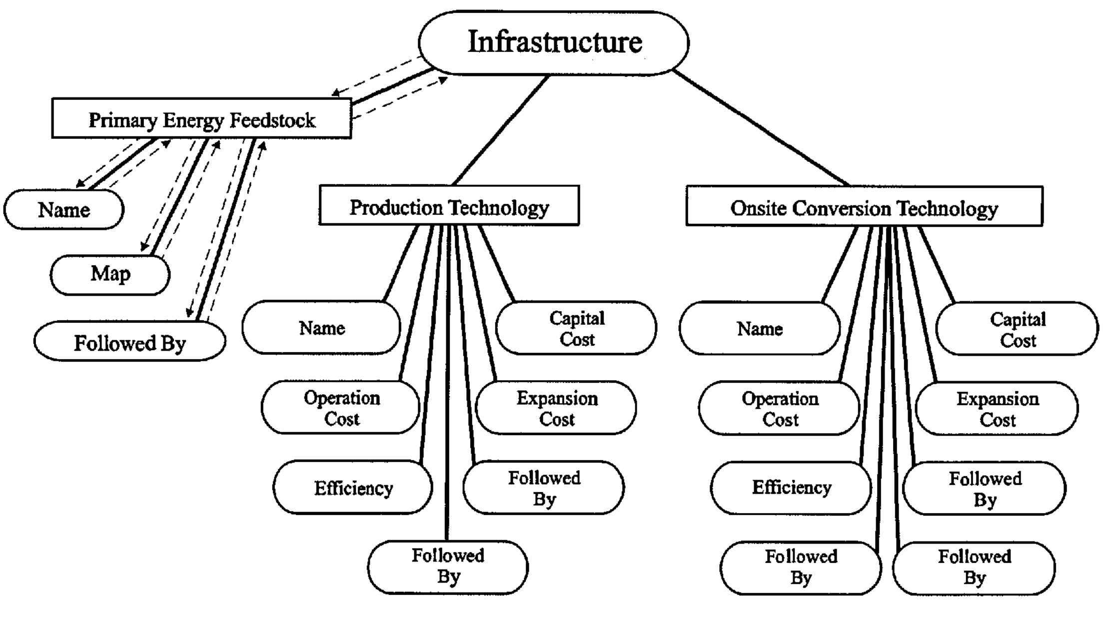

Figure 4.10: Tree-like structure

The first node that DFS explores is the "infrastructure" node. This node is divided into "primary energy feedstock", which is in turn divided into "name". As it can be witnessed in Figure 4.9 the "name" node does not have any other branch (or children as it is usually referred to) and thus, DFS goes back to the "primary energy feedstock" node and explores the "map" node, as it is indicated by the dotted arrows in Figure 4.10. It follows the same procedure until it completes the tree. The dotted arrows show the path that the search procedure follows. The tree in Figure 4.10 is a simplified and incomplete version of the actual tree of the model but serves as an example in order to explain DFS.

The data obtained from the input file for each node are imported into matrices. The model is able to support three kind of parameters, two concerning time and one concerning locality. Time parameters may be either time-variant or time-invariant parameters. Locality parameters are maps that give information about the renewable energy resource potential in Great Britain. Every stage of the fuel chain has its own corresponding matrix. The last step includes the exportation of the resulted matrices that are imported to the next subsystem. The data that are exported by this subsystem includes the parameters of each stage of the superstructure, the possible technological options in every step of the superstructure, the fixed and variable costs of every stage and all the necessary technical characteristics of all the technologies. The model can include an unlimited number of fuel chain options, stages in every fuel chain and technological options in each stage of every fuel chain. Figure 4.11 presents the inputs and outputs of the User Interface Subsystem.

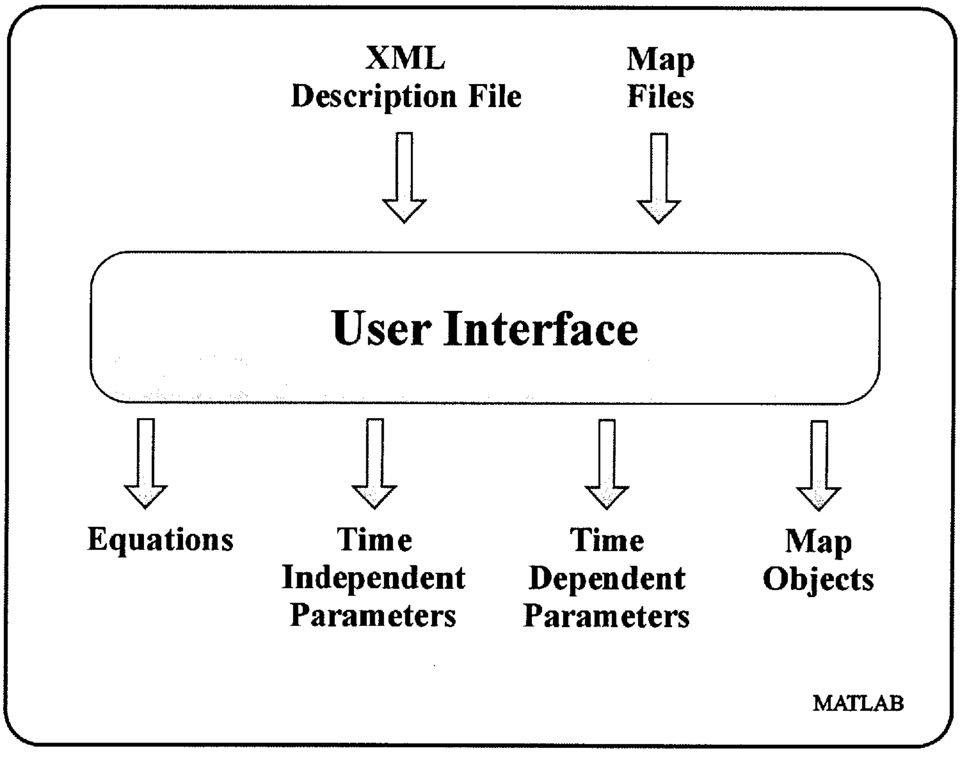

Figure 4.11: Inputs and outputs of user interface subsystem

4.11.2 Model Builder Subsystem

The convenience of use and "beauty" of the model arise from this very subsystem. The importance of this subsystem lays on the ability to eliminate the requirement from the user to form equations. More specifically, the inputs that pass into the model are in the simplified form of values and parameters. Then, this subsystem employing an "abstract" method is able to use the input data in this plain form and produce the desired results. This "abstract" method refers to the black-box design of the software into which when the data are imported preprogrammed logic is utilized in order to return the outputs. Thus, the model can be used by users that do not have any knowledge of MATLAB.

The Model Builder subsystem is responsible for two tasks. At first, the geographical optimisation stage is implemented into this subsystem. The map segmentation and resource optimisation are carried out providing the possible starting points of every fuel chain. Afterwards, for every fuel chain the capital, O&M and probable expansion costs and the corresponding equalities and inequalities are calculated. The resulted costs and sets of equalities and inequalities are added to the cost objective function, set of equalities and set of inequalities, respectively. When this is completed for all pathways under study, the Model Builder subsystem has produced the overall cost objective function, which is going to be minimized, and the overall sets of equalities and inequalities in which the objective function is subject to.

The procedure that is followed in order to form the objective function and the set of equalities and inequalities is a recursive procedure that starts from the primary energy feedstock, which is the beginning of the every fuel chain, and ends at the market that constitutes the end of the fuel chain. More specifically, when that data are passed from the UI to the Model Builder subsystem the latter calls a function that starts from the primary energy feedstock assembles its corresponding data and for every subsequent stage of the chain calls itself assembling the data of the corresponding stage until the point the next stage is the market. With this recursive procedure the model builder subsystem builds the model (and for this task takes its name) and transforms it into the mathematical form that is necessary for the MATLAB function that solves the problem. The outcomes of this subsystem are imported to the next and final subsystem, the MILP Solver. Figure 4.12 demonstrates the flowchart of the algorithm that is performed in the Model Builder subsystem.

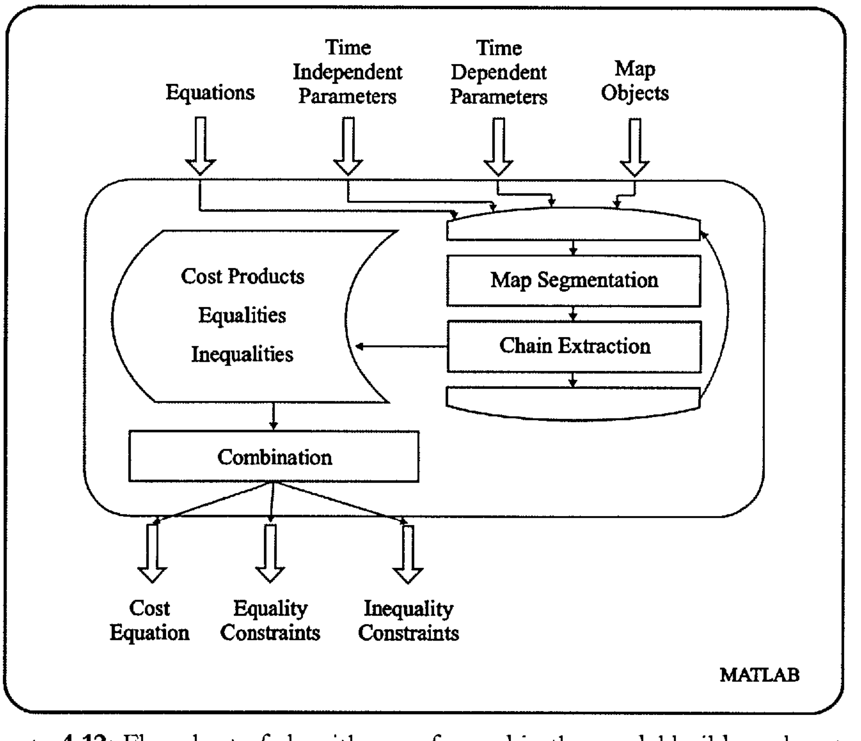

Figure 4.12: Flowchart of algorithm performed in the model builder subsystem

4.11.3 MILP Engine Subsystem

The final subsystem uses the overall objective function, the set of equations and the set of inequalities imported from the Model Builder subsystem to solve the problem and return the results (Figure 4.13).

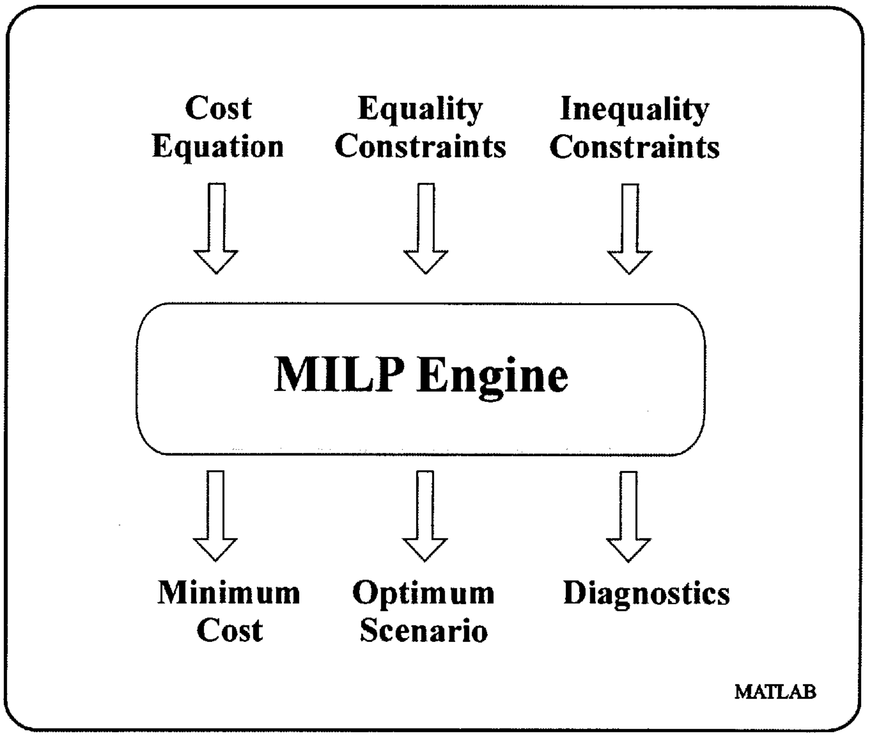

Figure 4.13: Inputs and outputs of MILP engine subsystem

This subsystem uses the linprog function of MATLAB with the only difference that involves the definition of the parameters that need to take only integer values. The linprog function is the function that solves linear programming problems in MATLAB. More specifically, in order to solve the problem it is not necessary to write a new algorithm but to use the linprog function and write a differentiation. This differentiation is the MILP function that includes the linprog function. The MILP function is a wrapper of linprog, namely an interface for linprog that solves MILP problems.

The linprog function includes an objective function that can be either maximized or minimized subject to a number of constraints. Its general form is:

$$\min_{x} f^T x \qquad \text{such that} \qquad \begin{aligned} A\,x &\leq b \\ Aeq\,x &= beq \\ lb \leq x &\leq ub \end{aligned}$$

where *f, x, b, beq ,lb* and *ub* are vectors and *A* and *Aeq* are matrices (Mathworks, 2005). In the problem of the present study, *f* is the objective function that is the cost function and *x* is a matrix containing the unknowns, namely everything that the linprog is called to give values. The matrices *A,b* and *Aeq,beq* contain the "architect" of the model, for example efficiencies, and the first pair corresponds to the inequality constraints and the second pair to the equation constraints. The *lb* and *ub* vectors are the lower and upper limits for the matrix with the unknowns, *x*, and assist in solving the problem more effective. Figure 4.14 shows the algorithm that is carried out in the MILP Engine subsystem.

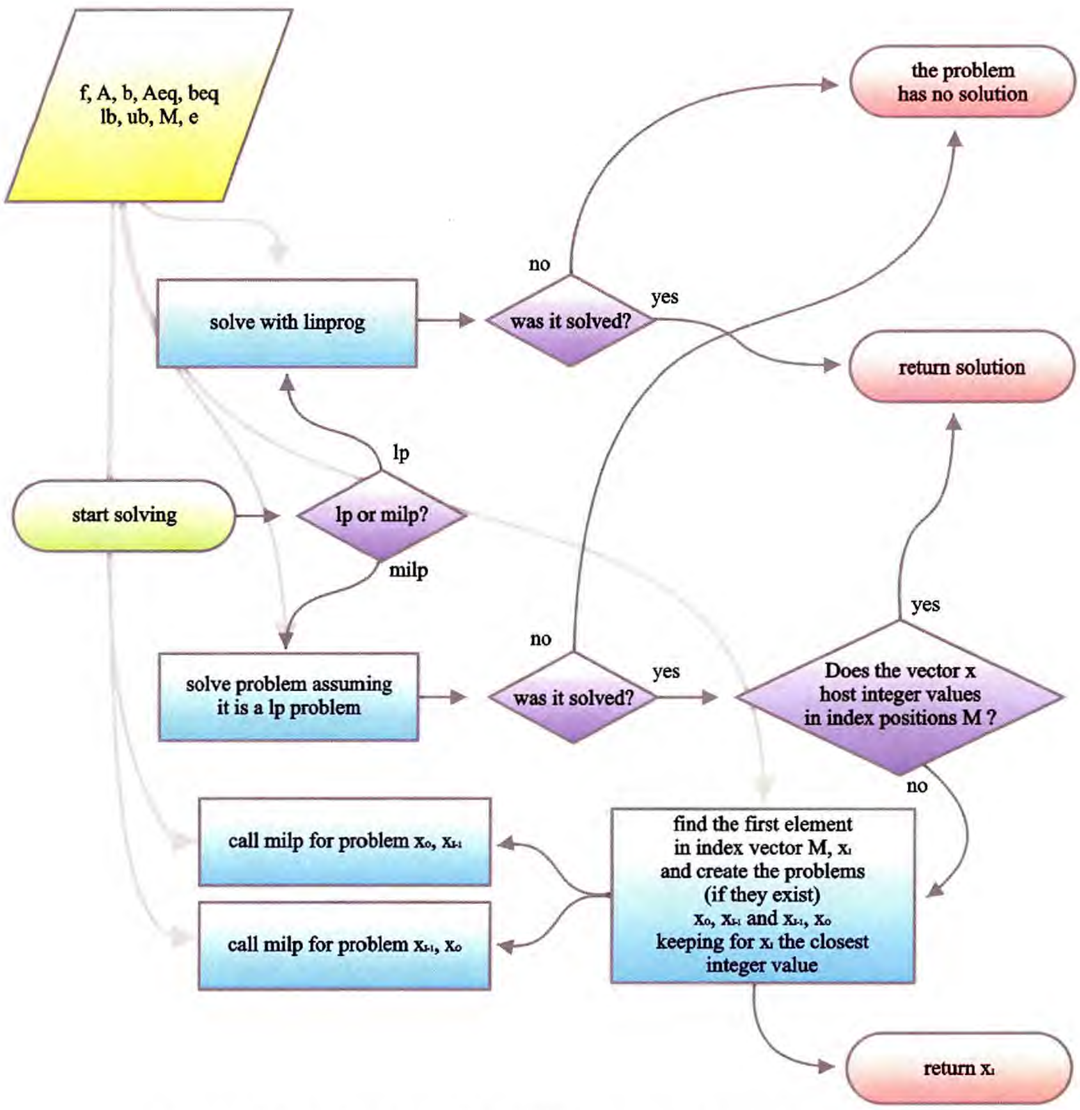

Figure 4.14: Flowchart of the MILP engine subsystem algorithm

The yellow side parallelogram in the top represents the data that are imported into this subsystem and start the MILP subsystem procedure. The light grey arrows represent the data flow and the dark grey arrows show the procedure flow. The main node of this algorithm is at the beginning where the decision on whether some of the variables in x need to take integer or real values is taken. In the former case the problem is solved twice for every integer variable in x in order to find the optimal value between the two closest integer values of the selected real value.

The results are returned in the form of a number that represents the total infrastructure cost and a text document that includes all the logical decisions (eg the use or not of a primary energy feedstock, or the expansion of a production facility) during the selected time horizon. The results are passed from the MILP Engine subsystem to the GUI that depicts them schematically. As the results, especially in the case of large problems that include numerous different pathways, include a lot of information that it is impossible to be contained in the GUI, all the numerical solutions are presented in a text file. The GUI shows the geographical region under study after the map segmentation and resource optimisation have been carried out and all the fuel chains and their starting points that have been selected.

Adding together the three subsystems creates the pyramid as demonstrated in Figure 4.15. Figure 4.15 is a more detailed version of Figure 4.8 showing the inputs and outputs of every subsystem specifying the inputs of the model, how they are transformed and the outputs.

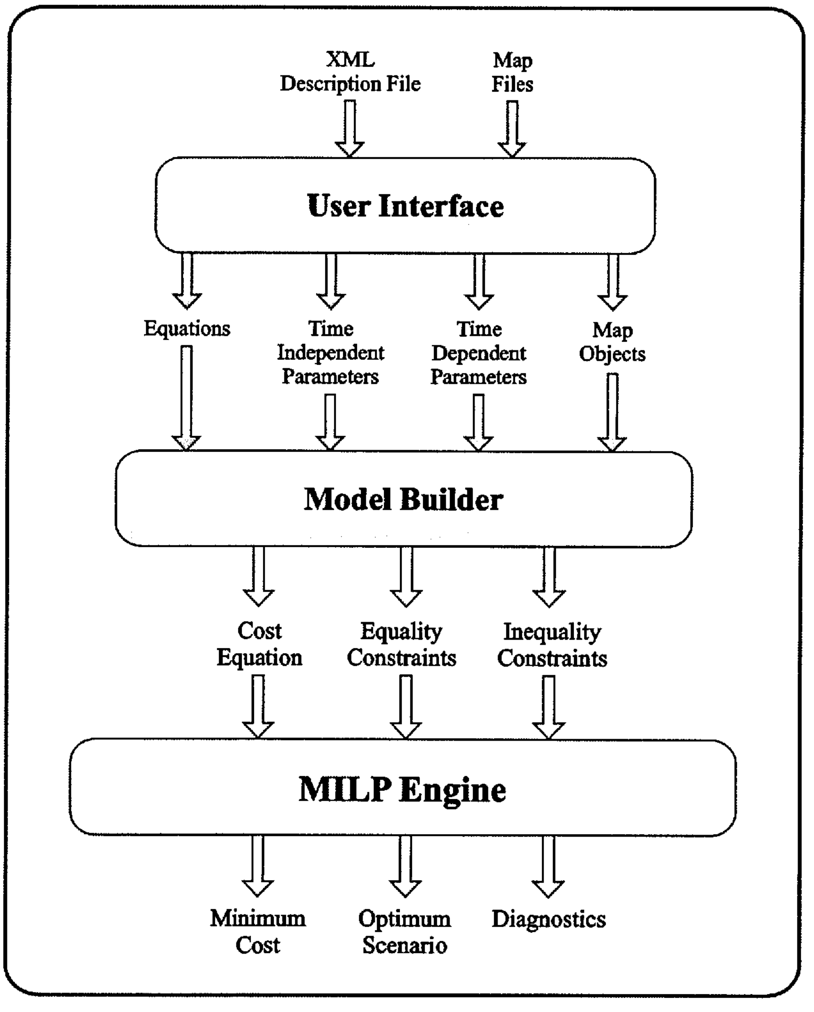

Figure 4.15: The software of the model that consists of three interconnected subsystems. The inputs and outputs of every subsystem are specified.

4.12 Graphical User Interface

The GUI is the chosen way of entering data into the model. It is the mode of interaction between the user and the model. It passes the input data into the UI subsystem and after the simulation shows the results obtained from the MILP Engine subsystem. Thus, the GUI and the pyramid constitute a circle as shown in Figure 4.16.

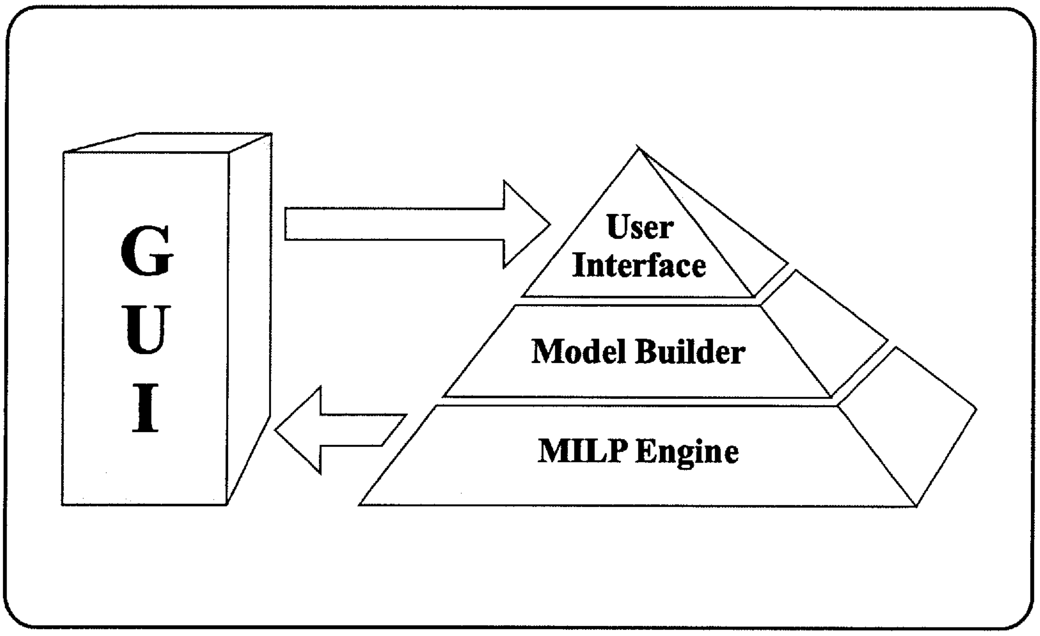

Figure 4.16: The model software with the GUI

The data of the desired renewable hydrogen infrastructure development under study that enters the model through the GUI involve the formation of the fuel chains, which includes the selection of technologies for all the stages in a fuel chain, the choice of the geographical region under study, the choice of demand centres and the setting of the technical and economic values of all the parameters. That means, that without any change in the model (the three subsystems), results can be obtained for any desired hydrogen delivery pathway either using wind energy or biomass or all renewables for any geographical region assuming one or many supply centres by just choosing the desired settings from the available options in GUI. For the creation of the fuel chains the user can choose the preferred option for every step of the chain by a wide range of alternatives available in a dropdown menu (one for each step) in the GUI. The selected geographical area is entered in the model in the form of a map which can be loaded from any mounted file system in the computer. Figure 4.17 illustrates a screenshot that shows the initial appearance of the GUI before anything is selected.

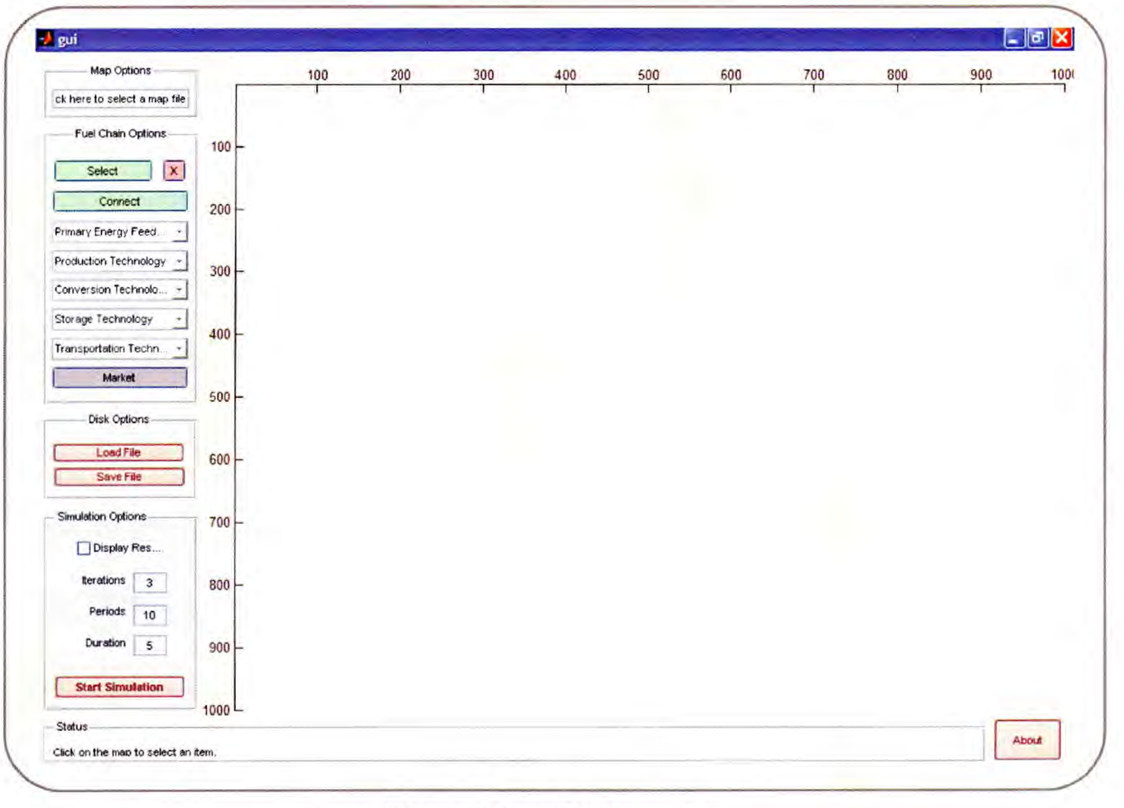

Figure 4.17: GUI screenshot

As the window takes up the full screen on the left hand side there is the menu column, which includes all the possible options for every component of the infrastructure and a number of alternatives concerning the simulation. The first item of the menu bar enables the loading of the map files. These files include maps for the selected geographical region, the renewable resource potential and generally any other data that used to be entered in the form of maps. Although these maps can be entered into the model, only the map of the geographical region is visible in the GUI. The grey free space in Figure 4.17 is substituted by the map of the selected geographical region when the latter is loaded.

The next item of the menu, titled 'fuel chain options' contains five dropdown submenus that correspond to the various stages of the fuel chain. So, there is one submenu for the primary energy feedstock, for the hydrogen production technology, for the conversion method, for the storage method and for the transportation method. All the submenus include all the possible options for every stage. Selecting the preferred technologies from the available options of the submenus and clicking on the geographical map form the pathways that compose the renewable hydrogen infrastructure. When a technology is selected, a matrix appears on the map in which all the technical and economic data are entered. By combining different options of this submenu numerous different infrastructures can be obtained, for example infrastructures that produces hydrogen only from wind and solar or from wind and biomass or use both liquid and compressed gas hydrogen. The model is able to support all the possible renewable infrastructure types and for each one to determine which is the least cost development strategy.

As the model can run for numerous delivery pathways it was considered essential every designed infrastructure if desired to be able to be saved. This is the purpose of the third item of the menu the 'disk options'. The chosen settings can be saved by clicking on the 'save file' tab and the GUI can return to those settings by clicking the 'load file' tab. The last item of the menu allows to select the number of regions that the geographical area will be divided into, the number of changes the fuel chains can experience (the word change refers to the activation, expansion, reduction and deactivation of a fuel chain), and the lifetime if each change. The label 'map segmentation iterations' divides the area under study into equal in terms of energy regions according to the value assigned in the corresponding box. Because this label refers to iterations and not to the numbers of regions if for example it is desired to separate the map into four regions the required value that should be set in the box is two.

The label 'periods' is responsible for the maximum number of changes the fuel chains are allowed to experience. The minimum number for this label is two as the first change is the activation of a fuel chain. This label gives to the user the ability to determine the 'life' of the fuel chains, for example to choose whether the fuel chains can have many small changes or a few large changes. However, it is possible if it is preferred this decision to be taken by the model by setting a very large value. The last label refers to the lifetime of each period (change). As for the 'period', setting a high value to the 'duration' leaves to the model the change lifetime decision. These two labels allow the user to determine the time horizon. The multiplication of these labels defines the planning horizon. For example, for the selected 50 years horizon one possible combination is to set 'periods' to 10 and 'duration' to 5. The last tab of the menu as it is evident by its name, 'start simulation', begins the simulation.

Figure 4.18 illustrates a screenshot showing the appearance of the GUI for an example showing six different onshore wind energy pathways. The selected geographical area is GB and the demand centre is London. Every step of the fuel chain is represented by a different colour in order to make the appearance of the design more legible. Every stage has a coloured matrix into which the corresponding data are entered such as the capital cost, the O&M cost, the efficiency, the location. The fuel chains start from the top left with onshore wind energy, which is the selected primary energy feedstock (red colour). After the production of the feedstock is the production of hydrogen fuel (blue colour). The first two steps are the same for all the fuel chains that is why they are only present once. The matrices with the yellow colour represent the conversion technologies and in this example there are two; compression and liquefaction. The purple matrices correspond to the storage stage. As it can be seen, these matrices are present twice, in the fourth and the sixth line. This is because the latter are the storage at the forecourt. The light blue matrices are the transportation technologies that all but one are connected to the forecourt storage and then to the white matrix, which is the final one and represents the market.

The positions in which the technologies are placed are abstract. The reason for this is that the model decides where the position of all the technologies should be and thus when the simulation ends returns the results with the exact locations of all the selected technologies. As a result, the positions of the technologies at this stage do not matter. However, it is possible if a technology is preferred to be at an exact point in GB to be located there by entering the coordinates of this point into the parameter *location* of this technology. All the fuel chains conclude at the same point that of London, the demand centre, which is represented by a red dot in the map. The dot is not abstractly placed is located according to London's coordinates.

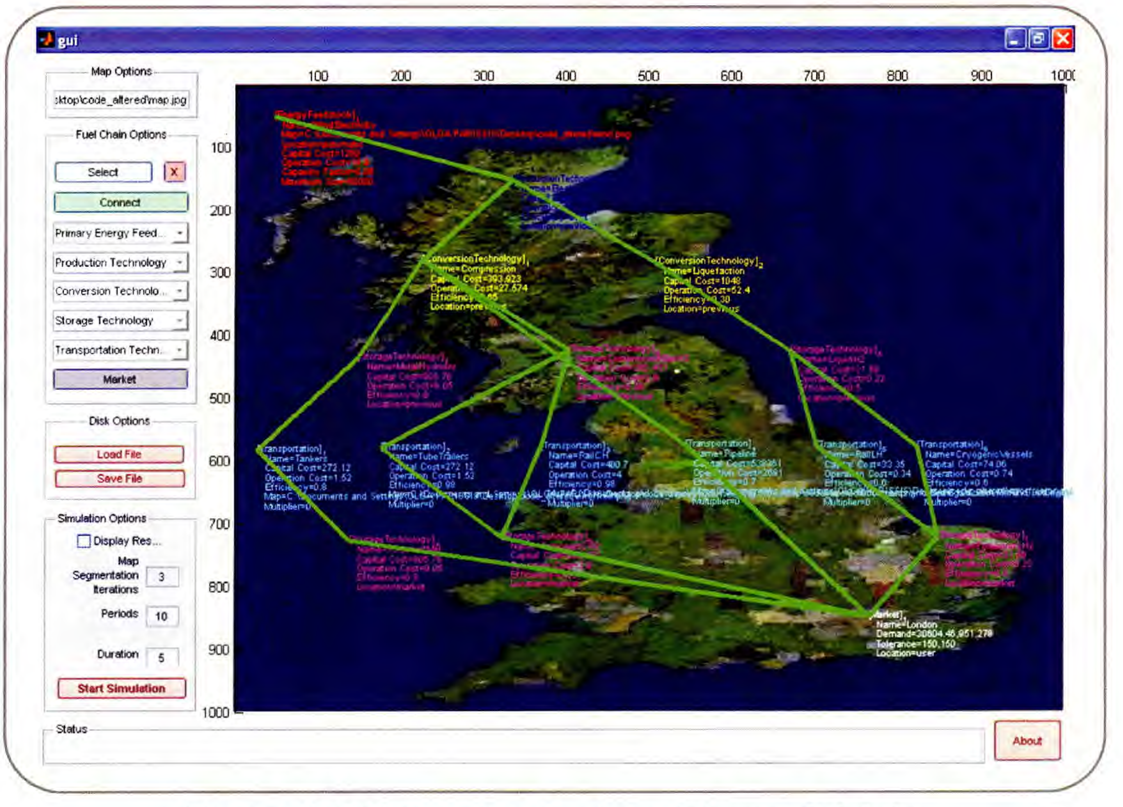

Figure 4.18: GUI screenshot of onshore wind energy fuel chains

4.13 Limitations of the Model

A model is a representation of a real system that attempts to explain the behaviour of some aspect of it but is always an approximation and thus is less complex than reality. For this reason limitations are intrinsic to models. Model limitations can be in the data supporting a model, in the model's design or in its implementation, which may include assumptions relative to the model application or concerning model applicability. The limitations of this modelling study are discussed in groups. The groups are divided according to the part of the model that the limitations refer to.

Image Processing

As it has been mentioned before, a number of data are entered into the model in the form of maps. The model can not support maps that have not undergone a certain processing. All the maps are required to be of one colour (grayscale) that are either in the form of grayscale or RGB colour space with one colour representing areas of the same values. Moreover, areas of zero value or areas that are not desired to be included in the simulation should have transparent colour, for files that support transparency such as .png and .tif, and black colour for all other files. Lastly, the maps can be in any image format that is based on the simple reference of colour of every pixel, such as .bmp, .jpg, .gif, .png and .tif and not descriptive files and vector files such as .svg, .emf and .wmf.

Map Segmentation

The model is able to run simulations for any number of map segmentation iterations. However, there is an optical limitation in the segmentation process. When the region under study is segmented into areas every segment has a different colour and thus it is distinguishable from the others. However, when the results produce more than 256 segments some of the colours are repeated and thus some of the segments have the same colour. This repetition may produce an optical problem in the appearance of the segmentation. The reason that the maximum number of colours is 256 is that this number is the maximum number that an 8 bit number can give. Therefore, the maximum map segmentation iteration number is 7 and produces 128 segments. It is important to mention, that the results of the model are not affected by this limitation. So, the model can run simulations with any number of segments. This limitation affects the segmentation results but only optically.

The geographical region under study is entered into the model in the form of a geophysical map. The dimensions of the map can vary but there is a minimum in the size of the map. This minimum is determined by the map segmentation iterations. For example, if the number of iterations is 5 then the produced segments are 32 and thus the minimum size of a map should be the size of a 36 pixel map in order every segment to correspond to one pixel. However, the selected geographical region it is unlikely to be of such a small size that is represented by a 36 pixel map and thus this limitation may never create any problem.

Primary Energy Feedstock

The selection, production and location of the primary energy feedstock are based on the maps of the renewable energy resource potential. Every primary energy feedstock has its corresponding map. The model is able to take into consideration only one map for every primary energy feedstock. This may not be a limitation for some primary energy feedstocks. For example, in the case of wind energy this is not a limitation as for this renewable energy source the only necessary map is a map showing the wind speeds of the region under study. On the other hand, in the case of energy crops the resource potential may not depend only on one factor and thus on one map. In the latter case it is necessary to include more than one map such as maps showing the available land for cultivation and the appropriate land for the cultivation of a specific energy crop. In this case as the model is restricted to consider only one map as input for every primary energy feedstock the combination of maps is required. This can be done using the GIMP software and following the procedure that was described in the image processing Section 4.7. This limitation is also true for the transportation stage as this stage also includes maps.

The inclusion of the first stage of the fuel chain, the primary energy feedstock production, into the GUI is necessary for all simulations. Even if a simulation examines pathways that do not include the feedstock production stage but begin with the production of the fuel, the primary energy feedstock production stage has to be entered in the GUI. This necessity is applicable only for the beginning (feedstock production) and the end (market) of the fuel chains. In order to run the model these stages are compulsory but all other stages in between are not. The reason for this necessity is because the amount of hydrogen that every fuel chain may possibly produce is entered into the feedstock production matrix at the GUI. However, the model is able to run simulations with pathways without feedstock production. This is feasible by entering zero to all values of the feedstock production matrix, apart from the amount of hydrogen, at the GUI.

Market

As it is the case for the feedstock production stage, the market is necessary. However, in this case this may not be considered a limitation as it is unlikely to form a pathway without an end point. The model is restricted to include only one market. This was considered adequate as it satisfies the requirements of the case study that is included in this thesis. Nevertheless, the inclusion of more than one market is possible but requires a modification in the resource optimisation stage. Moreover, the model considers the market place as a point in the map and thus does not include the distribution of the fuel within the market place. If the distribution of the fuel is desired to be examined the model is able to support the corresponding map showing the market place in detail but an additional static algorithm is necessary aiming to determine the optimal places for the establishment of the refuelling stations.

The amount of the demand that the infrastructure has to be able to cover is entered in the GUI in the form of a function. The demand is a function of the time variable. If the demand function includes known functions such as cosine, sine or tangent, these functions have to be consistent with the Maple syntax. This is necessary as the MATLAB's symbolic computational tools are a subset of Maple.

4.14 Conclusions

This Chapter described the complete procedure that was followed in order to develop the renewable hydrogen infrastructure development algorithm. The tools that have been used to create the algorithm, the structure, the mathematical model, the implementation of the model have all been explicitly laid out.

The model has been designed aiming to explore the fundamental issues surrounding the development of a renewable hydrogen infrastructure. It produces the spatial and temporal infrastructure build-up decisions that minimize the overall cost. It compares several hydrogen pathways technically and economically and includes the regionally specific data to determine the optimal plan for meeting a specified demand.

There are three features of the hydrogen infrastructure development algorithm of this study that constitute its strongest and distinguished it from other works. Firstly, its originality in the design and the way it addresses the infrastructure development issue. The algorithm is a combination of various different technological fields, some of which have never been used before in this field. It includes the use of MILP, MATLAB, XML, GIMP and GUIDE. All these tools have reinforced its capabilities but also have increased the difficulty of creating it. Moreover, the results of the model are not just a comparison of a number of fuel chains but a plan showing explicitly how a hydrogen delivery system is possible to be built for any desired region.

Secondly, its generality as it may be considered a generic framework for modelling the development of hydrogen delivery systems. The flexibility with which the general structure of energy demand can be defined and the detailed treatment of fuel chain formation are vital for the application of the model to a wide range of geographical areas with different data structures. This model provides a behaviour template contrary to other studies that provide an equation template. For this reason, the model is able to support completely different simulations such as simulations that include renewable or non-renewable energy sources, whole fuel chains or part of them, existing or new facilities, short or ling time horizon.

Lastly, its potential to examine even more in depth issues pertinent to the infrastructure development. The present state of the algorithm examines the design of a hydrogen delivery system taking into account all the necessary parameters for a detailed simulation. These parameters were determined from both the literature and discussions with experts. However, the model is designed in such a way that with little or any modification can include more parameters. For example, as it can be seen from the application of the model in subsequent chapters the simulations do not include the dispensing stage. However, if it is desired the model is able to support this inclusion. The latter inclusion is one of those that do not require any modification.

Having described and explained the hydrogen infrastructure development algorithm, the next Chapter presents the application of the model and aims to show and test its performing capability.

CHAPTER 5

Testing

5.1 Aim and Scope

The next step after constructing a model is to check the accuracy of its predictions. The testing procedure is necessary as it evaluates the model's credibility, validity and uncertainty of its results. Moreover, it assesses the model's sensibility based on scientific knowledge, whether the assumptions are reasonable and the predictions match the observed data. A model is a representation of a system that allows for investigation of the behaviour of the system and the prediction of future outcomes. Thus, a model is not reality but an imitation of reality and considering that the reality itself is not an ideal experiment its imitation has by definition flaws. However, whilst "all models are wrong" (Sterman, 2000), there are degrees of wrongness and it is important to rule out some basic errors. This elimination is feasible through testing. It is worthwhile to mention, though, that testing can never be complete, it can only show the presence of errors, not their absence.

In this Chapter the hydrogen infrastructure model is subject to testing. The focus of this Chapter is how the optimal decisions, the outputs, are produced from the input data, rather than on how the input data are gathered or estimated. Naturally, as the input data determine in a great extent the outputs it is important to be representative and valid for real cases. The theoretical assumptions and values for all parameters are showed and explained and the results are presented and interpreted. The interpretation and discussion of the results are carried out with particular attention to the behaviour of the model rather then the numerical outcomes.

5.2 Testing Strategy

There are three basic criteria for evaluating a model: correctness, completeness and consistency. A model is correct when it is equivalent to some reference standard that is regarded as a reliable source. This standard may be either a reference model that serves as a basis for determining whether the model under test is behaving correctly or a human expert who judges based on its knowledge. A model is characterised complete if it includes all the elements that are considered necessary in order to describe the system being modelled sufficiently. The decision whether an element is necessary or not depends on the level of maturity and scope of the modelling. Lastly, a model is consistent if there are no contradictions among the elements of the model. Consistency depends on whether the relationships among elements allow a concept to be represented in more than one way (Sterman, 2000).

There are several ways to test a model. Each approach has its limitations. A model can be compared to reality by comparing its results to historical behaviour. By entering data from the past into a model events that have already occurred can be simulated and the results can be compared and thus prove the validity of the model. This is a useful test only in cases where past data are available. Apart from the past, the results of a model can be compared to reality by looking at the future. The prediction of a model can be verified by waiting until the event that was modelled occurs and its behaviour is according to the model's predictions. This method is more limited than the previous approach as it is restricted to the modelling of events with a very short time horizon. Thus, it can certainly not be applied to the hydrogen infrastructure development model as the creation of a fuel infrastructure is a venture with a large timescale. Besides, the problem of this study is modelled aiming to foresee the best solution for the future and thus to provide a tool for the formulation of the appropriate policy in the present.

Another way of testing a model is by comparing its results to a reference model that represents in the same way the same system. This method is not applicable in the present study as there is no other algorithm addressing the issue of the development of a hydrogen delivery system in such a way as the one presented in this study. Naturally, some general tendencies that have been concluded in other studies may be compared, for example the predictions that some technologies are more expensive than others. However, this model does not only compare technologies and pathways but produces a development plan which is formed in a different way than in any other study.

The hydrogen infrastructure development model has undergone several tests from the early stages of its development until the point it was completed. Testing is not a judgemental step at the end of the model development process but is a continuous process that guides development. In order for the model to reach the point of completion it has passed through testing that varies depending on the part of the algorithm that is under examination. Testing was implicit to the bug-catching process that occurred throughout the modelling process and included dimensional consistency, checking output against actual outcomes, bug fixing, correct representation in the GUI, robustness under extreme conditions and sensitivity analysis.

5.2.1 Dimensional Consistency

The first check to make on a model is for dimensional or unit consistency in order to avoid situations where metres added to metres per second and ensure that all functions are consistent. This model is dimensionally consistent. The input data that enter the model pertinent to costs can be entered in any currency as long as all the costs are converted into the selected currency. The amount of produced hydrogen is given in Watts (W). So, the demand is entered in W, the costs are given in any currency per W, for example £/W and the transportation costs are entered in any currency per kilometre, for example £/km, with the exception of electricity transportation that is given in any currency per W, for instance £/W.

5.2.2 MATLAB Software Check

The mathematical model is implemented into software that was built in the MATLAB environment. When writing code in MATLAB, as in many other software, MATLAB returns warnings reporting errors in case mistakes have occurred. Thus, the software that implements the mathematical model was tested automatically by the MATLAB environment. The fact that the model runs without errors signifies that the code is correct. Nevertheless, based on this fact it can not necessarily be drawn conclusions for the quality of the code, for example whether it has a long or short simulation time. Moreover, if the mathematical model is able to run correctly in the software it shows that the software is built correctly but does not imply that the mathematical model is correct.

5.2.3 Robustness

The model has to behave robustly but intuitively in extreme conditions. For example, if the cost of a pathway falls to nearly zero, the model must select this pathway to cover the demand or if there are limited resources and large demand the model must conclude that the resource of the geographical region are not sufficient to satisfy the demand. This is necessary to be carried out for all parameters. Two variables were selected and their interaction was compared to their expected relationship. The model performed as expected as each parameter was varied in this way. Robustness testing was quite useful as it showed a number of bugs, which were fixed.

5.2.4 Sensitivity Analysis

Sensitivity analysis is conducted when the model is complete to determine the amount and kind of change produced in the model predictions by a change in a model parameter. Performing a sensitivity analysis can show if a model resembles the system under study, the factors that mostly contribute to the output variability, the model's parameters that are insignificant, if there is a region in the space of inputs for which the model variation is maximum and if and which factors interact with each other (Sterman, 2000). Sensitivity analysis has been performed twice. A limited analysis is described in this Chapter and an extensive analysis is presented in Chapter 7.

5.2.5 Illustrative Example

As the predictions of the infrastructure development model cannot be verified from any other reference model the only way to prove that is a valuable and reliable tool is by running a simplified simulation, the outcomes of which could almost be predicted even without the use of the model, and compare the actual outputs with model's outputs. Thus, the behaviour and performing capability of the model could be illustrated and the validity of the results could be proved. In a way this test includes and shows the results of all other tests that assist in the formation of the final, complete and correct state of the model that produces credible outcomes. So, this process is more like a proof than a test.

5.3 Example Formulation

The simplified simulation includes GB as the geographical region under study and aims to produce a hydrogen infrastructure development plan for London, which serves as the urban centre that constitutes the market. More specifically, the example illustrates the development of a renewable hydrogen supply network able to deliver hydrogen fuel to London based on one renewable energy source and six different fuel chains. The selected renewable energy source is onshore wind energy. Although the selection of the energy that is used as a hydrogen primary energy feedstock may be considered relatively arbitrary, there is a reason behind it. As wind power has boomed significantly over the past years, likewise its technology has been greatly developed. It is a promising energy source as it combines mature and relatively low cost (compared with other renewable energy sources) electricity-generating technologies. Moreover, Great Britain is very well endowed with wind energy resources and thus wind power may be one of the main contributors in the production of hydrogen fuel.

The six fuel chain configurations under study are the following:

1. Electricity generated by wind energy is used for electrolytic hydrogen production that is followed by compression and storage in tanks as a compressed gas. It is transported by road (trucks) and stored in cylinders at the forecourt;
2. Wind-based electrolytic hydrogen is compressed and stored in tanks. Hydrogen is transported by rail and stored as compressed gas in cylinders at the forecourt;
3. Wind-based electricity is used to generate hydrogen through electrolysis that is stored in metal hydrides in tanks and then delivered by road at the refuelling station where it is stored in metal hydrides;
4. Wind-based electrolytic hydrogen is compressed and transported through pipelines at the refuelling station;
5. Wind-based electrolytic hydrogen is liquefied and stored in cryogenic vessels followed by road transportation (trucks) and storage in vessels at the forecourt;
6. Wind-based electrolytic hydrogen is liquefied and stored in tanks. It is transported by rail and stored in tanks at the delivery point.

All the configurations include on-site electrolysis. In terms of storage all but 4 assume on-site and forecourt storage. Rail option has not captured high attention as hydrogen transportation method but because it is a technically viable option (Amos, 1998) is included in the simulation.

These pathways are illustrated schematically in Figure 5.1. The technologies that form the chains are technologies that are commercially available and have been used either in greater or lesser extent in projects. However, a slight exception may be considered that of the rail transportation option not for its feasibility but for its non-existent application as a hydrogen transport alternative so far.

Figure 5.1: Fuel chains under study

It can be witnessed that the primary energy feedstock and the hydrogen production technology are the same for all fuel chains. For the chosen production method, there are two advanced electrolyser technologies that can be used, the alkaline and the polymer electrolyte membrane (PEM) electrolyser. However, in this simulation only the alkaline is used. The reason for choosing the former type is its suitability for large systems. PEM electrolysers are currently available for small capacities and thus can not support the development of a fuel infrastructure that requires large amounts hydrogen fuel. However, they may be appropriate for forecourt electrolysis but since that option is not considered in any of the six chains PEM technology is not included in the example. In the case where pipelines are used as a transportation method (fuel chain number 4) it is assumed that pipelines also serve as a storage means. This is feasible by changing the operating pressure which causes a change in the quantity of hydrogen gas contained in the pipeline network (Amos, 1998).

The collection of technical data which are included in the chains was achieved by means of literature and commercial information review. Most of the required economic data were mainly obtained from a study analyzing the cost of hydrogen infrastructure for Buses in London undertaken at Imperial College London (Shayegan, 2003). For the technical data, efficiencies, the values from two reports were used (Amos, 1998; Hawkins, 2006). Table 5.1 lists the main parameters and their corresponding values that are used in the example.

Technology	Parameter	Value
Primary Energy Feedstock Wind Energy	- Capital Cost - O&M Cost - Capacity Factor	- 1120 €/kW - 15 €/kW - 30%
Hydrogen Production Electrolysis	- Capital Cost - O&M Cost - Efficiency	- 600 €/kW - 12 €/kW - 72%
Hydrogen Conversion Compression	- Capital Cost - O&M Cost - Efficiency	- 393.923 €/kW - 27.574 €/kW - 85%
Hydrogen Conversion Liquefaction	- Capital Cost - O&M Cost - Efficiency	- 1048 €/kW - 52.4 €/kW - 70%
Hydrogen Storage Compressed Gas	- Capital Cost - O&M Cost - Efficiency	- 292.431 €/kW - 2.9 €/kW - 85%
Hydrogen Storage Liquid Hydrogen	- Capital Cost - O&M Cost - Efficiency	- 31.69 €/kW - 0.22 €/kW - 70%
Hydrogen Storage Metal Hydrides	- Capital Cost - O&M Cost - Efficiency	- 905.76 €/kW - 9.05 €/kW - 80%
Hydrogen Forecourt Storage Compressed Gas	- Capital Cost - O&M Cost - Efficiency	- 292.431 €/kW - 2.9 €/kW - 85%
Hydrogen Forecourt Storage Liquid Hydrogen	- Capital Cost - O&M Cost - Efficiency	- 75.67 €/kW - 0.52 €/kW - 70%
Hydrogen Forecourt Storage Metal Hydrides	- Capital Cost - O&M Cost - Efficiency	- 1,616 €/kW - 16.16 €/kW - 80%
Hydrogen Transport Compressed Hydrogen by Road	- Capital Cost - O&M Cost - Efficiency	- 272.12 €/kW - 1.52 €/kW - 85%
Hydrogen Transport Compressed Hydrogen by Rail	- Capital Cost - O&M Cost - Efficiency	- 400.7 €/kW - 4 €/kW - 85%

Hydrogen Transport Liquid Hydrogen by Road	- Capital Cost - O&M Cost - Efficiency	- 33.35 €/kW - 0.35 €/kW - 69%
Hydrogen Transport Liquid Hydrogen by Rail	- Capital Cost - O&M Cost - Efficiency	- 74.06 €/kW - 0.74 €/kW - 69%
Hydrogen Transport Metal Hydrides by Road	- Capital Cost - O&M Cost - Efficiency	- 295 €/kW - 2 €/kW - 85%
Hydrogen Transport Pipeline	- Capital Cost - O&M Cost - Efficiency	- 2,692 €/km - 53.84 €/km - 95%
Tolerance	- Upper Limit - Lower Limit	- 2 MW - 2 MW

Table 5.1: Parameters and values of the example

As it is shown in the table all the values are in euros. As the selected supply centre is London the result will be converted to UK pounds. All the capital costs, except from those of road and rail transport, include the cost of the equipment and the installation cost. For reasons of simplicity the expansion costs are assumed the same as the capital costs. However, for the majority of the technologies this is not an assumption but a fact.

The cost of road and rail transport are assumed 0.508€/km and 1€/km, respectively (Shayegan, 2003). For the transportation of the fuel by road and rail it is assumed that the existing road and rail networks are used. The possibility of extension of the network is not included. Naturally, in the case of pipelines that there is no existing network the construction of a pipeline system is considered. Apart from the length, the capital cost of the pipelines depends on the diameter of the pipes. The cost that is included in this example corresponds to pipelines with flow of around 274 kg/h. The resource potential of the selected renewable energy source is given by using a map showing the average wind speeds of Great Britain.

Apart from the parameters in the table there is only one more parameter that is included in the example, the demand for hydrogen energy. Figure 5.2 shows the hydrogen demand for London over the planning horizon which spans from 2010 to 2060. It is considered that at the end of the time horizon the infrastructure will be able to produce sufficient amount of hydrogen to fuel all vehicles in London. The reason for assuming a complete switch to renewable hydrogen fuel is to test the model under extreme conditions. In the beginning of the timescale hydrogen demand is expected to be restricted to fleet vehicles and then will gradually be increased along with the number of fuel cell vehicles. The demand is assumed that increases linearly over the course of the fifty years and thus is given by:

$$\text{Demand}: y = ax + b$$

where a is the rate of change of the demand, x is time and b is the initial demand at the beginning of the introduction of hydrogen fuel into London. The demand figures for the requirements in transport energy of London were obtained from Greater London Authority (TfL, 2005). It is assumed that the road transport energy demand is steady over the planning horizon and thus the model is based in current transport energy figures. That means that the current demand is considered the amount of hydrogen fuel that is aimed to be delivered by the infrastructure at the end of the time horizon.

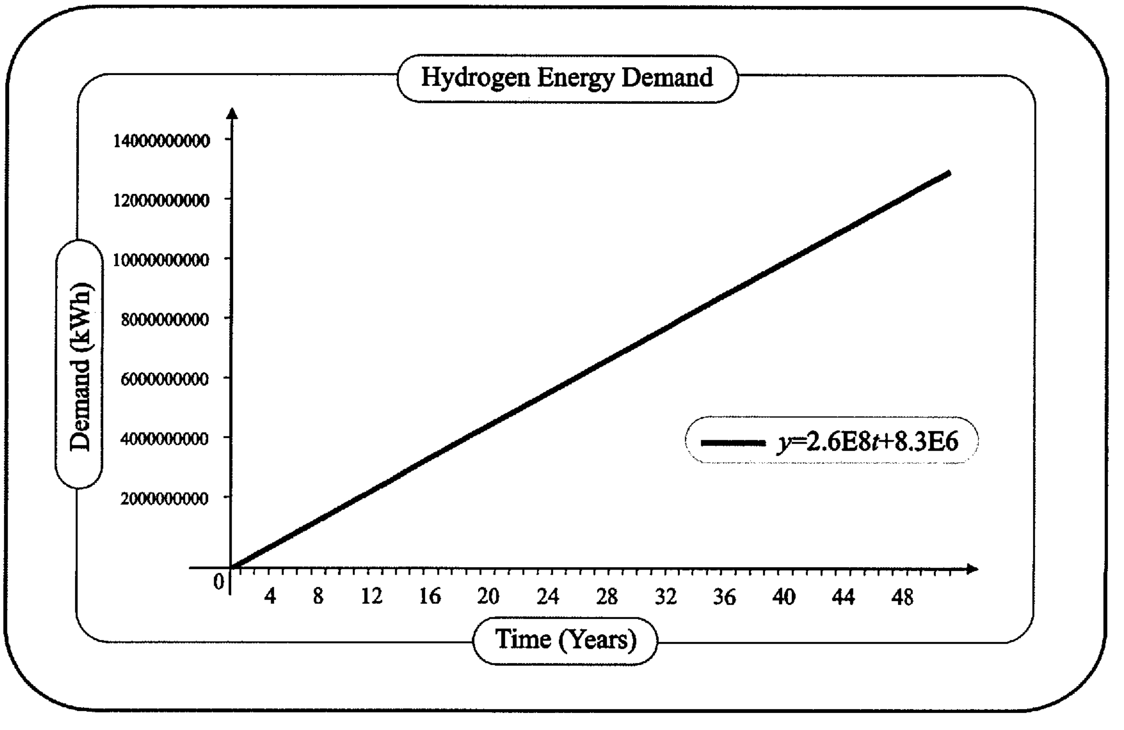

Figure 5.2: Hydrogen demand over the 50 years time horizon

Initially, it is assumed that around 2000 cars run on hydrogen fuel. These cars are all considered to be fuel cell vehicles. This is clarified because although internal combustion engine vehicles may also be powered by hydrogen, they have different energy consumption. In the present example all calculations are made using the energy consumption of fuel cell vehicles which is 1.2 MJ/km. In order to meet the initial demand the infrastructure has to be able to produce around 8.3GWh of hydrogen energy in the first year. This is the value of *b* as it can be seen in the equation included in Figure 5.2.

Having as a starting point 2000 vehicles means that in order to achieve a complete switch to hydrogen in the transport sector (of London) by the end of the planning horizon, a 268 GWh increase in hydrogen energy is required every year. This is translated in an increase of around 64 thousands cars per year. Thus, at the end of the time horizon, year 2060, the infrastructure is required to supply 13,145 GWh of hydrogen energy. This energy is sufficient to power around 3 million vehicles. Figure 5.3 shows the increase of fuel cell vehicles per year during the 50-year time horizon.

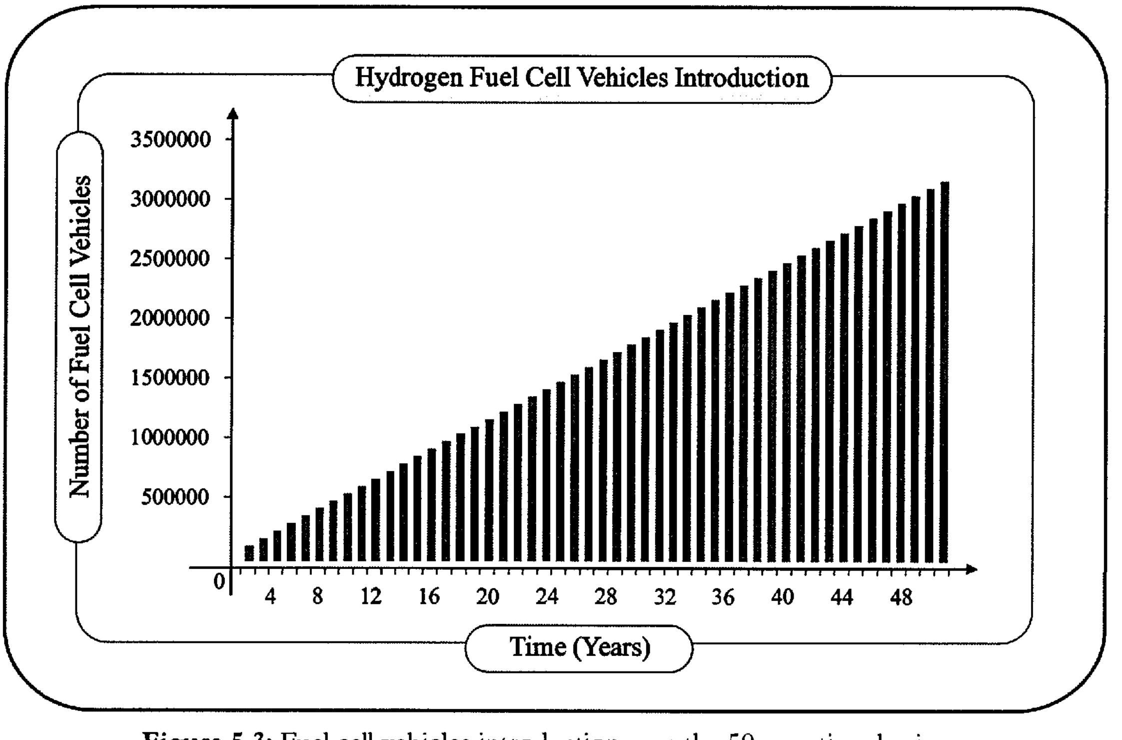

Figure 5.3: Fuel cell vehicles introduction over the 50-year time horizon

Figure 5.4 illustrates a screenshot showing the appearance of the GUI for the example under study. The fuel chains start from the top left with onshore wind energy, which is the selected primary energy feedstock (red colour). The first two steps are the same for all the fuel chains that is why they are only present once. As it has been mentioned in section 4.12 the positions in which the technologies are placed are abstract. All the fuel chains conclude at the same point that is London, the supply centre, which is represented by a red dot in the map. The screenshot in Figure 5.4 shows how the data of Table 5.1 are entered into the model. The screenshot presents all the necessary parameters and their values that are included in this simulation.

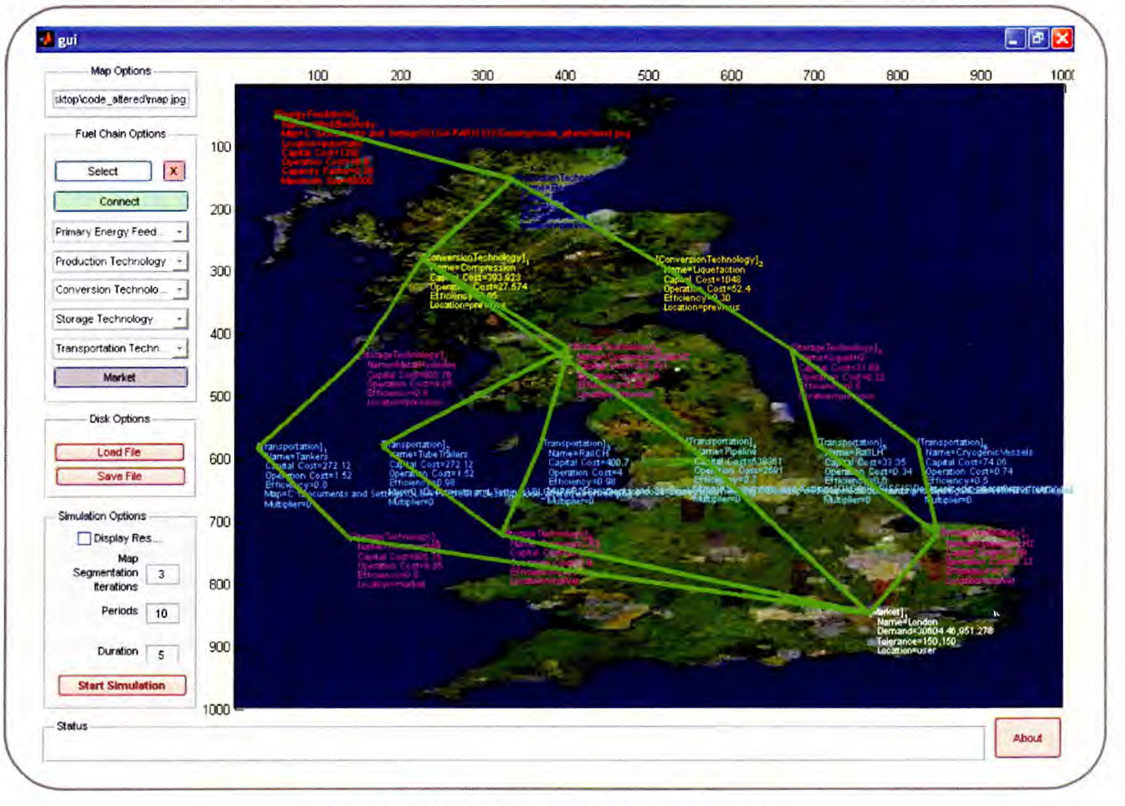

Figure 5.4: GUI screenshot of simulation

For reasons of legibility the following table (Table 5.2) shows the matrices of one technology of each step. These matrices are simplified and adapted to the present simulation. In the primary energy feedstock matrix the last parameter, called *maximum size*, is the maximum capacity of the renewable energy facility. This parameter is necessary in order to avoid unrealistic outcomes. For example, if this parameter was excluded the model would have concluded that the best solution would have been the construction of a massive wind energy park that would have produced all the required demand. In terms of mathematics this is correct but in reality this is impractical. For this reason, a maximum size of onshore wind parks is included that is assumed to be 50MW. Although in the last two years in the UK there are onshore wind parks with larger than 50MW capacity (with the largest at Hadyard Hill in South Ayrshire with an impressive 120MW capacity commissioned in 2006), the majority is less than 50MW (BWEA, 2006).

The parameter *location* which is present in all matrices, apart from the transportation stage, refers to the position of each step. There are four different possibilities as inputs for this parameter. Firstly, when the parameter is set to *automatic*, as in the case of the primary energy feedstock, the position is determined based on the maps. Secondly, when the parameter is set to *previous*, the position of the technology is determined after the simulation and is selected according to the model's predictions. Thirdly, when the input is *market*, as in the case of forecourt storage, the position of the technology is predetermined. This position is at the point of the supply centre. Lastly, when the user wants to include a stage at a certain point has to locate that stage at the correct point in the map and set the parameter *location* to *user*.

At the left hand side of the screenshot the selected infrastructure pattern can be seen. The number of map segmentation iterations is 6, which produces 64 segments. The time horizon of the simulation is 50 years. The infrastructure development has been divided in two periods of 25 years each. The selected timescale is considered rational taking into account that the simulation aims to produce a plan for an infrastructure that will be able to cover London's road transport demand. The development of such an infrastructure is a project with long-term time horizon.

Primary Energy Feedstock	
Name	Wind electricity
Map	Onshore wind energy map
Location	Automatic
Capital Cost	1120
Operation Cost	15
Expansion Cost	1120
Capacity Factor	0.3
Maximum Size	50000
Lifetime	25
Production Technology	
Name	Electrolysis
Capital Cost	600
Operation Cost	12
Expansion Cost	12
Efficiency	0.72
Location	Previous
Lifetime	15
Conversion Technology	
Name	Compression
Capital Cost	393.923
Operation Cost	27.574
Expansion Cost	393.923
Efficiency	0.85
Location	Previous
Lifetime	25
Storage Technology	
Name	Compressed gas
Capital Cost	292.432
Operation Cost	2.9
Expansion Cost	292.432
Efficiency	0.7
Location	Previous
Lifetime	10

Transport Technology	
Name	Compressed gas by road
Capital Cost	272.12
Operation Cost	1.52
Expansion Cost	272.12
Efficiency	0.85
Lifetime	40
Market	
Name	London
Demand	15302.23, 951.278
Tolerance	2, 2
Location	User

Table 5.2: Input data into GUI

5.4 Results

Running the model returned the results shown in Figure 5.5 and Table 5.3. GB has been segmented into 64 regions and each one is represented by a different colour in the map. The straight lines in Figure 5.5 show the starting points of the fuel chains that are the locations of the primary energy feedstock production plants[2]. The positions of the starting points are shown in the screenshot and their exact locations, namely the geographical coordinates, are specified in the text editor that includes all the numerical results that are not shown in the screenshot due to space reasons. The fuel chain configurations that are represented with green lines are those that are selected. The other chains are with black coloured lines, indicating that are not selected. The pathways appeared in this figure comprise the fuel chains that have been selected throughout the planning horizon and thus form the least-cost infrastructure development plan.

[2] In order to avoid any misunderstanding, the lines in the electronic form of the figure start correctly at the mainland. However, previous printed forms of similar figures have shown some lines starting from the shore near the mainland. In case this happens to this figure as well, the reason why it happens is the printing procedure.

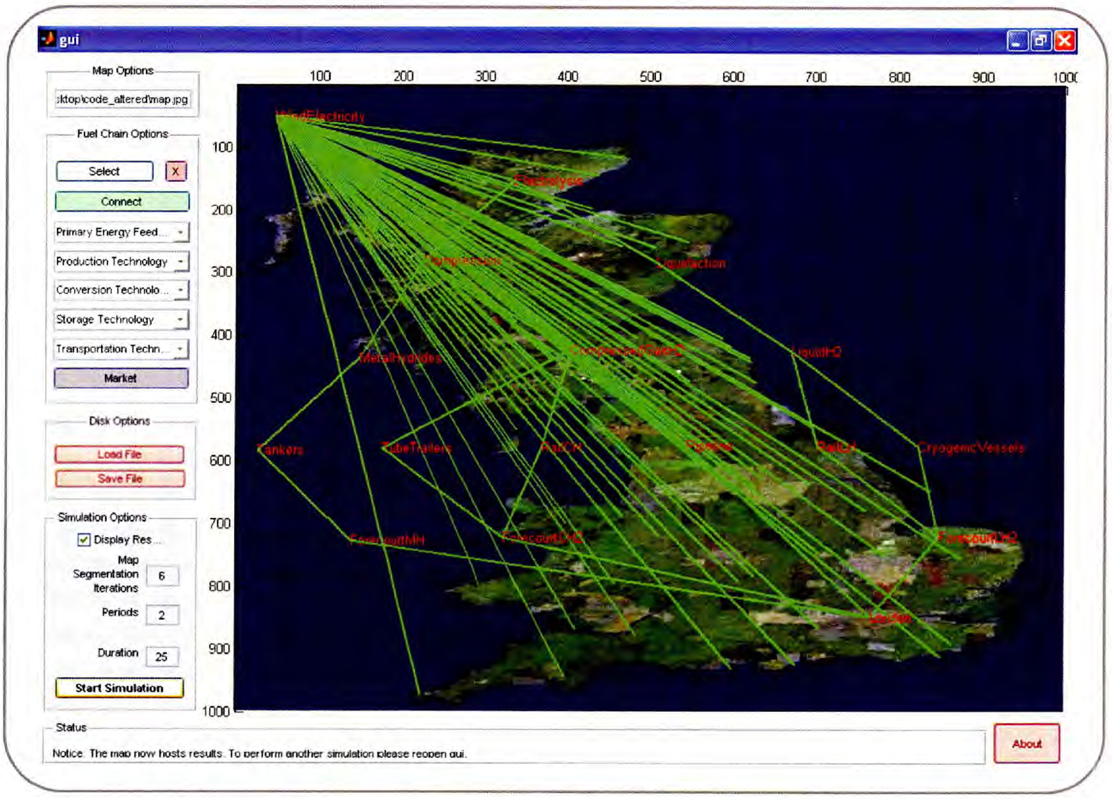

Figure 5.5: Screenshot of the results of the renewable hydrogen infrastructure model

The straight green lines represent the fuel chains that are necessary to be formed in order the infrastructure to supply the required amount of hydrogen and the four green lines symbolize the four different chain configurations. For the establishment of a hydrogen delivery system, the model selects the formation of fuel chains of four out of the six configurations under study. Overall, the model activates 207 fuel chains that break down to:

- 58 fuel chains of configuration 1;
- 58 fuel chains of configuration 2;
- 33 fuel chains of configuration 3;
- 58 fuel chains of configuration 4;
- 0 fuel chains of configuration 5;
- 0 fuel chains of configuration 6.

Fuel chain configuration 1

This configuration is selected from the beginning of the infrastructure development. The model activates 33 fuel chains of this configuration operating at maximum capacity, namely the starting point is a wind energy farm of 50MW capacity that is considered the maximum plant capacity. This is not a surprising result as this configuration includes technologies that combine relatively reasonable costs with good efficiencies. These fuel chains are chosen to operate throughout the planning horizon. In terms of the geographical allocation of the primary energy feedstock production, most of these 33 fuel chains are allocated in the segments that include areas of the highest wind resource of GB. These areas are mainly in the northern part of GB and some in the eastern part.

In the middle of the time horizon, the increasing demand is partly satisfied by the activation of an extra 25 fuel chains of configuration 1. These pathways start at the 25th year with maximum capacity and continued until the end of the horizon. The model activates fuel chains of this configuration in all but six segments. These six segments cover the Midlands. As it can be seen in the onshore wind energy map in Appendix A, the wind energy resource in that area is not particularly good as the annual mean wind speed is around 5-6m/s. So, in order to obtain a wind park of 50MW capacity in these segments more wind turbines are required than in segments of better resource. That means that a 50MW wind park in these segments is more expensive than a 50MW wind park in segments of better resource. This reasoning is incorporated into the model and the exclusion of fuel chains in these six segments proves the model's correct behaviour.

Fuel chain configuration 2

Fuel chains of this configuration, like chains of configuration 1, are selected from the early years of the introduction of hydrogen fuel. Thirty three fuel chains are selected for activation with capacity that of the maximum allowed. These chains are activated at this capacity until the end of the horizon. Again the geographical allocation of wind energy parks excludes the segments of poor wind energy resource.

At the second period, 25 more fuel chains of this configuration are formed operating at the maximum allowable capacity. These chains operate throughout the second period. As it can be seen from Figure 5.1, fuel chains of configuration 1 and 2 are identical apart from the transportation stage that is cheaper in option

1. Thus, as all other parameters are the same this stage determines which configuration is the cheapest option. As it can be witnessed from the values in Table 5.1, configuration 1 is more economical than configuration 2. Generally, for the given data these two configurations may be regarded the more economic options. This conclusion is in total agreement with the predictions of the model that justifiably preferred more fuel chains of configurations 1 and 2. However, the number of fuel chains of configuration 4 is also 58 but the difference is that although the total number for the whole horizon is the same, the amount of hydrogen produced is not the same. Pathways from configuration 1 and 2 produce more hydrogen.

A reasonable question arising at this point is why the model does not activate only chains of configuration 1 that is the cheapest option and activates chains of all configurations. The answer lays in the design of the model. The model has been built in such a way that prohibits the creation of identical fuel chains in the same region due to mathematical reasons and also because this is not considered realistic. Thus, the maximum number of chains of each configuration is equal to the number of segments. So, when a fuel chain has been selected for all segments and the demand has not been covered, the model in order to meet the remaining demand activates the second least cost option. In this case, the maximum number of fuel chains of every configuration is 64, which is the total number of segments.

According to the results, the economic advantage of configuration 1 over 2 due to the transport stage is outweighed by the economic advantage of 2 over 1 due to the primary energy feedstock stage in certain segments. More specifically, for the same segment the transport stage cost difference makes option 1 cheaper than option 2 and thus the model selects the first option. However, between the activation of an option 1 chain in a segment of poor resource of 1 and of option 2 chain in a segment of good resource the model chooses the second option. This is the reason why the model does not choose to activate option 1 in the six Midlands segments.

Fuel chain configuration 3

This configuration is selected in the middle of the planning horizon. The model in an attempt to meet the increasing demand of the second period activates the 33 fuel chains of this configuration with capacity 18. From all the selected configurations this one is selected only at the second period. By looking at Table 5.1 it can be argued that this fuel chain configuration is more expensive than configurations 1 and 2. The reason why the model selects these chains is that when the cheapest options have already been selected (as the number of segmented regions is 64, 64 is the maximum number of a fuel chain configuration), the model is obliged to activate the next least cost configuration because it has to satisfy the demand. That means that if the map was segmented in more regions the selection might have been different. However, the capabilities of the pc that the model runs did not allow for higher map segmentation iterations. In this case, though, the cheapest options, configuration 1 and 2, have not been selected 64 times but 58, however the model instead of selecting the remaining six activates chains of configuration 3. This decision shows that the model takes into account all the necessary factors as the selection of a relatively more expensive configuration in a high resource segment is better than of a cheaper option in a low resource segment as is the case of these six segments.

Fuel chain configuration 4

The remaining demand for the first period of the infrastructure is covered by the activation of 33 fuel chains of this configuration having as a starting point 30MW wind farms. After the 25th year these fuel chains are expanded to 50 MW and at this capacity operate during the second period (from year 26 to year 50). In the second period, 25 more fuel chains of this option are also selected with the maximum plant capacity. Although at first this configuration seems quite expensive due to the transport stage, it has two advantages: firstly, the considerably higher efficiency of the transportation method comparing to other options and secondly the lack of storage. The exclusion of storage step eliminates storage costs and further reduction in the amount of delivery hydrogen. More specifically, every stage in a fuel chain has a specific efficiency and thus inevitably an amount of hydrogen is lost in every stage. By excluding storage (both onsite and forecourt) this loss is minimized and considering that this configuration has the highest overall efficiency makes it fairly attractive.

Fuel chain configuration 5

Fuel chains of this configuration are not selected neither at the first nor the second period. The reasons why this configuration is not preferred is firstly the considerable more expensive conversion technology and secondly the lower efficiencies in all stages than the other options, apart from the primary energy feedstock production and hydrogen production stage that are common for all configurations. Thus, although this configuration is more economical in some stages, such as the storage and transport stage, its overall efficiency outweighs this economic advantage.

Fuel chain configuration 6

The difference between this configuration and configuration 5 is the transport stage. The latter has cheaper transport cost than configuration 6. Thus, since configuration 5 is not selected reasonably configuration 6 is not selected as well. Generally, the model does not activate any fuel chain that includes liquid hydrogen technologies. For the present simulation fuel chains of configuration 5 and 6 might have been selected if the demand would have not been covered by activating 64 fuel chains of other configurations and thus the model would have been obliged to activate more chains whether they are expensive or not to cover the demand or in the case there is a segment with such a high resource that its exploitation is preferred even for configurations that are not very efficient.

Conclusively, according to the results the least-cost renewable hydrogen infrastructure development for London within the 50 years time horizon consists of 207 fuel chains. The overall cost for building a renewable hydrogen infrastructure able to deliver sufficient hydrogen energy to power all the vehicles of a large metropolitan centre like London amounts to 25.5 billion pounds (36.8 billion euros). This capital investment includes all the necessary costs for the entire infrastructure development and operation throughout the 50-year time horizon. This is not a discounted cost.

The following section includes a discussion of the results and the behaviour of the model explaining the reasons why the model selected the aforementioned development plan and thus establishing the validity of the model.

5.5 Discussion

According to the predictions of the model, the hydrogen delivery network that would be able to meet London's demand consists of 207 fuel chains. At first glance this number might seem unrealistic but there are two arguments that may improve this picture. Firstly, it should be reminded that in the present example it is assumed that at the end of the 50 years time horizon a complete switch to hydrogen shall be achieved. Dealing with a problem of such a high demand, it is sensible to expect that the appropriate infrastructure would be of a large size in order to be able to deliver hydrogen energy to fuel all the vehicles of a large urban centre. Thus, an infrastructure with a small number of fuel chains for this problem is highly unfeasible.

Secondly, the model develops an infrastructure based solely on one renewable energy source. The nature of this energy source is one of the factors that determine the total number of fuel chains that comprise the infrastructure. More specifically, the features of onshore wind energy that affect the fuel chain number are the capacity factor and the maximum allowable capacity of a wind energy plant. For the former the value of 30% is used (BWEA, 2006) and for the latter 50 MW is assumed the maximum capacity of a wind park. For example, if the primary energy feedstock was offshore wind energy because of the higher capacity factor (40%, BWEA, 2006) and the larger maximum allowed capacity (100 MW) the total number of fuel chains would have been considerably smaller.

A reasonable question arising by observing the results is why the model did not activate only chains of configuration 1 that was the cheapest option and activated chains of all configurations. The answer lays in the design of the model. The model has been built in such a way that prohibits the creation of identical fuel chains in the same region, as this was not considered realistic. Thus, the maximum number of chains of each configuration is equal to the number of segments. So, as configuration 1 fuel chains had already been selected for the areas with the highest wind resource in all segmented regions, the model in order to meet the demand activated the second least cost option, which is that of configuration 2 fuel chains.

As the maximum number of chains of each configuration is equal to the number of segments, the infrastructure pattern is affected by the number of segments. However, this is true only for a small number of segmented regions. Increasing the number of segmented regions makes the results insensitive to this behaviour. This is true as the size of the segments is inversely proportional to the number of times a configuration can be used. In this simulation the maximum number of chains of each configuration is 64, which is the number of segments. The number of regions that the map is segmented in this study is determined by the capabilities of the computer. If the map had been segmented to more than 64 regions, the model would have selected more fuel chains of configuration 1.

It is apparent from Table 5.1 and from the predictions of the model that configuration 1 is cheaper than configuration 2. However, this conclusion is relative. It is true under certain circumstances. More specifically, the comparison leads to that conclusion if the configurations are compared for the same position in the map. To put it differently, configuration 1 is always more economical than configuration 2 if all the costs are included except from the transportation cost. The latter is not the cost of the transport equipment technology, for example a truck, but the cost to travel the fuel a certain distance. So, when the model compares configurations 1 and 2 in the same point, which means the same distance from the market, the first prevails, in other cases the distance becomes a factor. This is the reason why the model in the first period does not activate 64 and 3 chains of configurations 1 and 2 respectively but activated 33 of each. So, up to a point in the map the cost of the transport equipment prevails the distance from the starting point of the chain to the market and makes configuration 1 the best option, from that point onwards the distance outweighs the cost difference and makes configuration 2 the more suitable option.

Broadly speaking, from the results of the model it may be concluded that from the six configurations under examination, a sequence may be formed showing the configurations in terms of there attractiveness. Starting from the optimal this sequence is:

- configuration 1;
- configuration 2;
- configuration 4;
- configuration 3;
- configuration 5;
- configuration 6.

It is very important to mention that this sequence is valid only under certain circumstances. More specifically, it is valid when the configurations are compared as steady state chains. This sequence is in agreement with the expected outcomes as these can be predicted by looking at Table 5.1 that shows the parameters and their values and gives a vague indication on the economics of the configurations. For a more solid verification as some issues may not be evident by looking at the table the comparison was also carried out manually. The mathematical calculations based on the data of Table 5.1 are in accordance with the sequence. These calculations justified some actions of the model that at first they may not be understood, for example the reason why the model finds configuration 3 more attractive than configurations 5 and 6. The former includes a storage option (metal hydrides) that is considerably more expensive than the others (liquid storage). However, configuration 3 has better efficiencies than configurations 5 and 6 and as the demand level of the simulation is high and the amount of hydrogen is large the difference in the amount of fuel that the configurations are able to deliver is substantial. Conclusively, the cost difference due to the storage cost factor is outweighed by the efficiency factor.

However, the model does not only compare steady state fuel chains but compares and evaluates fuel chains taking into account region-specific framework conditions. These conditions make a configuration that is considered more economical at one point to be more expensive at another. The example showed in this Chapter is a relatively simple simulation with a limited number of technologies – simple for the capabilities of the model – in order to show the behaviour of the model and how it takes into account all the factors and the trade-offs between them in order to obtain the results. So, the configuration sequence is not of particular importance as there is no optimal configuration because this is very relative but there is an optimal infrastructure development plan. The model tries to consider all the input ingredients (fuel chain configurations and region specifications) in order to create the best possible recipe (development plan).

One of the factors that determine the running time of the model is the complexity of the simulation. For very simple simulations the model produces the results in a satisfactory time, for complex simulations that represent large scale problems the running time of the model is larger. The complexity of a simulation does not only refer to the number of fuel chain configurations but also the number of segments and periods. For medium and large scale problems the model requires computers with minimum 1024MB/Mo RAM. The simulation of this Chapter was run in a computer of 512MB/Mo RAM. Although the simulation is simple, the computer was not able to produce results for larger number of map segmentation iterations and periods.

In summary, from this simulation the following main conclusions can be drawn:

- the analysis of the results derived from the model verifies the model's predictions. Running the model for a simplified simulation allowed showing and understanding the behaviour of the model and how the model deduces the results. The actual results of the simulation derived by the model are consistent with the expected results derived both by logic and mathematical calculations;
- The onshore wind energy resource of GB is able to satisfy all the demand for hydrogen fuel in London. This is not a surprising conclusion as the simulation has only one demand centre. Although this market has a high level of demand the geographical region under study is quite large and particularly endowed with wind energy resources. However, the example considered that the total available resource is not restricted by factors, such as the exploitation of the resource for electricity or combined heat and power. Although these factors were not included, the fact that each

configuration can be activated only once in every segment automatically restricts the resource;

- Examining the least-cost way to develop a fuel infrastructure is a complex task that depends on many factors. Even in this example that included only 6 fuel chain configurations and one renewable energy source the results can not be easily obtained without the use of the model. Actually, results from a steady state comparison can be drawn but results from an economic and resource optimisation is quite difficult and extremely time-consuming to be obtained without the use of the model.

5.6 Sensitivity Analysis

The overall cost of a hydrogen infrastructure development is affected by various factors. Naturally, it is heavily dependent on the infrastructure size, which in turn is determined by the demand of the supply centre. Some factors, like O&M costs, influence the overall cost but do not affect the choice of configurations that form the infrastructure. These factors usually have a relatively small impact on the total cost. This is reasonable because, for example the O&M cost is a fairly small factor comparing to other factors such as the capital cost that shapes to a great extent the overall cost of a chain. There are, though, other factors that not only have an effect on the total cost but their values greatly determine which fuel chain configuration is selected. The latter category includes factors such as the efficiency of the technologies or the maximum allowable size of the production plant. There is not a golden rule indicating which factor plays more important role as this is quite relative. A primary energy feedstock technology with relatively low capital cost, efficiency and maximum allowable plant size may be outweighed, and thus dismissed, by another option which is more expensive but has higher efficiency and/or maximum plant size.

The total cost is sensitive to the number of regions the GB map is divided. Running the model several times for different map segmentation iterations shows that the relationship between the overall cost and the number of regions is conversely proportional. Thus, as the number of segmented regions increases the total cost decreases. This behaviour is showed in Figure 5.6. For Figure 5.6, the number of periods is constant for all runs and equal to 2.

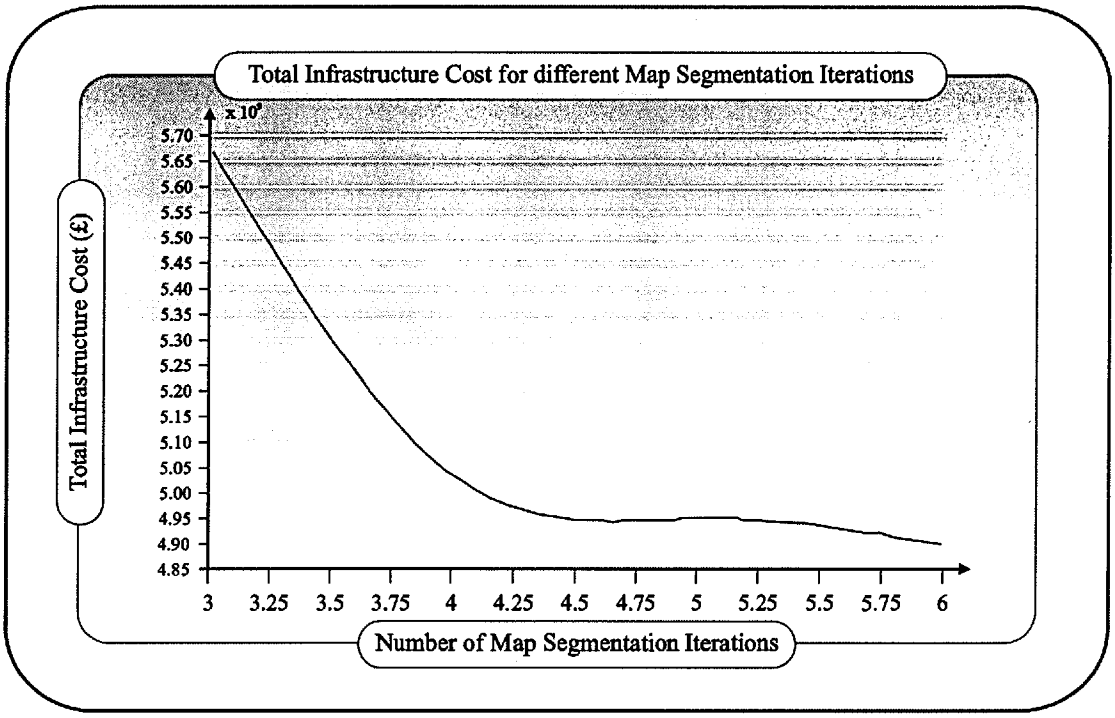

Figure 5.6: Effect of map segmentation iterations on total infrastructure cost

The reason for this behaviour is that when the map is segmented in more areas the maximum number of use for each configuration is larger as every configuration can only be used once in each segment. When all the fuel chains of the cheapest option have been activated and the demand has not been covered the model is obliged to activate more fuel chains to produce the required amount of fuel from the second cheapest option. So, when the number of segments increases the model activates more of the economical fuel chains and thus the overall cost decreases. More segments means better optimisation as the selection of fuel chains is not affected by the maximum number of use constraint. This is evident in Figure 5.6. After a certain point the overall cost is slightly sensitive to the number of regions. After this point, the total cost is not further minimized and can be considered steady.

This point is different for every simulation and it depends on several factors, such as the demand and the number of fuel chains under study. For example, if the demand of the simulation was considerably smaller this point would be more towards the left side of the graph (without changing the number of fuel chain configurations). The same effect would have if the number of fuel chain configurations under examination was larger (without changing the demand). So, the elimination of the maximum number of use constraint is not necessarily achieved with low demand level or large number of pathways but from all the specifications that form a simulation. There is though one factor that removes the constraint regardless of the simulation characteristics. This is a large map segmentation iteration number that produces a substantially large number of segments. Figure 5.6 is not based on the simulation's results simply because for map segmentation iterations less than 6, the demand in the case of the onshore wind energy infrastructure can not be satisfied as the maximum number of fuel chains of every configuration is greatly restricted. For this reason a simulation with the same configurations but both onshore and offshore wind energy is considered. The numerical outputs of this simulation are outside the scope as the aim of this simulation is to show the relation of cost with the map segmentation iteration parameter.

Another logistic factor that influences the overall cost is the number of periods that the planning horizon is divided into and the duration of every period. These factors are determined by the user. Generally, the higher the number of the periods the higher the total cost. Figure 5.7 shows the effect of the number of periods on the total cost. For this graph, the onshore wind energy example has been used, as the number of regions is constant and equal to 64. The model has run for 5 different periods including 2, 4, 5, 8 and 10.

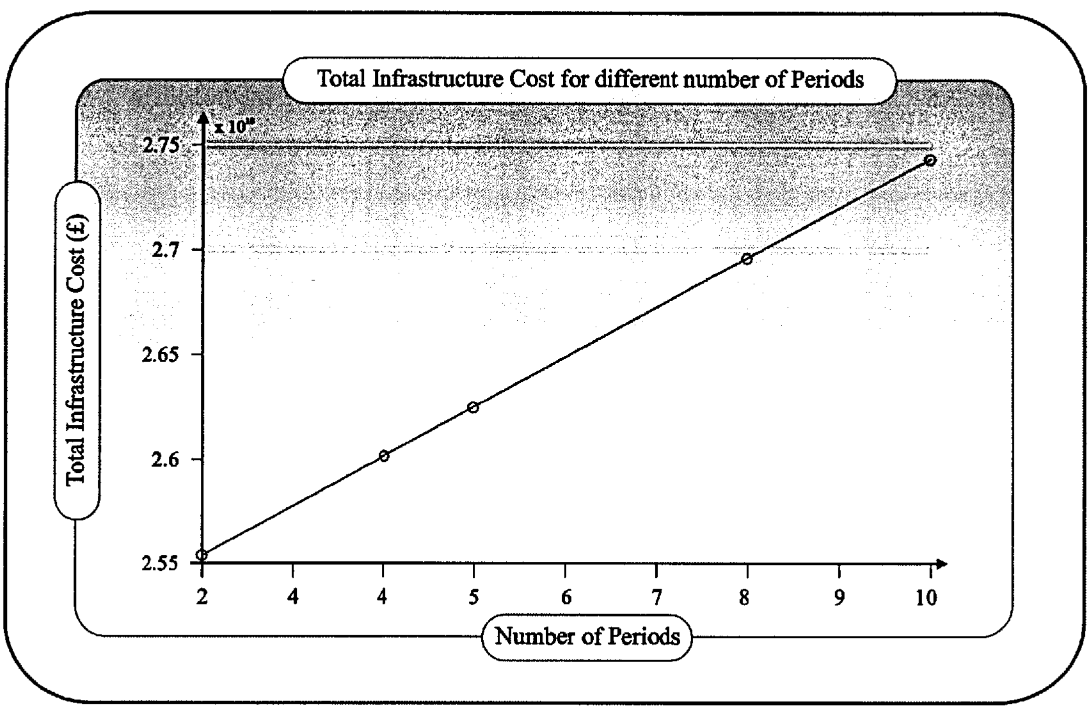

Figure 5.7: Effect of periods on total infrastructure cost

The period parameter represents the time variant behaviour of the chains, namely the changes that occur in the lifetime of a chain such as the expansion. When the number of periods is increased the accuracy of the model's predictions is increased resulting in more realistic solutions. This is more comprehensible if it is considered that the model is trying to fit a behaviour of energy, of hydrogen energy in particular, in a 50-year time horizon and thus the more points (periods) the simulation includes the more accurate results are attained.

The infrastructure cost is the combination of all the costs included in all the stages of all the selected pathways. However, the order of magnitude of the overall cost is determined by the costs associated with the primary energy feedstock and hydrogen production plant. It is important to mention that the overall cost and the structure of the hydrogen delivery pathway depend to a great extent on the baseline values assumed for all the input parameters of the model. A change in these values may affect the overall cost and the selected infrastructure pattern.

5.7 Conclusions

In this Chapter the hydrogen infrastructure development model was subject to testing. The testing strategy that was followed was described in detail. Every test that was carried out has been described along with its outcomes, the interpretation of the outcomes and the significance.

The behaviour and the predictions of the model were examined by running an example simulation. This simulation was simplified and represented a relatively small scale problem. The reason for this simplification was the prediction, to some extent, of the expected results based on the logic, the relative knowledge and the mathematical solution in order to be compared to the actual results of the model. The model delivered the formation of an infrastructure development plan for London based on the wind energy resource of GB and six different fuel chain configurations. The main focus of the simulation was not the numerical outputs but the understanding and testing of the decision making of the model. According to the results, the analysis of the results and the sensitivity analysis, the model produces credible outputs and responds properly to changes in parameters.

The next Chapter marks the start of the case study of renewable hydrogen infrastructure development for supplying a large urban centre, undertaken with the new modelling tool.

CHAPTER 6

Case Study

6.1 Introduction

As the behaviour of the model and the accuracy of its results have been tested, in this Chapter the application of the model in a large scale problem is presented. As a case study for the new modelling tool, the development of renewable hydrogen infrastructure for London is examined. This case study is a large scale simulation as it includes a considerable range of renewable energy sources and a large number of different fuel chain configurations. Preliminary results of a similar simulation were written and presented at a conference (World Hydrogen Energy Conference, Lyon, June 2006) entitled: *The Design of a Renewable Hydrogen Fuel Infrastructure for London.* However, the model has been improved since. Although both versions of the model are correct, the current version is more evolved, closer to reality and takes into account more factors.

This Chapter begins with the selection of the urban centre under study. The description and justification of this choice are laid out. The Chapter continues with the presentation of all the specifications that are included in the simulation, such as the renewable energy resources of GB, or the hydrogen technologies, or the demand. All the parameters, their values and the assumptions are introduced and discussed.

6.2 Selection of Urban Centre

As it has been discussed in Chapter 3, the UK's capital is an urban centre that has several reasons to be considered as one of the first cities that may succeed in the deployment and establishment of hydrogen fuel and its infrastructure. The promotion of hydrogen may be benefited by the fact that hydrogen fuel serves various purposes of the local Government. Hydrogen has ensured London Mayor's attention as it can be used as a means of tackling London's pollution problem, one of his key policy objectives. Moreover, the Mayor contemplates that facilitating hydrogen fuel cells constitutes an incentive for the development of other clean technologies but also expands an industry that has positive implications for the future and the economy of the city.

On national level, as London is the capital of the country and has national resonance by supporting the establishment of a hydrogen delivery system may constitute a paradigm that could influence other cities and thus fan out the development of hydrogen infrastructure to the rest of the country (GLA, 2004). The above picture becomes more promising considering that London is a city that offers skilful academia, research councils and companies that actively work in the field of hydrogen technologies. Research Councils have funded a number of projects aiming to assist the progression of hydrogen technologies and evolution of hydrogen refuelling infrastructure.

Considering the above interest, London represents an ideal case study to examine the potential of supplying renewable hydrogen urban centres. There are three reasons for this selection. Firstly, it is worthwhile to investigate possible options for delivering hydrogen to an urban centre that has shown significant activity in this field and has already decided that hydrogen fuel will play an important role in its sustainable energy system that aspires to develop. Secondly, studying the establishment of a hydrogen infrastructure for London assists in the understanding of the requirements for such venture and provides useful insight into city-specific issues arising from the introduction of hydrogen in a large urban centre. Thirdly, because London is the biggest energy demand centre in the UK and the largest city in Europe. That makes the development of a hydrogen delivery system for such a large urban centre a large-scale problem that can demonstrate the capability of the model in dealing with such problems.

London is a large city, densely populated. Formally, the urban centre under study is the geographical area of the Greater London Authority that was established in 2000 and covers 32 boroughs and the City of London (GLA, 2004). The Greater London Authority area's extensive public transport system, the level of mayoral control of public transport and its high number of taxis and small delivery vans, offers a massive opportunity for developing the use of hydrogen. This may provide a niche market for hydrogen fuel and hydrogen fuel cells in which the new products can begin a technological process of learning by doing, economies of scale and start the creation of network effects.

This case study examines the options for supplying a new, green and thus environmentally benign fuel to London. Hence, it considers hydrogen produced exclusively from renewable energy sources. The available renewable energy resources that are used as primary energy feedstocks are both from inside and outside London. The production of renewable hydrogen fuel from renewable energy sources inside London faces great limitations, especially in the short term. London is a large metropolitan centre, whose urban environment restricts the types of renewable technologies that are suitable. For instance, wind energy's combination of relatively low costs and technical maturity cannot be greatly exploited in London due to the lack of a substantial number of suitable open spaces. In addition, due to the high population of London the demand for renewable hydrogen fuel would be significant, especially over the time the infrastructure would gradually be expanded.

Generally, solar energy, wind energy and biomass are the renewables with the greater potential of producing hydrogen in London. As far as wind energy is concerned, at present there are a few demonstrating wind turbines systems in London like the two wind turbines constructed in Dagenham (GLA, 2004a). London being an urban centre has sites with lower or more disrupted wind speeds than sites in rural areas. However, there are some locations with good wind speeds such as Thames Gateway, where wind speeds are among the highest in London. Another possibility of utilizing wind energy is the installation of wind turbines on building's roofs. Normally, urban renewables are small and medium scale constructions. There are, though, some places that may be suitable for larger installations, for instance large wind turbines or PV arrays on noise barriers along roads (GLA, 2007). The latter is presently quite expensive but considering it will meet its long term economic targets, along with wind energy they will offer great opportunities for London in the future.

Biomass is a renewable energy source with great potential in London due to its significant available resource, especially wastes. This large resource may work as a benefit for hydrogen production since due to the exhaustion of existing disposal sites and the awareness of the environmental implications of such sites, the increase of this resource will lead to the imperative need of alternative use of wastes, one of which is the production of renewable hydrogen.

The fact that London has a considerable renewable energy resource available for the production of hydrogen does not imply that hydrogen will be produced by these resources. Hydrogen has to compete with all the other possible end-uses which can also be produced from renewables. The judge of this competition is the local Government. The Mayor of London in an attempt to contribute significantly to national energy policy objectives and targets has developed a strategy aiming to increase the use of London's renewable energy sources. London aims to generate 665GWh of electricity and 280GWh of heat from its renewable energy resource by 2010 (GLA, 2004).

However, in Mayor's plan this amount of renewable energy is mainly intended to be used for power applications (like houses) and hardly for the mass production of renewable hydrogen fuel. The limited available resource of renewable sources that makes London's renewable energy targets quite challenging coupled with the fact that renewable hydrogen is not top priority in local Government's energy agenda lead to the conclusion that London's renewable energy resources will probably not be sufficient for the production of renewable hydrogen fuel, even in the short term where the small proportion of hydrogen vehicles would require relatively small amounts of hydrogen fuels.

Renewable hydrogen fuel may be supplied, though, by renewable resources outside London using UK's indigenous resources or even outside the UK. The UK is very well endowed with renewable energy resources, with a slight exception in the case of geothermal energy. All of these resources may have the potential of supporting renewable hydrogen's production. This support is crucial especially in the long term where hopefully the demand of renewable hydrogen fuel will be large.

In the near future, the UK renewable sources that will play a major role in the generation of hydrogen fuel are onshore and offshore wind energy. The wind resources of UK along with the marine resources are the best in their categories in Europe. Of these resources, offshore wind power is the only large (order of multigigawatts) UK resource that thus is able to provide significant amount of renewable hydrogen fuel (H2, 2004). Conclusively, wind power could assist in the uptake of renewable hydrogen fuel in transportation in the short term and in conjunction with the other renewables in the long term could complement the development of the hydrogen infrastructure in London.

Like conventional fuels, renewable hydrogen may be produced from foreign resources and transported into the UK. Importing renewable hydrogen allows the UK to benefit from the large renewable resources of other countries like hydropower in Iceland or biomass in Brazil. A possible route of hydrogen supply to the UK will be the transmission of solar energy-derived hydrogen in North Africa by gas pipelines across the Mediterranean Sea, all through Europe and north into the UK. Another possibility will be the transportation of liquid hydrogen, that would be produced by hydro power in Canada, by ocean tanker (H2, 2004). From an economic perspective, in the near future the exploitation of renewable resources in the UK may be a more attractive option as the distance of foreign resources may greatly affect the costs of some of the steps in the fuel chain. Moreover, ventures like that usually take place when the new fuel is relatively more established and thus the demand is large and not at the early stages of the introduction of hydrogen fuel.

6.3 Simulation Specifications

This section gives a description of all the characteristics of the London simulation. It includes all the parameters, values, choices and assumptions of the case study. Figure 6.1 demonstrates the superstructure of the simulation that shows the renewable energy sources and hydrogen technologies that are considered in the case study.

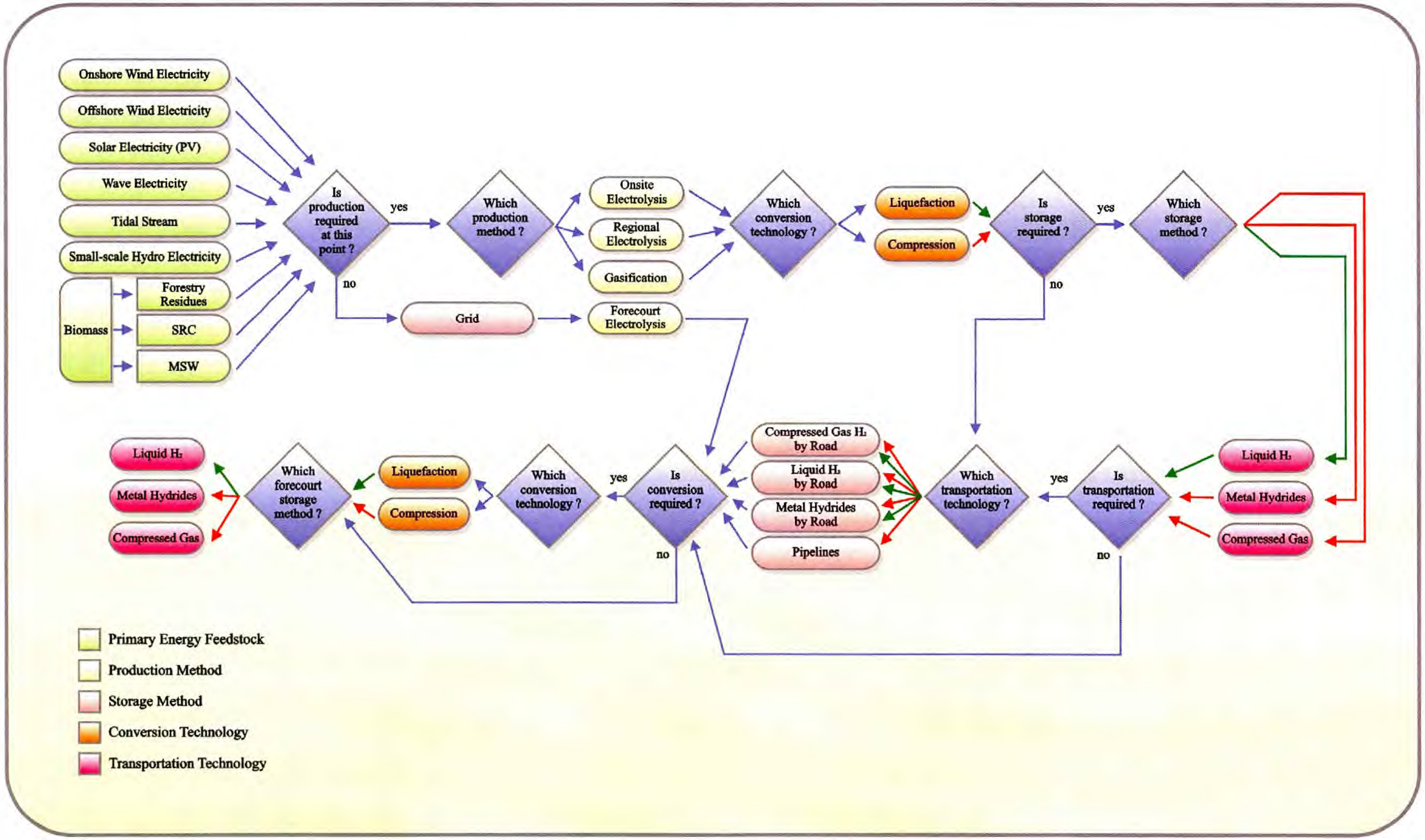

Figure 6.1: Superstructure of the London simulation

6.3.1 Renewable Energy Sources

GB renewable resources are very large. Various studies have been carried out, mainly analysing the production of electricity from renewable resources (ETSU, 1994; ETSU, 1996; ETSU, 1999; ETSU, 2001a; ETSU, 2001b; ETSU, 2001c; ETSU, 2001d; Garrad Hassan and Partners, 2001; Chris Blandford Associates, 2000; Sustainability North West, 2001; Land Use Consultants, 2001). Across these studies there is no consistent methodology and coherent assumptions. For these reasons the outcomes of the resource assessment analysis vary from study to study.

An absolute and exact assessment of the GB's renewable resource potential for hydrogen production is outside the scope of this study. It is important to note that the development and exploitation of renewable resources for hydrogen production has to compete with other end-uses such as electricity and heat. However, this case study does not examine the available renewable resources for hydrogen production within these constraints but the development of a hydrogen delivery system for London considering that the GB renewable resources are available to be utilized for the production of the necessary amount of hydrogen fuel to meet London's demand. The required hydrogen is assumed to be produced from electricity generated by renewable schemes that are not already existent in GB.

GB is very well endowed with renewable energy resources, with a slight exception in the case of geothermal energy. It has some of the best renewable energy resources in Europe, with wind power considered the largest (order of multigigawatts) among them. There are some renewable resources in GB that are either purely theoretical – generic but limited in GB – or already fully exploited (ETSU, 1999). These are:

- Large hydro power;
- Solar thermal;
- Tidal barrage;
- Geothermal energy (both aquifers and hot dry rock);
- Photoconversion;

- Ocean thermal energy conversion.

The above renewable sources are either fully exploited or not considered feasible in GB and thus are not considered in the simulation.

The renewable resources that are considered exploitable in GB are the following:

- Wind energy (onshore and offshore);
- Solar energy (photovoltaics);
- Small hydro energy;
- Wave energy;
- Tidal stream;
- Biomass – Energy crops;
- Biomass – Agricultural residues;
- Biomass – Wastes.

As it was mentioned in Chapter 4, the renewable resource potential input data are in the form of maps. The maps showing the resource potential in GB of the selected renewables along with all the parameters and their corresponding values of all the renewable energy sources that are used within the simulation are presented in Appendix A.

6.3.1.1 Wind Energy

GB has substantial wind energy potential. It has approximately 40% of the total realisable wind energy resource in the EU. The case study includes both onshore and offshore wind energy. The theoretical GB resource of the latter is much larger than the land-based resource (Boyle, 2000). In GB, wind energy is the third largest contributor to renewable energy after biomass and hydroelectricity (DTI, 2007). There are currently 145 wind parks, both onshore and offshore, in the UK with a total installed capacity of 2141MW (BWEA, 2007). Generally, the sites that are considered appropriate for the construction of wind parks are these with average wind speeds around 8-10m/s. However, as the power in the wind is proportional to the cube of the wind speed, sites with fairly good average wind speeds (5-6.5m/s) can also be used for wind parks. For both onshore and offshore wind energy resource maps are used that include sites that range from low wind speed sites (>5 m/s) to high wind speed sites (< 10m/s for onshore and <14m/s for offshore).

The UK onshore wind farms currently in operation range from a capacity of a few MW to 97MW. The latter is the capacity of the Black Law A wind farm in South Lanarkshire that was constructed in September 2005 (BWEA, 2007). The only wind parks with capacity that exceeds 90MW are the Black Law A and the Farr Windfarm in Highland, which has a 92MW capacity (BWEA, 2007). Generally, in the UK judging from the already existing wind farms the largest wind park projects are around 50±10MW capacity. For this reason, in the simulation it is considered that the maximum capacity of a wind energy plant is 50MW. It is worthwhile to mention, though, that the largest onshore wind farm in Europe is currently under construction on the Eaglesham Moor, south of Glasgow. The Whitelee project is planned to have 140 turbines and a staggering 322MW capacity (BWEA, 2007).

In the case of offshore wind energy, this assumption is different. Most modern offshore projects have been built with 2-3 MW turbines and in the near future this will rise to 3-5 MW and are usually larger than onshore projects. In the UK, the largest offshore farms in operation have around 90±10MW capacity (BWEA, 2007). However, the offshore projects that have been approved and those that are under construction (the 500MW Greater Gabbard and 1000MW London Array in Thames Estuary, the 108MW Ormonde off Walney Island) show that this number is going to increase greatly (BWEA, 2007). Marrying the capacity trend and the existing capacity in order to capture the trend but also to be realistic, the maximum capacity of a single offshore wind energy plant is assumed 130MW.

6.3.1.2 Solar Energy

Solar resource is huge and is available at any location on the surface of the Earth. In GB, by tilting a surface to an angle the amount of solar radiation falling on it is greater than falling on a flat surface (Solar Trade Association, 2005). The map that is used as the input data for the solar energy resource shows the average solar radiation falling on one square metre surface inclined at 30 degrees to the horizontal, measured in kilowatt hours. Solar energy can generate electricity through PV that can be used as stand alone units, grid connected systems or integrated into building materials. For the present study, large PV systems are considered, as they offer the advantage of large-scale electricity production.

In 2003, the total capacity for photovoltaics (PV) in the UK was approximately 6MW, which is a small fraction of its potential (DTI, 2007). Worldwide, there are a few large scale solar power plants, like the Solar Energy Generating Systems in the Mojave Desert and the Nevada Solar One. The former is a group of nine solar power plants that commissioned between 1984 and 1991 and produce 354MW. The latter is located in Boulder City in Nevada and has a 64MW capacity (Nevada Solar One, 2006). More very large installations are under way such as a 40MW plant in Spain, a 64MW plant at Moura in Portugal and 116MW system at La Sabina in Southern Portugal (Milford, 2007). However, GB does not have large areas of isolated land like deserts and thus large scale installations of these levels are considered not feasible due to land use constraints. Nevertheless, the rhythm of development is rapid and the gap between existing installations and those proposed for very large scale PV systems has narrowed considerably. Considering the 12MW PV plant at Erlasse in Germany, the 11MW system at Sepra in Portugal and the 10MW PV installation at Pocking in Germany and taking into account that there are now over 150 installations larger than 1MW operating in the world (Milford, 2007), the maximum capacity for a single solar energy plant in GB for the present study is assumed 10MW.

6.3.1.3 Small-scale Hydro Energy

Hydroelectric power has the largest share of renewable electricity in the UK. At present, 0.8% of UK's electricity is produced from hydroelectric schemes. This is equivalent to 4244MW of hydropower capacity (DTI, 2007). In GB, all large-scale hydroelectric sites have been either utilised or categorised as areas of great natural beauty. Thus, it is considered unlikely that further large-scale hydroelectric deployment will be approved. According to the Department of Trade and Industry, a large-scale hydro plant is considered the one that its capacity exceeds 20MW. Hydro plants with capacity less than 20MW and less than 1MW are categorised as small and micro-scale respectively (DTI, 2007). As large-scale exploitation is greatly restricted the simulation considers only small and micro-scale hydro installations. The hydro energy resource map depicts the small-scale hydroelectric potential in GB showing the mean annual precipitation.

6.3.1.4 Wave Energy

The UK has wave energy levels that are among the highest in the world. Currently, in GB there are only two wave energy schemes with total capacity 1.25MW (DTI, 2007). There are five main types of machines that can generate electricity from waves: floating device, underwater buoyant device, hinged flap device, oscillating water column and overtopping device (EMEC, 2007). Every technology has its own advantages and disadvantages. However, the thing that they have in common is that they are not yet at commercial stage. They have certain difficulties to overcome such as the device survivability in extreme wave conditions or the irregularity in wave amplitude, phase and direction that means it is difficult to achieve the device's maximum efficiency over the entire range of excitation frequencies (ETAP, 2007).

Wave energy has only small-scale (order of kilowatts) prototype plants around the world. The world's biggest commercial wave plant is a wave farm currently under development in Scotland that was announced on February 2007 and includes four Pelamis machines, the offshore wave energy converter, with a combined output of 3MW (ETAP, 2007). Apart from the technical immaturity and the small-scale exploitation, wave energy's capital costs are high. Generally, wave energy is relatively new and currently not economically competitive with more mature renewable energy sources like wind energy. So, although GB has a substantial wave energy resource is not included in the simulation. Even if it was included as the model performs an economic minimization the high capital cost in combination with the very small plant capacity would have eliminate any possibility of selecting wave power as a primary energy feedstock for hydrogen production.

6.3.1.5 Tidal Stream

Generally, the best potential tidal stream sites in GB are on the west coasts of England and Wales. Like wave energy, tidal stream is a renewable energy source with considerable potential in GB but at present its technology and economics restrict to a great extent its deployment. Tidal stream technology is still in its infancy and there is only one project currently operating in GB, the Seaflow project. The latter is the world's first tidal stream device off the north Devon coast installed in 2003 with capacity 300kW (DTI, 2007). For the installation of large-scale tidal stream schemes it seems that there is still a long way. At the moment, tidal stream is not considered an attractive commercial investment option.

Although given the resource potential tidal stream may be used for the production of renewable electricity in the future assuming the required progress in the technology and reduction in costs, due to its current stage it is not included in the simulation. Apart from the technology that is at prototype stage, the simulation includes a high level of demand and thus the inclusion of medium and large-scale installations is preferred. In the case of tidal stream, medium and large-scale installations do not exist. Even in the case of assuming the development and feasibility of such installations the cost of large-scale tidal stream exploitation at the moment cannot be quite determined. There are only cost predictions and estimates for large tidal stream farms that not only vary from study to study but also their degree of accuracy is quite disputable.

6.3.1.6 Biomass – Energy Crops

Among energy crops, short rotation coppice (SRC) of willow is selected for its excellent potential rapid growth. Of all the energy crops grown in the UK, willow SRC is perceived as the most promising. SRC is perennial, thus minimising energy and fertiliser inputs (ETSU, 1999). The SRC is grown on a rotation of 2-4 years, with current typical yields in the UK of 10 oven dry tonnes per hectare per year (odt/ha/yr) (Bauen, 2001). Yields are expected to increase to 15-20 odt/ha by 2020/25 (DEFRA, 2002; ETSU, 1999). A plantation could be viable for up to 30 years before re-planting is required. Better plant husbandry, variety selection and breeding are also expected to increase disease resistance and biological stability (ETSU, 1999).

Willow SRC is included in the Energy Crops Scheme, introduced by DEFRA in 2000 in partnership with the Forestry Commission (DTI, 2002). Willow has already been used in commercial or near commercial operations in the UK. The first commercially grown SRC in the UK was to provide fuel for the ARBRE gasification and electricity generation project in Eggborough, Yorkshire, and covers 2,000 ha (Bauen, 2001). The scale of the SRC scheme used in the simulation is equivalent to that needed to power a 30 MWe integrated gasification and combined cycle electricity generation plant, as this scale is thought to be feasible for local generation in the UK (ETSU, 1999).

For the case of energy crops the resource is entered into the model in the form of a map that is the result of the composition of two different maps. The first map is a map showing the agricultural land classification of England. Agricultural land is divided into classifications by the physical and chemical limitations of the land for agricultural use. The determining factors that are taken into consideration and their effect on the versatility of the land and the reliability of the crop yields are climate (rainfall, transpiration, temperature and exposure), relief (slope) and soil (depth, texture, structure, stoniness and available water capacity) (Royal Commission on Environmental Pollution, 2004). The Agricultural Land Classification system has divided land into five grades ranges from grade 1 (the most versatile) to 5 (the least versatile) (DEFRA, 2006). England has approximately 2.5 million hectares (Mha) of grades 1 and 2 land, 6Mha of grade 3 land and 3 Mha of grades 4 and 5 land. England and Wales use this classification and Scotland uses seven grades (Royal Commission on Environmental Pollution, 2004). Due to the difference in the classification system and the lack of map showing both England and Wales classification, the simulation includes the possibility of generating feedstock for hydrogen production that can be produced from energy crops cultivated within the English agricultural land.

For the production of biomass feedstock it is not assumed that the 5 grades of English agricultural land are all available as this land is also used for other purposes such as food production. The latter is likely to continue on grades 1, 2 and 3 land. For energy crops land of grades 3, 4 and 5 may be available. However, grade 5 land is not considered a strong candidate due to very poor soil quality and the exclusion of some of the promising areas based on environmental impact assessments. Thus, in the simulation it is assumed that areas from grades 3 and 4 land are available for energy crops production. According to studies of the National Farmers' Union, up to 20% of crops grown in the UK could be available for non-food uses by 2020 (DEFRA, 2003; MAFF, 1988).

Naturally, in order to explore the appropriate sites for the production of SRC the available land that this production can take place is not enough. Data concerning the suitable conditions for the plantation of this crop are necessary. These data are the second map that is used for this renewable energy source. The climate is an important factor that determined the yield of the crop. SRC requires considerable amounts of water and its growth is substantially reduced when is cultivated under dry conditions. Thus, wetter regions of England may be better for growing SRC than others (DTI, 2003a). The second map shows the effective precipitation, the difference between precipitation and evaporation from grassland, across GB. It can be witnessed that the western part of England is more suitable for SRC plantation where rainfall is the greatest.

6.3.1.6 Biomass – Agricultural Residues

Agricultural industry produces many different kinds of residues that can be used for hydrogen production. In the present simulation, the kind that is considered is forestry residues such as leaves, branches, lops, tops, damaged or unwanted stem wood which are produced from operations like thinning and logging of plantations and trimming of felled trees. The yield of forestry residues is approximately 1.5odt/ha/yr (Bauen, 1999), with an energy content of 19GJ/odt irrespective of species (ETSU, 1999). In the present study, the maximum amount of biomass feedstock that can be used in every forestry residues route is equivalent to power a 20MWe gasification plant. Around 4 Mt of forestry residues are produced each year in the UK (Bauen, 2001). However, this amount is not the accessible resource. It has been estimated that 1.4 Modt of this amount can be removed and used (Bauen, 2001). The map of forestry residues used in the simulation indicates the corresponding resource for GB per year.

6.3.1.7 Biomass – Wastes

Biomass is also considered a primary energy feedstock in the form of wastes. The category of wastes that is included in the simulation is the biodegradable fraction of municipal solid waste (MSW). MSW is considered a promising option as it overcomes some of the barriers of other renewable sources such as resource restrictions (as in the case of hydro and geothermal energy), expensive electricity generating technologies (as in the case of solar energy), lack of mature and commercial technologies (as in the case of wave and tidal energy). In addition, the use of wastes to produce hydrogen has the dual beneficial effect of reducing the amount of disposed wastes and ensuing environmental repercussions and generating an environmentally benign fuel.

The MSW that is included in the case study is the wastes originated mainly from households, sewage sludge, public areas, institutions and services in London. Annually, London produces 3.5 million tonnes of wastes (Think London, 2005). Due to the increase of these wastes existing landfills are being exhausted and harmful emissions are increasing at alarming rate. Wastes are the only renewable energy source in the case study that its resource includes only London's wastes resource. For this reason there is no waste resource map in Appendix A. Although in this case the resource for the production of the primary energy feedstock is within the supply point due to the urban environment of the demand centre the location of feedstock production facility is assumed to be outside the city. The amount of biodegradable MSW used in the simulation is equivalent to that needed to power a 30 MWe feedstock production facility.

6.3.2 Hydrogen Technologies

The hydrogen technologies that form the fuel chains under examination are selected based on options that are commercially available and have been used either in greater or lesser extent in projects (including pilot projects). As it can be witnessed in Figure 6.1, the case study includes the following technologies:

- production technologies: electrolysis (onsite, regional and forecourt) and gasification;

- conversion technologies: compression and liquefaction;
- storage technologies: compressed gas hydrogen, liquid hydrogen and metal hydrides (onsite and forecourt);
- transport technologies: compressed gas hydrogen by road or pipelines, liquid hydrogen by road, metal hydrides by road and electricity grid.

In the case of hydrogen production, renewable electricity is converted to hydrogen through electrolysis. Electrolysis is the only electricity-to-hydrogen technology considered as other technologies are still at experimental stage as it was concluded in the literature review. However, the simulation involves three different electrolysis options: onsite at the primary energy feedstock production site, regional where electricity is transported through the electric grid network from the feedstock production site to the hydrogen production site and forecourt where hydrogen is produced at the refuelling station. Since the location of onsite electrolysis is the same as the location of the primary energy feedstock production facility, the place of the electrolysis plant is one of the results of the optimisation. For forecourt electrolysis the location is determined before the simulation and it is at the refuelling station.

In the case of regional electrolysis the location of the electrolysis plant is also determined before the simulation by the user. The case study considers 7 different regions for regional electrolysis in GB. The number and location of these regions has been selected based on the Transmission Network Use of System (TNUoS) charges of the National Grid. The TNUoS charges for generation and demand depend on the zone the electricity is produced or consumed respectively. The zonal transmission charging for demand is divided into 14 zones with demand tariff ranging from 0.5£/kW to 22£/kW (National Grid, 2007). The selected regions include zones 1, 3, 6, 7, 8, 9 and 11. As it can be seen from the map of the demand zones in Appendix A, this selection involves regions from various locations such as the northern and southern part of GB, the Midlands, the eastern and western part of GB. The reason for not choosing all the demand zones is the size of the current simulation. This case study is a large-scale problem that has been solved in only one computer. Choosing 7 demand zones – more than half considering that zone 12 is the selected urban centre and it is assumed that no large facilities would be built within the city, in particular in a radius of 50km with city centre being the centre of the circle – is regarded as a sufficient number as it minimizes the simulation time without restricting greatly the regional electrolysis pathway.

Conventional alkaline electrolysis is the only technology currently available for electrolysis at scales greater than 2 MW. Given that the focus of development of the other electrolysis technologies is generally on small-scale onsite units, this is likely to continue to be the case in the medium term. Thus, in the simulation the alkaline technology is considered.

Biomass-produced hydrogen can be obtained both from gasification and pyrolysis. However, only the first is included in the simulation. The reason for this selection is threefold. Firstly, pyrolysis has lower efficiency than gasification. Secondly, the latter is more mature technology and thirdly at the moment pyrolysis is more expensive due to higher capital costs. However, because pyrolysis route has co-products opportunities, as the bio-oil that is produced is the basis of several processes for the development of fuel chemical and materials, it may be more economical. Nevertheless, these opportunities are not included in the case study so gasification remains the more economical route.

For hydrogen production by gasification, all process equipment is well established and in commercial use, except for the gasifier itself (Williams *et al.*, 1995). All the equipment needed to produce hydrogen from coal gasification, a very similar process, is available. According to the way the fuel flows in the gasifier, the gasifier technology can be categorized into: fixed-bed, entrained-flow and fluidized-bed systems (United Technologies Research Center, 2002). The technology that is considered for the biomass pathways in the present simulation is the fluidized bed as it has been demonstrated in a number of projects, operating over a wide range of conditions and using a variety of biomass feedstocks (Ciferno and Marano, 2002).

For the biomass routes as most biomass feedstocks are bulky and of relatively low energy density the cost of transportation becomes greatly expensive outside a radius of 80 to 120km. In this study, the gasification plant is assumed to be within a radius of 50km from the biomass feedstock production location.

In the case of hydrogen storage, compressed gas and liquid hydrogen are the two most commonly used methods. Metal hydrides are also included because although as an on-board storage option has still to overcome the weight problem, for stationary applications is considered a viable option. All the other storage technologies that were discussed in Chapter 2 are still at development stage and thus are excluded. Pipeline delivery can also be used as a form of storage, by allowing pressure changes in the system. This is currently done with natural gas to help manage demand fluctuation (Dincer, 2002). As a result, no storage at production sites or at the forecourt will be considered for fuel chains involving pipeline transport.

In the case of transport technologies, hydrogen can be transported as a compressed gas, a cryogenic liquid or a solid metal hydride. The methods of delivering hydrogen include truck, rail, ship and pipeline. For understandable reasons ship is not included. Moreover, the rail option, although feasible, is not included because it has not been used yet. For road transportation, trucks containing tubes, liquid tanks and hydride containers are used for compressed gas, liquid hydrogen and metal hydrides transport, respectively. It is assumed that the trucks use the existing road network of the British mainland. Moreover, the costs of transportation technologies have been calculated assuming that the maximum delivery distance a truck can cover in one day is 100km (one-way). Thus, as the tubes, tanks and containers carry fixed amount of hydrogen once the delivery distance exceeds 100km extra trucks are required to maintain the same throughput.

For the transmission of electricity, the electricity grid network in GB is used[3]. The maps showing the demand and generation zones in GB along with the corresponding tables that the data have been taken are presented in Appendix A. Naturally, from offshore wind parks the construction of cables is involved that connects the park to the gird. However, in terms of electricity transmission costs apart from the cost for offshore cables, costs for the upgrading of the grid have also been included. The development and upgrading of the grid is an issue that needs tackling in order to ensure the grid access of the continuously increasing renewable capacity (BERR, 2004). So, although it is assumed that the electricity

[3] The electricity transmission efficiency of the grid network is included in the simulation.

uses the existing network the cost of reinforcing the grid to handle the renewable developments within the time horizon has been taken into account. The derivation of this cost has been based on data from the Renewables Innovation Review that estimates that for a 8-10GW increase of renewable capacity the grid's upgrades amount to £1,125 million. Moreover, £601 million are also required for the distribution systems (DTI, 2004a).

Apart from the renewable energy resource and the zonal transmission charging maps, there is another map that has been considered presenting the designated areas in GB. This map has been used in order to avoid considering areas that they may have a considerable renewable energy resource but can not be used for specific reasons. The areas that are excluded are national parks, areas of outstanding natural beauty, natural scenic areas and heritage coast (DEFRA, 2005).

The collection of technical and economic data those are included in the simulation have been obtained by means of literature and commercial information review. The gathering of the necessary data has been tried as much as possible to be achieved from the same source in order the data to be as coherent as possible. However, this is not possible for all the input parameters as there is not a single source that includes the values for all the parameters in the simulation. Due to space reasons all the parameters and their corresponding values of all the hydrogen technologies included in the case study are listed in Appendix A.

The costs listed in Appendix A are aggregate costs. For this reason the capital costs of technologies, for example an electrolysis plant, are assumed equal to the expansion costs, the expansion of an already existing electrolysis plant. All the values of the input cost parameters are presented in euros. The final result is converted to UK pounds. Generally, costs can be entered into the model in any currency as long as they are all in the same chosen currency.

6.3.3 Demand

This section presents the method that has been used and the calculations and assumptions that have been made to obtain the demand for the simulation. The time scale of the simulation is a 50 year time horizon as major infrastructure transitions usually occur over a period of fifty years. The development of the infrastructure has 5 periods of 10 year duration each. In the spirit of examining what would be required to develop an infrastructure for a significant level of demand, an aggressive commercialization scenario it is assumed where at the beginning hydrogen co-exists with carbon fuels and at the end of the simulation London's road transport system is aimed to be free from carbon.

The development of a hydrogen fuel delivery system is influenced by the interactions of complex technological, political, economic and social factors, whose evolution cannot be predicted with certainty. Moreover, the hydrogen infrastructure is expected to evolve around the development of the hydrogen market. Naturally, the demand of hydrogen fuel in the future - which is inherently uncertain - is not known but it can only be predicted.

Generally, in all studies dealing with relative issues a demand scenario or forecast is produced. This analysis does not attempt to forecast hydrogen fuel demand or fuel consumption within the planning time horizon of the case study. More specifically, although a demand profile is predicted, this is done as a means in an attempt to produce the demand input data for the simulation and not as a goal of this study to predict future hydrogen demand. The analysis does not produce demand scenarios of possible hydrogen fuel penetrations as it does not examine the possible ways of establishing a hydrogen market. Nevertheless, the production of the demand profile has been carried out in such as way in order to ensure as much as possible its reliability. The aim of this analysis is to make a rational assumption on the demand behaviour supposing that the demand of hydrogen starts from zero at the beginning of the simulation and at the end of the planning horizon is enough to cover all London's road transport demand. It examines the demand growth in the selected time horizon and the production of the necessary hydrogen to replace petroleum-based fuels at the end of the horizon. So, the method that is described in this section has been followed aiming to produce an equation representing the behaviour of demand. In order to obtain a valuable, appropriate and dependable equation its derivation is based on trends from previous years and data of reliable sources.

The demand for hydrogen has been calculated based on data from National Statistics reports. Figure 6.2 shows the trend in petroleum consumption by transport mode from 1980 to 2005 in the UK. The figure includes the overall amount of petroleum including petrol, diesel, marine and aviation fuels. Transport petroleum consumption has reached 58 million tonnes of oil equivalent in 2005 that is a 65% increase from 1980 level (DfT, 2006).

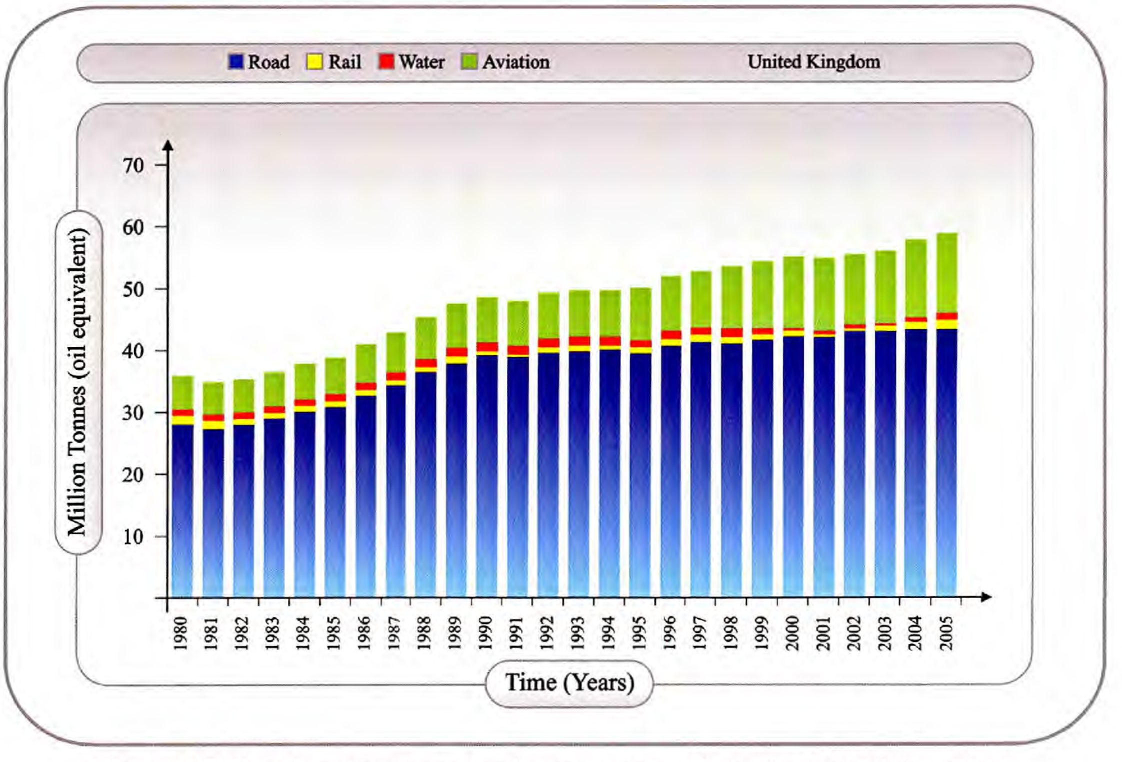

Figure 6.2: Petroleum consumption by transport mode in the UK: 1980 to 2005. (Source: DfT, 2006)

It can be witnessed from Figure 6.2 the majority of petroleum is consumed by road transport. During the first decade road transport has been increased more sharply but afterwards its increase is smoother. From the fuel consumption figure only the blue region of every column is considered that represents the road transport fuel consumption. However, in the case study the infrastructure is desired to deliver enough hydrogen to cover London's road demand therefore the only London's fuel consumption is required. Unfortunately, the Transport Trends

2005 report does not include a detailed breakdown of fuel consumption by region and thus London's energy use has been derived from Figure 6.3.

Figure 6.3 shows transport energy consumption in London by mode. Overall, in 2002 London consumed around 31,674GWh (TfL, 2004). Although the report was published in 2005 the graph corresponds to 2002 figures. Frustratingly, the more updated versions of this report (years 2005 and 2006) do not include fuel consumption figures.

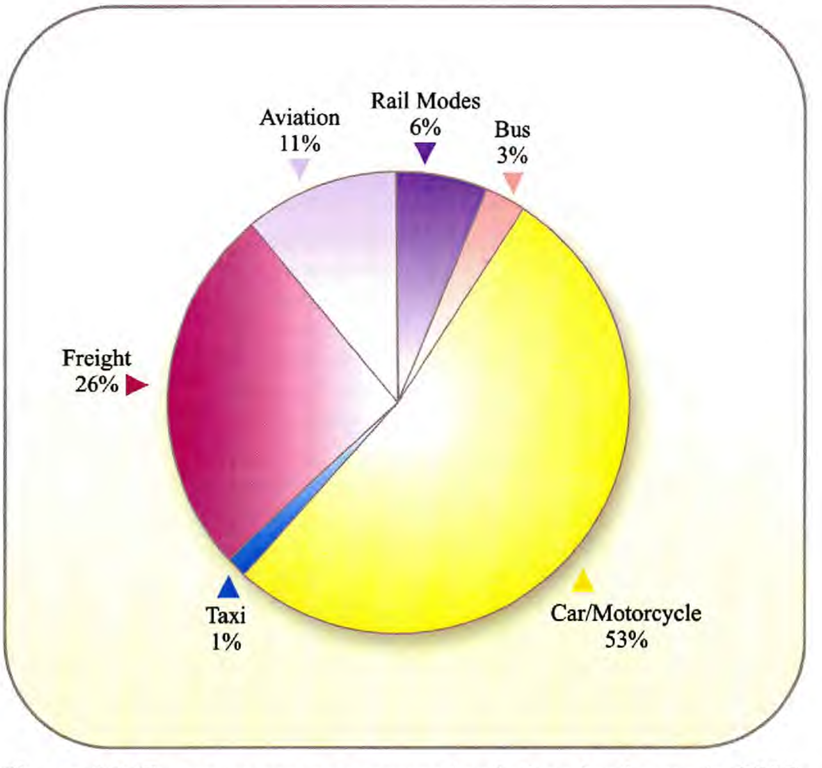

Figure 6.3: Transport energy consumption in London by mode (2002).
(Source: TfL, 2004)

Road transport accounts for 83% that equals to around 26,289GWh/year. Considering that hydrogen fuel cell vehicles have efficiency of almost twice greater then gasoline internal combustion engine vehicles this number is translated into 13,145GWh/year hydrogen energy.

Knowing the fuel consumption of London for 2002 from Figure 6.3 and the fuel consumption of UK for 2002 from Figure 6.2 and assuming that 1 ton of oil equivalent is equal to 11,634kWh the London's consumption percentage of the overall UK's consumption has been obtained. This percentage is equal to approximately 5.3%. Due to lack of available data it has assumed that this percentage is steady from 1980 to 2005. Thus, the London' consumption has been calculated and according to these data the following graph has been plotted.

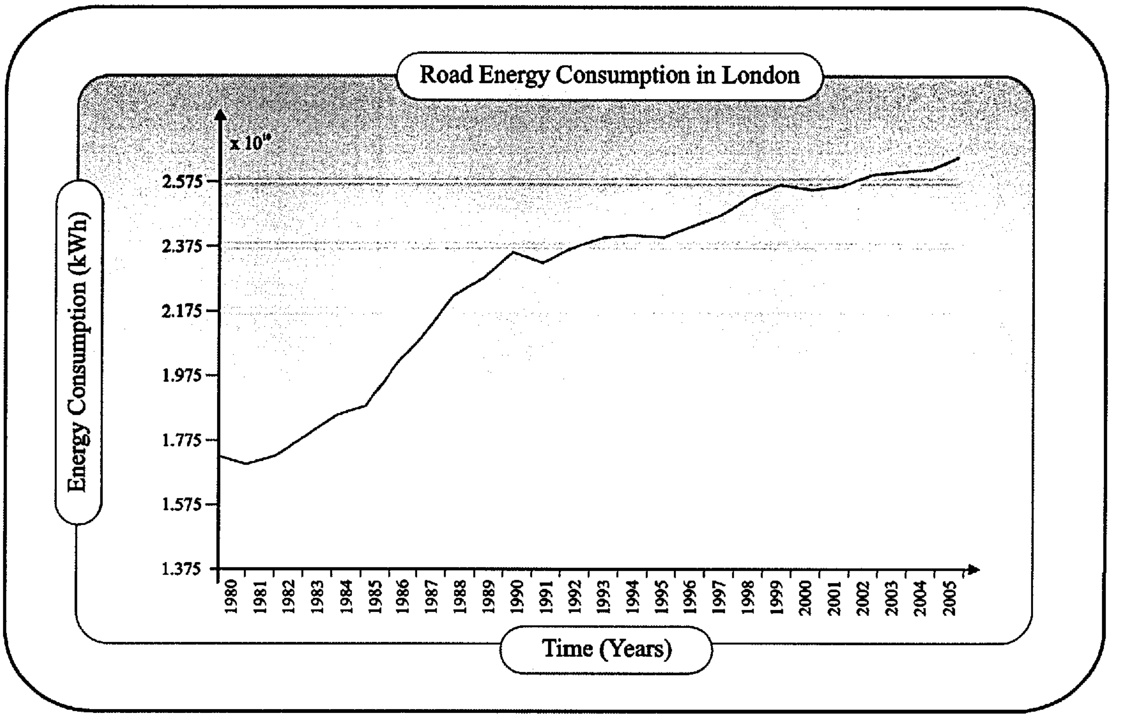

Figure 6.4: Road transport energy consumption in London from 1980 to 2005

Figure 6.4 is used in order to estimate the demand for hydrogen for the future, specifically for the next 50 years that is the selected time horizon. Since, the graph covers the period to 2005, the hydrogen demand for the period of the next 50 years is estimated by extrapolating the trend from this graph. The graph in Figure 6.4 shows the energy consumption of oil and thus in order to obtain the required hydrogen energy the data have been divided by 2. The extrapolation has been carried out in MATLAB and the following graph has been produced:

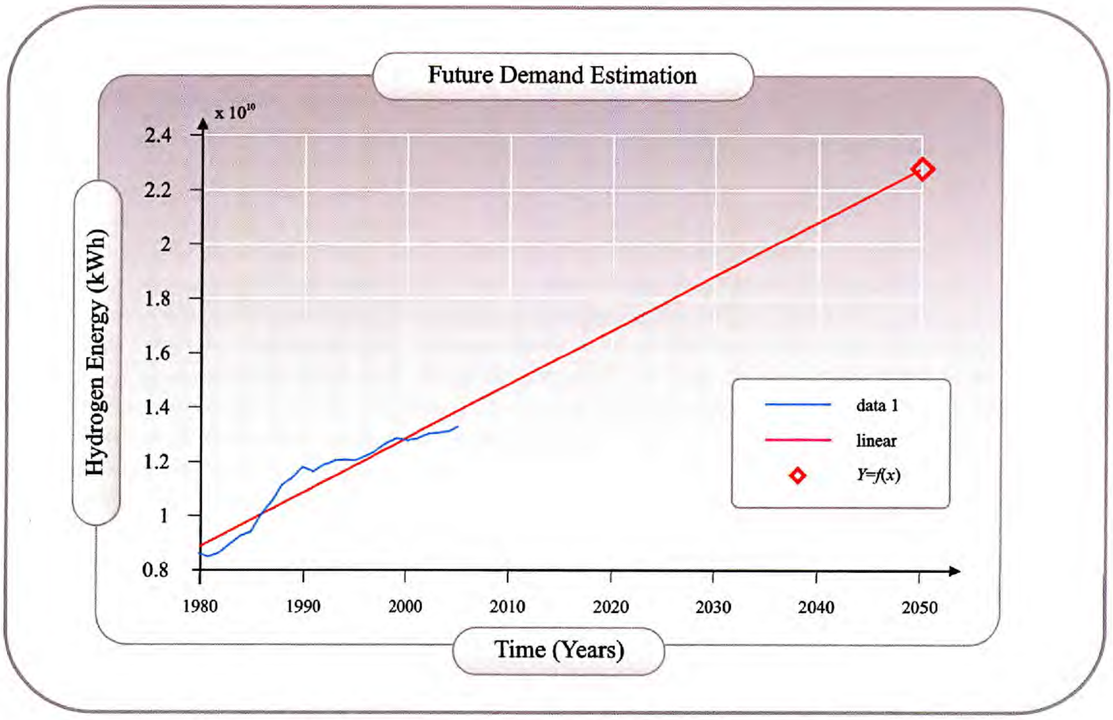

Figure 6.5: Linear extrapolation of hydrogen demand function

All the possible extrapolations, including linear, quadratic, cubic and 4th to 10th degree polynomial, have been checked and tried in order to obtain the best possible fitting. The quadratic, cubic, 5th and 6th degree polynomial have not been selected because the demand from the middle or at the end of the horizon is greatly reduced. Certainly, this scenario is not valid. The 4th, 7th, 8th, 9th and 10th degree polynomial do not reduce the demand in the course of the horizon but they increase demand though in such a large extent that it is not quite realistic. The behaviour of future demand is not known and thus it cannot be absolutely certain whether a scenario is valid or realistic but given the demand from past years it can be assumed that the behaviour of past years may continue to some extent in the future. For this reason, linear extrapolation has been chosen. It produces an equation of demand that is quite consistent with the past behaviour. This equation is:

$$F(x) = 1.9784E{+}008x - 3.8284E{+}011$$

However, this equation cannot be used in the model in this form. The reason why it can not be entered in the model is that the simulation considers that hydrogen demand starts from zero at the beginning of the 50 years time horizon and is equal to London's total road demand at the end of the horizon. So, the equation needs to start from zero. For this reason, the function is multiplied with sine:

$$F(x) = \sin(x\,\pi/100)\,(1.9784E{+}008(x + 2007) - 3.8284E{+}011)$$

This form can be entered into the model; however, it has undergone another process. Generally, polynomial forms are preferred over forms with sine, or cosine or any other trigonometric. In order to eliminate the sine in the function the Taylor series expansion has been used. Taylor series is the power series of the form (Mathworks, 2005):

$$\sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}\,(x-a)^n$$

The Taylor series is a representation of a function as an infinite sum of terms evaluated from the values of its derivatives at a single point (Mathworks, 2005). When a function has a Taylor series that is convergent to the function, usually as the degree of Taylor expansion rises it approaches the correct function.

The demand function has been Taylor expanded for a number of different degrees of expansion. The selected degree is 9. For the first 9 degrees the change in demand is noticeable after the 10th degree the change in demand is quite small. So, the last factor of the function is becoming so small that affects slightly the demand. That means that more terms will not produce a better approximation and so the 9th degree may be considered the best approximation that can be obtained.

Conclusively, the demand function that is entered into the model for the London simulation is the following:

$$F(x) = 1.42E{+}008x\pi + 2E{+}006\pi x^2 - 1.78E{+}005/75x^3\pi^3 - 2.47E{+}003/75\pi^3x^4 + 1.78E{+}005/1.5E{+}007x^5\pi^5 + 2.47E{+}003/1.5E{+}007\pi^5x^6 - 1.78E{+}005/6.3E{+}012x^7\pi^7 - 2.47E{+}003/6.3E{+}012\pi^7x^8$$

At the end of the 50 year time horizon the infrastructure is required to deliver to London around 24,113GWh hydrogen energy. Every fuel chain depending on the amount of hydrogen that produces can deliver fuel to more than one refuelling station. Considering the throughput of a medium sized refuelling station in the UK around 2.12 million litres per year and the average fuel consumption of the UK vehicle fleet 0.096l/km, the hydrogen demand of a medium refuelling station has been calculated and found equal to 0.6t/d (Howes, 2002)[4].

6.4 Summary

Before the presentation of the results of the simulation this section summarizes and reminds the main characteristics of the case study. The model is used to compare different fuel chains in order to form a development plan for a least-cost renewable hydrogen infrastructure able to deliver enough hydrogen to cover London's road transport demand within a 50 year time horizon.

Hydrogen fuel is produced from the exploitable renewable resources of GB and in the case of wastes from the MSW generated within London. The hydrogen technologies included in the simulation comprise options that are either approaching the middle or the end of the long road towards the stage of widespread use. The technologies that are used in the case study and form the fuel chains under comparison include 7 primary energy feedstock production technologies, 2 hydrogen production technologies, 2 conversion technologies, 3 storage technologies and 5 transport technologies. Table 6.1 shows all the options for every stage of the fuel chains.

[4] The calculations assume a lower heating value of hydrogen of 10.783 MJ/Nm^3, a density of hydrogen of 0.0899kg/Nm^3 and an energy use of fuel cell vehicle of 1.2MJ/km.

London Renewable Hydrogen Infrastructure	
Renewable Energy Sources	
Wind Energy	Onshore and Offshore
Solar Energy	Photovoltaics
Hydro Energy	Small-scale Hydro
Biomass - Energy Crops	Short Rotation Coppice of Willow
Biomass - Agricultural Residues	Forestry Residues
Biomass - Wastes	Municipal Solid Waste of London
Hydrogen Technologies	
Hydrogen Production Technologies	Electrolysis (Onsite, Regional, Forecourt)
	Gasification
Hydrogen Storage Technologies	Compressed Gas
	Liquid Hydrogen
	Metal Hydrides
Hydrogen Transport Technologies	Compressed Gas by Road
	Liquid Hydrogen by Road
	Metal Hydrides by Road
	Pipelines
Electricity Transmission Technology	Electricity Grid Network
Infrastructure Demand	
Demand Target at the End of the Time Horizon	24,113 GWh
Infrastructure Parameters	
Supply Centre	London
Time Horizon	50 years
Periods	5
Period Duration	10 years

Table 6.1: Summary of London infrastructure simulation characteristics

The next Chapter presents the results of the modelling of the different pathways and a discussion of their implications. A sensitivity analysis is also introduced and discussed, to examine the model outputs to changes in data and assumptions.

C H_2 A P T E R 7

Results, Analysis and Discussion

7.1 Introduction

In this Chapter the results of the modelling work are presented and discussed. A sensitivity analysis is then carried out to investigate the influence of the parametric variation on the outputs of the model. In addition, a policy discussion is followed indicating some of the main challenges that renewable hydrogen infrastructure developments face and how policy intervention may assist in overcoming these challenges. At the end of this Chapter, a number of alternative applications of the model are discussed.

7.2 Presentation of the Results

The hydrogen infrastructure development algorithm has been used for the case of London in an attempt to determine the least-cost infrastructure development plan. For the formation of this plan the model has compared 244 different fuel chain options. These options are depicted in Figure 7.1. Figure 7.1 shows the different fuel chain options that have been examined and compared. All the fuel chains are depicted having the as a starting point the primary energy feedstock production and conclude to the market. The latter is the same for all pathways while the former may be one of the 7 options of the top row that shows the renewable energy sources and their corresponding icons.

From the 244 fuel chain configurations, the majority involves the production of hydrogen from renewable electricity. The biomass routes consist of 12 pathway options. This impressive difference is due to the location of the hydrogen production plant. In the case of biomass, it has been considered that the plant is within a 50km radius from the biomass feedstock production facility while in the case of renewable electricity there are more options considered for the distance between the feedstock production and the hydrogen production plant. More specifically, the simulation includes the fuel production facility at the renewable energy scheme or at the refuelling station or in any other area between the renewable energy scheme and the refuelling station. For the third option as it has been stated in the previous Chapter, 7 different locations have been considered. However, due to the results that showed that regional is preferred over onsite electrolysis it has been deemed proper to examine more locations.

The area of GB has been divided into 64 segments. This segmentation has been implemented solely because for such a large-scale problem a larger segmentation could not be solved by one computer. This technical restriction is more comprehensible if it is taken into account the number of combinations that the model forms and compares. Although, the number of fuel chains under comparison is 244, the actual number of delivery patterns that is considered is considerably larger. For example, for an onshore wind energy fuel chain (a fuel chain that has as a starting point an onshore wind park) the location of the wind farm greatly affects the cost of this chain. The cost of hydrogen that is delivered from fuel chain 1 in Figure 7.1 that starts with a wind farm in Scotland is not the same with the fuel chain 1 that instead of Scotland starts from Wales. So, every fuel chain pattern is combined with possible locations for starting points. So, the model more specifically compares 244 fuel chains and their corresponding combinations. The number of combinations is equal to:

$$\text{Fuel chain options x Periods x Number of segments}$$

So, for 10 fuel chain options, 5 periods and 64 segments, which correspond to map segmentation iterations 6, the number of combinations is equal to 3,200 and for the same number of pathways and periods but 128 segments, which is the next possible iteration, the number of combinations increases to 6,400. Considering that the present simulation has 244 fuel chains becomes apparent why 64 segments have been selected.

The infrastructure development has been divided into 5 periods of 10 years each. The results are laid out from the beginning until the end of the time horizon for every period in detail. The results of the modelling are presented with reference to Figure 7.1 for ease of comprehension. Every pathway in Figure 7.1 corresponds to a number and these numbers will be used throughout the remaining text. Moreover, the final infrastructure development plan is also presented in a graphical form at the end of the results section. The Figure includes the icons and the code numbers from Figure 7.1.

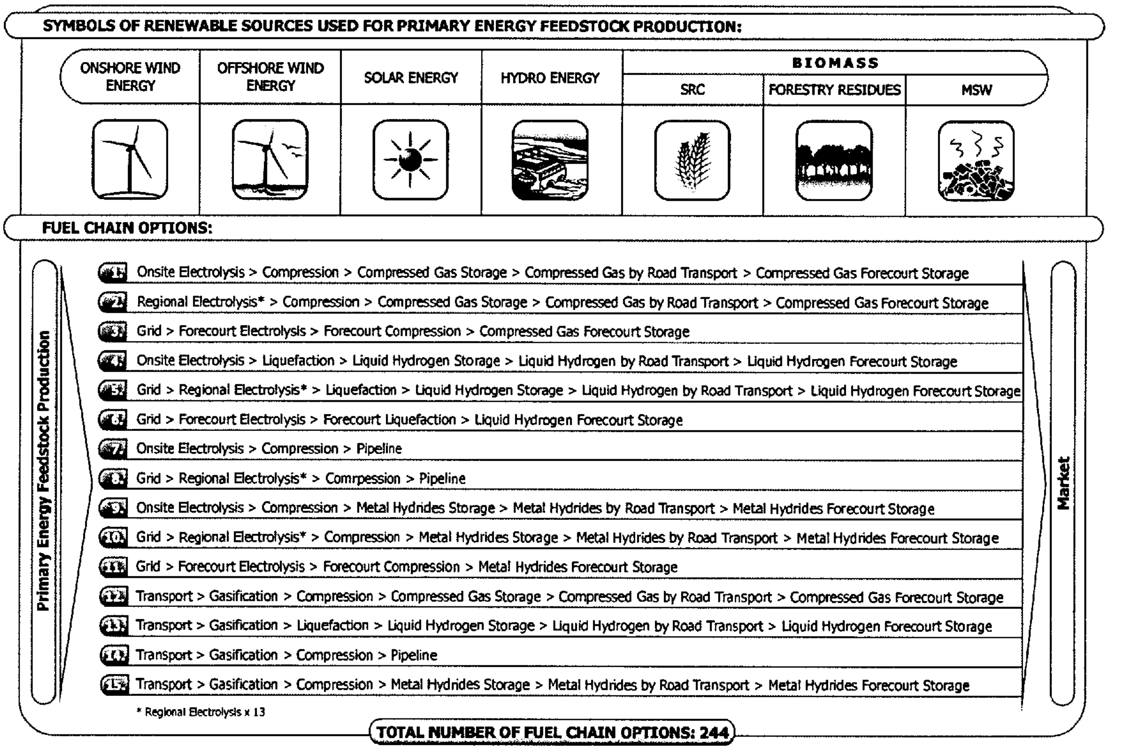

Figure 7.1: Fuel chain options under examination

First Period

In the early stages of the infrastructure development the model has chosen to produce most of the hydrogen fuel through biomass routes. The majority of the required hydrogen fuel is produced from wastes and the selected configuration is fuel chain option 14. The model activates 64 pathways of this configuration, which is the maximum number a fuel chain can be activated. The capacity of all these chains is a 10MW gasification plant. The fuel chain starts from the waste collection point, where MSW is gathered and delivered by trucks at the gasification plant. At the latter, hydrogen is produced and transported through pipelines at the demand centre. MSW is generally considered a cost-effective route to hydrogen. The results are in accordance with this perception as this route has been selected a large number of times and at the beginning of the horizon. This behaviour is reasonable as this is the only route that the production of the primary energy feedstock for hydrogen generation is free and the distance between the hydrogen production plant and the demand centre is short.

For the delivery of hydrogen, pipelines have been selected and used also as a storage means at the refuelling station. Among the different available options for hydrogen transport, such as compressed gas, metal hydrides, liquid hydrogen or pipeline delivery, the latter has been most probably selected firstly because of the amount of hydrogen and the delivery distance. Generally, pipelines are preferred for high flow rates and short-to-medium distances. This fuel chain would have been selected more times if the restriction of the resource would have been eliminated. As it has been mentioned in the previous Chapter MSW is the only renewable energy source in this simulation that its resource is limited to London's capacity. If the amount of available MSW was larger the model would have selected more pathways from this configuration. This is discussed and analysed in detail in the sensitivity analysis that follows the results Section.

The remaining demand for the first period is covered from forestry residues, SRC and onshore wind energy routes. The selected configuration of the two biomass feedstocks is option 14. One chain of each feedstock is activated with forestry residues chain having the maximum allowable capacity that of a 30MW gasification plant and SRC chain a 6MW gasification plant. The primary energy feedstock production facilities of both fuel chains are close to the demand centre. The same is true for the onshore wind energy fuel chain. Two option 7 fuel chains have been selected and both have as a starting point a wind farm of 50MW capacity. As the wind farms are relatively close to the market onsite electrolysis is preferred over regional electrolysis. For fuel chain options that include onsite electrolysis, the location of the hydrogen production facility is determined by the location of the primary energy feedstock production facility. For fuel chain options that include regional electrolysis the position of the hydrogen production facility is at a certain point regardless of the position of the feedstock production facility. Thus, for wind farms that are relatively close to the market onsite electrolysis fuel chains are a better choice than regional electrolysis chains because they exclude the transmission of electricity over large distances but include a small delivery distance between the point of hydrogen production and the refuelling station. On the contrary, for wind farms far away from the market regional electrolysis chains are a more suitable option as it will be seen in the subsequent periods. Overall, in the first period 68 fuel chains have been activated in order to cover the demand of this period.

Second Period

In the second period, the increasing demand has been covered with the expansion or operation of the existing fuel chains and the activation of 49 more chains. The latter chains include onshore wind energy, forestry residues and energy crops.

One of the selected onshore wind energy pathway patterns is fuel chain option 8. This option has 13 alternatives each one for different electrolysis location. The 13 locations correspond to the 13 demand zones of the National Grid. Out of the 13 location options the chosen one is the demand zone 7. Eighteen fuel chains are formed having as a starting point a wind park of the maximum allowable capacity, that of 50MW. All the wind parks are located in the Northern part of GB (in the area of demand zones 1 and 2) and the electricity they produced is transported through the grid to the electrolysis plant that is located at zone 7. As every demand zone is a relatively large area the electrolysis plant have been placed approximately in the middle of every zone. The produced hydrogen from the electrolysis plant is transported through pipelines to the demand centre.

In this case, onshore wind regional electrolysis fuel chains are preferred than onsite electrolysis chains because the selected sites for the wind farms are distant from the market. Generally, the resource of wind energy is considerably larger at the Northern part of GB which is very far away from the market. So, for a wind energy onsite electrolysis fuel chain hydrogen is produced in the north and has to be transported over a large distance in order to be delivered to London. For a wind energy regional electrolysis chain electricity is produced in the north and is transmitted through the grid to the electrolysis plant, which is closer to London and thus hydrogen has to be transported over a much shorter distance. From the results, it may be concluded that it is cheaper to transport electricity than hydrogen over large distances. So, the model by selecting regional electrolysis has combined the exploitation of the best wind resource and a cost effective way of hydrogen delivery. So, due to the geographical allocation of the wind resource onshore wind energy regional electrolysis fuel chains have been selected considerably more times than onsite electrolysis fuel chains.

As the good onshore wind energy sites in the southern part of GB are significantly lower than that in the northern part of GB, onshore wind energy option 7 fuel chains have been selected 3 times. The 3 option 7 chains have been activated with wind farms of 50MW capacity as starting points. The locations of these farms are in the south part of GB and close to the market.

The 64 waste chains that have been activated in period 1 are expanded to maximum capacity that of 17.36MW. Fuel chain 14 option is activated 6 times with forestry residues as the primary energy feedstock. The amount of forestry residues exploited is enough to power a 30MW gasification plant. Forestry residues combined with fuel chain 13 option are also used 3 times operating at maximum capacity. These 9 forestry residues fuel chains are relatively close to London in the southwest part of GB. From the same regions 8 more forestry residues fuel chain 12 option are selected with capacity 30MW.

Another biomass route that has been selected in this period is the energy crops pathways. Three chains of the SRC 14 option and 8 chains of 12 option are selected to operate at maximum capacity, 30MW. The selected SRC and forestry residues fuel chains have as starting points feedstock production facilities located at the southwest region of GB. The SRC option 14 fuel chain that has been activated in the first period with 6MW capacity is expanded in this period to maximum capacity, which is 30MW.

Overall, in this period 49 chains have been activated, 65 have been expanded and 4 chains have continued operating at maximum capacity. At the end of this period, the infrastructure consists of 118 fuel chains.

Third Period

As the demand increases over the time horizon the infrastructure grows in order to deliver to London the required amount of hydrogen fuel. The fuel chains that have been selected in the two previous periods continue operating in this period. However, the increasing demand results in the activation of more fuel chains. From the fuel chains that are formed in this period, the majority of hydrogen energy is produced from wind energy. Eighteen offshore wind energy chain 8 option are formed. Fifteen of them are operate at maximum capacity, 100MW, and 3 have 36MW capacity. In the case of offshore wind energy there is no onsite electrolysis pathway so the model has to choose between regional and forecourt electrolysis. All the selected offshore chains include the installation of offshore wind parks in the north where the offshore resource is the largest. The electricity produced from the offshore wind farms is transmitted through undersea cables to the mainland and then is transmitted through the grid at the electrolysis plant that is located at zone 9. Onshore wind energy has also been selected for the activation of 19 fuel chains of option 8 with regional electrolysis at the same demand zone and capacity of 50MW.

From the biomass routes 20 fuel chains are selected. These chains break down to 14 SRC chains and 6 forestry residues chains. The former include 11 chains of option 11 and 3 chains of option 14. The latter comprise 1 chain of option 14 and 5 chains of option 11. Apart from forestry residues option 14 chain that is activated with 3.5MW capacity, all the others operate at maximum capacity, which is the same for residues and energy crops and equal to 30MW. Although the difference in the production costs of SCR and forestry residues is small, the relatively large difference in the establishment costs is quite likely the reason why more SCR chains are selected than forestry residues chains. Moreover, the vast majority of these chains has as a starting point renewable energy schemes situated at the south part of GB.

Overall, in this period the model has selected 57 additional fuel chains and at this stage the infrastructure includes 175 fuel chains from 5 different renewable energy sources.

Fourth Period

All the selected fuel chains so far continue operating throughout the 4th decade of the infrastructure development venture. A fuel chain can be activated throughout the 50-years planning horizon, however many of the technologies included in a fuel chain do not have a lifetime of 50 years and thus could not last for all the horizon. For all the stages in a fuel chain every technology that "expires" is replaced by a new one. So, fuel chains that have been activated from the first or any previous period until this period or the next one have underwent the appropriate replacements.

Onshore wind energy is selected as the primary energy feedstock for 7 fuel chains of option 8 and one option 7 chain. All these chains start from a 50MW wind farm that produces the electricity that is transmitted through the grid to the regional electrolysis facility at zone 9. The locations for the wind farms that have been selected are all in the northwest part of England except from the option 7 chain that is relatively close to the market.

The majority of the additional fuel chains in this period use biomass as the primary energy feedstock. Forestry residues are used as a feedstock for 4 option 14 chains and 19 option 13 chains. All of these chains have the maximum allowable capacity that is equal to 30MW. Moreover, the 14 option chain that has been activated with 4.5MW capacity in the previous period is expanded to maximum capacity in this period. The starting points for the chains activated in this period are in the south and southwest part of GB. For the forestry residues chains although there are segments in the north or middle part of GB that contain a promising resource and thus could be selected as feedstock production locations, their distance from the supply centre is the determining factor that prevents their selection. For example, if the model has to choose between pipeline delivery and liquid hydrogen delivery the location of the feedstock production greatly affects the selection because the former method may be cheaper than the latter method for a segment close to London but it can be more expensive for a segment far away from London. This is the reason the infrastructure does not involve a single pattern but is a mixture of different fuel chain options.

According to the input data, SRC due to the lower production cost and higher yield may be considered a relatively less costly biomass feedstock from forestry residues. This may also be concluded from the large number of SRC chains that have been selected in this period. Overall, the model selected 50 chains with SCR as a primary energy feedstock. These chains break down to: 12 option 14 chains, 37 option 13 chains and 1 option 12 chain. Apart from one of the option 14 chains that has 4.5MW capacity all others have the maximum capacity, which is 30MW. The locations of the primary energy feedstock production for all the chains are between the middle and south of England in order to minimize hydrogen transportation costs.

In total, throughout this period the model has formed 81 additional fuel chains and in conjunction with the existing ones the number of total chains of the infrastructure has grown to 256.

Fifth Period

In the last decade of the infrastructure development in order the targeted demand at the 50th year to be met 40 more fuel chains have been selected and one has been expanded. The former chains include fuel chains that use onshore wind energy, forestry residues and SRC as their primary energy feedstock.

The onshore wind energy pathways are 5 chains of option 8 and have as a starting point a 50MW wind farm. The forestry residues pathways include 11 chains of option 14 and operate also at maximum capacity, which in the case of forestry residues is 30MW. The larger number of fuel chains that have been activated in this period are SRC chains. In total, 24 fuel chains that use SRC as a primary energy feedstock have been selected and one has been expanded. The latter is the option 14 chain that has been activated in the fourth period with capacity 4.5MW. In this period it is expanded to maximum capacity that is 30MW. The SRC fuel chains that are activated in the fifth period include 22 option 14 chains and 2 option 13 chains. All of them have a capacity that is equal to 30MW.

Every fuel chain is considered that may deliver hydrogen fuel to more than one refuelling stations depending on the capacity of the renewable energy scheme that has as a starting point. The maximum capacity of a renewable electricity production facility is different for each renewable energy source and thus the number of refuelling stations a fuel chain can supply varies.

The average throughput of refuelling station in the UK in 2005 was 3.64 million litres per year (UPEI, 2006). The average fuel consumption of the UK vehicle fleet in 2005 was 0.075l/km (DfT, 2006). These data have been used to calculate the daily travel demand per station, of around 132,968km/day. Then assuming this is provided entirely by hydrogen fuel cell vehicles, this translates to a hydrogen demand of 1.1t/d. A fuel chain that delivers the power output of a 50MW plant, which is the case for an onshore wind energy fuel chain operating at maximum capacity is able to provide hydrogen fuel to maximum 5 refuelling stations. For offshore wind energy fuel chains this number is larger because the maximum capacity for an offshore wind farm has been assumed double than that for an onshore wind farm. Thus, fuel chains using offshore wind energy as a primary energy feedstock may supply to maximum 12 refuelling stations. The biomass fuel chains may deliver hydrogen fuel to maximum 4 or 8 refuelling stations. The latter value corresponds to SRC and forestry residues pathways and the former to waste pathways and is lower mainly due to the restricted resource and to a lesser extent due to the lower gasification efficiency.

At the end of the time horizon, the infrastructure is able to cover the road transport demand of London by delivering hydrogen fuel from 296 fuel chains. So, according to the results of the model the least-cost renewable hydrogen infrastructure development plan for London for a 50-year time horizon consists of 296 delivery pathways that use the GB resources of 4 different renewable energy sources, onshore and offshore wind energy, forestry residues and SRC energy crops, and the London's resource of municipal solid waste. The overall cost of this venture amounts to 11.2 billion pounds (16.1 billion euros). This capital investment includes all the necessary costs, such as capital, O&M costs, feedstock costs, transportation costs, for the entire infrastructure development and operation throughout the 50-year time horizon. This is not discounted in financial sense. The produced hydrogen infrastructure development plan for London is depicted in Figure 7.2.

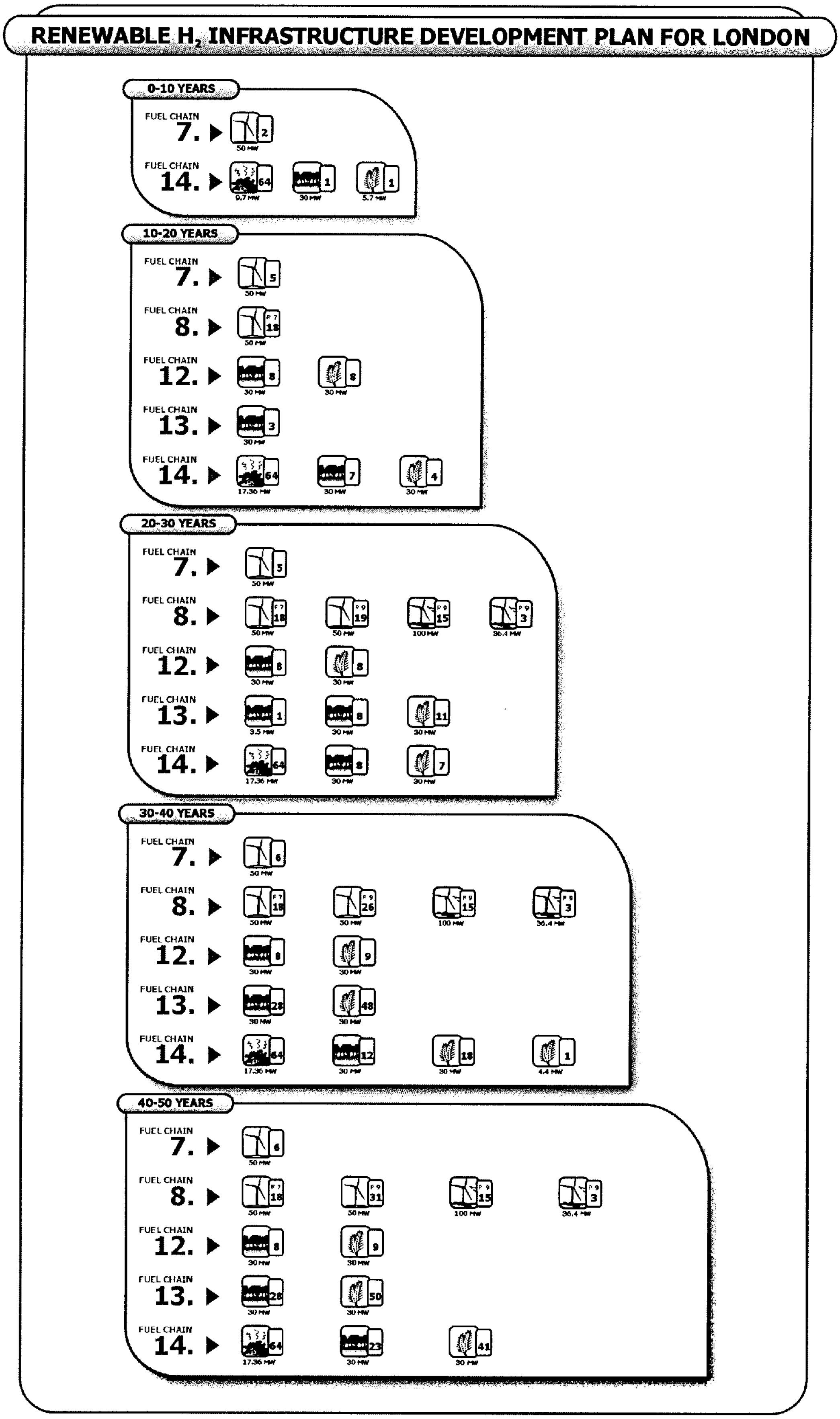

Figure 7.2 Renewable hydrogen infrastructure development plan for London

In general, the values used in the simulation could be characterized as moderately optimistic for entry market stage, but yield an overall cost comparable to published estimates. More specifically, Mintz *et al.* (2002) has examined the cost of some hydrogen fuel infrastructure options and concluded that the cost of a hydrogen infrastructure that delivers fuel sufficient to power 100 million fuel cell vehicles is around 285 billion pounds (500 billion dollars). Considering that the London infrastructure aims to power 3.5 million vehicles the cost of 11.2 billion pounds is a good analogy. Moreover, Ogden (1999) studying the hydrogen infrastructure development for Southern California found that the range of infrastructure capital costs for a system serving 18,400 fuel cell vehicles is around 0.8-6.5 million pounds(1.4-11.4 million dollars). Adapting this range to the number of London's cars for the sake of comparison shows a close agreement with the model's result.

It is worthwhile to mention that if the simulation included other demand centres the infrastructure development would have been different from that presented in Figure 7.2. It would have been a completely different simulation. In a simulation that includes more than one demand centres, the model forms the appropriate pathways for each one. The inclusion of more than one demand centres is another case than shows noticeably the importance of examining the development of a hydrogen infrastructure using an approach that incorporates region-specific framework conditions and resource optimisation. These features enable the model to compare different fuel chains based not only on technical and economic criteria but also on the resource potential of the region and the location of the demand centres in order to select the least-cost pathways for each supply centre. So, a fuel chain that may be preferred for a specific market may not be the best choice for another market.

7.3 Sensitivity Analysis and Discussion

The results from the model are subjected to a sensitivity analysis to investigate the influence of a variation in the model parameters in the outcome of the model. A sensitivity analysis has been conducted on each of the parameters feeding into the model – listed in Appendix A. Variations in the model parameters have an effect on the final model output with some parameters having a greater influence on the results than others. In this case, this influence may be either on the resulted overall cost of the infrastructure or the final pattern. More specifically, a change in a parameter may result in a higher or lower infrastructure cost without changing considerably the pattern, namely the type or size or number of fuel chains that have been selected, or in a higher or lower cost that combines significant changes in the pattern.

All the parameters have been varied over a range of values and the changes in the results have been recorded. The outcome is presented in the form of a spider diagram that shows the changes of a result as a function of the percentage change in a number of parameters. This diagram shows the changes in the total infrastructure cost, however as a number of changes lead to changes in the pattern diagrams showing the changes in the pattern are also used. Table 7.1 shows the parameters used and the range over which they have been varied. The Table includes the parameters that cause a large or medium variation and the pattern diagrams are formed only for the parameters that cause significant variations in the infrastructure pattern. The Table presents the absolute and relative variation. The former is a fixed size change in the parameter and the latter is a certain percent change in the parameter. In the case of the absolute variation the original value is also presented.

Parameter	Min.	Original	Max.	Remark
Onshore wind energy capital cost (€/kW)	763	1120	1444	Lowest and highest value encountered in the literature.
Onshore wind energy capacity factor (%)	25	30	40	The range of -5/+10% covers all values for the onshore wind energy capacity factor in the literature.
Onshore wind energy maximum plant capacity (MW)	20	50	90	Based on the existing onshore wind farms in GB.
Offshore wind energy capital cost (€/kW)	1250	1650	2050	This range covers the range of data that have been collected for offshore farms.
Offshore wind energy capacity factor (%)	35	40	45	The range of -/+10% covers all values for the offshore wind energy capacity factor in the literature.
Offshore wind energy maximum plant capacity (MW)	70	100	150	Based on the existing onshore wind farms in GB.
Biomass feedstock cost (SRC) (€/kW)	-20%	-	+20%	Little information has been available on biomass costs, however, they are unlikely to vary widely.
Biomass maximum plant capacity (MW)	20	30	50	This range covers a number of values in the literature.
Biomass feedstock lifetime	-30%	-	+30%	Variation in the duration of harvesting before re-planting.
MSW resource (tonnes)	-40%	-	+100%	Variation in the amount of available MSW for hydrogen production.
Electrolysis plant capital cost (€/kW)	-30%	-	+30%	This range covers a wide range of values encountered in the literature.

Parameter	Min.	Original	Max.	Remark
Electrolyser efficiency (%)	60	70	75	The value of 60 is current electrolyser's efficiency and the value of 75 is considered conceivable.
Electrolyser lifetime	10	15	20	The value of 20 may be considered highly optimistic, though not unrealistic.
Gasification plant capital cost (€/kW)	-40%	-	+40%	The range -/+40% allows for technological improvements given that hydrogen gasification is at the early stage of commercialisation.
Gasification efficiency (SRC-forestry residues) (%)	50	55	58	Range given in Williams (1995) for different gasifier types.
Gasification efficiency (wastes) (%)	45	50	55	This range covers a number of values encountered in the literature.
Compression capital cost (€/kW)	-20%	-	+20%	Established technology.
Compression efficiency (%)	80	85	85	Compression's efficiency varies by size and pressure and the range of values chosen is representative of this variation.
Liquefaction capital cost (€/kW)	-40%	-	+40%	Liquefaction is at a relatively early stage of commercialisation so a wide range is used.
Liquefaction efficiency (%)	70	75	83	This range covers all values for liquefaction efficiency encountered in the literature.
Compressed gas storage capital cost (€/kW)	-40%	-	+40%	The tank cost varies by type and material and the range of -/+40% is representative of this variation.
Liquid hydrogen storage capital cost (€/kW)	-40%	-	+40%	The dewar cost varies by type and material and the range chosen is representative of this variation.

Parameter	Min.	Original	Max.	Remark
Compressed Gas and Liquid Hydrogen Storage Lifetime	5	10	15	This range covers a number of values encountered in the literature.
Compressed gas transport capital cost (€/kW/km)	-40%	-	+40%	Tube trailers vary by operating pressure of the truck and storage capacity of the tube trailer and thus a large variation is considered.
Liquid hydrogen transport capital cost (€/kW/km)	-40%	-	+40%	The tank trailer varies by storage capacity of the tank trailer and the range chosen is representative of this variation.
Pipeline capital cost (€/kW/km)	-20%	-	+100%	There is a wide range of values in the literature. The value of the base case is an optimistic estimate and thus the upper range is higher than the lower.
Electricity grid transmission cost ((€/kW)	-20%	-	+20%	Variation in the cost of development and upgrading of the grid.

Table 7.1: The parameters varied in the sensitivity analysis

As it can be observed from Table 7.1, the percentage variation of the parameters is from small to large scale. There are even some parameters whose values are doubled. These wide ranges has been selected in order to demonstrate the response of the model in small, medium and large variations and how the infrastructure pattern is changed in order to ensure that for every set of input data the least-cost infrastructure development plan is selected.

All outputs are related to the base case that consists of the infrastructure that includes 296 fuel chains and costs 11.2 billion pounds corresponding to the central estimate data (full list in Appendix A). The pattern of the base case infrastructure is depicted in Figure 7.3. Figure 7.3 shows the five periods of the infrastructure development and the number and type of fuel chains in every period. The selected fuel chain options and primary energy feedstocks are represented by the corresponding code numbers and icons of Figure 7.1. Any pattern produced from the parametric variation that greatly differs from the base case is depicted in the same diagram type for ease of comparison.

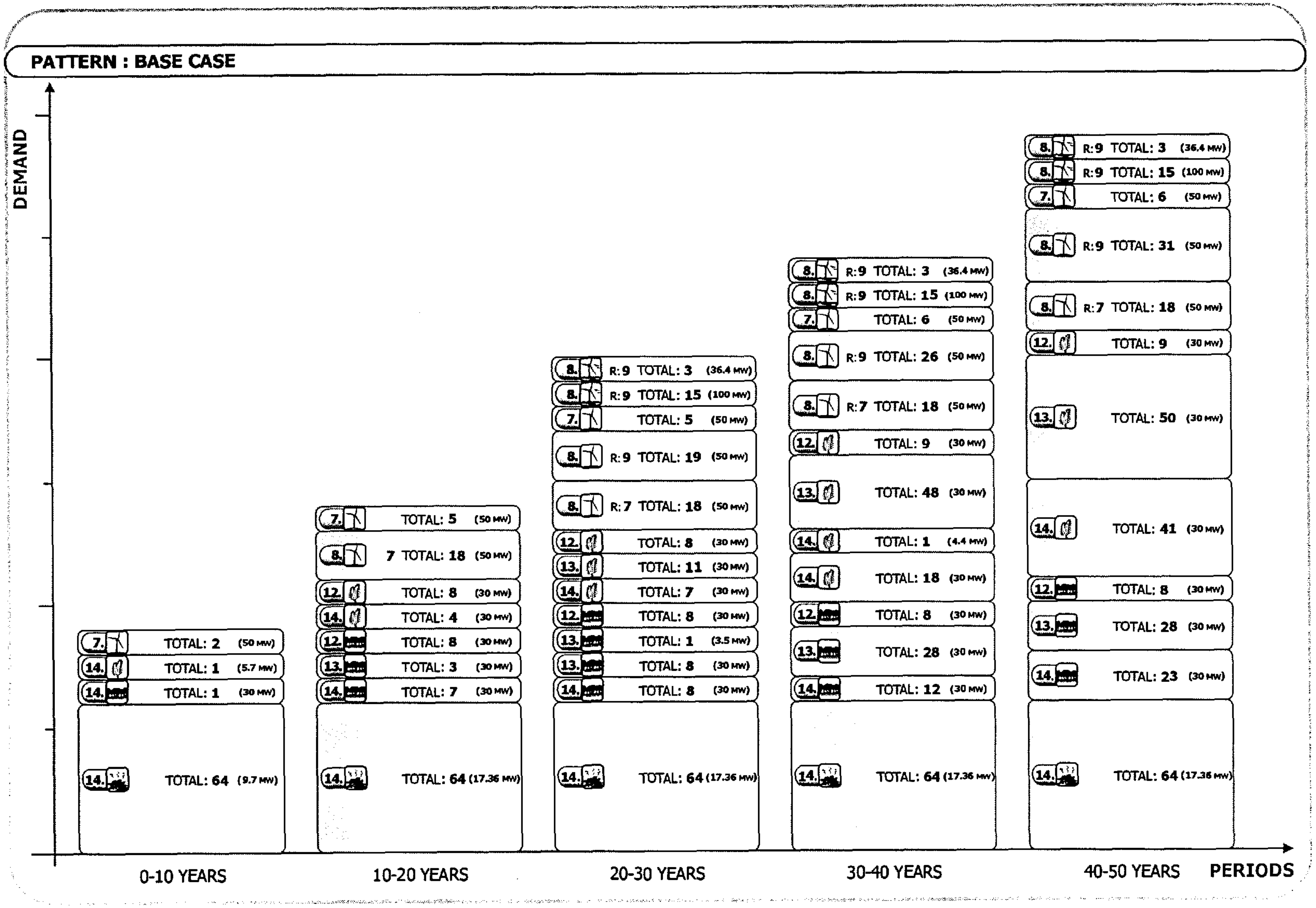

Figure 7.3: The base case infrastructure development plan

Figure 7.4 shows the sensitivity of the infrastructure cost to a range of parameter variations. The results that rise from left to right have a positive correlation to a change in input values. The others have a similar negative correlation. The former category includes capital and O&M cost parameters and the latter the efficiency, capacity factor, lifetime and maximum plant capacity parameters. The model has been sufficiently sensitive to allow variation of all parameters a result that indicates that the problem under study has been modelled in a satisfactory manner. It should be mentioned that the scales in Figure 7.4 are the same, to allow comparison of the gradients of the lines.

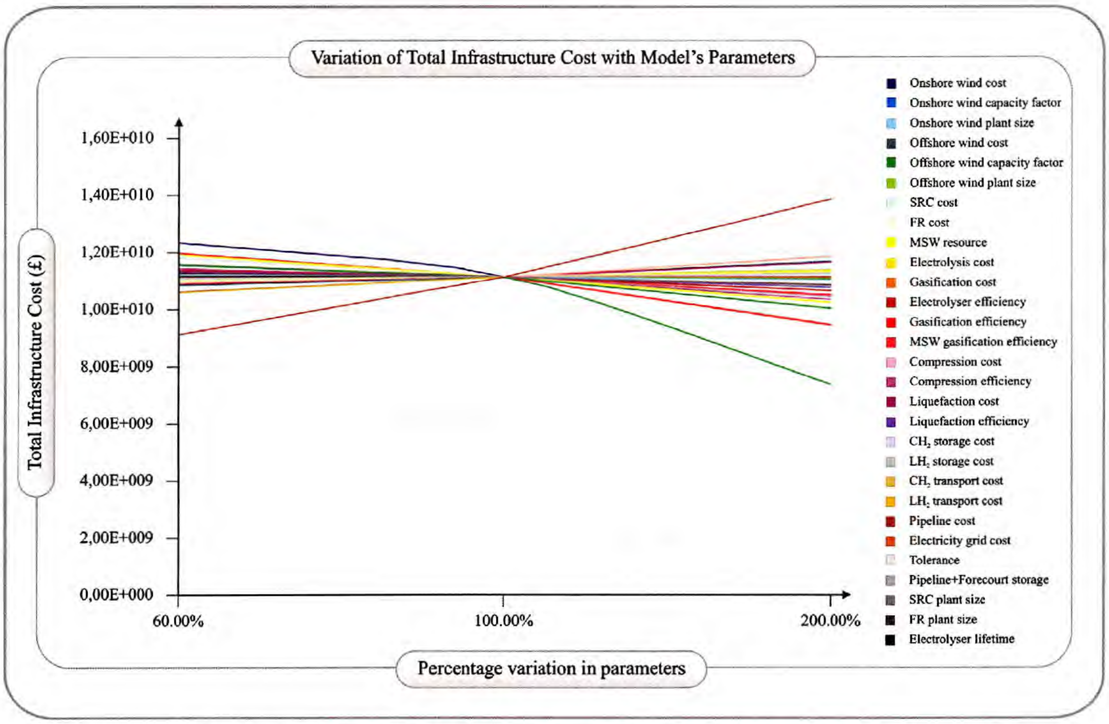

Figure 7.4: The sensitivity of the total infrastructure cost to parameter changes (1)

Figure 7.4 includes all the parameters of Table 7.1. As it can be witnessed some lines have a steeper gradient than others. As the number of parameters in the Figure is fairly large and the variation of parameters that produce a moderate change may not be obvious a second graph has been produced that zooms into Figure 7.4. Both figures present the results in a spline line chart. This kind of chart joins the data points by smooth spline curves instead of straight lines. Generally, splines are preferred over straight lines as most of the phenomena in nature follow spline lines.

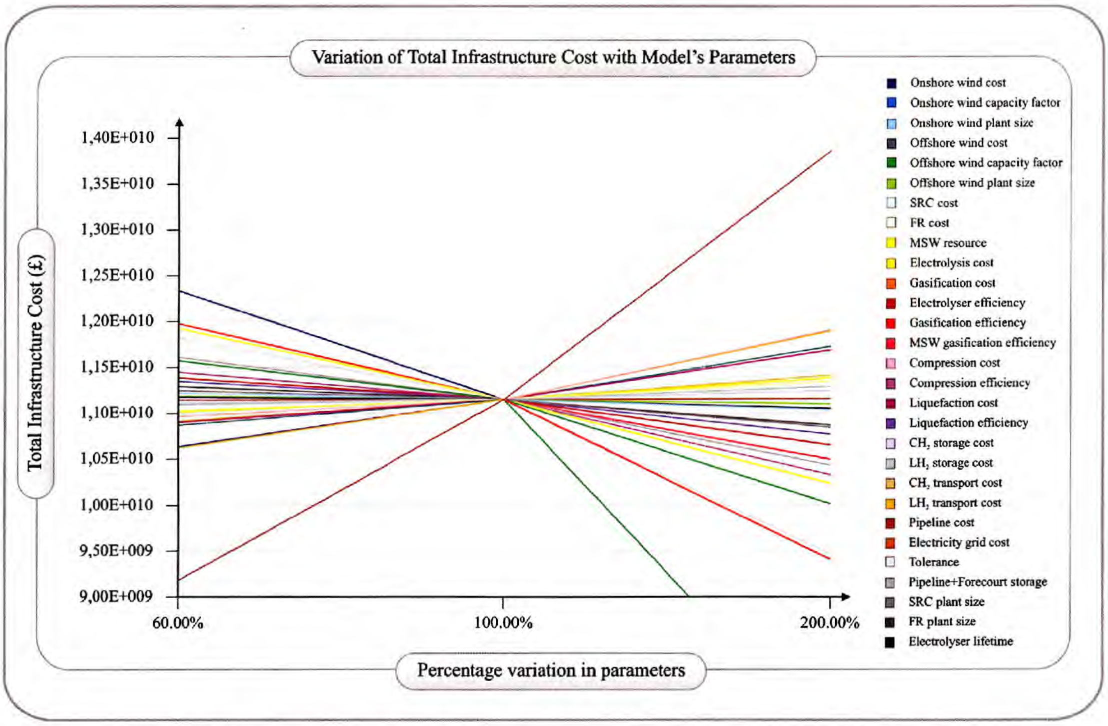

Figure 7.5: The sensitivity of the total infrastructure cost to parameter changes (2)

It may be concluded from the above charts that the overall infrastructure cost and the selected pattern are affected by numerous factors. The factors that cause greater variation in the overall cost are the lines in Figure 7.4 that have the steeper gradients. However, there are lines that correspond to moderate gradients but cause significant variations in the final results. This conclusion is not directly obvious in the graph because the graph presents only the overall cost but it becomes evident when the selected infrastructure pattern is taking into account. More specifically, there are some parameters that their variation produces an increase to the total cost but does not change the selected pattern, while there are others that their increase produces a change in the pattern and thus the cost does not increase significantly. For the latter parameters, if the model would have selected the original pattern the cost would have been greatly varied but because the model for every set of parameters selects the least-cost pattern it does not select the original pattern but a new one with a cost closer to the base case cost and thus the change in the cost appears smaller. This is the reason why in this analysis both changes in the cost and the pattern are discussed as they are closely interwoven.

One of the parameters that significantly change the results is the pipeline capital cost. The reason for this influence is twofold. The first reason concerns the wide range of values that has been encountered in the literature for the capital cost of the pipeline. The value that has been selected for the base case is a fairly optimistic estimate and thus in order to incorporate a representative range in the analysis a significantly high upper range value has been selected. So, the variation of the pipeline cost has been one of the largest.

Secondly, the fuel chain option that includes pipeline delivery has one advantage over the other options than contain other delivery methods. This advantage is the lack of storage at the production site and the refuelling station. This option is the only fuel chain configuration that does not include a storage stage as it has been considered that the pipeline acts as storage and so no onsite and forecourt tank storage are necessary. This exclusion entails the elimination of the capital and O&M storage costs and also of the hydrogen energy losses relative to the storage step. Hydrogen energy is transferred from the point of production to the point of use through each step of the fuel chain. In every step, as the efficiencies of the technologies are less than 1 an amount of hydrogen energy, either small or large depending on the efficiency of the technology, is lost. In the pipeline fuel chain option, the losses are considerably reduced both due to the high efficiency of the pipeline and to the exclusion of storage at two points in the fuel chain. This makes this option quite attractive and as the base case results show is has been selected a considerable number of times. Therefore, as a fuel chain option that has been greatly selected variations of the parameters of this option affects the overall result to a great extent than parameters of fuel chain options that have not been selected at all or only a few times.

This is evident from the results of the pipeline capital cost variation. Reducing the cost of the pipeline brings down the cost from 11.2 billion pounds to around 10.2 billion pounds. This significant cost reduction is not accompanied by a significant change in the pattern. The pattern is similar to the base case with the only changes that the capacities of a few pipeline fuel chains have been increased and the overall number of pipeline pathway options has been increased by a small amount. This minor change in the pattern is reasonable considering that the pipeline fuel chain option is a pathway that has already been greatly selected in the base case. The large number of this option included in the pattern is the reason why the variation of this parameter resulted in a significant infrastructure cost reduction.

Increasing the cost of the pipeline produces more interesting results firstly because this pathway is at a great extent included in the base case and secondly because this variation is larger. In this case the cost of the pipeline has been considerably larger than in the base case. The results show that this variation changes significantly both the cost and the infrastructure pattern. The latter is depicted in Figure 7.6.

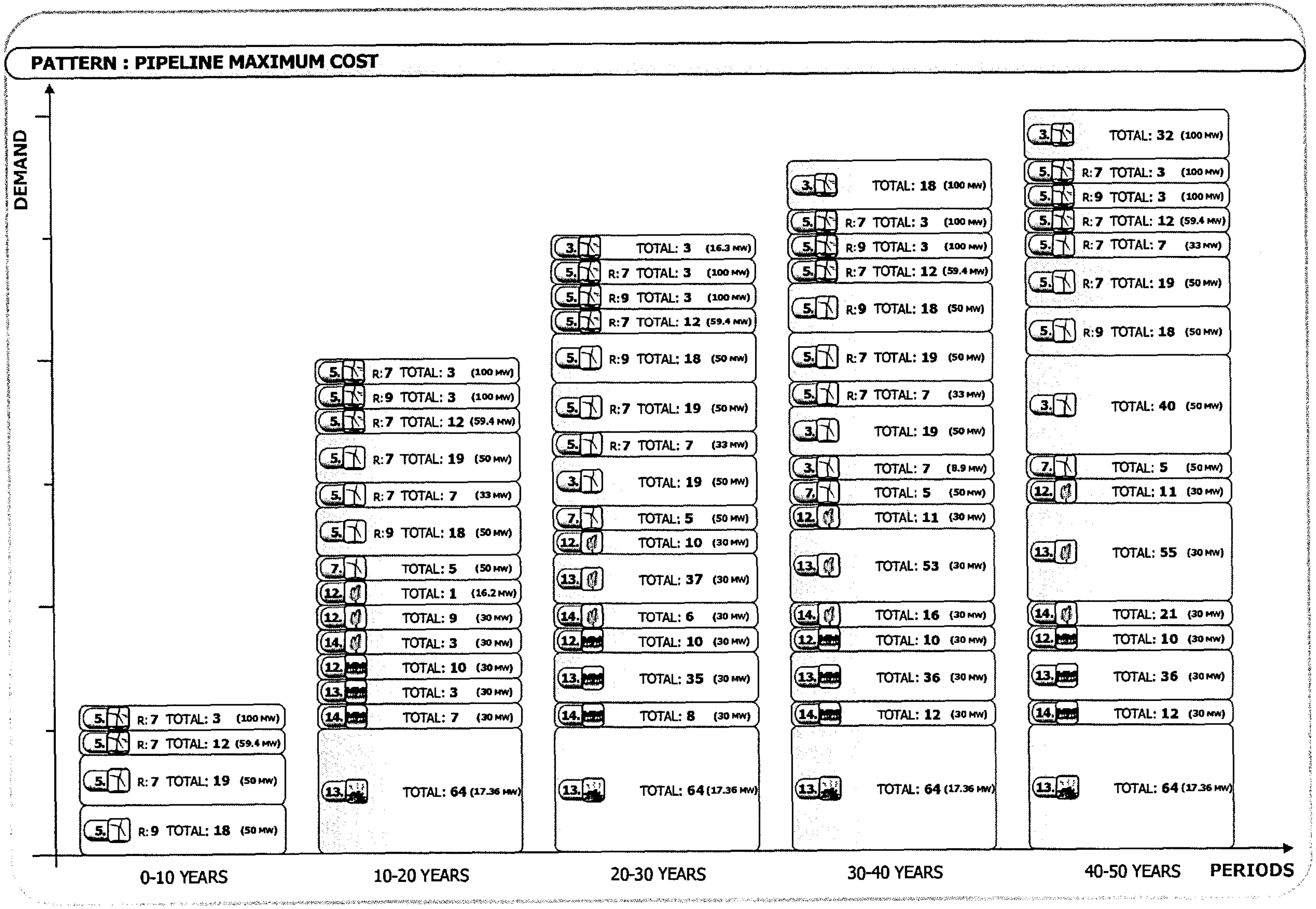

Figure 7.6: Infrastructure pattern for pipeline capital cost variation (maximum value)

The total infrastructure cost for this pattern is around 13.9 billion pounds. This delivery network consists of 368 fuel chains. As it can be seen from the diagram the pattern contains the same types of renewable energy sources but includes differences in the selected chain options. In this pattern, wind energy is selected more times than in the base case. Specifically, throughout the time horizon 108 onshore wind energy chains and 47 offshore wind energy chains are selected. The pipeline delivery of the base case has been substituted by liquid hydrogen delivery. The chains, though, start from the same demand zones, zones 9 and 7. Fuel chains of option 7 are the only wind energy chains that include pipeline delivery. This may be explained as the starting points of these chains are close to the demand centre, whereas the chains that contain liquid hydrogen delivery in this pattern start from the northern part of GB. So, for long distances liquid hydrogen has been preferred over pipelines but for short distances still pipelines are favoured.

Another noteworthy point that can be seen in Figure 7.6 is the inclusion of forecourt electrolysis chain options. Option 3 fuel chains have been selected both for onshore and offshore wind energy and in particular from these primary energy feedstocks this option has been selected more times than the other options. The selection between onsite, regional and forecourt electrolysis apart from the difference in the capital cost is also determined by the cost of transportation technologies. Due to the resource optimisation the model tries to activate fuel chains in the best possible locations for the production of the primary energy feedstock from renewable energy sources. When the resource optimisation determines these locations based on the renewable resource afterwards the fuel chain optimisation determines the suitable locations taking into account all the parameters of each fuel chain. In the case of electrolysis, when the wind farm location is selected a comparison between the transportation technologies is taken place. If the transportation of hydrogen is cheaper than the transmission of electricity then onsite electrolysis is the preferred option. If the transmission of electricity is cheaper than hydrogen transportation then the selected option will be between forecourt and regional electrolysis. The former option includes a high capital cost and no hydrogen transportation while the latter option includes a lower capital cost but hydrogen has to be transported from the electrolysis plant to the market. In the base case the high capital cost of forecourt electrolysis made the regional electrolysis option more cost-effective. However, this is true for demand zones 9 and 7 that have been selected. In the pattern of Figure 7.6, the large increase in the cost of pipeline has reversed the situation and thus forecourt electrolysis for some locations is now the preferred option.

Generally, for wind farms that are relatively close to the market the cost of electrolysis plays a major role in the selection decision as the proportion of transportation costs are minimized because the delivery distance is not very large. In this case, onsite electrolysis becomes again a competitive option. Then the comparison is between onsite and regional as forecourt has been excluded due to the considerably higher capital cost. For wind farm locations closer to the market than the predetermined location of the regional electrolysis plant, onsite electrolysis chains are preferred. For this reason, in this pattern onsite electrolysis chains have been selected, however only 5 times. This number is small because of the resource distribution of the onshore wind energy resource in the GB. For example, if the market was Edinburgh that is situated in an area of strong wind resource the pattern would have not been the same. These results also show the importance of resource optimisation in producing an infrastructure development plan and the correct implementation of such an optimisation by the developed model.

The difference in the cost of pipeline delivery also affects the biomass routes. The number of chains that used pipeline delivery in the base case has decreased both for SRC and forestry residues chains. Moreover, hydrogen produced from MSW instead of being transported by pipelines in this pattern is transported as liquid hydrogen. According to the pipeline cost variation results, it may be concluded that the large variation of one parameter that greatly affects the results, such as the pipeline cost, evoked a good response of the model.

Generally, the variation of a component's parameter that is a higher proportion of the fuel chain cost is considerable. The sensitivity of costs to the cost of each component increases with decreasing number of components. Therefore, a variation in the cost of one component that may not have been included in the model is likely to have a greater impact on the fuel chains with fewer stages. Since the pipeline fuel chain option plays a significant role in the base case infrastructure pattern the model was run for a simulation that includes forecourt compressed gas storage stage in the pipeline fuel chain option in order to examine the effect on the results. The cost of the pipeline in this simulation is the base case cost. The infrastructure pattern for this simulation is illustrated in Figure 7.7.

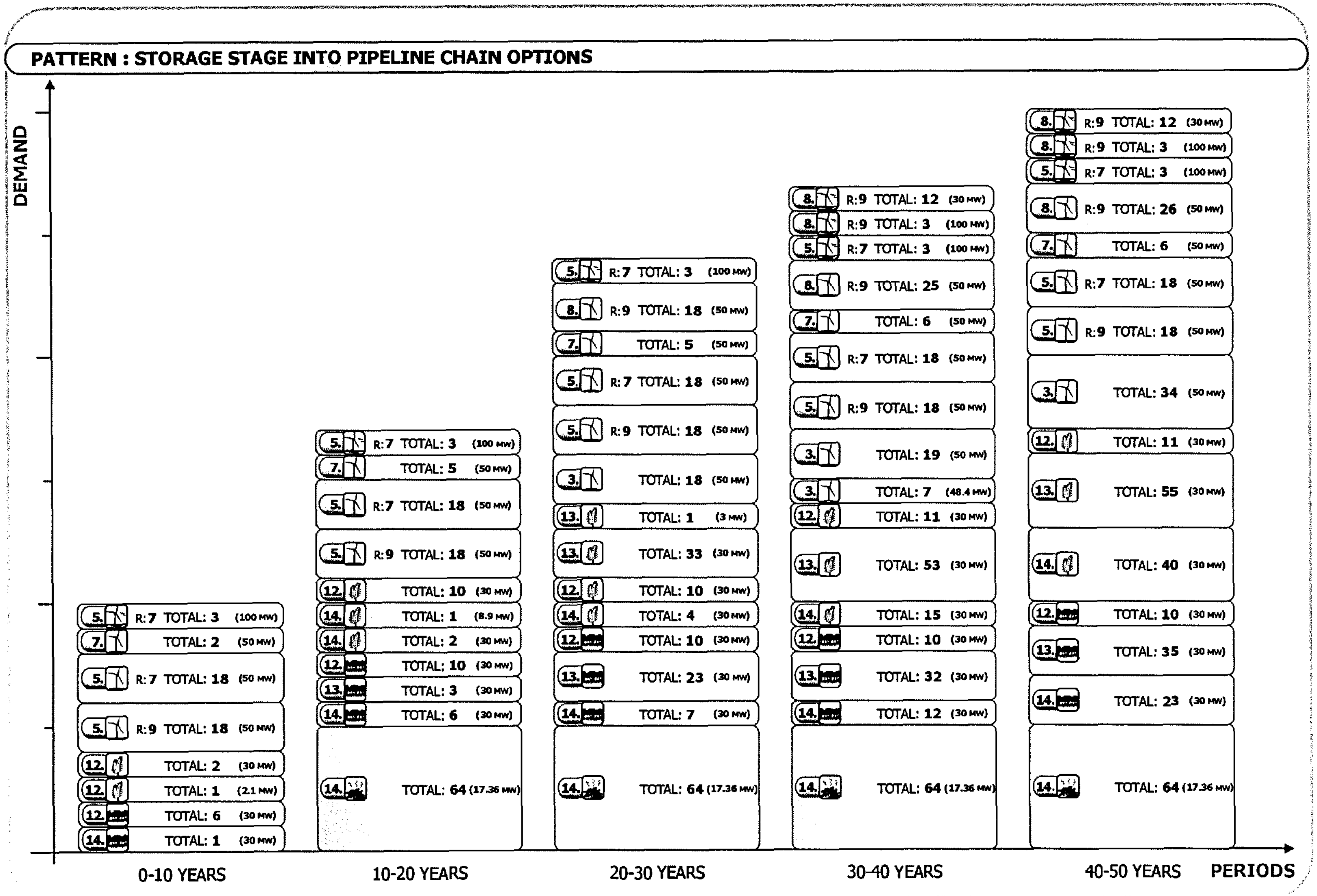

Figure 7.7: Infrastructure pattern for inclusion of storage stage in the pipeline fuel chain options

This hydrogen network costs around 12.9 billion pounds and includes the formation of 358 fuel chains. This pattern may be described as in between the base case and the pattern of Figure7.6. One of the differences from the base case is that wind energy chains that include liquid hydrogen delivery and forecourt electrolysis chains have been selected. On the other hand, the difference from the pattern of Figure7.6 is that pipeline delivery options have also been activated not only for onsite electrolysis. This shows that liquid hydrogen and pipeline delivery are the candidate options for transportation over medium to long distances. Compressed gas delivery is almost always selected for shorter distances.

From this simulation it may be concluded that pipeline fuel chain options even when the advantage of the elimination of storage stage is removed are still preferred in certain cases. The inclusion of storage stage has reduced the difference in cost between liquid hydrogen and pipeline delivery options and this is evident by the fact that the pattern of Figure 7.7 does not include one option a large number of times but both options in a relatively similar frequency.

Similar behaviour has been recorded for the variation of the liquid hydrogen and compressed gas transport cost parameters. More specifically, in each case the model decreases or increases, depending on the variation, the number of chains that include the corresponding transport technology. Figure 7.8 and Figure 7.9 show the influence of increasing the cost of compressed gas transport and liquid hydrogen transport respectively on the infrastructure pattern.

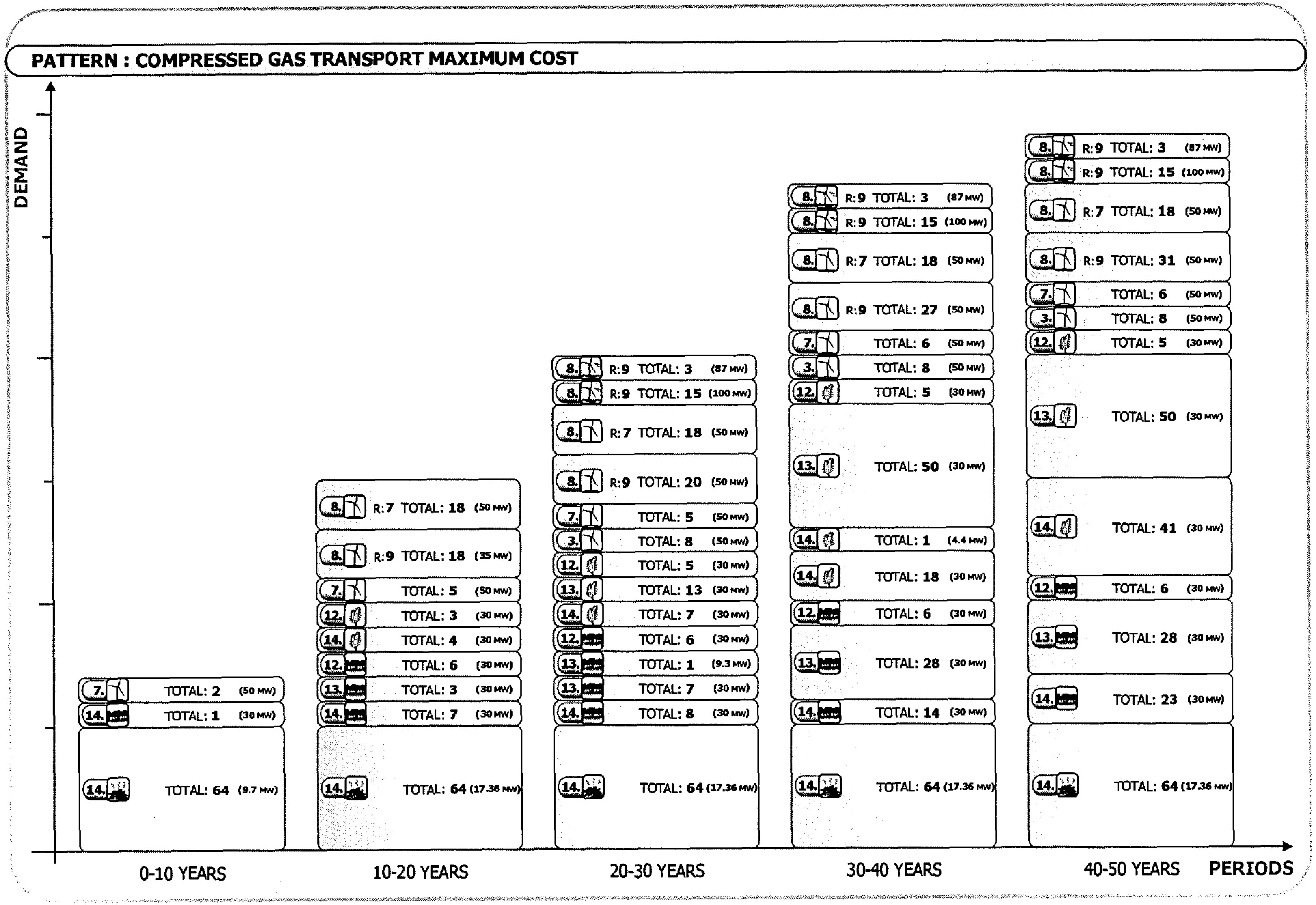

Figure 7.8: Infrastructure pattern for compressed gas transport capital cost variation (maximum value)

The cost of the development plan of Figure 7.8 is 96.2 million pounds more expensive than the base case. It can be seen in the above diagram that the chain options that include compressed gas transport have been decreased in relation with the base case. Moreover, in both the above and below diagram the response of the model to significant changes in the transport method costs can be observed. When the hydrogen transportation costs are changing forecourt electrolysis becomes competitive as the total fuel chain cost of this option stays the same due to the lack of hydrogen transport stage but the cost of regional and onsite options increases as they include the parameter of hydrogen transportation that has been increased. Thus, the difference in the costs of these options is getting smaller and for some locations the transportation cost overcomes the high cost of forecourt electrolysis and thus the latter option is selected. This is the case for the 8 option 3 chains that have been selected as it can be seen in Figure7.8.

Similar behaviour can be observed in Figure 7.9. In this case the cost difference with the base case is around 301 million pounds. The reason why this cost difference is greater than the compressed gas transport cost variation is that the base case pattern consists of considerably more fuel chains of the liquid hydrogen transport option. As it can be seen from the following diagram liquid hydrogen transport fuel chain options have been reduced and 18 option 3 fuel chains have been activated.

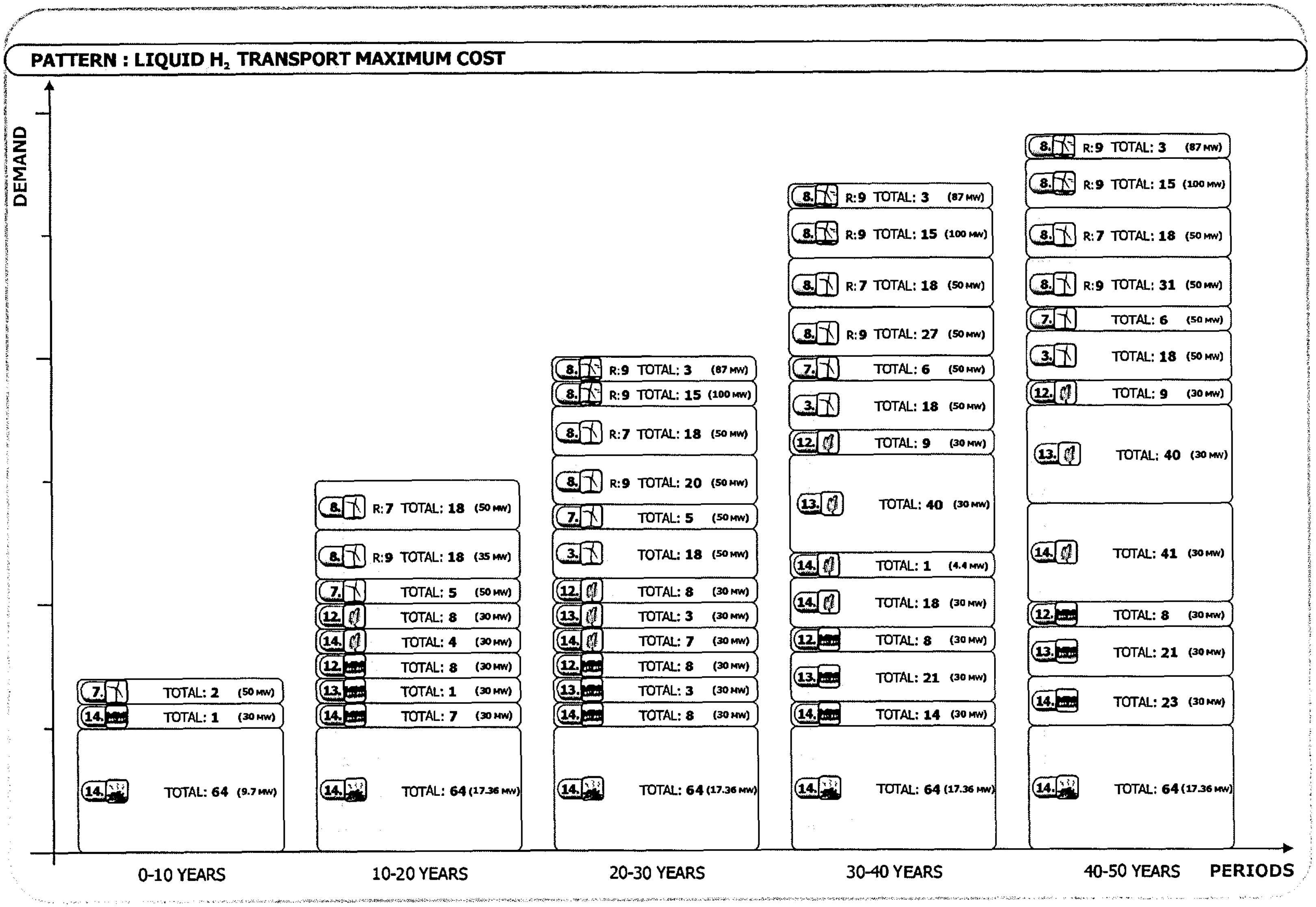

Figure 7.9: Infrastructure pattern for liquid hydrogen transport capital cost variation (maximum value)

In both cases the selected forecourt electrolysis chains are option 3 chains that include hydrogen as a compressed gas. This shows that for forecourt electrolysis the compressed gas conversion and storage has been preferred over liquid hydrogen conversion and storage. The liquid hydrogen forecourt electrolysis option has a cheaper forecourt storage cost and a more expensive conversion technology cost than the compressed gas forecourt electrolysis option. The selected patterns show that lower forecourt storage cost of liquid hydrogen has been outweighed by the significantly lower forecourt conversion technology of compressed gas. This is reasonable considering that the cost difference of these two forms of hydrogen is considerable larger in the case of conversion than storage technologies.

The reduction of the liquid hydrogen and compressed gas transport costs produce infrastructure patterns similar to the base case. However, these patterns result in considerable reductions in the overall infrastructure cost. The largest reduction has been the variation of the liquid hydrogen transport parameter for the same reason described above the largest increase has occurred. The total cost of the hydrogen network is 10.6 billion pounds for the liquid transport cost variation and 10.9 billion pounds (24 million pounds reduction) for the compressed gas transport cost variation.

Another parameter that affects the results both in terms of the overall cost and the selected pattern is the liquefaction cost. More specifically, increasing the value of the liquefaction cost entails changes in the overall infrastructure cost without considerable changes in the pattern, while decreasing this value leads to variation in the cost and the selected pattern. In the former case, the infrastructure costs approximately 11.36 billion pounds and has reduced the number of SRC and forestry residues fuel chain options that include liquid hydrogen. The reason for reducing only SRC and forestry residues options is that they are the only fuel chain options that include liquid hydrogen. In the latter case, the cost is reduced to around 10.9 billion pounds (24.66 million pounds reduction). This variation has made liquid hydrogen fuel chain options more attractive than in the base case and this is obvious from the pattern of Figure 7.10.

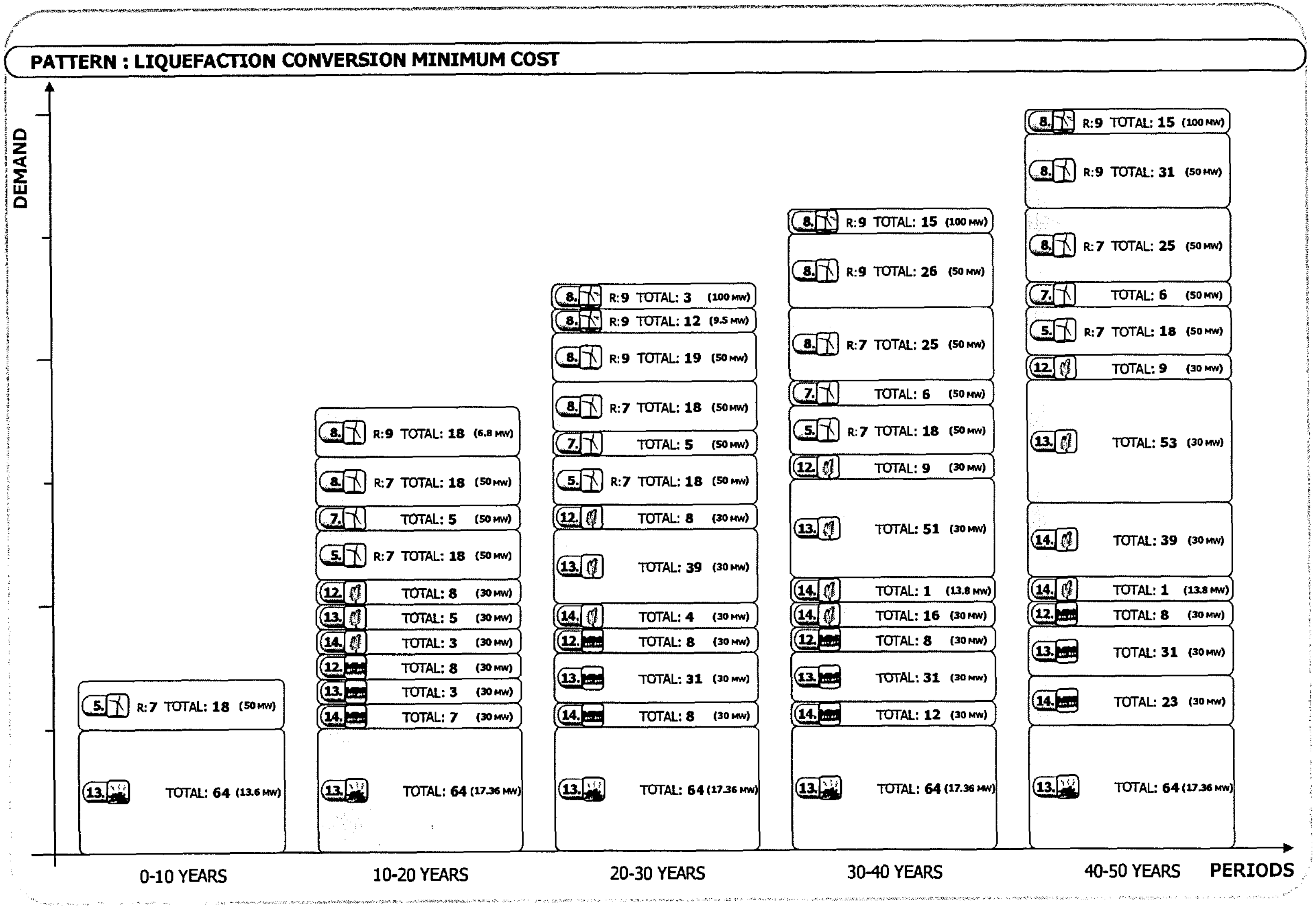

Figure 7.10: Infrastructure pattern for liquefaction conversion capital cost variation (minimum value)

There are three main differences in the pattern of the above diagram in relation to the base case. Firstly, the MSW fuel chains activated in this pattern consists of fuel chains of option 13 instead of option 14 of the base case. Secondly, the onshore wind energy fuel chains that include regional electrolysis in demand zone 7 deliver the produced fuel both in liquid form and in compressed gas form through pipelines while in the base case only pipeline delivery has been selected. Lastly, the number of fuel chains that include liquid hydrogen is greater than that of the base case.

As it can be seen in Figure 7.4 the increase in the efficiencies of the technologies result in a reduction in the overall cost and vice versa. Generally, the changes in the efficiency values as their range of variation is relatively small produce a change in the total infrastructure cost but do not change the pattern largely. From the variation of the efficiency figures, the larger change in the pattern, which comparing it with other parametric variations is a small change, is produced from the increase of the onshore wind energy capacity factor. The pattern of this variation is depicted in Figure 7.11.

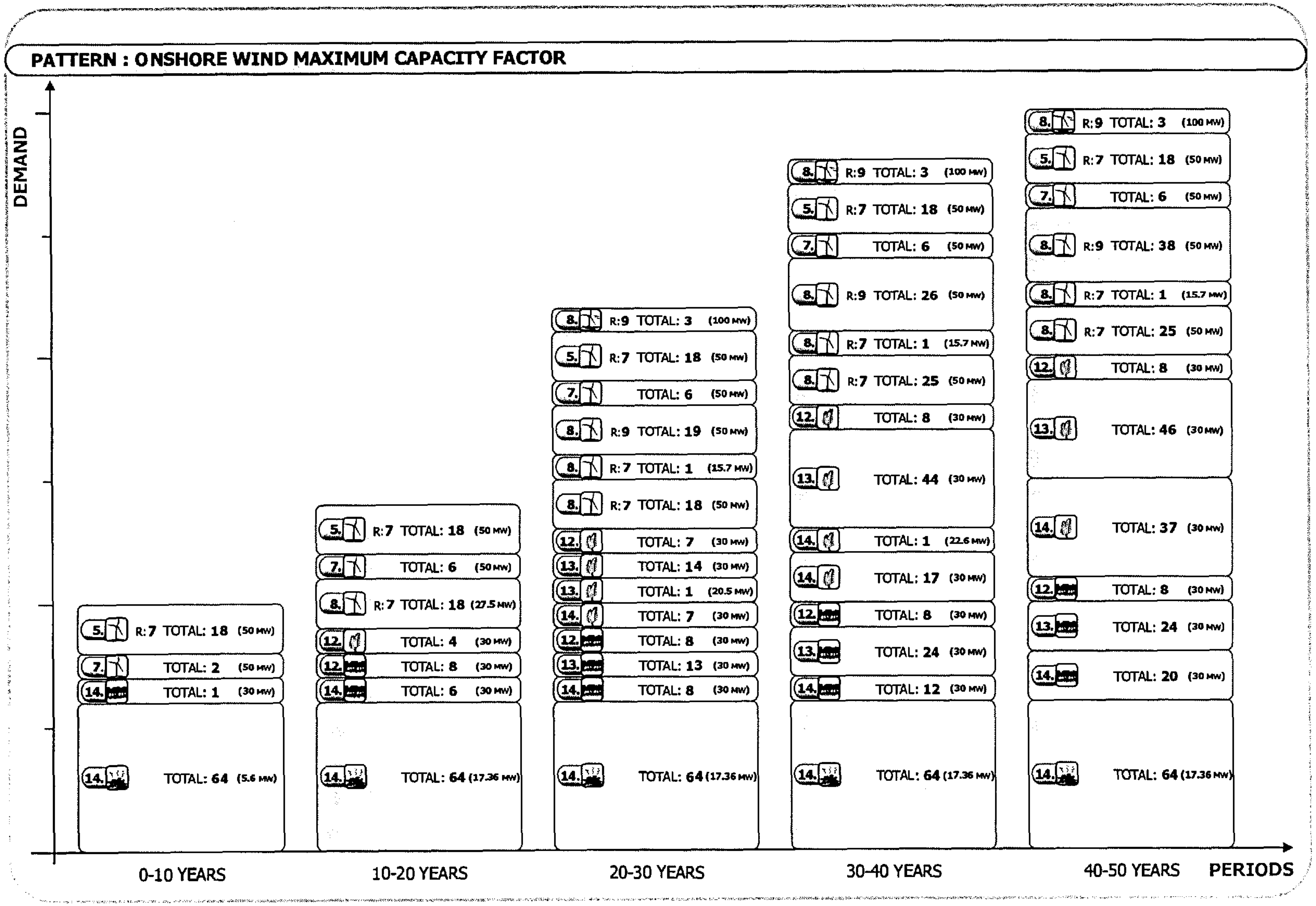

Figure 7.11: Infrastructure pattern for onshore wind energy capacity factor variation (maximum value)

The pattern of the above diagram includes considerably more onshore wind energy chains. The advantage of offshore over onshore wind energy has been minimized as the difference in their corresponding capacity factors has been reduced. The improved capacity factor in conjunction with the lower than offshore costs led to the activation of 35 more onshore wind energy chains and deactivation of 15 offshore wind energy chains than in the base case. The cost of this pattern is lower than the base case and equal to 10.7 billion pounds.

Generally, onshore wind energy is a renewable energy source that has been selected a substantial number of times. For this reason the parametric variation of onshore wind parameters affects considerably the results. This variation affects the overall cost and also produces a number of changes in the pattern. Increasing the capital cost of onshore wind energy evokes the reduction in the overall number of selected onshore wind chains. This is evident in Figure 7.12.

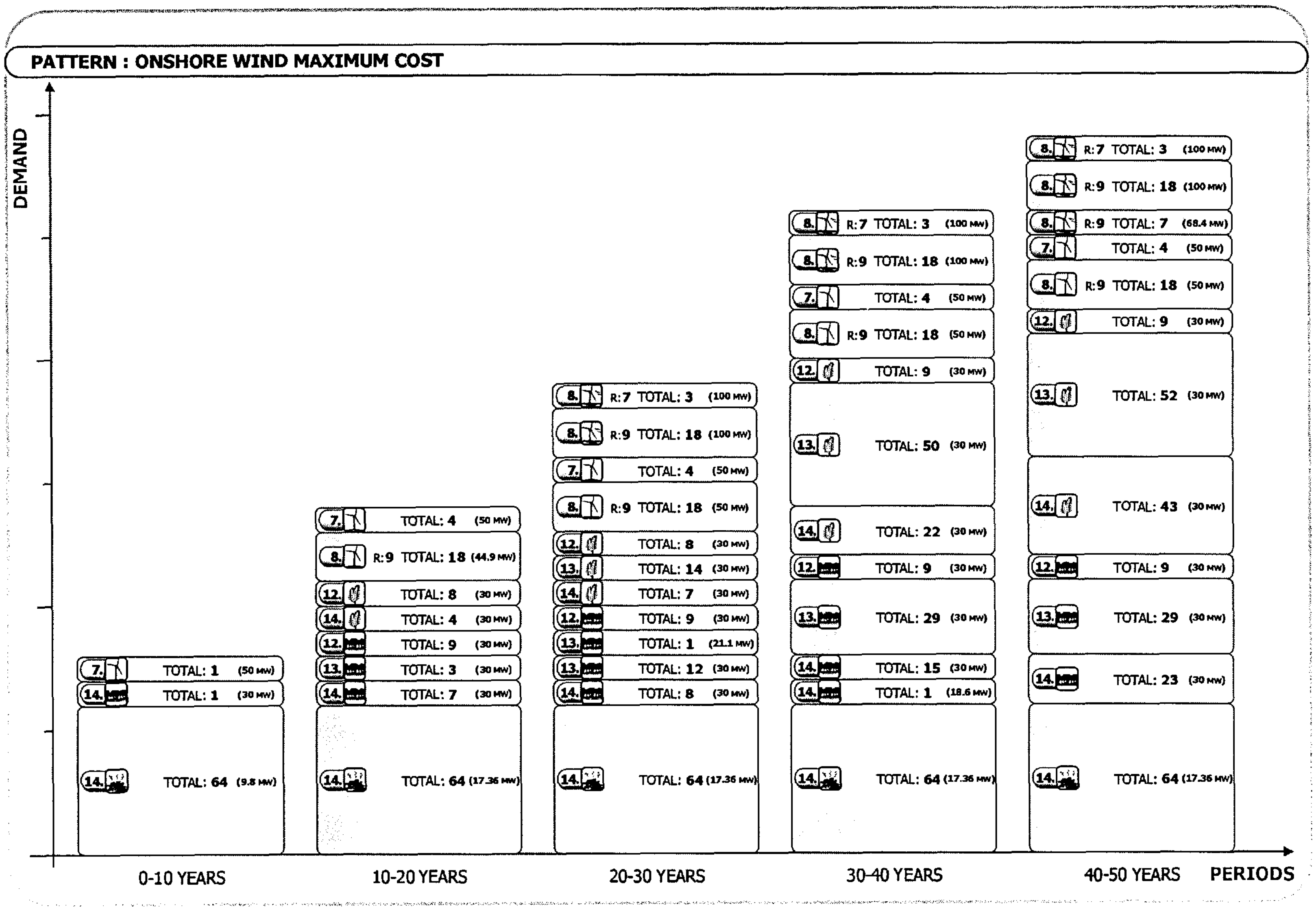

Figure 7.12: Infrastructure pattern for onshore wind energy capital cost variation (maximum value)

The overall infrastructure cost for this pattern is about 11.3 billion pounds. The decrease of onshore wind chains has been accompanied by an increase in offshore wind fuel chains and in forestry residues and SRC fuel chains. This shows that the model has responded well to the new set of data and has delivered the least-cost pattern under the new circumstances.

Conversely, decreasing the capital cost of onshore wind energy produces a hydrogen network of lower cost with a large number of onshore wind energy chains. This variation has brought the overall cost down to 10.7 billion pounds. This cost is similar to the infrastructure cost of the onshore wind energy capacity factor variation but the latter is larger by 10.6 million pounds. The pattern that corresponds to the onshore wind capital cost variation is depicted in Figure 7.13.

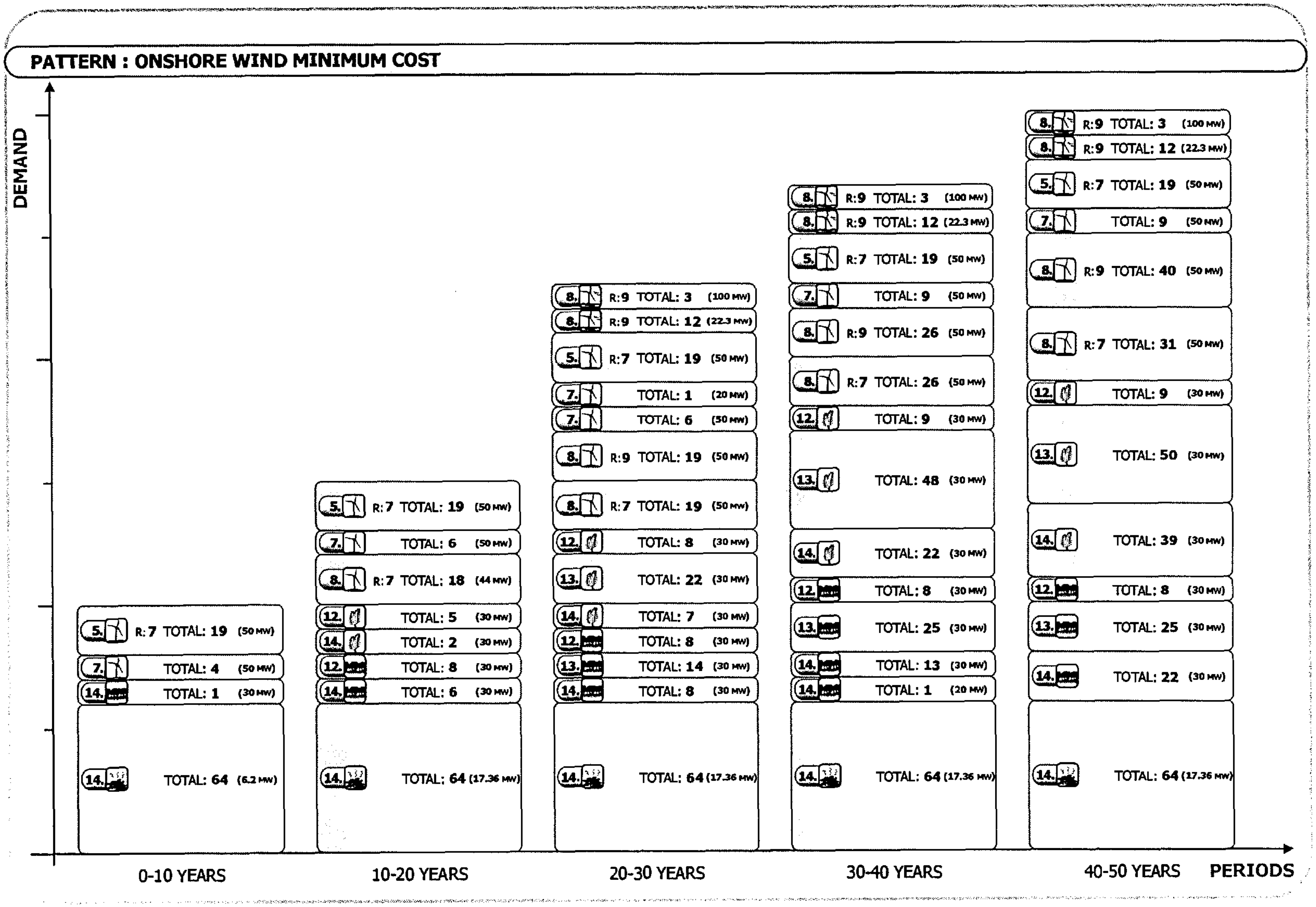

Figure 7.13: Infrastructure pattern for onshore wind energy capital cost variation (minimum value)

Variations in the cost of biomass feedstocks also affect the overall cost as like onshore wind energy biomass is a renewable energy source that has been selected a substantial number of times. However, due to the small range of variation and the fact that biomass routes are regarded as relatively cheap renewable hydrogen delivery pathways and thus for a small variation have still been considerably selected the change in the results is not drastic, especially in the pattern. For example, the increase in SRC cost produces and increase of 67.7 million pounds, while the decrease a 73.1 million pounds reduction. For forestry residues these figures are 54.2 million pounds and 60.4 million pounds, respectively. SRC chains result in larger variations due to the larger number of times that have been selected in all the produced patterns. Generally, for lower biomass feedstock costs the overall cost is reduced and the number of selected biomass fuel chains is raised. Alternatively, the cost is increased and the number of selected biomass chains is moderately reduced.

In the case of MSW, variation in the cost has not been possible since it has been considered that this primary energy feedstock based on the existing policy in London and taking into account that their exploitation may assist in the landfill sites exhaustion problem is free of charge. However, an interesting change in the results is produced by varying the available resource. As it has been mentioned in Chapter 6, the simulation considers only that the available MSW resource for hydrogen production is the amount of MSW that is produced in London.

By observing all the aforementioned pattern diagrams it may be concluded that MSW chain option 13 and 14 are the only options that have been activated 64 times, which is the maximum number of times a fuel chain option can be selected for the chosen map segmentation. This may be interpreted as an indication of the low cost of this delivery option. If the resource would have been larger then the model would have selected more options with MSW as a primary energy feedstock. The reason for choosing 64 chains is that the amount of MSW produced in London annually provides sufficient energy for 64 chains of around 17.36MW capacity each maximum. The verification of this conclusion can be seen in Figure 7.14

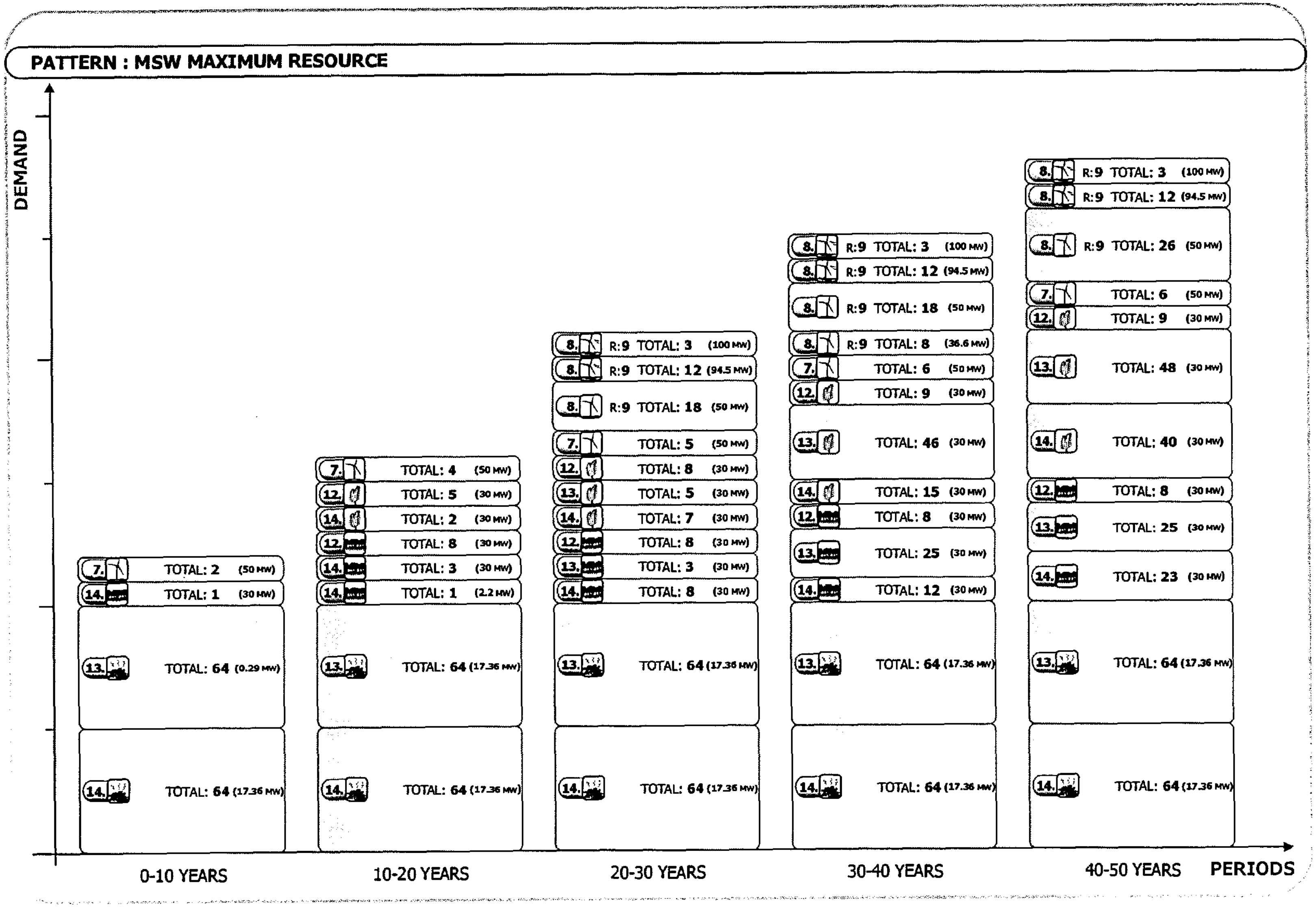

Figure 7.14: Infrastructure pattern for MSW resource variation (maximum value)

The pattern of the above diagram corresponds to a simulation that includes twice the MSW resource of the base case. As it can be witnessed, more MSW fuel chains have been selected. More specifically, the number of MSW chains is double than that of the base case. Like in the base case, the number of selected MSW chains is the maximum number a fuel chain option can be selected. Considering that the primary energy feedstock is free of charge and the transportation distance between the production point and the refuelling station is small it is comprehensible why the MSW route has been activated to such a large extent. From these two factors the latter influences the MSW fuel chain to a greater extent than the former. In particular, if the price of the primary energy feedstock was non-zero and the distance between the gasification plant and the market was small, still MSW routes would have been selected to a large extent but if the delivery distance was significantly large then MSW chains would have been selected to a moderate extent.

The cost of developing the infrastructure showed in Figure 7.14 is around 10.2 billion pounds, approximately 9.17 million pounds more economical than the base case. Conversely, decreasing the MSW resource leads to an overall cost of around 11.9 billion pounds. For the latter variation the change in the pattern does not include changes in the type of options only small changes in number of times the biomass routes have been selected.

Generally, the analysis has showed that the model has responded well to parametric variations and has demonstrated how these changes affect the overall infrastructure cost and the selected pattern. It is worthwhile to mention that varying the parameters has produced various patterns but there have been two renewable energy sources that have been always excluded from the resulted patterns. These are solar energy and hydro energy. The reason for this exclusion is the characteristics of each one.

More specifically, hydro energy has two features that caused its exclusion. Both features stem from the fact that only small-scale hydro has been considered as only this scale has a remaining available resource in GB. The first impact of this restriction is the considerably small plant capacity. The sites available for small-scale hydro installation are sites with potential output in the range of 0.025-5MW.

Moreover, small-scale hydro is significantly more expensive than large scale. So, the model if it is necessary to deliver at a particular point in the time horizon up to 5MW there are a lot more options that may provide this amount with lower cost. However, hydro energy has a high capacity factor but as the results showed this advantage was not enough to overcome its weaknesses.

Solar energy in terms of maximum plant capacity is better than small-scale hydro energy but its efficiency and cost are the determining factors that cause its exclusion. The range of variation with values that have been encountered in the literature did not change this situation. Generally, solar energy may be selected as a primary energy feedstock if the cost of the electricity-generating technology drops significantly and technical improvements are achieved. This is more likely to happen in the next five to ten years provided that the PV market will continue to grow.

7.4 Policy Considerations

As it has been seen from the modelling results the development of a new fuel infrastructure is a complex and large capital investment venture. Generally, the transition to new transport fuels is especially problematic because of the diffuse nature of the transport system. In the case of hydrogen fuel, in particular, this transition becomes more challenging as hydrogen has a few private benefits compared to petroleum-based fuels. The use of hydrogen fuel will benefit the society as a whole in the long term but it will not offer to its consumers immediate returns in order to offset the higher purchase cost. Therefore, the introduction of hydrogen fuel and its widespread use are almost impossible without drastically different market conditions and new policies.

Policy support is even more necessary in the case of the development of an infrastructure that delivers hydrogen that is produced exclusively from renewable energy sources. Although some renewable energy technologies are technically mature and widely used the cost of generating hydrogen from green electricity is still higher than that from fossil-based electricity.

The model of the present study is a tool that may be used in order to produce a least-cost infrastructure development plan under a large number of different conditions. However, the determination of the way the infrastructure may be developed is one factor that is necessary for the implementation of this task but it should be accompanied by policy intervention that using the model's results may identify the requirements and thus the necessary actions in order to achieve the successful implementation of this task. Metaphorically, the model can be seen as the driver of the car that may drive down the road from petroleum-based fuels to renewable hydrogen fuel and the policy intervention as the fuel that has to power the car. For the completion of this journey both these factors are necessary.

Of course, the car in this metaphor is the fuel cell car as the development of a hydrogen delivery system is necessary to be accompanied by the introduction of hydrogen fuel cell vehicles. This coupling, though, involves one of the obstacles that impede the use of hydrogen as a fuel. It is the classic chicken and egg problem that puts the vehicle manufacturers and the fuel suppliers in a vicious circle that each one is unwilling to make the step towards hydrogen if the other one does not make it.

Every beginning, particularly the beginning of a challenging task, is difficult but it is necessary in order to reach the end, the fulfilment of the task. The role of the Government is to assist in the beginning and get the hydrogen transport economy started.

As the use of hydrogen as a transport fuel would contribute significantly to the reduction of carbon emissions, the improvement of air quality, the reduction of noise and the increase of energy security, it should be supported by the energy, transport and environmental policy framework. In particular, the implementation of the development infrastructure plan produced from the modelling work could have a significant impact on CO_2 emissions, especially because the simulation includes the substitution of 100% of transport fuel with renewable hydrogen fuel. This substitution would reduce to zero the emissions of CO_2 produced from the transport system of London. Specifically, London emits 42 million tones of CO_2 annually. The transport sector is responsible for 20% of this, which is around 10 million tonnes and the road transport accounts for approximately 80% of carbon dioxide emissions (UITP, 2006). So, at the end of the 50-year time horizon that the infrastructure will be able to deliver fuel sufficient to meet all road transport demand in London the emissions of CO_2 from that sector in London would be zero minimizing London's CO_2 emissions by 8 million tonnes.

It should be mentioned that hydrogen produced from renewable electricity has zero emissions while hydrogen generated from biomass routes are assumed to be zero net emissions. The CO_2 emissions produced when biomass is converted to hydrogen would be absorbed during the plant growth cycle.

The amount of carbon emissions saved by using renewable hydrogen fuel in London is 8 times more than the carbon savings achieved By the Renewable Transport Fuel Obligation that will be introduced by the Government in 2008-09. According to this Obligation, fuel suppliers have to ensure that a proportion of the transport fuel comes from renewable sources (DTI, 2007a).

Considering the strict targets with regard to the reduction of greenhouse gases that the UK government has committed itself, with the most challenging one being that of a 60% reduction of CO_2 emission, with respect to 1990 emission levels by 2050, renewable hydrogen can play a major role since it is a superior alternative in terms of CO_2 emission reductions among other low carbon options. This advantage comprises a substantial argument for greater promotion of hydrogen fuel in reflection of this improved environmental performance.

London may be regarded as a vital place in the UK that may achieve the creation of a hydrogen transport system due to the political support in hydrogen and fuel cells, the wide public transport system, the level of control of public transport by the mayor, the numerous fleet vehicles, its international status and the collaboration between government, financial, institutional and academic organizations (LHP, 2004). Although it seems that London has the conditions for succeeding in the introduction of hydrogen fuel is not currently among the leading countries in hydrogen developments such as Germany, the USA and Japan. One of the reasons for this situation is that the latter countries invest strongly in hydrogen and fuel cells technologies.

Although the UK may not dedicate to hydrogen technologies the funds that other countries offer it may be maintained that hydrogen is gradually climbing the energy policy agenda. This is obvious comparing previous policy reports with current reports. Generally, the willingness to support hydrogen of the former reports is substituted with a more drastic promotional action plan in the latter reports. The action proposed for the development of hydrogen and fuel cell technologies as it is stated in the last Energy White Paper that has recently been published in May 2007 includes the launch of a demonstration programme in September 2006 that offers £15 million funding over three years (DTI, 2007a).

The Mayor of London continues supporting hydrogen and fuel cells in recognition of their potential to assist in achieving his Energy Strategy and London Plan. The London Hydrogen Partnership is the main mechanism for facilitating the development and deployment of hydrogen and fuel cell technologies. Moreover, Transport for London also supports hydrogen fuel by continuing operating hydrogen-powered buses and thus accelerating their commercialization. As part of the London Hydrogen Partnership Transport Action Plan, Transport for London will introduce 10 more buses running on hydrogen by 2010 (GLA, 2007).

Although attention and support has been given on hydrogen and fuel cell technologies there are certain challenges related to the implementation of a renewable hydrogen infrastructure. As it has been seen from the modelling results, creating a large-scale infrastructure involves the considerable exploitation of renewable resource. The challenge is not whether GB has sufficient renewable resource to produce hydrogen fuel but how much of this resource may be available for hydrogen production. The development and exploitation of renewable resources will take time and the generation of hydrogen fuel has to compete with electricity production and heat. The opportunity of using hydrogen fuel generated from renewables in the transport sector must be examined taking into account these constraints.

The judge of the competition for the renewable resource exploitation is the Government. The latter aims to use the renewable resource in such a way so as to ensure the fulfilment of its energy policy targets. Judging by its action plans, it seems that the Government gives priority to power applications over hydrogen fuel production. The reason for this preference may be that the utilisation of renewables for power applications is associated with less technical and economical obstacles than for hydrogen fuel production. Thus, in the short-term power applications may contribute more significantly to national energy policy objectives and targets. This picture is getting worse for hydrogen considering that among the different kinds of renewable energy sources there are some resources that could not be used due to the small resource potential in the UK, like geothermal energy, and others due to the premature stage of their electricity-generating technologies, such as wave energy.

A possible way of ensuring the use of renewables for hydrogen production is by setting targets that will require the dedication of a percentage of renewable electricity to hydrogen fuel production. In the short-term this percentage may be small and as the infrastructure develops and the fuel cell vehicles increase the percentage should grow. With this method, renewable hydrogen may take part in the early stage of the infrastructure development a phase which is generally believed will be dominant from fossil fuel based hydrogen and thus ensures that non-renewable hydrogen is an interim step and not the final destination.

Another challenge that has to be overcome concerns the existence of early demand for hydrogen fuel. Generally, the cost of hydrogen improves with increase production due to economies of scale. However, even if fuel suppliers and vehicle manufacturers do coordinate the timing of infrastructure the process of hydrogen vehicles has to be competitive in order to be successfully deployed in the large numbers needed to ensure adequate fuel demand. A possible way of stimulating demand for vehicles is the introduction of hydrogen fuel in a niche market. In this case vehicles are deployed in a protected market that allows technological innovation and competition that will bring the cost down. Introducing hydrogen into a controlled setting associated with managed fleets offers also the benefit of reducing the emissions from fleet vehicles something which is not addressed in the congestion charging scheme as fleet vehicles are exempt. This becomes more promising considering that around 45,000 vehicles are exempt from the charge (GLA, 2003a). Another possible option for ensuring a demand for hydrogen vehicles is by offering subsidies or tax incentives to consumers or manufacturers for early hydrogen vehicles.

The launch of a hydrogen infrastructure is a collective action problem that requires the collaboration between different bodies. Stakeholders such as fuel suppliers, car manufacturers, government agencies, academia, should form partnerships and establish long-term technology and infrastructure development goals.

The Government is necessary to strongly support three main areas in order to facilitate the introduction of hydrogen fuel in the transport sector. Firstly, support to research and development in order to assist in the designing, developing and testing hydrogen technologies. Secondly, support to demonstrations in an attempt to stimulate the market of the new technologies. Lastly, support to commercialisation in order to succeed in getting the new technologies to the market.

As it has been seen from the modelling results the infrastructure consists of a number of different hydrogen delivery pathways. As a fuel hydrogen has a diversity of production, conversion, storage and transport methods and thus the support and promotion do not need to be committed to a single route. It is unlikely that hydrogen used for a large proportion of transport demand would be produced and delivered using one set of technologies.

Although, the funding for hydrogen and fuel cell vehicles is gradually increasing, the UK Government has to follow the examples of leading countries in the hydrogen field and increase the financial support considerably. Moreover, it may be more efficient to separate the funding for hydrogen and fuel cell technologies. A separate budget would give the opportunity to identify the political priority of hydrogen and fuel cells and the assurance to the industry that a specific fund is certainly available.

7.5 Critique of Selected Approach

In this study the issue of developing a renewable hydrogen delivery system has been addressed. The chosen way to deal with the infrastructure development problem has been the creation of a general modelling tool that can be applied and produce results under several different conditions. Naturally, like every approach it has its benefits and its drawbacks.

The comparison of the chosen approach with other methods that have been used to tackle the same problem is not particularly feasible. Given that nobody else has developed the same algorithm it is difficult to compare it. So, as the only similarity of this algorithm with others is the problem that it tries to solve comparing modelling approaches may not be totally correct. A more acceptable way of evaluating the developed algorithm is by referencing to the advantages and disadvantages it involves.

One of the noteworthy aspects of this approach is the degree of originality it includes. This fact comprises two significant elements. Firstly, it raised the difficulty of the implementation of the approach as there was not a reference or similar work that could have been a helpful guidance. Secondly, it allows the examination of the infrastructure problem from a different perspective showing possible points that are missed or not taken into account in a great extent in other approaches.

The second element becomes evident from the outcomes of the modelling work. According to the results of the model for the development of a hydrogen network for London, none fuel chain has been selected for the maximum allowable number, which has been 64. This shows that there is not a single route that is the absolute least-cost fuel chain option as a chain that is cheap in an area may be expensive in another area. This observation shows how important is the geographical optimisation as a factor in deciding which is the more economic pathway option. Geographical optimisation gave to the model the element of relativity that is undoubtedly an important feature in determining the solution of the infrastructure problem. The lack of this factor would have produced completely different results. It is important to mention that the production of a least-cost development plan is a task that includes several parameters that need to be taken into account and every resulted plan is given with respect to certain conditions.

The only route that has been selected 64 times was the waste-based fuel chain options. However, even in this case this is not an absolute conclusion as the waste fuel chain options were indeed activated the maximum number of times but under the conditions that the primary energy feedstock was free of expense and the distance from the production point to the market was very short. Changing these conditions would have produced different results.

This encompasses another strong point of the selected algorithm that is its generality. This approach provides application flexibility in examining infrastructure development options. It investigates different options and answers the question of which is the least-cost infrastructure development plan under a wide range of different conditions. These conditions may be different geographical area, market place, fuel chain options, renewable energy sources, available renewable resource, time horizon, demand figure. For example, the model may be used to produce a development plan for Paris including biomass resources or for Athens including wind energy resources.

Moreover, the model is constructed in such a way that changes in conditions do not require any change in the model. The only thing that is necessary in order to run different simulations is the production of the input XML file that includes all the input values for the parameters. This fact leads to another positive point which is the possibility of using this model without knowing MATLAB or linear programming and general any other tool that has been used to develop the model that broadens the range of possible applicants.

As it has been described in Chapter 4, the algorithm is not one single unit but consists of a number of individual parts. Having a modular model allows the substitution or change of one unit without the need to re-write or change the whole model. This construction has another important benefit concerning possible desired changes. The model can be extended without the need of changing its current form but only to incorporate the new inclusion. This is very important because it allows space for improvements without the need to start from zero so makes the addition or reduction of elements a fairly easy task.

Moreover, it is able to run small-, medium- and large-scale simulations and in a satisfactory time. This is significant because there are models that may produce valuable results when used for small-scale problems but their application is restricted only in problems of this size. The present model has been developed in such a way so as to solve even large-scale problems. Evidence of this capability is the selected case study.

The selection of LP for the mathematical formulation of the problem may be considered a successful selection as it solves large-scale problems, deliver results in a short time and produces valuable results. This is based on the fact that the modelled problem has to a large extent linear behaviour. However, for the non-linear behaviour LP may be regarded as a weakness as it can not incorporate non-linear behaviours. Generally, in nature nothing has linear behaviour but is not accidental that LP is greatly used as a method of programming. The exclusion of non-linear behaviour for the present problem that is characterised by a significantly large degree of linearity has been preferred over the omission of more important aspects. More specifically, with DP would have been quite impossible to solve the problem of the case study due to its size. Thus, considering the trade-off between LP and DP more elements are sacrificed by choosing the latter.

As it has been mentioned in Section 7.3, the produced overall infrastructure cost is not a discounted cost. The reason why the cost has not been discounted is that its inclusion increases the complexity of the model. Generally, simulations that include large number of segments and periods are complex and need more time and RAM to be solved. The simulation for London has 64 segments and 5 periods of 10 years duration, it could have also been run for 10 periods of 5 years duration or 50 periods of 1 year duration. However, for such a large-scale problem for more than 5 periods one computer was not sufficient to deliver results. The inclusion of the discounted cost would have entailed the decrease in the size of the simulation or the number of segments and periods. So, it has been considered more valuable to keep the size of the simulation to the maximum possible for one computer and exclude the discounted cost.

Another exclusion of the model may be regarded the dispensing stage and the dispersion of refuelling stations within the market place. The simulation considers the market as a point. The latter inclusion would have affected even greater the complexity of the simulation as it entails the addition of a new subsystem in the algorithm. Moreover, the focus of this study has been the delivery of hydrogen to urban centres and not the distribution of refuelling station within demand centres. However, this inclusion comprises an interesting recommendation.

Apart from the transmission of electricity that uses the electric grid, the distance that hydrogen is transported using any transportation method is calculated assuming that it is a straight line between the starting point and the end point. Naturally, this is not quite true in reality because roads and pipelines due to geophysical reasons may have not been or will not be constructed in a straight line.

Lastly, another factor that have been attempted to be incorporated into the model but it has not been achieved is the learning curve effect. The theory of learning curve is based on the concept that the cost of a technology decreases at a constant rate as cumulative production doubles. Especially, for hydrogen technologies that technical maturity has not yet been achieved the concept of the technology learning curve can be applied to estimate the capital investment requirements associated with the commercialization process of these technologies. The reason of this exclusion is based on the mathematical expression that describes this phenomenon. Learning curve is given by a power law function:

$$C_n = C_1 \, n^{-a}$$

where C_n is the cost of the nth unit of production;

C_1 is the cost of the first unit of production;

n is the cumulative cost of production; and

a is the elasticity of cost with respect to the output.

As it can be witnessed this is not a linear function and can not be incorporated in linear programming model. For this reason, it has been Taylor expanded in order to incorporate into the model only the linear part of this equation but unfortunately applying the Taylor series in the case of this function showed that there is no linear part in this equation and thus had to be excluded.

7.6 Alternative Applications of the Model

The model developed in this study allows the investigation of different fuel chain options in order to produce a cost-effective renewable hydrogen delivery system. The model has been used for the case study of London showing its performance and capabilities. The approach taken towards the renewable hydrogen network development choice and the methods used to implement the model can be used for a number of applications. This Section provides four applications that the model could be used and produced results.

7.6.1 Fossil Fuels as an Interim Step

Generally, the transport sector is characterized by a strong inertia to change. This phenomenon in conjunction with the fact that hydrogen fuel produced from renewable energy sources is not at the top of the Government's energy hierarchy justifies those who believe that at the uptake of hydrogen fuel fossil fuel will be the dominant primary energy feedstock. Apart from fossil fuels, hydrogen may be supplied in the beginning from existing refineries and chemical complexes. This beginning may bring the cost of production down and assist in the fuel and fuel cell technology market development opening the road for the truly sustainable fuel, which is renewable hydrogen.

The model is able to produce results for simulations that include non-renewable energy sources. These resources may be either fossil fuels or refineries or nuclear power or any other source that can produce hydrogen. Moreover, it may include existing facilities or assume the construction of new schemes. The inclusion of different options is not only applicable in the primary energy feedstock stage but in all fuel chain stages.

7.6.2 Renewable Energy Sources outside the UK

Like conventional fuels, renewable hydrogen may be produced from foreign resources and transported into the UK. Importing renewable hydrogen allows the UK to benefit from the large renewable resources of other countries like hydropower in Iceland or biomass in Brazil. A possible route of hydrogen supply to the UK will be the transmission of solar energy-derived hydrogen in North Africa by gas pipelines across the Mediterranean Sea, all through Europe and north into the UK. Another possibility will be the transportation of liquid hydrogen, that would be produced by hydro power in Canada, by ocean tanker (H2, 2004).

Simulations that include the production of hydrogen from renewable energy sources outside the UK may also be supported by the model. However, from an economic perspective, in the near future the exploitation of renewable resources in the UK may be a more attractive option as the distance of foreign resources greatly affects the costs of the transportation stage in the fuel chain.

7.6.3 Renewable Electricity Delivery

The model also can be used for the production, storage and transportation of green electricity. In this case the fuel chains have electricity as the final product that can be used for power applications. The model can determine the cost-effective way of producing green electricity and transmitted it to demand centres. This is useful for both centralized and decentralized applications. Moreover, the model can determine the way or the extent a region can be electrically autonomous by using its renewable energy resources.

7.6.4 Identification of Renewable Energy Sites

Another useful application of the model is the investigation of the renewable energy resources of a geographical region. Due to the resource optimisation stage, the model may determine the best possible sites for the installation of renewable energy schemes. This is quite useful as it may be used regardless of the end-use application of the produced electricity.

7.6.5. Applicability to Decentralized Energy Systems

In decentralised, or distributed, energy systems the energy in the form of heat or electricity is generated close to or at its point of use. Generally, it is believed that decentralised energy is important as a means of reducing carbon emissions from electricity production. For example, Greenpeace estimates that investing in a decentralised energy strategy would assist the UK in reducing half of all emissions from the UK electricity sector (PB Power *et al.*, 2006). However, others advocate that it is quite disputable whether decentralised power is inherently more efficient and better for the environment than centralised power. Malcolm Keay (2006) states that while decentralised power plants can be considered overall more efficient than centralised plants due to the elimination of transmission losses they are not necessarily thermally efficient.

Generally, the fact that a centralised system wastes a substantial percentage of energy used to fuel them while a decentralised system may provide a more secure, environmental friendly energy system that could revolutionise the lives of billions of people who lack access to basic energy needs and work hand-in-hand with renewable energy sources constitute a strong impetus for continuing investing in decentralised plants.

The developed model can be used for the establishment of decentralised energy systems. The model can examine different decentralised plant options in various locations finding the more technically and economically efficient way of creating such plants. Decentralised energy systems include high efficiency co-generation or combined heat and power, on-site renewable energy systems and energy recycling systems (PB Power *et al.*, 2006). The model is able to include all these systems.

It is worthwhile to mention the link between hydrogen production and decentralised electricity systems as quite a few hydrogen supporters argue that the implementation of a hydrogen economy is based on decentralised energy. More specifically, hydrogen fuel infrastructure developments can initiate by decentralised systems that could gradually introduce the fuel and eventually establish a clean transport system. The development of small-scale installations constitutes a relatively low-cost investment which is crucial for the uptake of a new fuel.

7.7 Conclusions

In this Chapter the results of the case study have been presented and a sensitivity analysis has been carried out in order to examine the influence of parametric variation on the outputs of the model.

For the case of London, in order to deliver sufficient renewable hydrogen fuel to power all the road transport of the UK capital a hydrogen delivery network of 296 fuel chains are required. This venture spans in a 50-year time horizon and the overall cost amounts to 11.2 billion pounds (16.1 billion euros).

The renewables that have been selected for the production of the fuel are onshore and offshore wind energy, SRC energy crops, forestry residues and MSW. The biomass routes have appeared as a relatively cheap renewable hydrogen delivery option, though the transportation of biomass feedstock that is generally expensive has been kept down due to the assumption that the gasification plant is within a 50km radius from the biomass feedstock production point.

The technical obstacles in the development of a renewable hydrogen fuel infrastructure are less than the economic and political obstacles. Policy intervention is necessary especially at the beginning in order to provide an early demand for hydrogen, establish partnerships among the stakeholders in order to coordinate the initiation of the infrastructure, promote the research and demonstration of hydrogen and fuel cell technologies aiming at the commercialization of these technologies and ensure that hydrogen from renewable energy sources is the final destination that will eventually substitute current fuels.

In the next Chapter, the conclusions of the study are summarised and areas that would benefit from further development are identified and discussed.

C H$_2$ A P T E R 8

Conclusions and Recommendations for further Research

8.1 Introduction

The primary aim of this study as was defined in Chapter 1 was the examination of different renewable hydrogen fuel chain options in order to supply an environmentally friendly fuel to cities in recognition of the necessity of a sustainable transport system free of carbon-based fuels and their ensuing harmful emissions.

To deliver the aforementioned aim a modelling approach was followed that included the development of an algorithm that compares and evaluates various hydrogen delivery pathways and their integration into energy systems, taking into account region-specific framework conditions. The developed algorithm was applied to the case study of London in order to explore least-cost renewable hydrogen infrastructure development plans able to delivery enough hydrogen fuel to cover all the road transport demand in London. This was a large-scale problem that showed the performance of the model and its capability to support the development of options for significantly large infrastructure developments.

In this Chapter, the conclusions of the study are summarized and recommendations for future areas of work are made.

8.2 Conclusions

8.2.1 Modelling Approach

The approach began by identifying key components that modelling methods dealing with infrastructure problems generally lack. Previous studies were used as a base for the development of the selected approach and particular attention was given to the features that other studies omit in order to comprise the characteristics of this algorithm in an attempt to provide an original and constructive contribution.

One of the most common omissions in studies that model the design of a renewable hydrogen network is an appropriate geographical representation of hydrogen network that takes into account the location and distribution of production sites, transport distances between the point of production and the demand centre, modes and costs. This feature was successfully incorporated into the model as it has been seen in the case study and allows the model to produce results concerning the specific locations of all the required facilities for all the stages in the fuel chain and derive the least-cost transport distances. The only limitation of this feature is the fact that the model calculates the distance between points considering it as a straight line which is generally not quite true in reality due to geophysical reasons.

Apart from the spatial optimisation, another important feature that is excluded from almost all studies that were reviewed is the resource optimisation. This feature comprises a strong advantage of this model as it enables it to determine the best possible way to exploit the renewable energy resources of a geographical region in order to provide the primary energy feedstock for the production of hydrogen. Moreover, is one of the reasons that enable the model to be used in alternative applications such as in determining the cost-effective way of producing green electricity and transmitted it to demand centres for power application uses.

As it was described in Chapter 4, the developed algorithm is a composition of a number of units that all work together to produce the results. From the simulations of Chapters 5 and 7 it may be concluded that all the units are coordinated correctly and produce an outcome that is the result of the combination of several parameters.

The developed model may be considered as a generic framework for modelling the development of a renewable hydrogen infrastructure that can be applied to different geographical areas. Moreover, it can deliver results under various conditions such as the design of a hydrogen infrastructure that combines renewable and fossil fuel sources. It is worthwhile to mention that the model is able to support small-, medium- and large-scale problems. However, its use in large-scale problems would be more beneficial if it is implemented in advanced computation systems or computer farms.

8.2.2 Hydrogen Infrastructure

The technologies of hydrogen and of renewable energy sources as a primary energy feedstock for fuel production that may be used to form the fuel infrastructure were discussed and assessed in terms of their technical and economic potential in Chapter 2.

Generally, technologies go through several stages in the long road from concept to widespread use. From the technologies that were reviewed some of them are still at the proof-of-technology stage, others are widely used and technically mature and others are struggling to transition from a proven technology to one in widespread use.

In terms of renewable electricity-generating technologies, onshore and offshore wind energy, biomass, hydro energy, geothermal energy are the renewables that their electricity-generating technologies have been widely used. Wave energy, tidal energy ands solar energy are lagging behind the other renewables due to technical and economic obstacles. However, for some renewables there are relatively new emerging electricity-generating approaches, such as hot dry rocks in the case of geothermal energy, but are still far from being commercially viable.

In terms of hydrogen technologies, this classification is also apparent. There are proven technologies and novel methods that still need considerable efforts in research and development. However, the considerable number of necessary hydrogen technologies to build the fuel infrastructure may be considered ready and their current technical status is not the major obstacle that impedes the initiation of the infrastructure.

Due to the different maturity level of the technologies the model was applied in the case study of London that included only relatively proven technologies and technologies that have been widely used.

8.2.3 Results of the Case Study

The renewable infrastructure development model was used in the case of London. The simulation examined the way a renewable hydrogen delivery system may be developed having as a demand centre London and using the renewable energy resource of GB, apart from MSW that only the London resource was considered, in order to deliver sufficient hydrogen fuel to meet all the road transport demand of London in a 50-year time horizon.

According to the model's results, the least-cost development plan consists of 296 fuel chains and the cost for implementing this plan amounts to 11.2 billion pounds. The renewables that have been selected to produce the primary energy feedstock for hydrogen production include onshore and offshore wind energy, forestry residues, SRC energy crops and MSW. At the end of the planning horizon, the infrastructure would be able to deliver 24,113GWh of hydrogen energy.

The results from the modelling work showed that the infrastructure development is comprised of a number of different pathways. This outcome demonstrates that there is not a single route that is the absolute "winner" as a hydrogen delivery pathway may be cheaper under certain conditions while by changing these conditions may become expensive. For this reason changing the conditions of the simulation will produce a different infrastructure development plan.

According to the modelling results, biomass routes may be considered a relatively economic renewable option for supplying hydrogen fuel to London. It should be mentioned that this conclusion is valid in the case the distance between the gasification plant and the biomass feedstock production facility is fairly small. Wind energy is also a promising renewable energy that may be used to produce hydrogen. Due to the geographical distribution of the UK wind energy resource and the position of the demand centre the wind energy routes the transportation stage was the crucial stage that determined the economics of the fuel chains. This was true for all renewable energy sources. Solar energy and hydro energy were not particularly favoured, the first due to high capital costs and the second due to the limited resource.

It is important to mention that in principal the results of the case study can not be compared with the results of other hydrogen infrastructure modelling studies. This is true as there is no other algorithm addressing the issue of the development of a hydrogen delivery system in such a way as the one presented in this study. The vast majority of hydrogen infrastructure studies examine and compare individual pathways that as the modelling approach and results showed are quite different and less complex than a study that tries to integrate all the necessary components of a hydrogen delivery system as this study. Moreover, there is an understandable difference among studies in terms of their input data and assumptions. However, some very general tendencies that have been concluded in other studies may be compared, for example the predictions that some technologies are more expensive than others under certain conditions.

Based on the results of the model it can be concluded that the model's predictions are in agreement with a number of infrastructure studies in terms of the primary energy feedstock used for hydrogen production. More specifically, among the different renewable energy sources under examination, biomass was considered a relatively cheap option with wastes slightly more preferred than forestry residues and SRC. Onshore wind energy was also an attractive renewable energy source. These conclusions are consistent with the outcomes of several infrastructure studies (Myers *et al.*, 2003; E4tech, 2004; Chen *et al.*, 2005; Mann *et al.*, 1998; Simbeck and Chang, 2002; Ewan and Allen, 2005).

Another general conclusion that can be drawn from the modelling results is the choice of transport technology based on criteria such as the demand and the delivery distance. Specifically, for very low demand compressed gas truck is preferred while for long distances and high demand liquid transport is more appropriate. Moreover, for short distances and large demand the preferred choice is pipeline delivery. These choices are in agreement with several projects focusing exclusively on the examination and comparison of different hydrogen transport technologies (Berry and Smith, 1994; Amos, 1998; Mintz *et* al., 2002; Castello *et al.*, 2005; Hawkins, 2006; Yang and Ogden 2007) or studying hydrogen pathways as a whole (Padro and Putsche, 1999; Ogden, 1999; Conte, 2001; Dincer, 2002; Dutton, 2002; Farrell *et al.*, 2003; Altmann *et al.*, 2004).

As it was apparent from the results and the sensitivity analysis, the geographical optimisation is an important factor that influences the results and thus needs to be taken into account. Because of the geophysical characteristics, the geographical distribution of the renewable energy resources and the geographical position of the demand centre for the region under study there is not a single route that is the absolute least-cost fuel chain option as a chain that is cheap in an area may be expensive in another area.

8.2.4 Policy Considerations

The development of a new fuel infrastructure is a complex and large capital investment venture that involves several parameters. The introduction of hydrogen fuel and its widespread use are almost impossible without drastically different market conditions and new policies.

Due to the wide range of environmental benefits that the uptake of hydrogen fuel may offer such as the reduction of carbon emissions, the improvement of air quality, the reduction of noise and the increase of energy security, it should be supported by the energy, transport and environmental policy framework.

There are three main areas that heavily need the Government's support for the implementation of the introduction of hydrogen fuel in the transport sector. Firstly, support to research and development in order to assist in the designing, developing and testing hydrogen technologies. Secondly, support to demonstrations in an attempt to stimulate the market of the new technologies. Lastly, support to commercialisation in order to succeed in getting the new technologies to the market.

In the UK Government, hydrogen and fuel cell technologies are gradually escalating in the energy policy agenda. However, more support is necessary if the UK wants to be among the leading countries, such as Germany, USA or Japan, in the hydrogen activities.

As it has been seen from the modelling results the infrastructure consists of a number of different hydrogen delivery pathways. As a fuel hydrogen has a diversity of production, conversion, storage and transport methods and thus the support and promotion do not need to be committed to a single route. It is unlikely that hydrogen used for a large proportion of transport demand would be produced and delivered using one set of technologies.

According to the modelling results, creating a large-scale infrastructure involves the considerable exploitation of renewable resource. However, the development and exploitation of renewable resources will take time and the generation of hydrogen fuel has to compete with other end use applications such as electricity production and heat. The opportunity of using hydrogen fuel generated from renewables in the transport sector must be examined taking into account these constraints. In order to ensure the use of renewables for hydrogen production the Government may set targets for the dedication of a percentage of renewable electricity to hydrogen fuel production.

Another barrier that impedes the uptake of hydrogen fuel is the existence of early demand for hydrogen fuel. Generally, the cost of hydrogen improves with increase production due to economies of scale. However, even if fuel suppliers and vehicle manufacturers do coordinate the timing of infrastructure the process of hydrogen vehicles has to be competitive in order to be successfully deployed in the large numbers needed to ensure adequate fuel demand. This barrier may be overcome by the introduction of hydrogen fuel in a niche market. The latter are protected markets that allow for technological innovation and competition, factors that bring the cost down.

8.3 Recommendations and Subjects for further Investigation

8.3.1 Model Enhancement

In the course of the model construction and the case study of London, a number of issues have been identified in which further work would be of benefit. These issues are possible model improvements on deliberate simplifications or assumptions.

As it was mentioned in Chapter 2, the input data related to the renewable energy resource of the geographical region under study are imported to the model in the form of a map. For every renewable energy resource only one map can be imported. In case a renewable resource is described by more than one parameters, such as the resource of SRC that it was evaluated according to the agricultural land quality parameter based on the Agricultural Land Classification system of England and the effective precipitation parameter, the composition of maps is necessary. In order to avoid this procedure and to be able to enter in the model various maps describing the renewable energy resource one more function needs to be added. The additional function will describe the efficiency of the resource with respect to the parameter that is presented in the map. This will enable the model to assess the renewable resource taking into account various parameters minimizing the effort needed to import these parameters.

Another interesting inclusion may be the addition of a map showing the height of measurement. This parameter will likely affect both the primary energy feedstock and the transportation stage. An example of the former stage is wind energy. For wind energy the height of measurement is of great importance as the wind speeds are different for different altitudes. In the case of the transportation stage has also an effect as the model will be able to distinguish the difference between a candidate wind park site at the top of a mountain and a wind park site in low land. The transportation cost of the latter is less expensive than the former. With this addition the model will be able to understand that difference. In other words, it gives to the model a third dimension.

The distance that hydrogen is transported between two points is calculated assuming that it is a straight line between the starting point and the end point. In order to avoid this simplification a new transportation shortest path algorithm that performs routing is necessary. An example of one algorithm that carried out this task is the A* (A star) algorithm. A* algorithm is a general search that finds the shortest path from a given initial node to a given goal node. However, the inclusion of this algorithm may increase significantly the complexity of the model. For this reason an alternative way of dealing with the issue of distance calculations is the designing of a simplified pathfinding algorithm based on the A* algorithm. This algorithm will use the transportation maps as an input data and will be able to evaluate the shortest path. The inclusion of a new transportation algorithm affects all transport modes apart from the transmission of electricity.

A further improvement in the model is the inclusion of discounted cost. Developing a renewable hydrogen infrastructure, especially in the case of a delivery system that is able to deliver large amounts of hydrogen fuel like the problem of the case study, is a project that requires long time horizons. The value of money today is different than the value of money in the future due to inflation. By discounting the overall infrastructure cost the model is able to take this effect into account and produce a more precise cost estimate.

As it mentioned in Section 7.5 of Chapter 7, the model does not include the learning curve phenomenon due to the non-linearity of the equation that describes this effect. A possible method that this effect can be incorporated into the model is by introducing an additional parameter that corresponds to the percentage that the cost of each technology decreases every year. Thus the mathematical formula of the learning effect may be used manually in order to calculate the cost reduction percentage and this percentage can then be imported in the model. It should be mentioned that in order to calculate correctly the cost reduction factor the increase of the cumulative production of a technology in a global level should be taken into account and not the increase of production in the region under study. This is the case as the cumulative production of only one country could not bring down the cost of a technology.

8.3.2 Suggestions for further Work

An issue that was not examined in the present study and constitutes a necessary component of a hydrogen infrastructure development is the geographical distribution of the refuelling stations within the city. The model considers the demand centre as a point and thus does not investigate the optimal dispersion of the refuelling stations in the city that hydrogen is delivered. The geographical allocation of refuelling stations is determined by a number of factors such as the city radius, the population size and the market penetration of hydrogen fuel cell vehicles. This task may be an independent algorithm or it may be included in the algorithm of the present study. The latter case is feasible due to the advantageous construction of the algorithm that is separated into subsystems and allows the addition of new subsystems without changing the existing ones. The additional algorithm would be responsible for the selection of the optimal locations within a city that refuelling stations may be allocated.

Developing a hydrogen infrastructure has to be combined with the introduction of vehicles running on hydrogen either fuel cell or internal combustion engine vehicles. In order to initiate the uptake of hydrogen fuel, hydrogen vehicles may be powered from fuel generated from non-renewable energy sources. The development of non-renewable hydrogen projects could facilitate the introduction of hydrogen vehicles and the establishment of some fuel infrastructure. This action combined with long-term policy measures may lead to a later switch to renewable hydrogen. For this reason, it would be interesting to run the model for a simulation that includes both renewables and fossil fuels in order to produce the least-cost infrastructure development plan for an infrastructure that uses low cost primary energy feedstocks that will assist in the initiation of the project and later substitution with the zero-emission renewable hydrogen fuel.

A worthwhile study would be the application of the hydrogen infrastructure development model of the present study to other cities or geographical regions in order to produce the least-cost infrastructure development plan for their specific conditions. Moreover, the resulted plan may be compared with the modelling results of the case study indicating the weaknesses and benefits of each place and identifying their degree of attractiveness in developing a hydrogen delivery network.

In this final Chapter, a number of improvements and extensions have been suggested. However, the modelling approach that was taken was proved to be useful in the present application and also its use may be considered beneficial to a wide range of energy related applications.

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APPENDIX

Name	Value	Unit	Source
Renewable Energy Sources			
Onshore Wind Energy			
Capital Cost	1120	€/kW	EWEA (2004) Turbine cost Komor (2004) Installation cost
O&M Cost	15	€/kW	EWEA (2004)
Maximum Capacity	50	MW	Assumption
Capacity Factor	30%		BWEA (2007a)
Lifetime	25	years	BWEA (2007a)
Offshore Wind Energy			
Capital Cost	1650	€/kW	EWEA (2004)
O&M Cost	30	€/kW	EWEA (2004)
Maximum Capacity	100	MW	Assumption
Capacity Factor	40%		BWEA (2007a)
Lifetime	25	years	BWEA (2007a)
Solar Energy - PV			
Capital Cost	5244	€/kW	Komor (2004)
O&M Cost	29.5	€/kW	Komor (2004)
Maximum Capacity	10	MW	Boyle (2002)
Efficiency	14%		Komor (2004)
Lifetime	25	years	Boyle (2000)
Small-scale Hydro Energy			
Capital Cost	2181	€/kW	Komor (2004)
O&M Cost	280	€/kW	Komor (2004)
Maximum Capacity	20	MW	Assumption
Capacity Factor	45%		Komor (2004)
Lifetime	50	years	Komor (2004)
Biomass - SRC of willow			
Establishment Cost	275	€/kW	Defra (2006a)
Production Cost	108.7	€/kW	Boyle (2000)
Transport Cost	0.015	€/kW/km	Bauen (1999)-monthly delivery, within 50km radius
Maximum Capacity	30	MW	ETSU (1998)
Yield	10	odt/ha/yr	Bauen (2001)
Lifetime	30	years	Boyle (2000)
Energy Content	19	GJ/odt	ETSU (1999)
Biomass - Forestry Residues			
Establishment Cost	635	€/kW	Howes (2002)
Production Cost	111	€/kW	Boyle (2000)
Transport Cost	0.022	€/kW/km	Bauen (1999)-monthly delivery, within 50km radius
Maximum Capacity	30	MW	ETSU (1999)
Yield	1.5	odt/ha/yr	Bauen (1999)

Biomass - MSW			
Lifetime	80	years	Howes (2002)
Energy Content	19	GJ/odt	ETSU (1999)
Road Transport Cost	0.043	¢/kW/km	Viridis *et al.* (2005)
Maximum Capacity	30	MW	ETSU (1999)
Thermal Efficiency	64%		Castillo (2003)
Lifetime	50	years	Assumption
Calorific value	10	MJ/kg	Castillo (2003)
Hydrogen Production Technologies			
Onsite Electrolysis			
Capital Cost	734.4	€/kW	Adamson (2004)
O&M Cost	22	€/kW	Mann *et al.* (1998)
Conversion Efficiency	95%		Ivy (2004)
Energy Efficiency	73%		Ivy (2004)
Overall Efficiency	70%		Ivy (2004)
Location	onsite		Assumption
Lifetime	15	years	Ivy (2004)
Regional Electrolysis			
Capital Cost	734.4	€/kW	Adamson (2004)
O&M Cost	22	€/kW	Mann *et al.* (1998)
Conversion Efficiency	95%		Ivy (2004)
Energy Efficiency	73%		Ivy (2004)
Overall Efficiency	70%		Ivy (2004)
Location	regional		In 7 different demand zones
Lifetime	15	years	Ivy (2004)
Forecourt Electrolysis			
Capital Cost	3650	€/kW	Adamson (2004)
O&M Cost	57	€/kW	Mann *et al.* (1998)
Conversion Efficiency	95%		Ivy (2004)
Energy Efficiency	78%		Ivy (2004)
Overall Efficiency	74%		Ivy (2004)
Location	forecourt		Assumption
Lifetime	10	years	Ivy (2004)
Gasification			
Capital Cost	712	€/kW	Mann (1995)
O&M Cost	34.2	€/kW	Howes (2002)
Efficiency (SRC+FR)	55%		Howes (2002)
Efficiency wastes	50%		Wallman *et al.* (1998)
Density of hydrogen	0.0899	kg/Nm^3	Castillo (2003)
Location	regional or onsite		Assumption
Lifetime	25	years	Howes (2002)
Hydrogen Conversion Technologies			
Large- and medium-scale Compression			
Capital Cost	589	€/kW	Amos (1998) (4.5-28.3MW)
O&M Cost	29.5	€/kW	Berry (1996) (5% of capital cost)
Efficiency	85%		Hawkins (2006)
Location	production site		Assumption
Lifetime	25	years	Syed (1998)

Forecourt Compression			
Capital Cost	830	€/kW	Amos (1998) (0.25MW)
O&M Cost	41.5	€/kW	5% of capital cost
Efficiency	80%		Hawkins (2006)
Location	forecourt		Assumption
Lifetime	25	years	Syed (1998)
Large-scale Liquefaction			
Capital Cost	1141	€/kW	Hawkins (2006) (1042kg/h)
O&M Cost	57	€/kW	Berry (1996) (5% of capital cost)
Efficiency	78%		Hawkins (2006)
Location	production site		Assumption
Lifetime	25	years	Syed (1998)
Medium-scale Liquefaction			
Capital Cost	1731	€/kW	Hawkins (2006) (417kg/h)
O&M Cost	86	€/kW	Berry (1996) (5% of capital cost)
Efficiency	78%		Hawkins (2006)
Location	production site		Assumption
Lifetime	25	years	Syed (1998)
Forecourt Liquefaction			
Capital Cost	2728	€/kW	Amos (1998)
O&M Cost	136.4	€/kW	Berry (1996) (5% of capital cost)
Efficiency	74%		Hawkins (2006)
Location	forecourt		Assumption
Lifetime	25	years	Syed (1998)
Hydrogen Storage Technologies			
Compressed Gas			
Capital Cost	348	€/kW	Amos (1998) (1240kg)
O&M Cost	3.3	€/kW	Ogden(1995) (0.95% of cap. cost)
Efficiency	90%		Hawkins (2006)
Location	production site		Assumption
Lifetime	10	years	Ogden (1995)
Forecourt Compressed Gas			
Capital Cost	486	€/kW	Amos (1998) (890kg)
O&M Cost	4.6	€/kW	Ogden (1995)(0.95% of cap. cost)
Efficiency	90%		Hawkins (2006)
Location	forecourt		Assumption
Lifetime	10	years	Ogden (1995)
Liquid Hydrogen			
Capital Cost	186	€/kW	Amos (1998)
O&M Cost	1.3	€/kW	Ogden (1995) (0.7% of cap. cost)
Efficiency	80%		Hawkins (2006)
Location	production site		Assumption
Lifetime	10	years	Shayegan (2006)
Forecourt Liquid Hydrogen			
Capital Cost	230	€/kW	Amos (1998)
O&M Cost	1.61	€/kW	Ogden (1995) (0.7% of cap. cost)
Efficiency	80%		Hawkins (2006)

Forecourt Liquid Hydrogen			
Location	forecourt		Assumption
Lifetime	10	years	Shayegan (2006)
Metal Hydrides			
Capital Cost	920	€/kW	Amos (1998)
O&M Cost	8.7	€/kW	Assumption (0.95% of cap. cost)
Efficiency	85%		Hawkins (2006)
Location	production site		Assumption
Lifetime	3	years	Hottinen (2001)
Forecourt Metal Hydrides			
Capital Cost	715.4	€/kW	Amos (1998)
O&M Cost	6.8	€/kW	Assumption (0.95% of cap. cost)
Efficiency	85%		Hawkins (2006)
Location	forecourt		Assumption
Lifetime	3	years	Hottinen (2001)
Hydrogen Transportation Technologies			
Compressed Gas by Road			
Capital Cost	3.84	€/kW/km	Hawkins (2006)
O&M Cost	0.01	€/kW/km	Hawkins (2006)
Efficiency	90%		Shayegan (2006)
Tube Capacity	400	kg/truck	Hawkins (2006)
Lifetime	40	years	Fiba Technologies (2006)
Liquid Hydrogen by Road			
Capital Cost	0.63	€/kW/km	Amos (1998)
O&M Cost	0.001	€/kW/km	Hawkins (2006)
Efficiency	95%		Shayegan (2006)
Tank Capacity	4082	kg/truck	Amos (1998)
Lifetime	30	years	Fiba Technologies (2006)
Metal Hydrides by Road			
Capital Cost	12.96	€/kW/km	Amos (1998)
O&M Cost	0.01	€/kW/km	Assumption
Efficiency	90%		Hawkins (2006)
Container Capacity	454	kg/truck	Amos (1998)
Lifetime	30	years	Assumption
Pipeline			
Capital Cost	154	€/kW/10^3km	Summerer (2004)
O&M Cost	4.62	€/kW/10^3km	Ogden (1997) (3% of cap. cost)
Efficiency	99%		Hawkins (2006)
Capacity	710	kg/h	Calculated based on data from Hawkins (2006)
Diameter	0.25	m	Summerer (2004)
Lifetime	30	years	Shayegan (2006)
Electricity Transportation Technology			
Electricity Grid			
Capital Cost	99	€/kW	Garrad Hassan (2003) (0.95% of cap. cost) Cost of Offshore grid connection
O&M Cost	35.6	€/kW	Berry (2004)

Electricity Grid			
Efficiency	92.4%		Howes (2002)
Generation Tariff	depends on generation zone	€/kW	National Grid (2007) Table A2 GB Generation Use of System Tariff Zones 2007/8
Demand Tariff	depends on demand zone	€/kW	National Grid (2007) Table A3 GB Demand Use of System Tariff Zones 2007/8
Lifetime	50	years	Assumption
Infrastructure Characteristics			
Time Horizon	50	years	Assumption
Number of Segments	64	segments	Assumption
Periods	5	periods	Assumption
Duration	10	years	Assumption
Demand Target at the end of the Horizon	24,113 or 2.75	GWh or GW	Calculated based on data from London Travel Report 2004 (TfL,2004) and Transport Trends 2006 (TfL,2006)
Tolerance Upper Limit	1	MW	Assumption
Tolerance Lower Limit	1	MW	Assumption

Table A1: Model input data

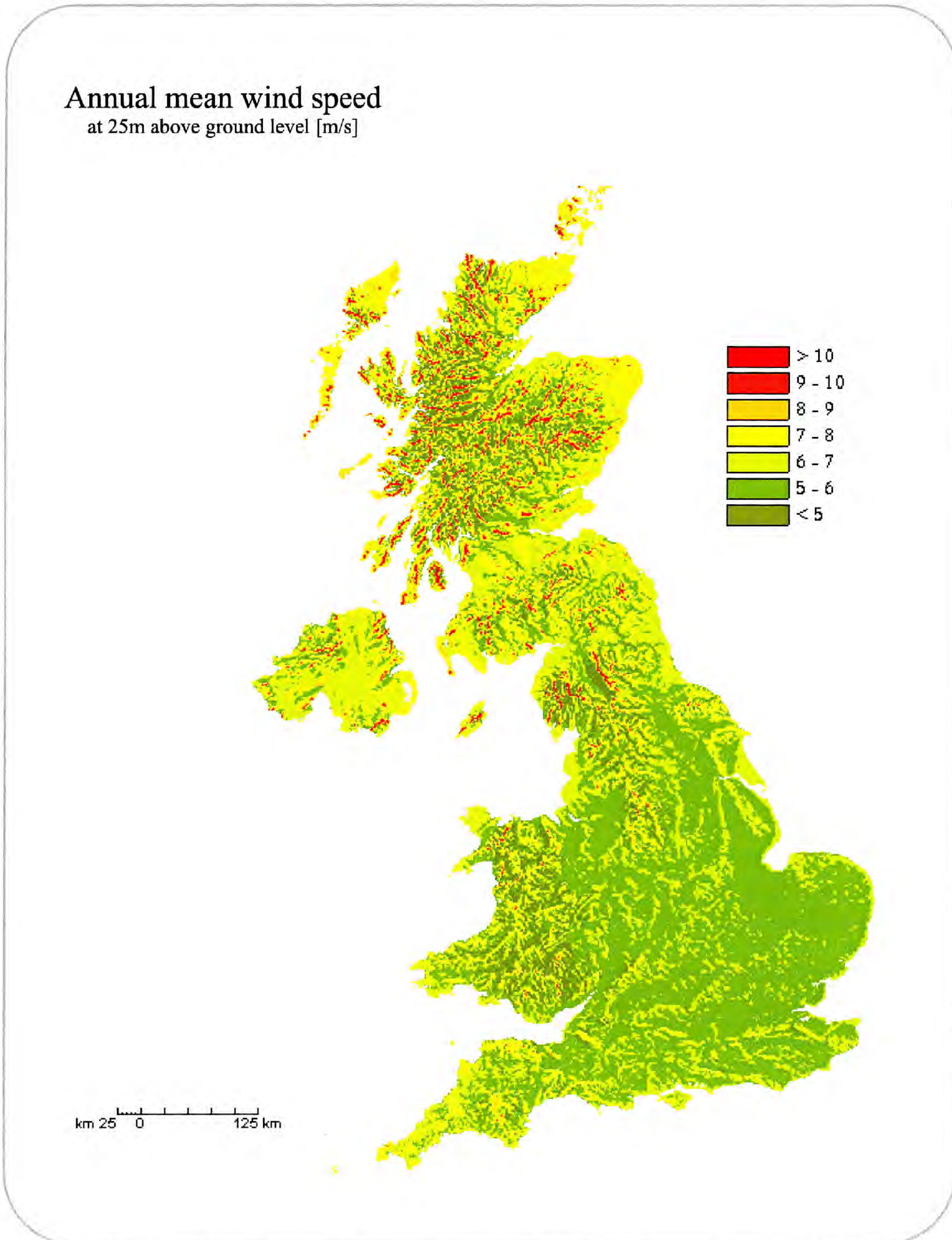

Figure A1: Onshore wind energy resource in the UK (Source: ETSU, 1999a)

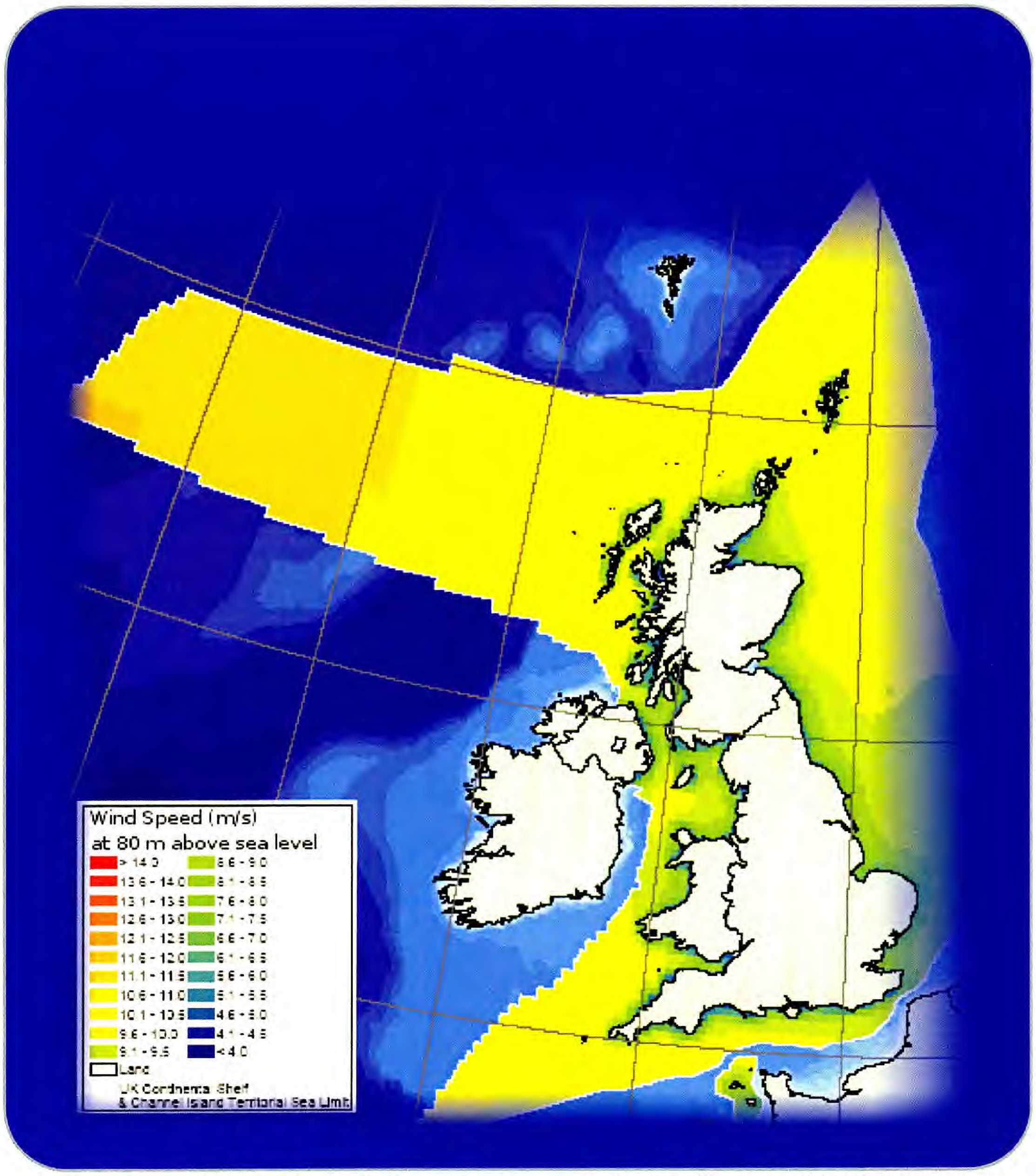

Figure A2: Offshore wind energy resource in the UK (Source: DTI, 2004b)

Figure A3: Solar energy resource in the UK and Ireland
(Source: Solar Trade Association, 2005)

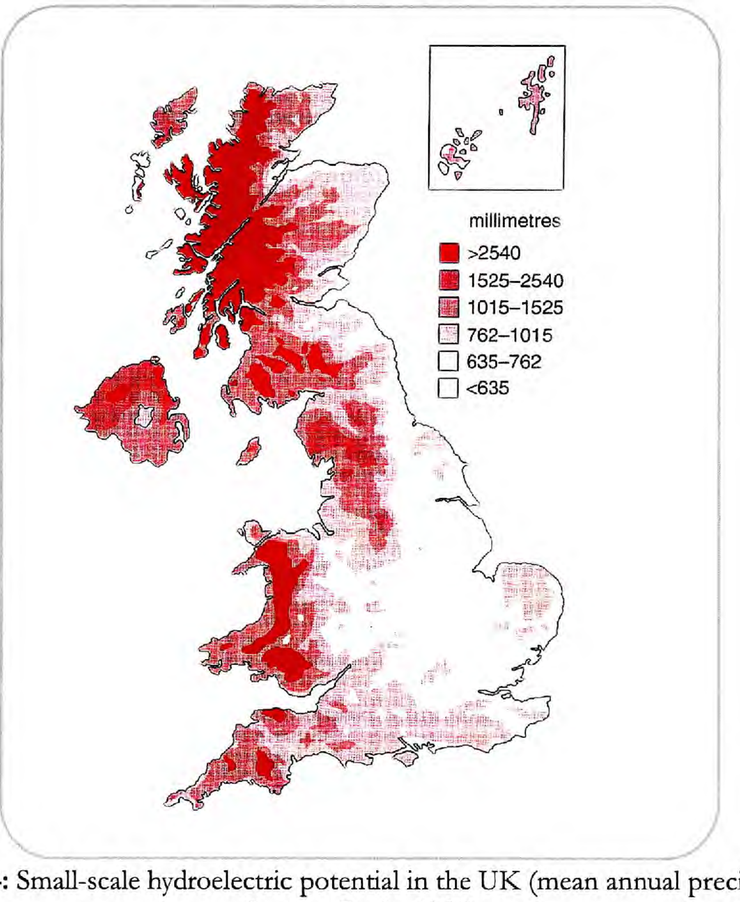

Figure A4: Small-scale hydroelectric potential in the UK (mean annual precipitation)
(Source: Boyle, 2000)

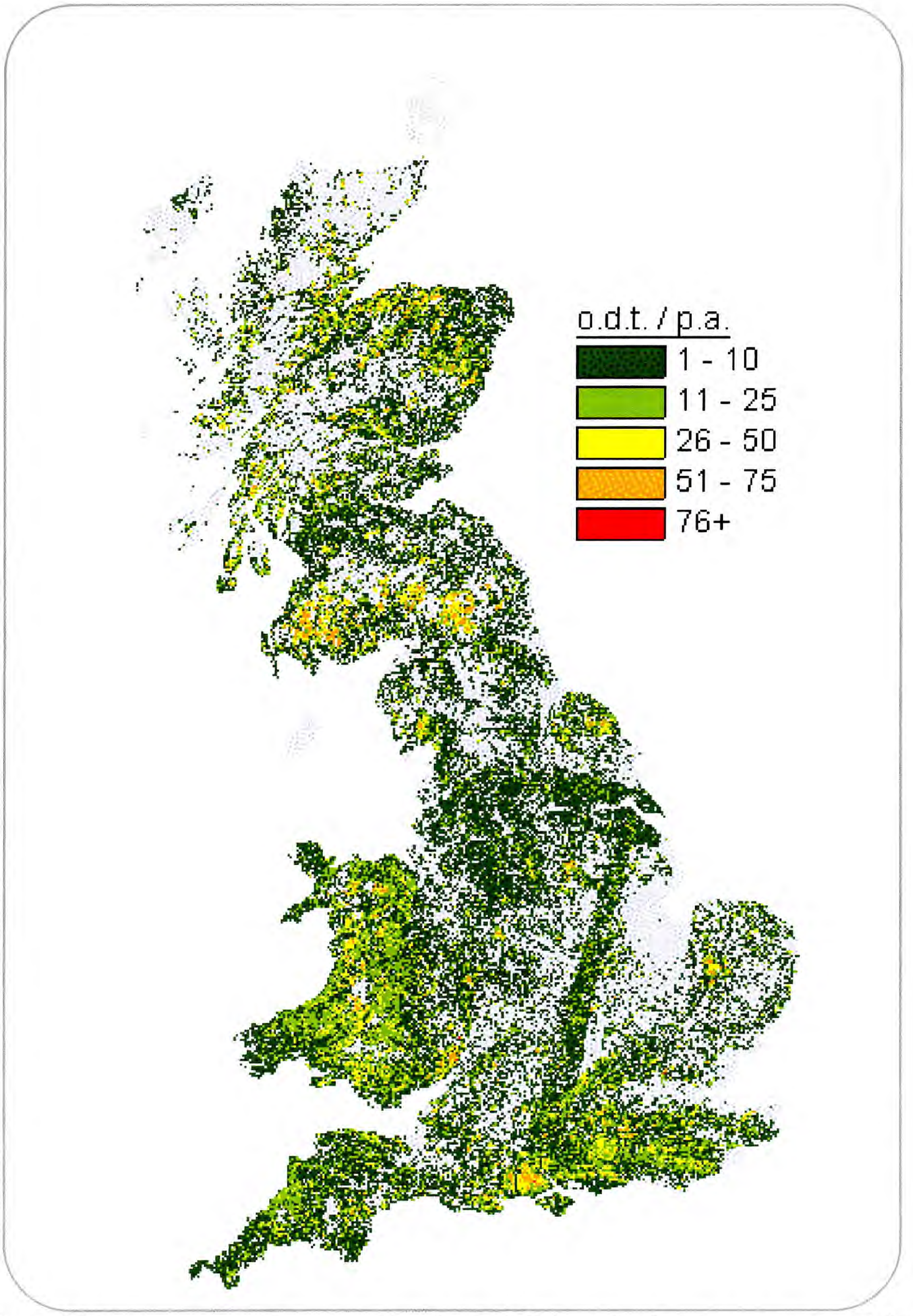

Figure A5: Resource map of forestry residues for the UK (oven dried tonnes per annum-odt/pa) (Source: Restats, 2005)

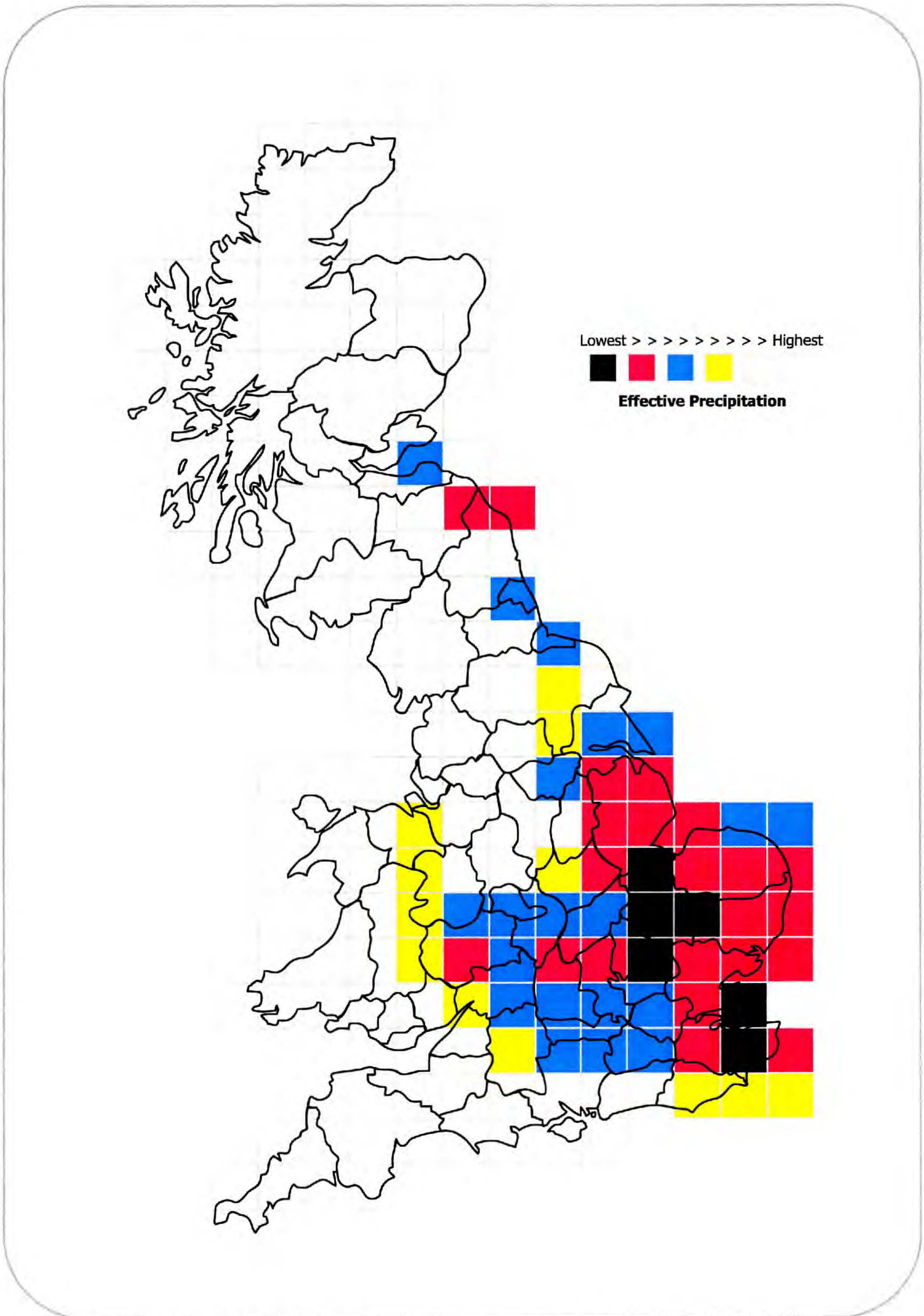

Figure A6: The effective precipitation across GB (Source: DTI, 2003a)

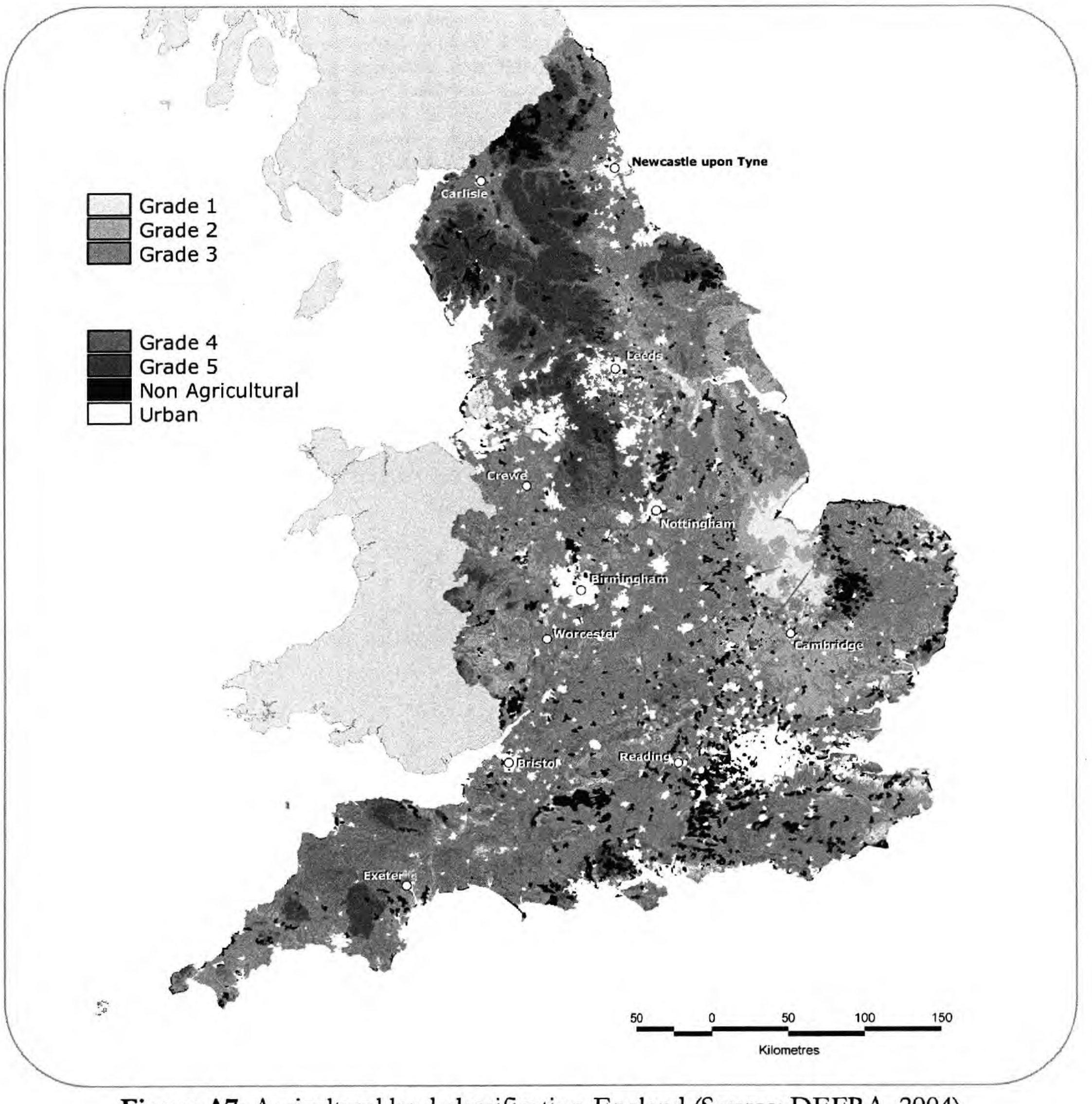

Figure A7: Agricultural land classification-England (Source: DEFRA, 2004)

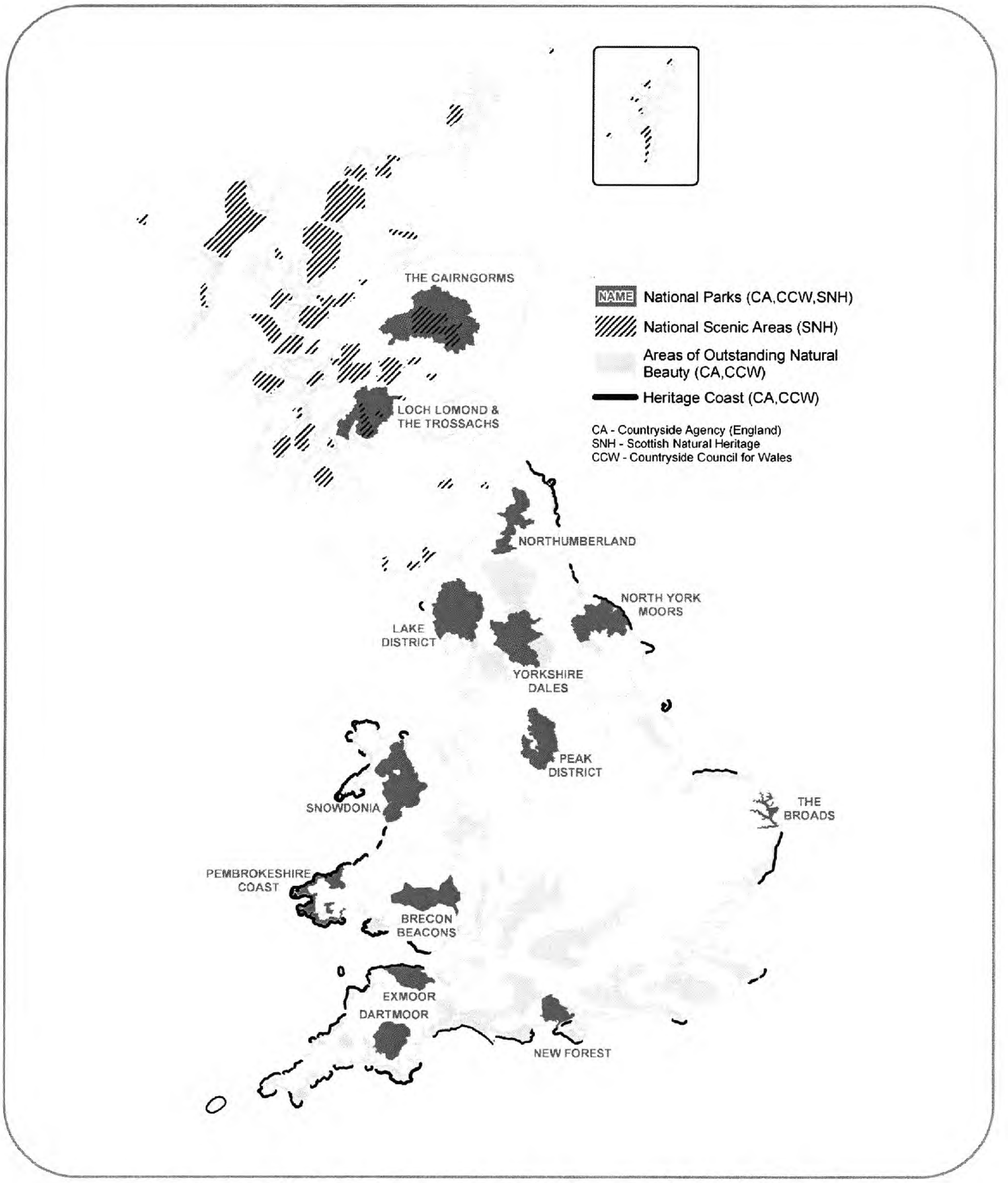

Figure A8: Designated areas in GB (Source: DEFRA, 2005)

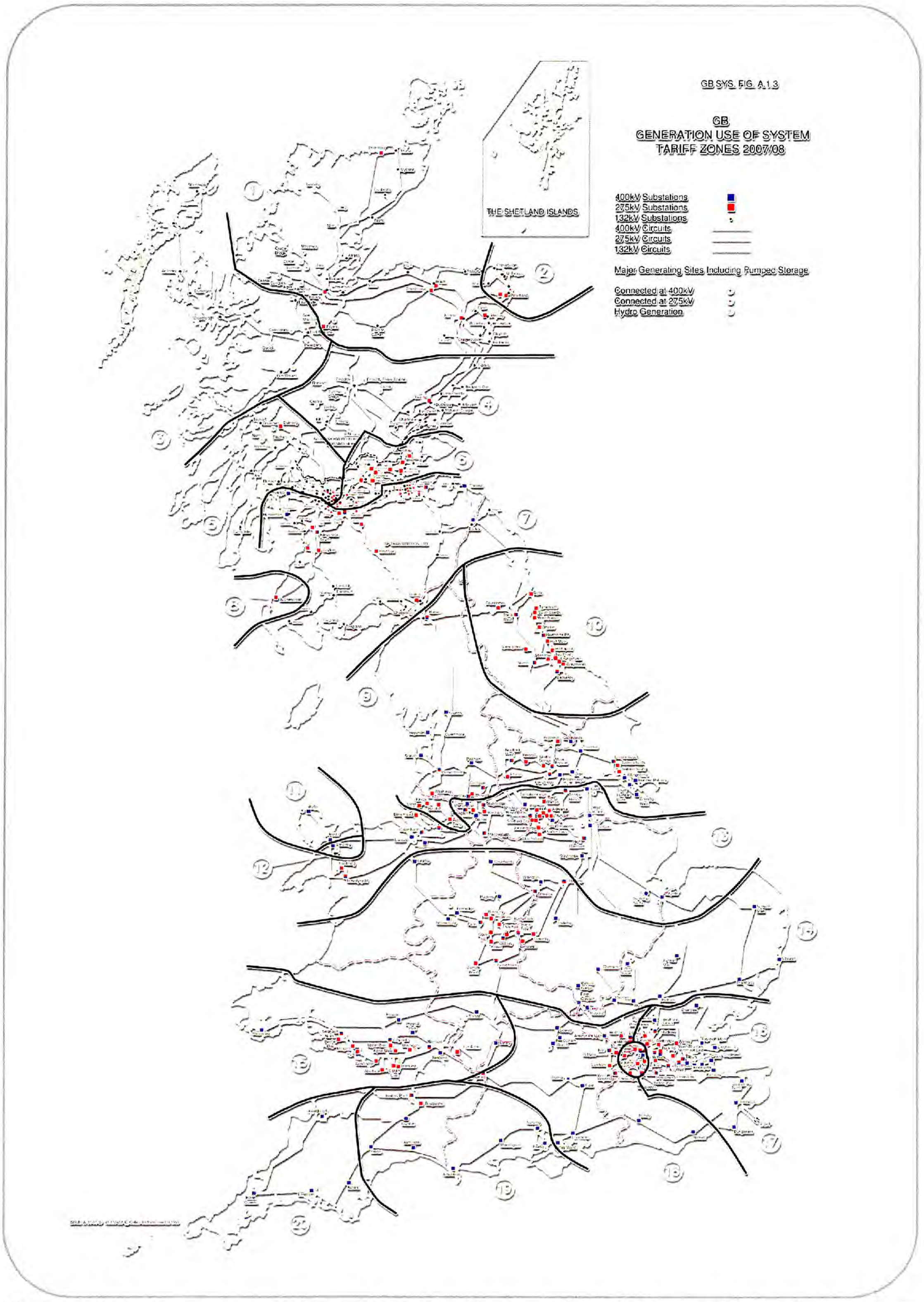

Figure A9: Generation use of system in GB-Tariff zones 2007/08 (Source: National Grid, 2007)

Generation		
Zone No.	**Zone Name**	**Zonal Tariff (£/kW)**
1	North Scotland	21,590831
2	Peterhead	19,233718
3	Western Highland & Skye	19,858255
4	Central Highlands	16,436431
5	Argyll	14,677167
6	Stirlingshire	14,031535
7	South Scotland	13,017061
8	Auchencrosh	10,137439
9	Humber, Lancashire & SW Scotland	5,883070
10	North East England	9,253848
11	Anglesey	6,409118
12	Dinorwig	9,281586
13	South Yorks & North Wales	3,996719
14	Midlands	1,973640
15	South Wales & Gloucester	-2,457186
16	Central London	-5,714694
17	South East	0,908414
18	Oxon & South Coast	-0,265230
19	Wessex	-4,098569
20	Peninsula	-8,568052
Small Generators Discount (not included above) **(£/kW)**		4,481939

Table A2: Final TNUoS Tariffs 2007/8 (Source: National Grid, 2007)

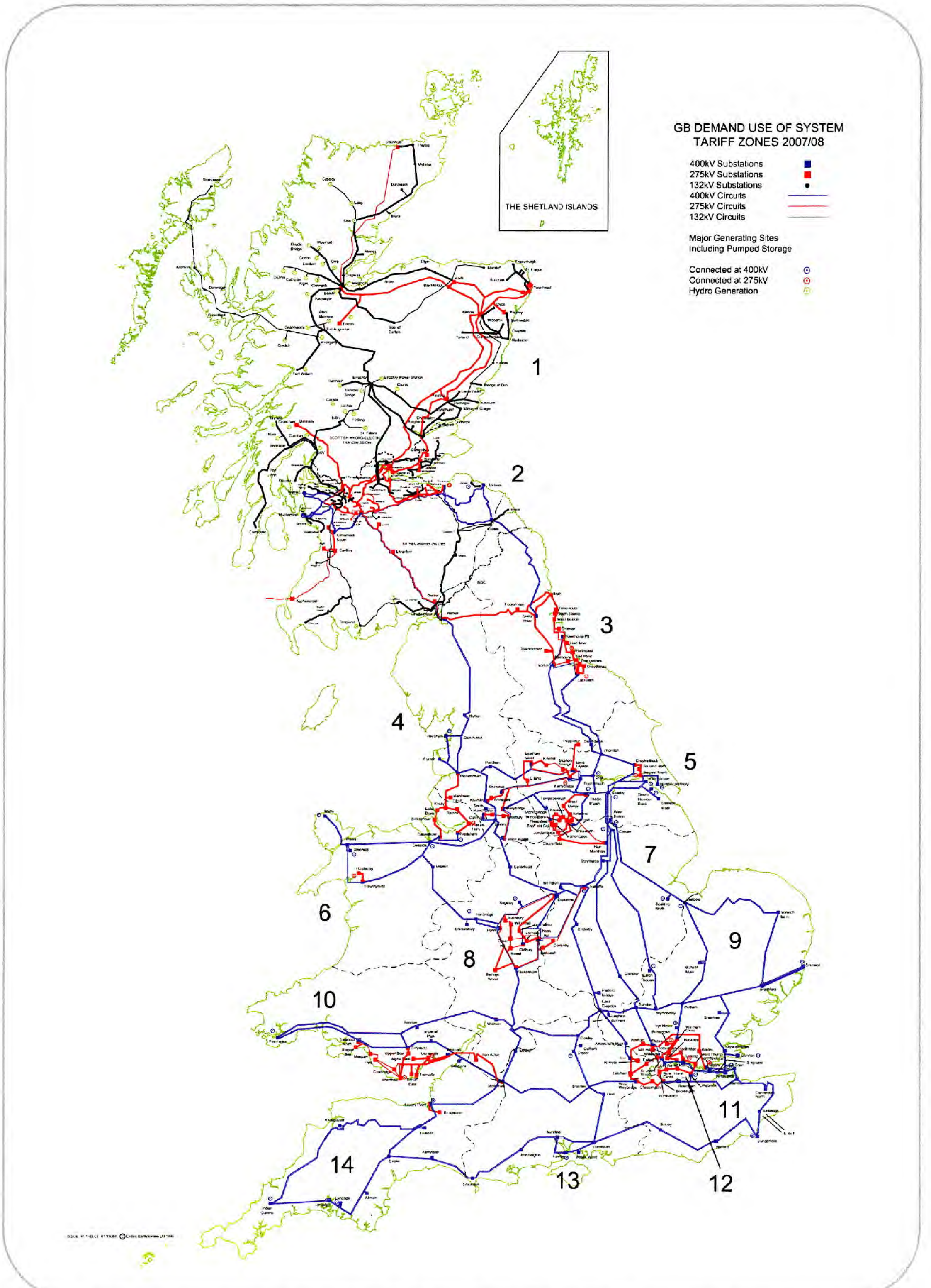

Figure A10: Demand use of system in GB-Tariff zones 2007/08 (Source: National Grid, 2007)

Demand

Zone No.	Zone Name	HH Zonal Tariff (£/kW)	NHH Zonal Tariff (p/kWh)
1	Northern Scotland	1,445659	0,183742
2	Southern Scotland	6,362303	0,830136
3	Northern	9,884146	1,287148
4	North West	13,646168	1,734890
5	Yorkshire	13,615270	1,750626
6	N Wales & Mersey	14,084355	1,805802
7	East Midlands	16,370802	2,129626
8	Midlands	17,807318	2,301762
9	Eastern	17,060375	2,240442
10	South Wales	21,537451	2,713949
11	South East	20,076054	2,586190
12	London	22,164365	2,710106
13	Southern	21,100281	2,738161
14	South Western	23,770560	3,000403
Demand tariffs include a 'small generators' adjustment of:		0,055127	0,007090

Table A3: Final TNUoS Tariffs 2007/8 (Source: National Grid, 2007)