DOCTOR OF PHILOSOPHY

# Decision support for lifecycle planning and risk management of small-scale biomass combined heat and power (bCHP) projects in the UK

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Aston University

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DANIEL WRIGHT

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“Everything is vague to a degree you do not realise till you have tried to make it precise”

Bertrand Russell.

## Dedication

Dedicated to Sally, my partner, and my family for their unrelenting support.

**Aston University**

# Decision Support for Lifecycle Planning and Risk Management of Small-Scale Biomass Combined Heat and Power (bCHP) Projects in the UK

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Biomass is projected to account for approximately half of the new energy production required to achieve the 2020 primary energy target in the UK. Combined heat and power (CHP) bioenergy systems are not only a highly efficient method of energy conversion, at smaller-scales a significant proportion of the heat produced can be effectively utilised for hot water, space heating or industrial heating purposes. However, there are many barriers to project development and this has greatly inhibited deployment in the UK. Project viability is highly subjective to changes in policy, regulation, the finance market and the low cost incumbent; a high carbon centralised energy system. Unidentified or unmitigated barriers occurring during the project lifecycle may not only negatively impact on the project but could ultimately lead to project failure.

The research develops a decision support system (DSS) for small-scale (500 kWe to 10 MWe) biomass combustion CHP project development and risk management in the early stages of a potential project's lifecycle. By supporting developers in the early stages of project development with financial, scheduling and risk management analysis, the research aims to reduce the barriers identified and streamline decision-making. A fuzzy methodology is also applied throughout the developed DSS to support developers in handling the uncertain or approximate information often held at the early stages of the project lifecycle.

The DSS is applied to a case study of a recently failed (2011) small-scale biomass CHP project to demonstrate its applicability and benefits. The application highlights that the proposed development within the case study was not viable. Moreover, further analysis of the possible barriers with the DSS confirmed that some possible modifications to be project could have improved this, such as a possible change of feedstock to a waste or residue, addressing the unnecessary land lease cost or by increasing heat utilisation onsite. This analysis is further supported by a practitioner evaluation survey that confirms the research contribution and objectives are achieved.

**Keywords**: Decision Support System, Biomass, Combined Heat and Power, Project Development, Fuzzy Set Theory.

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## Abbreviations and Acronyms

Abs. – Absolute
AD – Anaerobic Digestion
AHP – Analytical Hierarchy Process
AIRMIC – Association of Insurance and Risk Managers
ALARM – The National Forum for Risk Management in the Public Sector
ALARP – As Low as Reasonably Possible
bCHP – Biomass CHP
BERR – Business, Enterprise Regulatory Reform
BIS – Business, Innovation and Skills
c. – Circa
CAPEX – Capital Expenditure
CASE – Collaborative Award in Science and Engineering
CCL – Climate Change Levy
CHP – Combined Heat and Power
CHPQA – CHP Quality Assurance
CPM – Critical Path Method
DCF – Discounted Cash Flow
DECC – Department of Energy & Climate Change
DHN – District Heating Network
DNO – District Network Operator
DPCR – Distribution Price Control Review
DSC – Debt Service Cover
DSCR – Debt Service Cover Ratio
DSS – Decision Support System
DuoS – Distribution use of System
e.g. – For example (*exempli gratia*)
EBITDA – Earnings before Interest Tax Depreciation and Amortisation
ECA – Enhanced Capital Allowance
EfW – Energy from Waste
EPC – Engineering Procurement and Construction (turn-key)
EPR – Energy Power Resources
EREBUS – Engaging Research for Business Transformation
ESCO – Energy Services Company
ESRC – Economic & Social Research Council
EST – Earliest Start Time
EU – European Union
EUCS – End-User Customer Satisfaction
Exp. – Expected
F-CPM – Fuzzy – Critical Path Method
FIDIC - International Federation of Consulting Engineers
FiT – Feed in Tariff
FMEA – Failure Modes and Effects Analysis
GA – Genetic Algorithms
GCV – Gross Calorific Value
GIS – Geographical Information System
Gj – Gigajoule
GSS – Group Support System
GUI – Graphical User Interface
HAZOP - Hazard and Operability
HMRC -Her Majesty's Revenue & Customs
HSE – Health, Safety and Environment
i.e. – In other words (*id est*)
IDSS – Intelligent DSS
IEA – International Energy Agency
IEA-RETD – IEA-Renewable Energy Technology Deployment
IEE – Intelligent Energy for Europe
inc. – Including
Ind – Industrial
IRM – Institute of Risk Management
IRR – Internal Rate of Return
k – Thousand
kWh – Kilowatt
kWhe – Kilowatt Hour Electrical
kWhth – Kilowatt Hour Thermal
LA – Local Authority
LCOE – Levelised Cost of Electricity
LCOH – Levelised Cost of Heat
LEC– Levy Exemption Certificate
L-L – Left – Left (type fuzzy functions)
LP – Linear Programming
L-R – Left – Right (type fuzzy functions)
LST – Latest Start Time
MCDM – Multi Criteria Decision Making
MILP – Mixed Integer Linear Programming
MIS - Management Information Systems
MS – Microsoft

MSW – Municipal Solid Waste
MW – Megawatt
MWe – Megawatt Electricity
MWh – Megawatt Hour
MWhe – Megawatt Hour Electricity
MWhth – Megawatt Hour Thermal
NCV – Net Calorific Value
NIMBY – not in my backyard
N-LP – Non Linear Programming
NNFCC – National Non-food Crops Centre
NPV – Net Present Value
NREL – National Renewable Energy Laboratory
O&M – Operations and Maintenance
ODT – Oven Dry Tonne
OEM – Original Equipment Manufacturer
Ofgem – Office of the Gas and Electricity Markets
OPEX – Operating Expenditure
OR – Operational Research
ORC – Organic Rankine Cycle
pa – per annum
PDSS – Personal DSS
PERT – Project Evaluation and Review Technique
PESTLE – Political, Environmental, Social, Technological, Legal, and Economical
PMBOK – Project Management Body of Knowledge
PP – Planning Permission
PPA – Power Purchasing Agreement
PRM – Project Risk Management
PV – Photovoltaic
QI – Qualifying Index
QPO – Qualifying Power Output
Ref. – Reference
Res – Residential
RET – Renewable Energy Technology
RETScreen - Renewable Energy and Energy Efficient Technology Screen
RHI – Renewable Heat Incentive
RO – Renewables Obligation
ROC – Renewable Obligation Certificate
ROE – Return on Equity
RPI – Retail Price Index
SME – Small to Medium Sized Enterprise
SQP – Sequential Quadratic Programming
t – tonne
TFI – Total Fuel Input
TPO – Total Power Output
U.S – United States of America
UK – United Kingdom
WACC – Weighted Average Cost of Capital
WBS – Work Breakdown Structures
WID – Waste Incineration Directive
wk – week
yr – year

# 1. Introduction

## 1.1 Overview

Renewable energy technology (RET) deployment and investment continues to grow at an unprecedented rate, with 44% of the total worldwide generation capacity added in 2011 coming from renewable sources (excl. large hydro) [1]. Energy generated from renewable sources can help to reduce energy security issues and the United Kingdom (UK) dependence on fossil fuel imports [2]. The European Union (EU) Renewables Directive (Directive 2009/28/EC) [3], as part of the Climate-Energy Package, set legally binding targets for the Member States to collectively achieve a 20% production of total energy consumption from renewable sourced energy by 2020. Each member state is required to meet a proportion of this target based on their circumstances. Committed to achieving a 15% target, the UK has the largest relative percentage increase of all the Member States [4]. Furthermore, rapid growth in the renewable energy sector has led to many new entrants to the market of all sizes in an effort to capitalise on the new opportunities. Achieving the 2020 target is estimated by the Department of Energy and Climate Change (DECC) [5] to cost £110 billion[1].

Biomass is projected to account for approximately half of the new energy production needed to meet the 15% primary energy generation target by 2020 [6][2]. Yet current progress has been much slower than required, especially in the case of renewable heat. With project viability being highly subjective to policy and regulation [7], and meeting finance terms [8]. Combined heat and power (CHP) is the most efficient method of biomass combustion, yet UK capacity only grew by 1% between 2010 and 2011 [9]. Moreover, the ad hoc approach of many private developers pursuing their motives has led to a high number of projects failing principally at the development phase of the project lifecycle [4]. This has created an opportunity for the research to contribute by formalising and supporting the process of decision-making in the early stages of project development.

## 1.2 Biomass

Biomass is defined as "...organic materials of recent biological origin" [10:59] with bioenergy being utilised to define energy derived from biomass [11]. There are many biomass types but these can be broadly categorised as the following major groups, as shown in Table 1.1.

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[1] £75 billon on new generation capacity and £35 billion on upgrading the existing transmission and distribution infrastructure

[2] Technology breakdown (terawatt hours) for central view of deployment in 2010 (excl. renewable transport)

*Table 1.1 – Biomass groups and types* [12]

| Group | Types |
|---|---|
| Wood fuel | Forest wood fuel, arboriculture arisings and sawmill co-product |
| Waste Wood | Clean and contaminated wood |
| Energy Crops | Short rotation coppice, miscanthus, canary grass, eucalyptus |
| Straw | Cereals and oil seed crops |
| Waste | Sewage sludge, MSW (municipal solid waste) and commercial and industrial waste |
| Agricultural Waste | Poultry manure, cattle slurry and pig manures |

Within the body of the thesis, biomass is commonly referred to as a feedstock as it is used as an input to a conversion process. Biomass characteristics can vary widely because of many factors, but the major defining characteristics are the calorific value or the moisture content.

### *Calorific Value*

The calorific value, expressed in gross (GCV) or net (NCV) terms, is defined as the heat released during combustion per mass unit of fuel, with the latent heat from the vaporisation of water included in the gross value and not in the net value [13]. Many European countries utilise the NCV, whereas other countries such as the United States (U.S) use the GCV as a measure of efficiency in thermal systems [13]. Throughout the thesis the NCV is utilised.

### *Moisture Content*

Biomass moisture content varies greatly [11] and depends on many factors including seasonality, storage and composition (especially true for waste feedstocks such as MSW). Typically, biomass has a high moisture content which is expressed on a dry basis [13]. This is calculated simply as a percentage of the wet weight of the biomass minus the dry weight divided by the dry weight. As the level of moisture affects the calorific value of a given volume of a feedstock, within the thesis the calorific value is reported per oven dry tonnes (ODT) to avoid the issue.

The value of biomass as a feedstock also varies widely and depends on several factors. Energy density is a significant factor in the cost but so is commodity classification for those that have a standard, such as wood pellets (EN 14961-2) [14]. These feedstocks tend to have a higher value. Residues from industry or agriculture, especially those without an existing market, or wastes such as MSW have the lowest values. In the case of MSW or wastes that require the supplier to pay a landfill tax for disposal, the purchaser will likely be paid to use the biomass, resulting in a negative feedstock cost or 'gate fee'.

## 1.3 Bioenergy and Combined Heat and Power (CHP)

Bioenergy is a predictable and non-intermittent technology [6], not suffering from the supply issues of wind and solar technologies, although it is dependent on securing a continuous and suitable feedstock to maintain operation which usually incurs a cost not present in the aforementioned technologies. By better utilising the domestic biomass resource to produce energy, it is believed that there will be direct and indirect socio-economic and environmental benefits to the UK [15]. There are multiple bioenergy technologies for providing heat and power but as combustion is the most established commercially available thermal conversion technology [16], it is the one pursued in this research.

### 1.3.1 Combustion Technologies for CHP

Combustion is defined as "…[ideally] the complete oxidation of fuel" [11:11]. The combustion of biomass, and more recently fossil fuels, is the oldest and most widely applied form of energy conversion and is the predominant conversion method for bioenergy, representing over 90% of the global contribution to bioenergy [11]. With complete combustion, the carbon dioxide released from the conversion of biomass is limited to that absorbed by the biomass during its recent life and the process is therefore classified as greenhouse gas neutral [13]. However, there are some other pollutants from the complete or incomplete combustion of biomass that have an impact on the climate and environment [11].

Combined heat and power (CHP) is defined as "… the simultaneous generation of usable heat and power (usually electricity) in a single process" [9]. CHP, also known as cogeneration, differs from the typical UK approach to power generation as it captures the heat by-product from electricity production and utilises it for heating purposes. The most common applications for heat are for hot water, space heating or industrial heating purposes. Back pressure (Fig 1.1) and pass-out steam turbines are the most deployed technology for solid biomass combustion CHP in the UK [9], operating in a Rankine cycle. Back pressure steam turbines expand the full flow of steam to the exhaust pressure required for the site, whereas pass-out (extraction) condensing turbines can extract steam at an intermediate pressure with the remainder being fully condensed [9].

*Figure 1.1 – Schematic of a back-pressure steam turbine bCHP system [17]*

An alternative and rapidly emerging adaption is the use of organic oil as the heat carrying medium in the Rankine cycle instead of steam. Organic Rankine Cycle (ORC) systems may be superior to steam systems at smaller scales as they can operate at lower temperatures and pressure than steam systems and this contributes to lower operational and maintenance costs [18].

It is important to match CHP schemes to the local heat load, as they produce significantly greater volumes of heat than electricity (Table 1.2) and it is not possible to export the heat in the same manner as power to the distribution grid.

*Table 1.2 – Prime mover characteristics*

| Type of plant | Typical output range | Typical fuels | Typical heat to power ratio |
|---|---|---|---|
| Steam turbine[1] | ≥ 0.5 MWe | Any, used to produce steam | 3:1 - 10:1 |
| ORC turbine[2] | ≤ 3 MWe | Any, used to produce steam | 4.2 - 4.9:1[3] |
| Gas turbine[1] | ≥ 0.5 MWe | Natural gas, gas-oil, landfill gas, biogas or mine gas | 1.6:1, up to 5:1 with supplementary firing |
| Gas engine[1] | ≤ 4 MWe | Natural gas, landfill gas, biogas, mine gas | 1:1 - 1.7:1 |

[1] Taken from DECC [19] ; [2] Taken from Turboden [20] ; [3] Calculated as thermal power to hot water circuit / net active power efficiency of the Turboden systems [20]

Typically CHP schemes are developed close to ‘heat anchors’ that provide a somewhat secure and constant heat demand. The most common heat anchors are leisure facilities, hotels or hospitals [9]. A CHP scheme may provide heat to multiple premises but this requires the installation of a district heating network (DHN) which may be costly. In this instance, a heat dense site is ideal to reduce the cost and any system losses. CHP with DHNs also exist in the UK for, but not limited to, residential group heating or Government estate heating applications [9].

### 1.3.2 Operational CHP and Economics

There are currently[3] 1,880 operational CHP schemes in the UK, ranging from micro-scales of < 100 kWe to large scale of > 10 MWe, with the largest being 316 MWe. The operational schemes are predominantly fuelled by natural gas (70%) [9].

*Table 1.3 – CHP schemes by capacity size ranges 2011 [9]*

| **Electrical capacity size range** | **No. of schemes** | **Share of total (per cent)** | **Total capacity (MWe)** | **Share of total (per cent)** |
|---|---|---|---|---|
| < 100 kWe | 535 | 28.5 | 33 | 0.5 |
| 100 kWe – 999 kWe | 1,024 | 54.5 | 250 | 4.1 |
| 1 MWe – 9.9 MWe | 252 | 13.4 | 828 | 13.6 |
| > 10 MWe | 69 | 3.7 | 5000 | 81.8 |
| Total | 1880 | 100% | 6111 | 100% |

The table highlights the breadth of schemes operational in the UK. The scope of this thesis is limited to schemes ranging from 500 kWe to 10 MWe as at the lower end this is the minimum technical size for steam turbines [11, 19] and at the upper end there are decreasing possibilities to fully utilise the heat output. Schemes listed in the Ofgem (Office of the Gas and Electricity Markets) register over 1 MWe, have a total installed capacity of 2,193 MWe of which 1,233 MWe is classed as good quality CHP[4] [9], meaning that heat utilisation is an issue for the operational schemes.

The extent to which CHP, and most energy generating facilities renewable or otherwise, are built depends on two major factors: spark or bark spread economics and the payback term of schemes [9]. The spark or bark spread economics are essentially the gross margin between the wholesale electricity price and the cost of gas or biomass respectively [21], usually expressed in £/MWh. Studies have shown that gas CHP schemes are very sensitive to changes in the gas and electricity prices, which may happen asynchronously [22, 23]. However, biomass schemes face an additional economic challenge as their economic viability is also subject to changes in the feedstock market and in relation to the fluctuating price of gas and electricity. Long term deployment of bCHP (biomass CHP) schemes, especially over the low cost gas incumbent, will only happen when the bark spread is

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[3] 'Currently' meaning the end 2011

[4] See CHPQA in A2.5 in Annex 2

greater than the spark spread. This may occur naturally with rising gas prices or, more likely in the shorter term, increasing Government policy and support for bCHP under incentives such as the renewable heat incentive (RHI).

The minimum levelised unit cost (per MWh) to make a project viable is a more detailed indicator of the gross margin and suitability of an energy project. It is also widely used in industry by a range of decision-makers and therefore is applied within this research as opposed to the spread measure.

*Levelised Cost of Electricity and Heat (LCOE and LCOH)*

Levelised unit cost of electricity (LCOE) and heat (LCOH), also sometimes referred to as levelised energy cost[5], are frequently utilised by decision-makers within the energy industry to assess the viability of potential renewable energy projects and inform policy. The measures' simplicity and usefulness means that they are frequently applied to a wide range of low carbon or traditional fossil fuel generation technologies. The Department of Energy and Climate Change (DECC), the International Energy Agency (IEA), and the National Renewable Energy Laboratory (NREL) frequently apply the LCOE as a viability measure. In the UK, policy decisions are also often informed by levelised unit costs [24].

There are two methods to calculating the levelised unit costs are the discounting and the annuity method. It is possible for the two methods to produce the same output if some assumptions are held for the annuity method. However, as the discounting method is favoured [25, 26], it is the method applied within the thesis. The discounting method is the total present value of the costs divided by the total present value of electricity or heat produced over the project's lifetime. This gives the minimum unit cost of electricity (MWhe) or heat (MWhth) for a project to be viable.

### 1.3.3 Small-Scale bCHP and District Heating Networks (DHN)

Small-scale bCHP schemes are defined within the thesis as ranging from 500 kWe to 10 MWe. CHP is best suited to small-scale decentralised applications as it important to size for the heat and power loads of a specific site [27]. At the upper end of the defined range, a district heating network (DHN) will be required to utilise a significant proportion of the produced heat in order to be viable and

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[5] Within the body of the thesis LCOE and LCOH are utilised for levelised unit costs as LEC is a commonly utilised acronym for Levy Exemption Certificate

maximise production incentive[6]. Furthermore, there will likely be greater levels of unutilised or dissipated heat from the scheme. Heating networks currently supply less than 2% of the UK's heat demand [Ibid cited 28] and predominantly heat social housing, tower blocks and public buildings with fossil fuel CHP due to more favourable economics [28]. Moreover, smaller scale plants have been found to be less profitable than larger schemes [27]. It is also difficult to evaluate the investment opportunity of bCHP schemes due to high costs, high complexity and multiple sources of risk [29].

### *Failed bCHP Schemes*

Roves Energy were awarded a Government grant[7] of £960,000 in 2003 to build a 2 MWe bCHP scheme in the Swindon area that was subsequently withdrawn in 2008 due to lack of progress [30]. Corpach CHP, a partnership between ArjoWiggins paper mill and EPR (Energy Power Resources) Ltd., were similarly awarded a £5m Grant under the same scheme in 2003 to build a 5 MWe bCHP [31] yet the mill was closed in late 2005 [32]. Some schemes were more successful, such as Eccleshall biomass; earlier research [33] recorded this development as a 2.2 MWe CHP in development though it is now an operational 2.6 MWe power only plant [34]. More recently there has been the failed DHN bCHP scheme in Wick. The non-profit scheme started in 2004 with a proposed a 1.5 MWe/ 3 MWth CHP installation for the community that would have significantly reduced the residents' utility bills [35]. In 2011, the scheme was finally wound up with a total cost estimated of £14m in public subsidies without providing any low carbon energy and having to pay for re-converting properties to run on fossil fuelled systems again [36, 37]. Several other failed bioenergy projects have failed due to various barriers [38-40]. Although it is difficult to gather a complete picture of the bCHP schemes in development and operational in the UK, Annex 1 gives a snapshot of some recent schemes that are covered by this thesis.

The number of installed small-scale CHP schemes, utilising predominantly natural gas, shows that there is a market for CHP (Table 1.3). Other non-technological barriers are therefore slowing the development of biomass CHP. Yet DECC [28] has suggested that upgrading the existing gas CHP networks to low carbon alternatives is a future aim for the UK.

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[6] Renewables Obligation Certificate (ROC) uplift certification is assessed on the level of heat utilised in relation to the total fuel input. See Section 5.5.1 or Annex A2.5 for more information

[7] Department of Trade and Industry's Bioenergy Capital Grants Scheme

The cost of energy produced from biomass in comparison to fossil fuel sources such as natural gas or coal is one of the most significant barriers to biomass uptake in Europe [41]. Policy is the most powerful tool for helping to overcome this barrier and an overview of all the relevant policy for bCHP schemes is given in Annex 2.

Traditionally, small-scale RET schemes suffered from a lack of incentive support under the Renewables Obligation (RO) [4, 42] and there was a focus on renewable electricity production not renewable heat. However, the introduction of the renewable heat incentive (RHI) for encouraging heat production from renewable sources is likely to improve the economics for small-scale technologies such as bCHP. Statistics show that greater than three times the number of new CHP schemes were added in 2011 compared with 2010 [9] and this may have been partially influenced by the introduction of the RHI. DECC [43] is also currently consulting for the introduction of a rate specifically for CHP under the RHI that would significantly increase the incentive for production and in turn the economic viability of small-scale bCHP.

## 1.4 CASE Studentship Energy Company

The research project was co-funded by ESRC (Economic & Social Research Council) and EREBUS (Engaging Research for Business Transformation). The CASE (Collaborative Award in Science and Engineering) studentship company was a small to medium sized enterprise (SME) which aimed to develop and operate small-scale bCHP schemes in the UK. The company's vision was to implement and operate up to 10 small-scale bCHP schemes over a five to 10 year period. They were in the development phase of their first project when the research started and received planning permission after a year, but did not manage to develop the project much further than this or to secure project finance. The company went into administration and dissolution over 2012. To maintain confidentiality throughout the body of the thesis, they are referred to as Energy Company.

### 1.4.1 Problem Statement

Energy Company expressed that there was a difficulty for non-expert opportunist developers from SMEs, such as theirs, in analysing the viability and risk of potential bCHP projects in the early stages of development. Therefore, the problem is increasing and supporting the knowledge of this group of individuals without requiring consultancy from industry experts. Ultimately, the support system has to present the information in such a way that it is useable by the developer.

They also stated that it was difficult for an SME such as theirs to devote sufficient time to develop new employees' abilities to the point that they could function independently within the company.

Energy Company also stated that a series of tools that highlighted the variable relationships between feedstock characteristics, conversion technologies and bCHP plant location, would greatly increase the rate of training. Furthermore, they believed that a support tool would also benefit fully competent employees by streamlining decision-making and avoiding a reliance on cumbersome spreadsheets. Over the course of the interviews it became clear that the most helpful form would be an early stage project and risk management support system with the ability to handle uncertain or approximate information.

## 1.5 Aim and Scope of Work

The research aim is to develop a project development and risk management decision support system (DSS) for small-scale (500 kWe to 10 MWe) biomass combustion CHP schemes in the UK, to be utilised by developers, in the early stages of a potential project's lifecycle for the purposes identified in the problem statement. The research objectives, to ensure the aim is achieved, are to:

- $O_1$) analyse the current barriers to small-scale project financed bCHP schemes in the UK;
- $O_2$) review the current body of decision support system literature aimed at addressing the barriers of bCHP project development and risk management;
- $O_3$) develop a decision support system for small-scale bCHP developers at an early stage of project development with a mechanism for handling the uncertain or approximate information;
- $O_4$) implement the resulting decision support system in Energy Company's case study;
- $O_5$) seek further evaluation of the decision support system from industry practitioners.

The research contributes to knowledge on multiple levels by going beyond the problem statement and applying novel methods designed to support decision-making in bioenergy project development under uncertainty or in the presence of approximate information.

## 1.6 Thesis Structure

The structure of the thesis, for the remaining chapters is as follows. **Chapter 2** analyses the barriers to small-scale bCHP project development in the UK with a review of the necessary stakeholders and contracts required. **Chapter 3** systematically reviews the current DSS that address the barriers identified in the previous chapter, identifying the gaps that still exist in the field and supporting this with literature drawn from other disciplines. **Chapter 4** justifies the employed methodology for supporting the developer in project lifecycle planning and risk management in early project development and addresses the critical gaps of chapters 2 and 3. **Chapter 5** justifies the applied algorithms and equations utilised within the DSS for small-scale bCHP project development. The DSS is applied, in **Chapter 6,** to the Energy Company case study along within an analysis of possible contributing factors to the company's failure. The chapter is concluded with a discussion on how the DSS would have supported the company in identifying the barriers and risks associated with their project in the feasibility stage. **Chapter 7** supports the previous chapter by seeking further validation through demonstrating the DSS to several industry practitioners and the results are discussed. Finally, **Chapter 8** concludes the thesis with a discussion on the contribution and areas of further research. There are also 8 annex at the end of the thesis and these cover:

Annex 1: Small-scale bCHP schemes (1 to 10 MWe) recently in development or operational in the UK
Annex 2: Policy specific to small-scale bCHP project development in the UK
Annex 3: Practitioner validation questionnaire
Annex 4: bCHP DSS description
Annex 5 – 7: bCHP DSS project cash flow outputs under different incentives
Annex 8: Software installation instructions

### *bCHP DSS Software*

The bCHP DSS software developed within the body of the thesis and utilised for achieving the research aim is available for installation at the rear of the thesis. The installation instructions (Annex 8) and DSS description (Annex 4) contain all the necessary information required for operating the software. There is also a glossary for the key terms utilised within the DSS at the end of the thesis.

# 2. Barriers to Small-Scale bCHP Project Development in the UK

## 2.1 Introduction

The purpose of this chapter is to highlight the current barriers faced by practitioners in small-scale biomass CHP development. The chapter starts with an introduction to the bioenergy project development lifecycle (2.2) before moving on to the key project stakeholders and contracts (2.3-2.12) required for successfully developing projects. Section 2.13 concludes the chapter with a short discussion and summary of the barriers identified.

## 2.2 Bioenergy Project Lifecycle

The project lifecycle conceptualises the development of a project over time [44]. In the general project management literature, two examples are given by Adams and Barndt [45] and PMBOK [46], and four for renewable energy projects [6, 47-49] as shown in Table 2.1.

*Table 2.1 – Generic and RET project development lifecycle phases*

| **General definitions** | | | **Renewable energy technology definitions** | | |
|---|---|---|---|---|---|
| **Adams and Barndt [45]** | **PMBOK [46]** | **UNEP [49]** | **Carlos and Khang [47]** | **de Jager and Rathmann [48]** | **DECC [6][1]** |
| Conceptual | Starting the project | Planning | Development | Project development | Pre-scoping |
| Planning | Organising and preparing | Construction | Construction | Financial closure | Scoping |
| Execution | Carrying out the work | Operation | Operation | Construction | Application |
| Termination | Closing the project | | | Operation | Consent (planning) |
| | | | | Decommissioning | Logistics |
| | | | | | Development |
| | | | | | Operate |

[1] Refers to the stages for biomass non-domestic boilers as there was not a category for biomass CHP

DECC [6] had by far the most phases within the lifecycle with particular attention to the planning application and consent. They also make a distinction between the pre-scoping and scoping phases of the project lifecycle, reserving pre-scoping to the viability analysis conducted by the project sponsors before proceeding to the actual scoping phase. This implies that there must be an additional resource or cost commitment within the scoping phase before application. de Jager and Rathmann [48] explicitly define the financial closure of the project as a lifecycle phase but this was not the case for the other three categorisations. Furthermore, it is also worth noting that neither [49], Carlos and Khang [47] or DECC [6] have included the decommission (end of project lifecycle) phase.

As a project moves through its lifecycle, the level of risk and uncertainty decreases (Fig. 2.1) but this is usually at an increasing cost to the project. For example, the development costs are much lower than the construction costs, as is the financial impact of a change in or abandonment of a potential project at each phase [49].

*Figure 2.1 – Impact of risk and uncertainty on project time [46]*

As the project progresses, the sponsor is required to decide whether to continue with the venture, by likely investing more resources, or to abandon the project. This decision will depend on whether they can achieve the project objectives.

As covered in the problem statement, achieving the research objective requires the decision support system to aid the developer in the early stages of development when the project risk and uncertainty is high yet the cost of changes are minimal. Carlos and Khang [47] in their analysis of the pre-feasibility study, the first stage in the development phase (Table 2.2), highlights the broad range of activities conducted.

*Table 2.2 – Pre-feasibility study and project appraisal and investment decision stages in detail [47]*

| **Stage** | **Key activities** | **End products** | **Success criteria** |
|---|---|---|---|
| Pre-feasibility studies | Resource/fuel assessment | Feasibility study | Studies responds satisfactorily to all the requirements of the terms of reference |
| | Market assessment | | Studies recommend project viability considering all aspects of the project |
| | Environmental assessment | | |
| | Technical design, preliminary engineering | | |
| | Risk analysis | | |
| | Financial analysis | | |
| Project appraisal and investment decision | Validate results of feasibility study | Investment decision | Feasibility study validated and confirmed satisfactorily |
| | Identify and check assumptions used in feasibility study | | Project meets investment criteria of owner |

The broad range of activities reaffirms the level of uncertainty and risk in early pre-feasibility studies. A financial feasibility analysis is usually in the form of a cash flow projection of the possible revenues and costs over the scheme's lifecycle and this forward projection requires information of the projected operational assumptions. Within the operational phase of the lifecycle, the UNEP [49] report states there are likely to be several key risk sources, including: technology, market, supply, operating, political, legal and regulatory, financial and counterparty risks. They also add that determining a project to be not feasible in the feasibility study should not necessarily be viewed as a negative outcome, as it is better to identify this at the early stage before more funds have been committed.

### 2.2.1 Project Success Criteria

The key project success criteria are typically defined by the time, cost and quality project objectives, which are often referred to as the 'iron triangle' [50, 51]. These three core objectives have been shown from an empirical study of 236 project management practitioners to be by far the main criteria for judging project success [52]. Early research shows that this has been the case for at least past few decades, with Adams and Barndt [45] stating that the project's goal is defined by three things: a predetermined performance specification; time constraints and budget limitations. However, research has also found that many projects still suffer from significant cost and time overruns [53, 54].

de Wit [55] argues that time and cost targets may not be the most suitable method for measuring project success as there are projects that overrun on both objectives and are still considered successful. In the research context, these 'success' criteria are considered differently; achieving acceptable or viable cost and project duration objectives means that the project could be pursued by the developer. In the study of Carlos and Khang [47], one of the few sources on RET project development objectives, the interpretation of the critical success factors broadly agreed with the typical criteria. However, they then go further by creating specific success factors for each stage within the lifecycle, as partially covered in Table 2.2. The IEA-RETD [56] report also highlights the typical three objectives with the addition of safety and environmental impact for RET project risk management. They added that the cost and scheduling (time) objectives were critical as they are used for the project cash flow and to attract investment. Developing a bioenergy project requires large volumes of complex information to be gathered and processed by project developers. Moreover, this information tends to be fairly structured and accessible; although often not easily retrievable for use in a timely manner [57]. Finally, a study by Zwikael and Sadeh [58] found that increasing the quality of project planning in high risk projects increased the possibility of achieving the project objectives.

## 2.3 Project Stakeholders and Contracts

To successfully develop a project it is necessary to have contracts or agreements with several key stakeholders [59, 60]. Although there may be some different stakeholders and contracts required [49] depending on the type and size of the project, the problem is essentially similar, as shown in Figure 2.2.

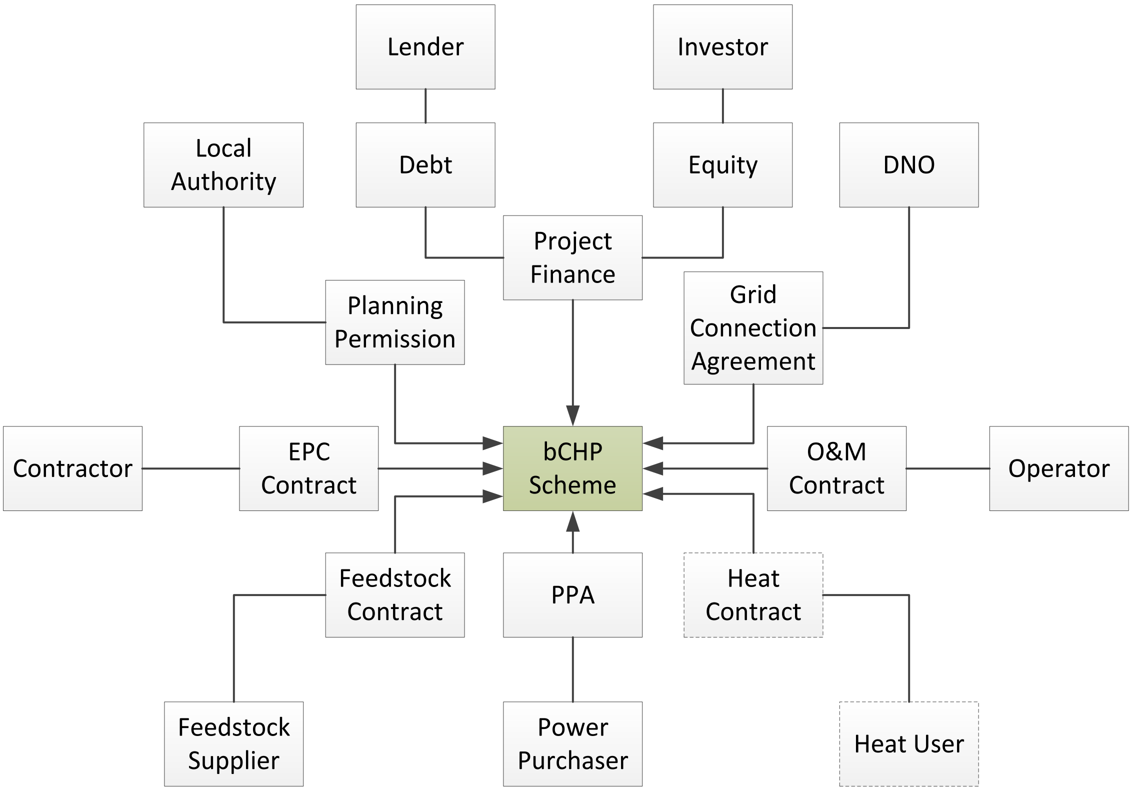

*Figure 2.2 – bCHP scheme stakeholders and contracts (adapted from* Yescombe [60]*)*

The simplified figure highlights the key stakeholders[8] required for project financing a bCHP scheme. The strength of the contractual arrangements between the parties is particularly crucial in securing project financing [61]. In some instances, there are multiple stakeholders e.g. heat user(s) or investor(s). Within the figure and covered in greater detail in Section 2.10, the heat user and heat contract are dashed to highlight a critical barrier specific to bCHP schemes. In the following sections,

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[8] Insurance has been excluded from the figure but has been applied in other research, as it is likely a condition of the lender

each stakeholder and their relationship to the project is covered in turn, along with the possible issues and barriers identified within the literature.

## 2.4 Project Finance

The two methods for asset financing projects are corporate and project financing. Corporate financing is on-balance sheet financing which de Jager and Rathmann [48] states is the more utilised method of finance and can be more favourable as lending terms are based on the risk of the company rather than the individual project. In cases where there is insufficient capital within the organisation to fund the project under corporate financing or the project sponsor lacks the necessary ‘track record’ to secure additional funding through the company, project financing is the alternative option. With project financing, capital is raised from a combination of debt, equity and credit sources and the loan structure relies on cash flows for payment and assets for security [62]. Project financing can be beneficial to small to medium scale developers as there is limited or no financial recourse, meaning they could pursue several projects without negative company-wide impacts [8]. Project financing is the method assumed in this research, although many parallels can be drawn with corporate financing. The main types of capital for project finance can be generally categorised as:

- senior debt;
- subordinate debt (mezzanine finance);
- equity.

Capital structure, often expressed as a ratio, is the mixture of debt and equity used to finance a project [8]. A project’s capital structure has a direct effect on the levelised unit cost when finance repayment and necessary covenants are included, as debt tends to be less costly than equity and is therefore generally preferred. The gearing of debt to equity is negotiated between the project sponsor and the lender and is subjected to many factors such as market expectations and project risk [63]. Typically, the lender is the primary enforcer of contracts to reduce risk exposure and will assess the track record or credit-worthiness of each party before choosing whether to lend [49].

### 2.4.1 Lender

Debt is a secured loan typically provided by banks. Lenders are typically risk adverse and wherever possible attempt to reduce unnecessary exposure as there is no financial reward for not doing so (unlike equity investment) [61]. Fabozzi and de Nahlik [63:67] cover the key characteristics a lender desires in a good project and sponsor:

- a professional and thorough feasibility study and financial plan;
- experience and track record in the contractor and operator;
- an assured market for the product [heat and power];
- recognition of political and country risks with an appraisal and control plan;
- confidence and continuity in the project manager and the management team;
- excellent reputation of the project management team;
- confidence and continuity in the operation and financial management of the plant throughout the project;
- confidence that there will be a high level of communication and that all necessary financial information will be given in the correct format and in a timely manner;
- the sponsor needs to have financial substance, be motivated by adequate profits made through dividends, and have had experience with project financing in the past and the potential problems ahead.

Debt finance terms are stipulated in the 'term sheet' issued by the lenders. This term sheet states the debt interest rate, debt term, maximum debt-to-equity ratio and necessary levels of debt service cover. Debt is repaid over the debt term in the form of a debt service payment; this is the principal and interest, usually paid annually. The additional cash flow required over the debt term is to protect the debt service payment if any unforeseen risks should occur or the project performs less well than expected. This is referred to as the debt service cover (DSC) and is calculated as a ratio (DSCR) of the net operating income divided by the debt service payment. The two main types of debt accessible to sponsors are senior and subordinated debt.

### *Senior Debt*

Senior debt constitutes the largest proportion of the capital structure and is not subordinate to any other liability [63]. By being the most senior liability for the project, it is the least costly form of finance.

### *Subordinated Debt (Mezzanine Finance)*

Subordinated debt is defined as "…fixed rate, long-term, unsecured and may be considered as equity by senior lenders for the purposes of computing debt-to-equity ratios" [63:100]. As it is unsecured and junior to senior debt, it often requires a higher rate of interest to be paid. In instances where the traditional senior debt and equity portions of the finance do not amount to the total capital required, subordinated debt can allow the project to go ahead, although the company would need to have sufficient cash flow to cover this additional capital cost.

### 2.4.2 Equity Investor

The equity investor may be the project developer or a third party investor and would want to ensure the project produces the projected return on its investment [49]. Equity is capital invested into the project by an investor or investors who are typically issued with shares and paid in return in dividends. Dividends are normally paid from the 'free cash flow' which is the cash flow after all operating expenses and debt have been serviced [59]. Equity investors are the last in priority of repayment [63] and are far less risk adverse as it is possible to have unbounded returns from the success of an investment [61].

Lenders require equity to constitute part of the capital structure of a potential project when project financing. As stated by Fabozzi and de Nahlik [63], equity is deemed by lenders to provide a 'margin of safety' by reducing the effect and size of the debt service on the project cash flow and by increasing the sponsors commitment to the project.

Dunlop [64] deconstructed the likely return on equity (ROE) threshold for equity investors in operational or near operational wind projects into its components. This was later updated by de Jager and Rathmann [48] and both are shown in Table 2.3.

*Table 2.3 – ROE components*

| **Component** | **Dunlop [64]** | **de Jager and Rathmann [48]** | **Description** |
|---|---|---|---|
| Risk free rate | 3% | 3 to 5% | Equivalent to 10 year Government bonds |
| Risk premium | 4% | 4 to 5% | Similar asset classes to wind power: water funds, comparable shipping deals etc. |
| Equity fund fees | 2%,3% | 2%,3% | Fund management fees and illiquidity premium as the stock cannot be sold easily |
| Technology premium | 3 to 5% | 3 to 15% | Technology risk premium, Dunlop states that established technologies, such as wind power, may not receive the premium |
| Regulatory premium | -3 to 3% | -3 to 3% | Regulation risk relating to support schemes and the energy market |

The estimates in Dunlop's [64] paper are typically lower than that of de Jager and Rathmann [48], this is possibly because his work was before the global financial recession. Dunlop [64] also mentions that it would be necessary in future for equity investors to accept the 'considerable' development risk of RETs, particularly in securing planning permission and grid connections.

## 2.5 Developer

Developers "…are concerned with operability and implementation of bioenergy conversion plants…" [65]. There are different types of developer and they will have their own motivation and objectives from a project. This may influence their approach to project development and to what they consider a successful project. A developer may also be the project sponsor if they have equity invested into the scheme or they may be a third party. A private 'for-profit' developer would place a greater emphasis on the return of the project as an investment opportunity. Their investment 'hurdle' rate would generally be higher than projects such as community or non-profit schemes. For example, community scheme developers would most likely have less of a 'commercial' interest as they are serving the community members [66].

Several barriers have been defined for developers, though the degree to which they impact may differ depending on the developer type. Risk in the development phase [64] and development or operational cost uncertainty were classified as significant barriers to bioenergy project development [65]. Project scoping viability was also identified as a significant barrier to the deployment of electricity only dedicated biomass power plants [6]. Furthermore, the DECC report goes on to add that the relatively long lead time for the development of biomass projects reduces financier confidence in Government policy, to the extent that it may hinder projects in the development phase. All stakeholders in an industry wide stakeholder analysis for the 2012 UK Bioenergy Strategy stated that they wanted the Government to set clear policy and to be mindful of this issue when making policy decisions [67]. Finally, the development of EfW (energy from waste) combustion plants faces additional barriers, namely from the increased level of public opposition [6].

## 2.6 Local Authority and Community

The Local Authority (LA) and community are key stakeholders to potential schemes as they strongly influence whether or not planning permission is granted. The LA is also responsible for administering the pollution control regime under the Clean Air Act 1993 [68] for non-waste biomass schemes under 20 MWth or waste biomass schemes under 3 MWth. Guidelines for local planning authorities to adhere to are set out in the Planning Policy Statement 22 [69]. Small-scale energy developments are specifically referred to and should be encouraged by local planning authorities through positive policies and local documents.

Local policy and community opinion has been shown to be a critical success factor for projects [70]. The most common barrier faced by developers with regard to this group is, what is often referred to as, NIMBYism [39, 41]. The ‘not in my backyard’ opposition of the local community in some instances was actually found to be a concern that the project only served to economically benefit the developer [39]. Rösch and Kaltschmitt [41] developed a list of some of the key concerns of local residents, such as the effect on:

- traffic;
- local employment;
- local and regional environment;
- attractiveness and image of the community.

However, community energy schemes have been shown to have less public opposition and a more positive perception generally [66, 71]. Local developers have also been found to be more trusted than national ones [72].

### *Planning Permission*

Planning Permission is considered a significant barrier to dedicated biomass project development in the UK Renewable Energy Roadmap [6]. Obtaining planning permission has for a significant time been a major barrier for bioenergy project development [Upreti and van der Horst, 2004 cited 4, 39, 72, 73], with research in the onshore wind sector showing the number of permission granted by appeal being alarmingly high, as is the non-reclaimable cost associated with the appeal process [74]. This is also the case more generally, and an issue in the UK Renewable Energy Strategy [4].

## 2.7 EPC Contractor

An EPC (Engineering, Procurement and Construction) or ‘turn-key’ contractor is the major contractor for the engineering, procurement and construction of the plant. EPC contracts are the most prevalent method employed in projects of this type, as financiers of biomass projects have been cautious and tend to ‘offset’ risk with EPC contracts [6]. The competencies, reliability and experience of the EPC contractor are defined as key success criteria [47]. In the case of the ARBRE gasifier project (2002), the EPC contractor suffered financial problems that not only delayed the plant but eventually contributed to the project failing [75].

### *Engineering Procurement Construction (EPC) Contract*

There are a range of standard construction contract types in the UK, and their use within the construction industry is common place [76]. Several bodies have produced their own form of contract and Conditions of Contract, but the one referred to in this thesis is the International

Federation of Consulting Engineers (FIDIC) form of contract. EPC/turnkey contracts are covered in the FIDIC Silver Book [77].

Contract types are primarily defined by their payment mechanism. In the EPC contract, the contractor is typically paid on a lump sum basis [76]. A lump sum is a fixed price agreed to carry out the specified construction work and it may be paid toward the end of construction or in instalments, depending on the agreement [76].

The primary mechanism for risk allocation within a project is the Conditions of Contract [53]. Within the EPC contract, the contractor is allocated most of the common risk within the project [76]. Contractors typically add a risk premium in the form of a contingency margin within the total project cost [78], though it is argued that this premium is often simply an arbitrarily chosen percentage of capital expenditure [53]. An Energy Company project stakeholder meeting suggested that the EPC contractor margin could be up to 20% of the project cost[9]. Moreover, high construction costs are considered another barrier to market energy for RETs [5].

## 2.8 Operator

The operator may be the project developer, one of the project sponsors or a third party chosen to run the scheme [49]. Mott MacDonald [79] states that the operating costs for small-scale CHP are likely to be higher than for power only plants with higher annual fixed costs (per MW) than larger, utility scale plants. Effective operations and maintenance (O&M) is essential for the operator to achieve the levels of performance required to meet availability and projected economic benefits [80].

### *Operations and Maintenance (O&M) Contract*

Operations and maintenance includes the “...fixed costs of operation, maintenance and administration (staff, insurance, etc.) and the variable costs of operation and maintenance, and repair (consumables, spare parts, etc.)” [81:12]. Stanford [82:108] states that CHP plant maintenance is highly complex and in most cases the owners tend to contract with the OEM (original equipment manufacturer) or a specialist third party contractor. However, this does not create a significant barrier to development and operation.

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[9] Project stakeholder meeting 20th January 2011

## 2.9 Feedstock Supplier

The feedstock supplier is a key project stakeholder as the largest operational expense is, in most cases, the supply of biomass. Adams, Hammond [65] noted several barriers to greater feedstock supply, with the most significant being competition with other investments, the uncertainty of funding and return on investment. Moreover, a drive toward enforcing sustainable biomass feedstocks under the production incentives [15, 67, 83] is believed may cause potential longer-term issues for the bioenergy sector. Feedstock sustainability and supply of sustainable feedstock are therefore possible barriers to future uptake [6]. The NNFCC [84][10] also found that certain feedstock markets are inaccessible because of a lack of supply chain infrastructure in the case of waste wood, or uneconomical as the incentive is too low (large scale RHI Tariff) in the case of industrial pellets.

### *Feedstock Contract*

Financiers typically attempt to reduce risk here, in a similar way to the EPC contract, by demanding a long-term feedstock supply contract [6]. In order to secure debt finance it is necessary for the feedstock supply contract length to match the duration of the debt-servicing period. E4tech [85] interviewed several industry professionals and found that long-term contracts can range from 5-15 years with 10 being the average – possibly due to this being the typical debt term. They also found that the majority of dedicated biomass power plants have or desire to have a long-term contract to secure supply and little is bought on the spot market, but only a few suppliers are able to offer long-term or indexed-linked contracts. The added security of a long-term contract does however restrict the developer to only use the contracted feedstock and not benefit from any favourable changes in the feedstock market. Hence why co-firing or EfW plants do not wholly contract for their required supply and purchase on the spot market [85]. Furthermore, as the sustainability criteria for biomass is under consultation, securing the required long-term feedstock contracts is risky as there is insufficient clarity in the current and future sustainability criteria [15].

## 2.10 Heat User

A heat user is defined as a potential purchaser of the heat from the CHP scheme. Acceptable uses, in the context of the RHI, are space and hot water heating, commercial or industrial heating requirement or other economically justified requirements [83]. The Enviros [86] report for BERR[11] on

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[10] National Non-food Crops Centre

[11] Business, Enterprise Regulatory Reform: disbanded and replaced with BIS (Business, Innovation and Skills)

the barriers to renewable heat found significant demand-side uptake barriers for non-domestic applications, these include:

- retrofitting costs;
- consumer confidence and perceived hassle;
- lack of skilled advisory personnel.

If a district heating network (DHN) is required to supply multiple heat users, the installation cost in new and retrofitted applications is a significant supply-side barrier [86], with DECC [28] estimating that the installed cost of district heating pipe may be as high as £1000 per metre. Poyry [87] attributes this high cost to several factors, including: high cost of laying the pipe; no UK pipe system manufacturing; lack of experience in the technology and overestimated construction risk contingency.

Consumer attitude is also a significant barrier. The NNFCC [84] report to DECC found that there is an unwillingness to sign heat off-take agreements and a belief that the necessary contracts to cover project financing would lead to a monopoly once established. DECC [28] suggests that increasing scale in DHNs may help to increase the attractiveness to investors and allow smaller heat users to connect on potentially shorter term or competitive contracts. However, this creates possible DHN sizing issues regarding the guaranteed base load and the possible load achievable [87], and potential large heat users that could act as an anchor heat load are often committed to long-term energy contracts [29]. Finally, Element Energy [29] found that that competition with the relatively low-cost incumbent and long-term return of DHN schemes act as a further disincentive.

### *Heat Off-take Contracts*

Due to the cost of installing a DHN, the payback period could be up to 20 years and therefore it is essential for the developer and potential financiers to have a high degree of confidence that there will be a sufficiently secure heat demand [28]. This is a complex problem to manage as it then becomes necessary to have a robust long-term heat off-take contract with one or multiple credible heat users to secure finance [79, 87]. Furthermore, the problem increases in risk the greater the number of private sector users [87]. This problem is noted by DECC [28] who add that this can be ensured by long-term contracts with low risk customers, such as public sector buildings and social housing. The majority of operational schemes in the UK fit into this category.

## 2.11 Power Purchaser

The power purchaser is a licensed supplier of electricity, who most likely has an obligation under the RO, or an aggregator [5], the most dominant being the ‘big six’ licensed electricity suppliers, however there are a total of 75 possible UK suppliers that are required under the RO to purchase a specified quota of electricity from renewable sources [88].

Often generators, that fall outside the Electricity Order 2001[12] [89], cannot directly supply electricity unless they are a licensed supplier and this has been too complex and costly for small-scale generators to pursue [5, 90]. However, Ofgem and DECC[13] have been working to reduce these barriers and further support small-scale suppliers in distributed energy generation by adjusting the Electricity Act 1989 [91] to better reflect a change in the private market since its inception [90]. Moreover, this helps to reduce the access to market barriers felt by generators [92], although the supply of electricity to consumers is likely to pose the same difficulties as heat sales (Section 2.10), as secure, long-term fixed off-take contracts would still be necessary for acquiring finance.

### *Power Purchasing Agreement (PPA)*

A power purchasing agreement (PPA) is typically a remuneration contract with an energy supplier or aggregator for electricity production, the associated incentives (such as ROC & LEC[14]) and other embedded benefits [92]. This contract is also subject to transaction costs by the supplier and a discount for the added long-term contract security [92], and this can be up to 10% of the market value of the electricity or associated incentives [93]. As with the other stakeholders, small-scale independent generators tend to require the same long-term, secure contracts to secure finance [94].

A survey of small-scale generators by Ofgem [92] found that new projects usually require longer term PPA contracts of a minimum of five years but usually up to 15, and those generators without still prefer to contract for the sale of power on an annual basis. They also found that although some generators overestimated the value of their power, they were generally content with the contract terms. Interestingly, they found that ROCs (Renewables Obligation Certificates) and LECs (Levy Exemption Certificates) were at least equally important, if not more important to a generator than the power produced. This is likely the case for three reasons: the current short-term PPA price for

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[12] Refer to Annex 2 under Section A2.4

[13] Previously BERR until disbanded

[14] Renewables Obligation Certificates (ROC) and Levy Exemption Certificates (LEC). See Section 5.5.1 or Annex A2.5 for more information

exported electricity is circa (c.) £40/MWhe[15] but the current ROC and LEC values per MWe far exceed this; the electricity supplier incurs a penalty if the Renewables Obligation quota is not met; and ROCs and LECs are tradable. However, a more recent call for evidence on long-term contracts indicates that developers feel the PPA market has severely worsened to the point of potential investment hiatus [94].

Due to the importance of the RO in driving the industry, developers and generators are worried that with the incentive being vintaged[16], conditions could become increasingly difficult for independent generators as there would no longer be sufficient motivation for suppliers to enter into PPAs to meet a quota [5].

## 2.12 District Network Operator (DNO)

The District Network Operator (DNO) is defined as a "…company responsible for the operation and maintenance of a public electricity distribution network" [95]. To attach a potential generator to the distribution network, a considerable amount of communication is required between the two parties [95]. Small-scale schemes are connected to the distribution grid, as opposed to the transmission grid for larger schemes, and therefore the DNO is the key stakeholder.

Each DNO possesses monopolistic operation in their region, and DNOs are therefore strictly controlled by Ofgem. Ofgem sets the maximum revenues allowed over a term, currently 2010 to 2015 under DPCR5[17], and actively attempts to remove market entry barriers for generators [96]. However, the recent survey by NNFCC found that the cost and timing of grid connections still remained the most significant barrier for developers [84]. An Ofgem [97] forum held in 2011, found that several industry stakeholders required greater information on the connection process and greater cost transparency from the DNOs. They also found the different approaches to charges and payment schedules for generators frustrating.

### *Grid Connection Agreement*

The DNO is obligated to offer terms for the connection of the proposed generator as stipulated under the Electricity Act 1989 [91] as a condition of their license [98], although DNOs have been

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[15] Interview with an Operations Manager at a biomass power station (September 2012)
[16] Not eligible for new schemes from April 2017
[17] The fifth Distribution Price Control Review (DPCR5)

previously accused of not approaching the connection of distributed generators in a “sufficiently positive way” [12].

The agreement has a number of parts that cover the connection, adoption, operation and/or use of the distribution network under the ‘Use of System’ [95]. The connection agreement charges include the initial cost of the connection work and the potential O&M costs, as well as any necessary network extension or reinforcement costs [95]. A key example is given by the DTI [95] for uncertain time scales and costs due to a DNO requiring consent under the Electricity Act 1989 [91] from land owners and local planning authorities for the installation of new lines [99]. Any opposition by land owners may require more drastic (land acquisition & Wayleaves)[18] and in turn costly action that ultimately resides with the developer, as the DNO is entitled to a reasonable return on their investment [96]. Furthermore, the adoption and operation agreements stipulate the control and ownership of the new assets and the interface between the network and the generating plant [95]. Finally, a distribution Use of System (DUoS) charge is incurred by the consumer for utilising the distribution network; this accounts for approximately 20% of the wholesale price of electricity [96]. It is not a cost incurred by generators in England and Wales as they have paid for any additional or future costs with the O&M agreement [95].

## 2.13 Conclusion

The Carlos and Khang [47] activities in Table 2.2 highlighted the broad breadth of key activities required to fully analyse the feasibility of a potential project in the early stages of development. The main project success objectives for most projects are delivering a project on schedule, on budget and to the quality required [45, 50-52]. However, schedule and cost overruns are still common [53, 54] and critical to renewable energy project development [56]. Furthermore, bioenergy projects are complex [57] and would benefit in terms of achieving the project objectives if there were better quality project planning [58]. To conduct a feasibility study it is necessary to forecast, with limited information, the potential project over its lifecycle. The quality of forecasting during the operational phase is critically important as this ultimately determines whether the project is viable in achieving the schedule and cost objectives. This process exposes the project to a diverse range of risk sources [49] that need to be considered.

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[18] Schedule 3 and 4 of the Electricity Act 1989

Lenders provide the largest proportion of capital and enforce the requirement for contracts that meet their standards and match the debt term to reduce their risk exposure [49, 61]. They also desire several key characteristics from a project developer, including having a thorough feasibility study and financial plan, and ultimately confidence in the project moving forward and handling future risk exposure [63]. Hence, it is also necessary to incorporate a risk management method, linked to the key project success objectives, to support developers in the feasibility study stage.

The aim of the research is to support developers by minimising the problem defined in the problem statement (Section 1.4.1) whilst also maximising the removal of the unaddressed barriers identified within this chapter. The research has achieved its first objective ($O_1$) by analysing the current barriers to small-scale bCHP schemes in the UK. Furthermore, many of the barriers covered can be wholly or partially quantified in either the project finance, scheduling objectives or within a risk management process. The literature review (Chapter 3) supports the research direction by critically evaluating the work to date in achieving these objectives and in removing the barriers identified within this chapter and summarised in Table 2.4.

*Table 2.4 – Summary of small-scale bCHP scheme project development barriers*

| **Developer** | **Local authority and community** | **EPC contractor** | **Feedstock supplier** | **Heat user** | **Power purchaser** | **District network operator** | **Operator and maintenance** |
|---|---|---|---|---|---|---|---|
| Development phase risk [64] | Local policy and community opinion – success factor [70] | Competencies, reliability and experience of the EPC contractor – success criteria [47] | Supply side – competition with other investments, uncertainty in funding and ROI [65] | Consumer confidence, perceived hassle and contract length [79, 84, 86, 87] | Complexity and cost of distributed generation [5, 90] | Cost and timing of grid connections [84] | Slightly higher costs [79] |
| Development or operational cost uncertainty [65] | NIMBYism – or genuine concern and motive [39, 41] | High construction costs and contingency margin [5] | Sustainability reporting drives [15, 67, 83] | Lack of skilled advisory personnel [86] | Access to market [92] | Information on the connection process [97] | |
| Project scoping viability [6][1] | Planning permission [4, 6, 39, 72, 73][2] | | Lack of supply chain infrastructure [84] | Retrofitting and DHN cost [86, 87] | PPA market conditions and terms [94] | Cost transparency [97] | |
| Long lead times [6] | | | Securing the necessary contract length [85] | Investment payback and attractiveness [28] | End of the RO [5] | Negative approach by the DNO [12] | |
| Government policy confidence [6] | | | Not able to utilise the spot market [85] | | | | |
| Government to set clear policy [67] | | | | | | | |
| EfW public opposition [6] | | | | | | | |

[1] Electricity only plants; [2] Upreti and van der Horst, 2004 cited in Upreti and van der Horst, 2004

# 3. Bioenergy Project Development and Risk Management Literature Review

## 3.1 Introduction

The chapter introduces decision support systems along with an insight into the classification, evolution and applications of the discipline (3.2). As the literature is systematically reviewed to ensure a thorough and unbiased analysis of the problem-based research question, it is necessary to cover the methodology applied (3.3). The following sections of the chapter analyse the systematic review results, along with any supporting or grey literature for project financial (3.4), scheduling (3.5) and risk management models (3.6). The chapter also analyses some key commercially available DSS (3.7) and then concludes with an analysis of the existing gaps (3.8).

## 3.2 Decision Support System (DSS)

The term 'decision support system' was coined by Gorry and Scott-Morton [100] when suggesting a framework for improving management information systems (MIS), but before this name had formally 'stuck' there were several different similar terms to refer to this new field [101:1]. The most comprehensive definition of a DSS is given by Eom [101:11], which draws on other definitions over the past four decades, he states that "...a DSS can be described as a computer-based interactive human-computer decision-making system that:

- supports decision makers rather than replaces them;
- utilises data and models;
- solves problems with varying degrees of structure;
- focuses on effectiveness rather than efficiency in decision processes (facilitating decision processes)"

The vagueness of this definition most likely stems from the diversity of applications since the beginning of the discipline.

### 3.2.1 Taxonomy

In 1980, in an effort to clarify the characteristics of the discipline, Alter [102:73] created a taxonomy of decision support systems that built on the earlier attempts at classifying the field by Gorry and Scott-Morton [100] and Anthony [103]. To create the taxonomy 65 systems were sampled, which Alter felt most of the sample fell 'reasonably' into seven categories (Table 3.1).

*Table 3.1 – Alter's DSS classifications [102:77-88]*

| | **File drawer systems (a)** | **Data analysis systems (b)** | **Analysis information systems (b)** | **Accounting models (d)** | **Representation models (e)** | **Optimisation models (f)** | **Suggestion models (g)** |
|---|---|---|---|---|---|---|---|
| Operation | Access to data items | Ad hoc analysis of files of data | Ad hoc analysis involving multiple databases and small models | Standard calculations that estimate future results on the basis of accounting definitions | Estimating consequences of particular actions | Calculating an optimal solution to a combinatoric problem | Performing calculations that generate a suggested decision |
| Task | Operational | Operational or analysis | Analysis, planning | Planning, budgeting | Planning, budgeting | Planning, resource allocation | Operational |
| User | Non-managerial line personnel | Staff analyst or non-managerial line personnel | Staff analyst | Staff analyst or manager | Staff analyst | Staff analyst | Non-managerial line personnel |
| Usage Patten | Simple inquiries | Manipulation and display of data | Programming of special reports, development of small models | Input estimate of activity; receive estimate monetary results as output | Input possible decisions; receive estimated monetary or other results as output | Input constraints and objectives; receive an answer that maximises the objective consistent with the constraints | Input a structured description of the current instance of a repetitive decision situation; receive a suggested decision as output |
| Time Frame | Irregular use, but can be used daily | In some cases, irregular; in others, daily, monthly, quarterly, or yearly | Irregular, on request | Often periodic, e.g., weekly, monthly, yearly | Either periodic, as part of an ongoing process, or irregular, as a tool for ad hoc analysis | Either periodic, as part of an ongoing planning process, or irregular, as a tool for ad hoc analysis | Daily use in some cases periodic in others |

It is also stated by Alter [102] that this taxonomy could be reduced to either a data or model-orientated DSS: data-orientated systems (*a. to c.*) are typically utilised at a non-managerial, operational level; whereas, model-orientated systems (*d. to g.*) are utilised at a managerial or analyst level with a focus on planning and resource allocation. The model-orientated tools tend to be used periodically or irregularly, the exception to this is the *suggestion model*, which has clear daily operational applications. As this research only requires model-orientated decision support tools, the data-orientated systems are no-longer addressed.

### 3.2.2 Evolution

As with any discipline, there is an evolution of the theory and areas of interest or application, and this is shown visually over a 40 year period in Figure 3.1.

*Figure 3.1 – DSS type evolution [104]*

Although it is not necessary to discuss all of the nodes in the DSS evolution figure, it is important to describe the key types of support system. Arnott and Pervan [104] found that the discipline is still predominantly focused on ‘personal DSS’, but some of the newer types are making inroads and these are introduced in Table 3.2.

*Table 3.2 – DSS types [104]*

The support system created for this research spans the *representation* and *optimisation* categories in Alter's classification (Table 3.1) which is fairly common as the majority of decision support systems in use today are in these categories [101].

### 3.2.3 Model-Oriented Characteristics

Decision support systems have several key characteristics, which have evolved significantly with the discipline over the past four decades [105]. This section briefly discusses the composition of what Alter [102] classified as a model-orientated DSS.

#### *User Interface*

The user's interface has developed greatly, Bennett [106] states that a computer screen, keyboard and a printer form the tangible components of the user interface, and basic computer code questions; requiring yes or no answers. Although the user's interface with the terminal has not changed much, it is no longer as simple as this, with much emphasis placed on the usability of a DSS and software selection. This is especially important with non-expert or trainee users of the system as this is likely to be integral to the decision support system's acceptance.

#### *Modelling Tools*

Model-oriented systems tend to utilise management science and operational research (OR) methods to achieve the necessary solution with these methods becoming increasingly 'embedded' in the support systems [101].

*Table 3.3 – Distribution of methods [adapted from 101:399]*

| | DSS sampling period | | |
|---|---|---|---|
| | **1971 - 1988** | **1988 - 1994** | **1995 - 2001** |
| Deterministic Model | 85 | 132 | 99 |
| Linear programming (LP) | 18 | 28 | 27 |
| Goal programming | 9 | 5 | 4 |
| Transport model | 6 | 18 | 1 |
| Network model | 15 | 23 | 17 |
| Inventory model | 8 | 7 | 3 |
| Integer programming (MILP) | 19 | 32 | 34 |
| Nonlinear programming (N-LP) | 6 | 11 | 6 |
| Dynamic programming | 4 | 8 | 7 |
| | | | |
| Stochastic Model | 58 | 57 | 41 |
| Queuing model | 3 | 1 | 2 |
| Markov process model | 6 | 4 | 3 |
| Simulation models | 41 | 41 | 28 |
| Decision trees/Game theory | 9 | 11 | 8 |
| Other stochastic models | - | 3 | - |
| | | | |
| Forecasting and statistical models | 40 | 47 | 39 |
| | | | |
| Others | 104 | 345 | 328 |
| Other MCDM[1] | 11 | 67 | 28 |
| MADM[2] | 5 | 43 | 10 |
| MOLP[3] | 5 | 10 | 1 |
| AHP[4] | 1 | 12 | 16 |
| Nonlinear goal programming | 0 | 2 | 1 |
| Spreadsheet models | 24 | 22 | 8 |
| Graphics | 46 | 81 | 18 |
| Artificial intelligence | 12 | 73 | 96 |
| Visual interactive modelling | 0 | 40 | 46 |
| Query language or 4GL[5] | 0 | 21 | 23 |
| Others | 0 | 41 | 109 |

[1] multi-criteria decision making; [2] multi-attribute decision making; [3] multi-objective linear programming; [4] analytical hierarchy process; [5] fourth generation programming language

Deterministic optimisation models are the most commonly utilised modelling tool group in Table 3.3. An optimisation model is defined as a "...model [that] provides a set of decision variables that optimise a well-defined goal – called an objective function" [107:43]. An example of this is the maximisation of profit subject to the constraints of the optimisation model (e.g. available labour resource). The OR tool most often used to achieve this is linear programming (LP) [101], which assumes that the decision variables and constraints in the optimisation problem are linear (a straight line if graphically displayed). In some cases it is necessary to use a non-linear programming (N-LP) method, though this can greatly increases the depth of complexity in determining the optimal solution. Stochastic models constitute another major branch of commonly employed methods. Probability distributions are used for one or more variables within a model to measure the effect of changes or uncertainty and the most common form of stochastic model is a Monte Carlo simulation

[108]. A Monte Carlo simulation estimates the stochastic or deterministic parameters by randomly sampling [109]. This method also requires a large number of iterations to produce the parameter estimates. Stochastic models are better suited to simulating uncertainty than deterministic models and are therefore widely used as a simulation technique for more complex or real-world systems [110]. However, it is important to note that this is not the only method suitable for modelling uncertainty or complex systems.

### 3.2.4 Issues

Even though a decision support system was chosen as the most suitable research method, this is not to say that the discipline is without issues. A review paper by Arnott and Pervan [111] concludes that the key issues can be categorised into eight groups (Table 3.4).

*Table 3.4 – Key issues for the DSS discipline [111]*

The most important issue in relation to the research objective is the lack of professional relevance and pragmatic application of decision support systems. Possible reasons for this disconnect are given by Rizzoli and Young [112] who found that decision-makers lack trust in a DSS even if it is proven to be effective, opting for their own often sub-optimal decisions. A case in point is a study of forestry operations decision-makers in Canada, who would rather rely on their own ability than computer software [Rooney, 1996 cited 57]. Similarly, Wierzbicki and Wessels [113:37] found that “the higher the level and experience of a decision maker, the less inclined she/he is to trust in various tools and methods of decision analysis and support”. However, it may be as Brown and Vari [114] suggested, “the practical impact of decision aids on business decisions is less easy to establish, due to the cloak of commercial secrecy…" with the successful DSS being used to achieve a competitive advantage more than for publication.

## 3.3 Systematic Literature Search Methodology

A systematic review is defined as "a review of the research literature using systematic and explicit accountable methods" [115:5]. Gough, Oliver [115] go on to add that the overall aim of conducting a systematic review is to have an explicit, rigorous and accountable method. In addition to this, the aim is to have a replicable review process. The systematic literature review method employed ensures that there is a thorough and extensive search of the existing bioenergy, renewable energy and other relevant literature.

The main advantages of a systematic review over a traditional (unsystematic) review is that it is an exhaustive and transparent search of literature with a well-defined question or hypothesis and it limits search and source bias [116]. Traditionally, systematic reviews were applied in the health care industry [117] but increasingly they are applied to other industries including energy [118]. A good example of this transition is a systematic evidence review conducted by academics for the Department of Energy and Climate Change to inform policy [119].

The method, like any other, is also subject to some criticism. Gough, Oliver [115] state that the process is considered by some as atheoretical, mechanical and ignores meaning, and too narrowly defines boundaries to reduce studies and in doing so removes potentially relevant research. The approach's empiricist epistemology is aligned with that of the research and therefore the method is well suited and steps are taken to avoid the search boundary criticism (Section 3.3.1). As stated, systematic reviews differ from traditional review by targeting a specific question or hypotheses [116]. The analysis of the resulting literature also focuses on what is known and giving recommendations for practice [120]. This approach is ideally suited for the problem focused review required to achieve the research aim.

### 3.3.1 Process

The process adopted in the research is based on Petticrew and Roberts [116] stages to conducting a systematic review and is as follows:

1. define question
2. set section criteria
3. set search string

4. first inclusion test
    4.1. set secondary search string
    4.2. repeat first inclusion test
5. secondary inclusion test (abstract relevance)
6. literature review (full text review)

Stages 4.1 and 4.2 are required to ensure that all the relevant literature is included in the systematic search after a lack of results for project scheduling and risk management was encountered. Although the lack of sources is attributed to the research gap, another search is conducted to reduce the possibility that it was due to the search term configuration.

### *Research Question*

In an approach similar to the formal question structures suggested by Petticrew and Roberts [116][19], the research question is deconstructed to its key parts to ensure that the scope is focused. The systematic research question is:

> What is the evidence that DSS (method) have been developed for achieving project schedule, cost and risk management (objective) in the feasibility stage of bioenergy or renewable energy project development (context)?

The research question is aligned with the chapter objective and to support the overriding research aim. Furthermore, the key parts of the question form search terms within the search string.

### *Selection Criteria*

The selection criteria are the first level filter for the literature results, and the main selection criteria are as follows:

- journal papers are at least 2 star as rated by the Association of Business Schools, using the current journal quality guide [121] with exceptions being made for journals that are not rated under this system such as biomass and bioenergy and renewable energy;
- grey literature from government bodies, consultancy firms or PhD theses;
- published in the past 10 years (2002 – 2012);

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[19] Within their book they refer to this as PICOC: people (decision-maker), intervention (DSS), outcomes (objectives) and context (bioenergy / RET project development)

- excludes review journals.

These are utilised along with the search terms to create the pool of literature that is fit for the purpose of answering the literature search question. Grey literature has been selected from a separate search as Google Scholar does not include this in their search engine.

### *Search Terms*

The search terms chosen give an exhaustive search of literature that is relevant to the literature search objective, as shown in Table 3.5.

*Table 3.5 – Search terms*

| | Context 1 | | Context 2 | | Method | | Objective |
|---|---|---|---|---|---|---|---|
| 1 | Bioenergy | 1 | Project development | 1 | Decision support system | 1 | Finance |
| 2 | Renewable energy | 2 | Feasibility study | | | 2 | Schedule |
| | | | | | | 3 | Risk management |

There are two sets of context for the search term, this assists in removing a large number of irrelevant sources. Renewable energy is incorporated to the search to assess whether a relevant DSS had been developed for another RET that could be applied to the review to assist in analysis. There are also method and objective search terms that align with the literature review question. A total of 24 search string combinations are possible and they are denoted by their reference code, for example “renewable energy” AND “project development” AND “decision support system” AND “schedule” equals 2.1.1.2. Bioenergy over biomass was tested for 1.1.1.1 to 1.1.1.3, and the use of bioenergy removed two irrelevant papers on wind systems but not any of the papers deemed significant for the second inclusion stage. There is only one method term as any deviation from this, such as ‘model’, ‘decision-making’ or ‘support system’ leads to large numbers of papers in the scoping review that are not relevant to the research question. Similarly to Martin, Muûls [119], Google Scholar is utilised as the search engine as it is not publisher or source specific and is therefore aligned with the method’s aim of reducing source or publisher bias. The search terms within the string are given the conjunction ‘AND’ and searched for anywhere within the article excluding citations. Search terms with more than one word, such as renewable energy have to occur in the article together and are allocated with “” to ensure this. Finally, a separate search is conducted on Google for grey literature that may be excluded from the Scholar search.

### *First and Second Inclusion Stages*

For the first inclusion stage, articles that have a context 1 and 2 term as well as a method and objective anywhere in the article and are within the selection criteria are retained. The literature is reviewed in more detail at the second stage, by analysing the abstract content, to ensure relevance and that a model or DSS is developed to support the decision-maker in achieving one or more of the objectives. Literature that passes the second inclusion test is fully reviewed in the chapter. The search results are shown in Table 3.6.

*Table 3.6 – Systematic search results (first search)*

| **Ref.** | **Total returned**[1] | **1st stage**[1] |
|---|---|---|
| 1.1.1.1 | 33 | 3 |
| 1.1.1.2 | 9 | 0 |
| 1.1.1.3 | 11 | 0 |
| 1.2.1.1 | 59 | 13 |
| 1.2.1.2 | 18 | 4 |
| 1.2.1.3 | 11 | 0 |
| 2.1.1.1 | 93 | 12 |
| 2.1.1.2 | 37 | 2 |
| 2.1.1.3 | 37 | 2 |
| 2.2.1.1 | 118 | 23 |
| 2.2.1.2 | 51 | 9 |
| 2.2.1.3 | 37 | 1 |
| **Total** | **514** | **40** |

[1] Individual rows included repeated literature and these are excluded in the totals

The systematic literature search yielded 40 possible papers that passed the first inclusion stage. However, it became apparent that there are large gaps in the existing literature for the second and third objectives (schedule and risk management). A second systematic pass of the literature with less stringent context search terms and a greater focus on the objectives ensures that literature is not simply missed. For the second search, the criteria is limited to bioenergy for the context and 'decision support system' for the method, with the objectives expanded to finance (1.1.1), schedule (1.1.2), risk management (1.1.3) and barrier (1.1.4). The results of the second search are given in Table 3.7.

*Table 3.7 – Systematic search results (second search)*

| Ref. | Total returned[1] | 1st stage[1] |
|---|---|---|
| 1.1.1 | 712 | 97 |
| 1.1.2 | 208 | 12 |
| 1.1.3 | 181 | 11 |
| 1.1.4 | 171 | 9 |
| **Total** | **1272** | **106** |

[1] Individual rows included repeated literature and these are excluded in the totals

The second search, aided by the inclusion of the barrier (1.1.4) search term, produces a greater number of possible literature sources in total and for the possible schedule and risk management gaps. As there are duplicates between the first and second literature searches these are combined to give a total of 135 papers.

### 3.3.2 Second Inclusion Stage

After the second inclusion stage, 31 literature sources are deemed to have significant relevance to the literature search question and are fully reviewed for the literature review. The key reasons for exclusion at the second inclusion stage are:

- not relevant or low relevance;
- not modelling based;
- social / environmental;
- review;
- representative GIS (geographical information system) only.

If a rejected literature source has more than one reason for exclusion, the primary reason is selected, and these are given in Figure 3.2.

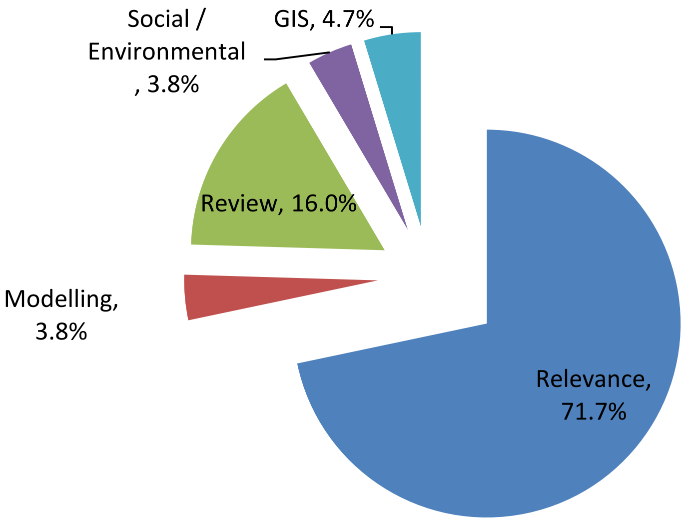

*Figure 3.2 – Reasons for exclusion*

The main reason for exclusion from this stage is the low level of or no relevance to the literature question. A high level of low or no relevance papers is a possible indicator that a larger literature search is conducted than required in some areas and this should ensure that relatively few sources, if any, are missed. Furthermore, a large number of DSS in the search utilise GIS, if this is limited to a representative spatial model then it is excluded from the study as with any papers that do not involve any modelling.

## 3.4 Project Financial DSS Research

As highlighted in the systematic literature search, the majority of sources come from the finance search term strings. The academic DSS literature is reviewed with regard to the financial analysis and methods employed and then the supporting grey literature is covered.

### 3.4.1 Academic Literature

The majority of papers chosen through the systematic search focus on the optimal location or supply chain configuration. Often these papers utilise a combination of GIS and linear programming in some form (MILP[20], LP, N-LP) with the economics of a decision being the objective function, such that the objective is financial and the constraints of the DSS are usually the configuration of the plant or supply chain, with an example being Frombo, Minciardi [122].

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[20] Mixed Integer Linear Programming

Single objective function DSS typically aim to maximise gross profit [122-127] or to minimise cost [128-133]. Accepting that bioenergy supply chain decisions are often dependent on more than an economic objective, Pérez-Fortes, Laínez-Aguirre [134] develop a multiple objective MILP (Mixed Integer Linear Programming) model to support decision-making. Their support system has a social, economic and environmental objective to demonstrate the possible trade-offs between the objectives that are often modelled individually. Similarly, an earlier paper by You, Tao [135] applied a multi-objective MILP model to support decision-making of biorefinery supply chains utilising the same objectives.

Aimed at investors as the decision-maker, Rentizelas, Tatsiopoulos [125] develop a two-step optimisation DSS utilising genetic algorithms (GA) and sequential quadratic programming (SQP). The application of this technique over the traditionally applied linear programming techniques is advantageous as it can handle a wider range of data, such as non-continuous and non-differentiable variables. A comparison against solely a GA or SQP optimisation method in a later paper [126] showed that the hybrid method performed better.

Ren, Zhou [130] paper also differs from the other optimisation papers employing a linear programming method or similar as it takes a bioenergy project centric view as opposed to the typical supply chain one. The optimisation model presented has an economic focus and incorporates technical, financial and locational demand factors to achieve the objective. Similarly, the Rentizelas and Tatsiopoulos [126] hybrid non-linear optimisation model for the siting of bCHP schemes is centred on facility location and also aimed at investors as the decision-maker.

The Grassi, Chokani [136] DSS for top-down techno-economic assessment of wind potential in Iowa consists of a GIS module to identify sites, an ‘energy generation and policy’ (EGP) module and an ‘economic and finance’ (EF) module to assess viability. They emphasise the importance of having conductive policy and the necessary economic return to drive RET deployment. The EGP module within their DSS calculates the production incentive revenue and the EF module calculates the CAPEX, OPEX and other costs such as tax and these are brought together to determine the break-even point and return on the investment for the project over its lifecycle. They also include the cost and terms of financing the project, which is often missed in the other DSS papers. Similarly, Messineo, Volpe [137] focus on the economic viability of small-scale ORC systems in a region of Sicily and include the debt and equity financing of the project, as do Sharma, Sarker [138]. Kahraman, Kaya [139] and Kahraman and Kaya [140] assess the economic value of a potential technology by using either the net present value (NPV), internal rate of return (IRR), cost benefit analysis or payback period. The importance of the break-even point in assessing a project's viability is also included in another DSS by Hong, Koo [141] but, along with Kahraman, Kaya [139] and Kahraman and Kaya [140], they neglect the cost and terms of finance. Grassi, Chokani [136] also state that the levelised cost approach or cash flow estimates are typically the two methods for estimating the economic performance of a RET. However, the academic literature tended to overwhelmingly utilise the cash flow estimates in preference of levelised costs. The exception being Kasmioui and Ceulemans [142], albeit for solely biomass not energy, to support decision-making.

Four multi-criteria papers were included in the systematic literature results that contained financial evaluating factors for projects, though this is at a more high level quantitative analysis with the use of Saaty's analytical hierarchy process (AHP) type scale (1-9) [139, 140] or similar scoring method [143, 144]. Multi-criteria decision-making (MCDM) does not provide sufficient depth for a financial analysis of potential projects to achieve the research objective.

Sharma, Sarker [138] are unique in their approach to planning and project development. The MILP methodology is not dissimilar to the others reviewed but there is a much greater emphasis on the requirements of shareholders and possible investors to a project. They utilise the free cash flow value as opposed to the typical NPV and this requires greater inputs on the financial covenants for financing the project. Covenants such as the debt to equity ratio, debt interest rates and return on equity produce a greater level of granularity for the decision-maker(s). Furthermore, the Yue and Yang [145] DSS features a combination of GIS and cash flow analysis to support decision-making not only for investors in projects but also policy makers, as they analyse several RETs and emphasise the importance in policy in driving deployment.

Finally, the vast majority of systematic literature review papers develop their own DSS for the purposes of the research. However, Brown, Yiridoe [146] and Yiridoe, Gordon [147] utilise AgSTAR Farmware software and Hong, Koo [141] utilise the Canadian RETScreen Software. These are covered in more detail in Section 3.7 along with the other notable software.

### 3.4.2 Supporting Grey Literature

The most noteworthy pieces of key grey literature from searching the literature during the course of the research and alongside the systematic approach adopted for the peer reviewed publications are interlinked. The work by conducted by Wiser and Kahn [148] and Wiser and Pickle [61] as part of the

Environmental Energy Technologies Division at the University of California and funded by the U.S. Department of Energy, is some of the earliest project deployment and financial viability analysis for RETs. The first report analyses the levelised unit costs of wind under different financing structures and configurations of project finance and terms. It was also partially published in the Energy Policy journal in 1997 [149]. The second report focuses on the role of policy and incentives in improving the financial viability of RETs, with 20-year discounted cash flow (DCF) analysis to highlight the cost of finance project. For this they also include the capital structure of the project (debt to equity ratio), return on equity, debt term, debt interest rate, debt amortisation (payment schedule) and the debt service cover ratio. These costs and terms are vitally important for project development and decision-makers as they effect the viability of a potential project but are widely missed in the academic literature with the exception of Sharma, Sarker [138]. A sensitivity analysis is utilised in both reports to show the effect of a change in a key variable on the levelised cost of energy.

The IEA-RETD[21] report by de Jager and Rathmann [48] similarly applies a project finance cash flow analysis for supporting their discussion and analysis of more recent policy and project viability in multiple developed countries, including the UK. It also cites the work of Wiser and Kahn [148] as the underpinning approach to their analysis, and similarly conduct a sensitivity analysis of multiple project financing variables and expresses this in a levelised unit cost form.

## 3.5 Project Scheduling DSS Research

The second objective for developing a bioenergy technology is to achieve a predetermined development schedule objective, and this is inextricably linked to the first, financial objective. Microsoft (MS) Project or similar project management software has a ubiquitous presence in most projects and therefore Gantt bar charts, work breakdown structures (WBS) and critical path method (CPM) tools are the most widely used [52].

### 3.5.1 Academic Literature

Throughout the academic literature there is little reference to the scheduling of tasks within a project, the subjective and uncertain development duration or the need for greater support. This is contrasting to the development phase risks highlighted by the developer’s concern for the implementation of bioenergy schemes [65], general riskiness perceived by investors [64] and long lead times [6].

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[21] International Energy Agency – Renewable Energy Technology Deployment

The importance of scheduling and the cost of delays for RET projects are mentioned in Grassi, Chokani [136] as a critical factor. However, the importance of scheduling is only mentioned from a cost perspective with no integration into their DSS. Similarly, Sharma, Sarker [138] account for planning and construction time horizons and the impact on the biorefinery project but do not model possible changes or uncertainty in these estimations. Kahraman, Kaya [139] and Kahraman and Kaya [140] incorporates the duration of preparation and implementation as evaluating technology factors within their fuzzy AHP technology assessment model with a pairwise analysis against other criteria within the model on a nine point scale. This may not benefit the decision-maker within the context of the research but adds some support to the importance of scheduling and task duration. Moreover, the bioenergy project centric papers [126, 130] focus on the financial objective of a project but neglect the risk and uncertainty in progressing through the project lifecycle. Finally, the linear programming group of optimisation models typically have one objective financial function and the multiple objective DSS [134, 135] add social and environmental objectives over project duration or scheduling ones.

### 3.5.2 Supporting Grey Literature

A report conducted for the European Commission by Ecofys and Golder Associates [150] analyses the bioenergy permitting procedures in EU Member States with a focus on the lead times and costs of developing projects. The report not only highlights that the permitting and in turn development process varies greatly between the Member States but also between projects. Benchmarking projects with a schedule duration objective is utilised to assess the case study projects. To conduct this analysis the critical path method is used to determine the duration of the tasks within the case studies. They found that the greater the number of tasks toward achieving the necessary permits, in the development phase, the greater the level of project development lead time uncertainty. Importantly, a greater level of planning has been shown to increase the possibility of achieving project objective [58] and therefore the planning of tasks within the development phase should help to mitigate the uncertainty in a project's lead time. The report supports this view by recommending that project developers "make a thorough review of all permits and steps needed for the permitting of the projected plant…a good overview of the serial and parallel steps, as well as of the responsible authorities for each sub procedure will give valuable help to plan the whole permitting process" [150].

The IEA-RETD [56] report on the quantification of risk and risk management in RET projects, reviewed in Section 3.6.2, states that a project schedule with the objective of "…understand[ing] project milestones, critical path, time float and logical links between project activities" is a critical component of a project. They also add that "for complex projects, a dedicated schedule risk analysis can also be performed on a probabilistic basis". Within their report they demonstrate a method for achieving this probabilistically and integrating it with the risk management process. Yet, there is no evidence in the current bioenergy or RET literature within the systematic review in targeting this aspect of project development.

## 3.6 Project Risk Management (PRM) DSS Research

A risk is defined as "…a measure of the probability and consequence of not achieving a defined project goal" [151:743]. The Project Management Institute – Project Management Body of Knowledge (PMBOK) state that project risk management (PRM) is the process of conducting risk management planning, identification, analysis, response planning and monitoring and control on a project [46]. They add that the risk may be positive or negative and the objective is to increase the probability and impact of positive risks whilst reducing the negative ones. In addition to the PMBOK standard there are British and international risk management standards that aim to support the project manager in the risk management process, such as:

- BS 8444 [152] Risk Management: Guide to Risk Analysis of Technological Systems;
- ISO 31000 [153] and supporting ISO 31010 [154];
- HMGOV [155] The Orange Book;
- IRM/AIRMIC/ALARM[22] [156] Risk Management Standard.

The phases of risk management advocated by each standard largely remain the same although different terminology may be used. The phases of risk management adopted throughout the research is the ISO 31000 [153] standard, as defined in Table 3.8.

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[22] Institute of Risk Management (IRM); The Association of Insurance and Risk Managers (AIRMIC); The National Forum for Risk Management in the Public Sector (ALARM)

*Table 3.8 – Risk management phases and definition [153]*

| Risk management phase | Definition |
|---|---|
| Identification | Process of finding, recognising and describing risks |
| Analysis | Process to comprehend the nature of risk and to determine the level of risk |
| Evaluation | Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable |
| Treatment | Process to modify risk |
| Monitor and review | Continual checking, supervising, critically observing or determining the status in order to identify change from the performance level required or expected |
| | Activity undertaken to determine the suitability, adequacy and effectiveness of the subject matter to achieve established objectives |

Risk and uncertainty is an inherent and common characteristic of any project. The best possible way to mitigate the negative impact of an occurring project risk is to employ efficient and effective project risk management (PRM) practices. Fabozzi and de Nahlik [65:298] supports this view by stating that "…[project risk management] is critical not only in controlling a project's operation but is what potential lenders look closely at in assessing the ability of the project sponsor to manage a project. It is essentially what lenders refer to as management quality". Furthermore, this is particularly pertinent to CHP systems that require a DHN as analysis by Poyry [87] found that industry experts perceive DHNs to likely "…return less income and create more uncertainty than other large scale investments".

### 3.6.1 Academic Literature

None of the systematically reviewed literature conducted risk management in a method similar to the ones defined nor do they attempt to include the cost of additional risk management or mitigation. However, risk or uncertainty is referred to in most sources and either included within their DSS as a sensitivity analysis or as an evaluating criterion in the multi-criteria research.

In the Grassi, Chokani [136] DSS for wind generation assessment, there are several references to the varying types of project uncertainty, such as adverse weather conditions, grid connection costs, maintenance costs and PPA uncertainties. Although the technology and target country are different, the majority of factors are aligned with those identified in Chapter 2. Their DSS does not have a risk management mechanism but they utilise an economic sensitivity analysis to show the effect of a change in a market condition (PPA price) on the average IRR.

Sensitivity analysis is the most common method for handling uncertainty. Messineo, Volpe [137] conduct a sensitivity analysis on the cost of feedstock and blend, plant size and operational hours for small-scale ORC systems. Similarly, Yiridoe, Gordon [147] conduct a sensitivity analysis when using the AgSTAR Farmware and Tittmann, Parker [127] run one alongside their MILP DSS. This is also the case for Kasmioui and Ceulemans [142] financial analysis of short rotation crops in Belgium but they do pay particular attention to the uncertainty and possible barriers to uptake. A sensitivity analysis is also present in the GIS and financial models of Yue and Yang [145] and Zhang, Johnson [157].

Little correlation exists between the complexity of the DSS and the level of risk or uncertainty analysis. Pérez-Fortes, Laínez-Aguirre [134] multiple objective supply chain optimisation model includes social, economic and environmental objective functions, yet there is a limited inclusion of uncertainty in the deterministic model with only a sensitivity analysis on the return of a project under different electricity prices for a Ghanaian case given. Moreover, of the two non-linear hybrid method models by Rentizelas, Tatsiopoulos [125] and Rentizelas and Tatsiopoulos [126] only the early research performs a sensitivity analysis on the assumptions within the intelligent DSS. They add that "…incorporating the effect of uncertainty in the model presented would be a challenging task" [125]. Furthermore, Ayoub, Martins [158] and Ayoub, Elmoshi [159] do not account for uncertainty in any form in their comprehensive two level planning and implementation DSS.

The Ren, Zhou [130] bioenergy project centric model also run a sensitivity analysis of the effects of changing key variables or assumptions with the addition of conservative estimates for uncertain biogas feedstock costs. Whilst, Sharma, Sarker [138] adds that deterministic estimates such as demand, yield and prices should only be used as preliminary estimates, and that they intend to add probabilistic stochasticity after validating their deterministic MILP model.

Of the stochastic models, Hong, Koo [141] were limited in their analysis of stochastic risk with the third party RETScreen software selected and opted for using the Crystal Ball software to conduct a probabilistic Monte Carlo analysis. They utilise lognormal distribution on two areas of particular uncertainty: future value discount rates and future heat and power utility rate changes; and the maintenance or 'repair rate' of the two comparable photovoltaic (PV) systems. Similarly, the Kim, Realff [124] DSS for optimally designing biomass supply chain networks for biofuels under uncertainty utilises a stochastic MILP method with 10 key uncertainty parameters and these are shown in Table 3.9.

*Table 3.9 – Key uncertainty variables [124]*

There are 12 or 14 in the paper as production yield and downstream transportation were divided into intermediate and final and there are two conversion technologies.

The effect on the model’s objective function was measured by changing each variable ±50%, in 10% intervals, and the top influencing uncertainty variables were chosen. These most significantly impacting variables are highlighted in the table. They are then entered into multiple Monte Carlo models with each permutation of the top variables being ±20% to assess the robustness of design and ultimately optimal design for the biofuel supply chain.

The comparative analysis of RETs for application in Turkey using a fuzzy analytic hierarchy process (AHP) by Kahraman, Kaya [139] and Kahraman and Kaya [140] includes technical risk as an evaluating criterion. The risk criterion evaluates the risk of a technology in relation to the other criteria on a fuzzy AHP scale using trapezoidal membership functions. This high level analysis of risk suits their purpose but is not sufficient for a developer during project development where quantification of risk is also required.

Finally, some of the literature avoided important uncertainties by simplifying the model [133] whilst others made no mention of risk, uncertainties or barriers [131, 132]. Within and when concluding their paper, You, Tao [135] state the importance of risk management and that an investigation into the different types of uncertainty and risk present is significantly important in creating resilient supply chains. However, they do not conduct any analysis of this kind within their model.

### 3.6.2 Supporting Grey Literature

#### *IEE Gasification Guide – Risk Analyser*

Developed for a EC Intelligent Energy for Europe (IEE) funded project, the objective of the research is to increase the development of small-scale commercial gasification systems by improving the awareness and understanding of health, safety and environmental (HSE) hazards over the project lifecycle [160]. The Risk Analyser [161] is essentially a DSS for HSE risk management and can be applied to a wider range of cases than solely gasification. The method applied for risk management is said to be a ‘functional analysis of the plant’ and based on Hazard and Operability (HAZOP) and

Failure Modes and Effects Analysis (FMEA). The stages of the risk management process within the software are as follows:

i. definition of process units (e.g. parts of the plant), functions (e.g. fuel supply to gasifier), parts (e.g. functions are fulfilled by parts) and operation modes;
ii. risk assessment of the functions with possible events and consequences using a risk severity and likelihood matrix;
iii. countermeasures or risk responses to the risks deemed unacceptable to reduce them to an ALARP[23] or acceptable level;
iv. summary of the risks and the risk management actions.

The method applied is primarily qualitative and this is most likely due to HSE focus of the model and that it does not cover the financial aspects of project development or risk management.

### *IEA-RETD Risk Management in Renewable Energy Projects*

A recent IEA-RETD [56] report develops a method for the quantification and management of risk in RET projects. The report utilises the techniques adopted in the more established energy and infrastructure industries as a result of conducting expert workshops. They add that "a key challenge in obtaining financing at a reasonable cost is the ability to quantify and manage the different elements of risk (i.e. organisational, political, technical, commercial) associated with RES [renewable energy systems] projects". The report goes on to summarise several barriers identified in RET development by KfW Bankengruppe [162], of which many align with the barriers identified in the previous chapter, such as: insufficient data for prudent project analysis (feedstock supply); long time horizon results in long risk exposure; high development costs; securing operating permission; long-term PPA; construction contact types and risk allocation. They add to this by stating that it is critical to understand and manage these risks.

The resulting methodology follows the generic risk management process: identification, evaluation, control (response), follow-up and feedback. The evaluation of risk is quantitative and qualitative, as opposed to the solely qualitative IEE Risk Analyser [161], with the use of risk mapping for qualitative risk and a probabilistic Monte Carlo analysis for the quantitative ones. These risk events are compiled to create a risk register. The quantitative analysis of risk utilises three point distributions (min, most likely, max) of a risk event that has a quantitative impact on the project cash flow or

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[23] As low as reasonably possible

schedule objective, with the financial cash flow outputs being similar to those covered in Section 3.4, but presented as cumulative probability curves for a confidence analysis of the possible project outcomes. The ability to respond to the quantitative risks identified is a distinguishing and beneficial characteristic of this method. Four risk response measures are possible: avoid, reduce, transfer or retain the risk event. Moreover, the first three of the four responses are proactive and the forth is reactive. The IEA-RETD [56] report adds that the action type and rationale for application of a risk response strategy is dependent on the severity or maturity of the risk event, with the latter indicating that it is more suitable to transfer the risk, and the cost/benefit of enacting a response strategy.

Finally, an earlier report by the IEA-RETD [48] from 2008, that focuses on the effects of policy in reducing financing costs for RET deployment, adds in the conclusion that the removal of risk through effective policies would not only remove the barriers to development but also reduce the levelised unit costs. The same interpretation should therefore hold true for effective risk management.

## 3.7 Existing Software

This section provides an overview of some of the key software for supporting decision-making in the bioenergy industry and that is relevant to the research. This is not intended to be a comprehensive list of available software, more those that are referred to or utilised in the systematic literature review. The AD (anaerobic digestion) Calculator is not utilised within the shortlisted DSS papers but has been applied in other research [163] and was highlighted by conversations with industry practitioners whilst conducting the research.

### *AgSTAR Farmware*

AgSTAR formed in 1994 and is a collaboration programme between the Environmental Protection Agency, Department of Agriculture and Department of Energy in the U.S. The purpose of the AgSTAR programme is to "…reduced methane emissions from livestock waste management operations by promoting the use of biogas recovery systems" [164].

The AgSTAR Farmware software is utilised in two of the papers [146, 147] of the systematic literature review to determine the economic feasibility of on-farm biogas energy production. The economic decision criteria to assess the feasibility of a scheme are the NPV, IRR and payback period for the proposed schemes and they state that benefit-cost ratios are also commonly utilised. The software is deterministic and does not have a risk analysis or uncertainty option. Furthermore, the software does not support the decision-maker in project task scheduling and planning through the lifecycle.

### *NNFCC AD Calculator*

Developed in partnership with the National Non-food Crops Centre and the Andersons Centre consultant practice, the AD Calculator supports the development and economic viability assessment of AD projects in the UK. The Calculator is MS Excel spreadsheet based and enables the decision-maker to model feedstock types, technologies and operating parameters to produces likely financial returns for a potential or existing project [165]. The software produces profit and loss, supply of funds and a balance sheet projection for the project over its lifecycle. The software is also deterministic and does not include any scheduling or risk analysis.

### *RETScreen*

The software is developed by the Canadian Government at its CanmetENERGY research centre of Natural Resources Canada and a network of experts from a range of sectors. The Renewable Energy and Energy Efficient Technology Screen (RETScreen) is also MS Excel based and supports decision-makers and professionals in assessing the financial viability of a wide range of projects [166]. RETScreen is also available in more than 35 languages and has been downloaded by more than 315,000 users.

The model produces similar financial outputs to the AD Calculator, such as a discounted cash flow analysis, IRR and project payback. It is utilised by Hong, Koo [141] in their optimisation study of solar PV installations onto an educational facility in Seoul. The RETScreen software is a more comprehensive DSS for assessing project viability of RETs and has the functionality to conduct a sensitivity analysis or Monte Carlo analysis on a number of techno-economic input variables to assess the impact on the financial viability or robustness of the investment. However, project scheduling or any time dependent planning are not including within the software.

*Table 3.10 – Existing software functionality comparison*

| Function | agSTAR Farmware | NNFCC AD Calculator | RETScreen | Comments |
|---|---|---|---|---|
| **Format** | Windows Desktop | MS Excel | MS Excel | Possible limitations of MS Excel based software, such as limitations on optimisation and usability |
| **Country** | U.S | UK | International | |
| **Finance** | NPV[1], IRR[2], Payback | DCF[3], NPV, IRR, Payback | DCF, NPV, IRR, Payback | Common financial elements included, but lack a break-even approach |
| **Scheduling** | Not included | Not included | Not included | Scheduling missing from all |
| **Risk Management** | Not included | Risk analysis only (sensitivity analysis) | Risk analysis only (Monte Carlo or sensitivity analysis) | All lack a complete risk management methodology |
| **Deterministic / Stochastic** | Deterministic | Deterministic | Both | Limited ability to accommodate uncertainty |
| **Strengths** | Developer focused, produces development plan type output | Developer focused | Flexible use, comprehensive | All have a development and project focus |
| **Weaknesses** | Limited to farm based application of AD | Limited to farm based application of AD | Lacks country specific incentives and policy | Complexity could inhibit non-expert developer usage |

[1]Net present value; [2]Internal rate of return; [3]Discounted cash flow

Table 3.10 gives an overview of the commercial DSS features and their respective strengths and weaknesses. Two of the three DSS are MS Excel based and one is a desktop application type programme. The desktop application is able to potentially benefit from more integrated features and analysis, such as the optimisation modelling techniques covered in the model-orientated systems (Table 3.3). The financial analysis techniques and outputs are similar across the commercial software and the other DSS covered. None of the systems utilise a break-even levelised cost approach (Section 1.3.2) to demonstrate to the decision-maker that the proposed scheme is not viable but could be if electricity is sold at a certain value for the duration of the project. This type of output functionality is beneficial to the user. The DSS are also largely representative of the academic literature in not including scheduling or a full risk management process. The primary strength of the commercial DSS is their developer and project focus. However, they are limited to AD in the case of agSTAR and the NNFCC systems, and may be too complex for non-expert or opportunist developers to utilise. These weaknesses are to be addressed for the DSS required for this research.

## 3.8 Existing Literature Gaps

The reviewed literature is representative of the distribution of methods covered in Table 3.3. The majority of DSS are deterministic and utilise some derivative of linear or non-linear programming for optimisation. A smaller number of systems adopt a stochastic type or multi-criteria models to reach a solution. Primarily, personal DSS are developed with a few notable exceptions that are defined as intelligent DSS through the application of GA, SQP or similar intelligent search algorithms [125, 126, 158, 159]. This is in line with the inertia and conservatism issue raised by Arnott and Pervan [111]. However, the professional relevance issue has not deterred a plethora of academic, commercial and grey literature support systems. The academic support systems have a greater focus on the spatial variables with the use of GIS and supply chain configurations. This is in contrast to the grey and commercial systems that have a greater project focus and, those reviewed, do not include GIS analysis or related supply chain decisions.

Overwhelmingly, project finance is the most covered project objective with existing decision support systems. Every DSS within the systematically reviewed academic literature has some assessment in either profit or cost terms with optimisation being the most common method. Optimisation is conducted with some form of linear programming in 15 of the papers with often only a financial objective. The financial DSS papers also typically give a limited assessment of risk or uncertainty by selecting a sensitivity analysis to account for any imprecision or uncertainty within their designed model. The vast majority of the systematic literature is also supply chain not project focused with the exception of Rentizelas and Tatsiopoulos [126] and Ren, Zhou [130]. Although they also do not include the importance project scheduling or risk management.

The grey literature is more applicable to the pragmatic problems faced by the developers of bioenergy projects. The work of Wiser and Kahn [148] and Wiser and Pickle [61], later applied in de Jager and Rathmann [48], gives a high level of financial analysis and includes the terms of project financing and levelised costs in their analysis, whereas the academic literature largely avoids this. The exceptions being Messineo, Volpe [137], Grassi, Chokani [136] and Sharma, Sarker [138] who incorporate the terms of finance. Furthermore, the commercial software also has a much more project based focus as opposed to the supply chain direction of the academic literature. The financial viability of a scheme is the key output in all three pieces of software, yet only the RETScreen DSS includes risk analysis functionality and all three exclude project scheduling or wider risk management.

A deterministic sensitivity analysis is the most common method throughout for handling uncertainty. It can quickly emphasise the effect of changing one variable on an output but is limited if there is only approximate variable definition or the effect of changes in multiple variables is required by the decision-maker. Although, several papers conducted sensitivity analysis on the variables deemed uncertain or significant, Kim, Realff [124] found the most significant variables relate to the supply of biomass, the facility or plant production and the output value and demand. This knowledge is useful in designing the system for small-scale bCHP project development.

Only two academic papers [124, 141], the RETScreen DSS and the IEA-RETD [56] opted for probabilistic Monte Carlo risk analysis, which is better suited to handling uncertainty in defining variables or modelling multiple variable changes. An alternative method suitable for modelling with uncertainty or imprecision is fuzzy set theory, also known as possibility theory, and this is applied qualitatively in Kahraman, Kaya [139] and Kahraman and Kaya [140] multi-criteria DSS. Fuzzy theory is also utilised for data mining in Ayoub, Martins [158]. Hong, Koo [141] have a limited inclusion for uncertainty by accepting that it is particularly pertinent for the financial and O&M aspects of the project over the lifecycle. Though none of the systematically reviewed literature papers apply risk management techniques similar to those advocated by ISO 31000 [153] or as demonstrated in the IEE [161] or IEA [56] reports.

Scheduling is widely neglected in all the literature sources and this represents a clear disconnect from the barriers covered in the previous chapter. A passive reference to the importance of project scheduling and development duration [136] or a simplified inclusion of the development and construction durations to measure the effect on the financial outputs [138] is not sufficient for achieving the research aim. This is not improved upon in the other project centric academic research [126, 130] or commercial software. However, the recent IEA [56] risk quantification model does include project scheduling with uncertainty and the effect of risk events impacting on the total project duration. Although, their method is not covered in detail within the report, they seem to apply a probabilistic project scheduling algorithm, similar to the Project Evaluation and Review Technique (PERT), that accounts for variable task duration and precedence relationships to determine the total project duration.

The systematic search of the academic literature and the supporting searches of the grey literature and existing commercial software highlights that there is a clear gap in the literature in answering the literature research question. This supports the research contribution and achieves the second research objective ($O_2$) as there is not a DSS for project scheduling, cost and risk management in the feasibility stage of bCHP project development. The reviewed literature explicitly shows that a trade-off between the two project objectives happens and this in the large majority of work is at the sacrifice of the project scheduling or duration objective. The academic literature also neglects the benefit of conducting a complete management of project risk with often only a deterministic sensitivity analysis. However, the grey literature gives this area more attention with application of qualitative [161] or quantitative and qualitative [56] risk management.

The IEA [56] risk quantification method is the closest body of work to that targeted within this research. The method described includes the project financial and scheduling objectives and the complete risk management process. Aspects such as, the application of a risk register, risk response strategies and their cost benefit evaluation in quantitative terms on the project objectives is most suited to the research objective. However, their method lacks UK specific calculations on the current incentive policy and therefore the barriers identified in the previous chapter [6, 67]. They also neglect the case of CHP systems and the effect of heat utilisation improving the economic viability of the project or utilising the widely adopted levelised unit costs [24]. Uncertain or approximate information is only available to the decision-maker at the feasibility stage and therefore requires either a probability or possibility theory based model. As there is insufficient information held by developers for a true stochastic analysis utilising probability functions from real data for the project objectives and risk management. It can only be conducted with assumed Gaussian type or triangular distribution functions as applied in IEA-RETD [56]. Therefore, the application of fuzzy set theory is preferential to achieving the research objective as it does not require a Monte Carlo engine, is conceptually easier to understand and is better suited to solving problems with approximate or imprecise information.

# 4. Methodology

## 4.1 Introduction

The chapter starts with the aim and research objectives of the research (4.2) and their translation into research questions (4.3). Following this is an overview of the entire research process and logic, given in the research framework section (4.4). The research paradigm (4.5) and design (4.6) are then covered in detail. Section 4.7 describes the assumptions and simplifications applied within the DSS along with a rationale for use. Finally, the chapter justifies the applied validation and verification techniques (4.8) to ensure that the research achieves the aim and research objectives.

## 4.2 Aim and Research Objectives

The research aim is to develop a project development and risk management decision support system for small-scale (500 kWe to 10 MWe) biomass combustion CHP schemes in the UK, to be utilised by developers, in the early stages of a potential project's lifecycle for the purposes identified in the problem statement (Section 1.4.1). The systematic academic and grey literature review confirmed that there is not an existing DSS that has achieved this aim. The research objectives, to ensure the aim is achieved, are to:

- $O_1$) analyse the current barriers to small-scale project financed bCHP schemes in the UK;
- $O_2$) review the current body of decision support system literature aimed at addressing the barriers of bCHP project development and risk management;
- $O_3$) develop a decision support system for small-scale bCHP developers at an early stage of project development with a mechanism for handling the uncertain or approximate information;
- $O_4$) implement the resulting decision support system in Energy Company's case study;
- $O_5$) seek further evaluation of the decision support system from industry practitioners.

The research contributes to knowledge on multiple levels by going beyond the problem statement and applying an original fuzzy methodology with the integration of linguistic controls designed to support decision-making in bioenergy project development under uncertainty or in the presence of approximate information.

### 4.2.1 Contribution and Originality

Several types of contribution to knowledge are possible, as covered in Phillips and Pugh [167] and Easterby-Smith, Thorpe [168]. Primarily, the research makes a methodological contribution to knowledge by the:

1. development of the fuzzy LCOE method;
2. adaption of the existing fuzzy critical path method (F-CPM) research by improving the reference function inputs to further support the practitioner with linguistic terms;
3. development of a fuzzy risk management method for bioenergy projects.

The research also generates a practical contribution as the produced DSS can be utilised in practice beyond the research project or be applied in further research. The analysis of current literature (Chapter 3) explicitly identifies the gap in knowledge and that an existing DSS has not been developed with the same objectives and this ensures that the research is original.

## 4.3 Research Questions

The research questions are structured to achieve the aim and objectives of the research:

- $Q_1$) what are the current barriers to small-scale project financed bCHP schemes in the UK?
- $Q_2$) what is the evidence that DSS have been developed for achieving project schedule, cost and risk management in the feasibility stage of bioenergy or renewable energy project development?
- $Q_3$) how would a DSS designed for small-scale bCHP developers at an early stage of project development with a mechanism for handling the uncertain or approximate information be configured?
- $Q_4$) how could the DSS have supported Energy Company in the development of the case study project?
- $Q_5$) do practitioners evaluate the DSS as successful in achieving the research aim?

The first and second research questions are answered in the second and third chapter respectively. Question 3 is partially answered with the selection of the project finance, scheduling and risk management objectives from Chapter 2, and the selection of fuzzy set theory from the literature review but is more fully addressed in the proceeding chapter. Finally, the remaining two questions are covered in Chapter 6 and 7 respectively.

## 4.4 Framework

The research framework (Figure 4.1) is designed to achieve the aim and research objectives. Split into four phases, the framework supports the problem identification, decision support system development, implementation and evaluation.

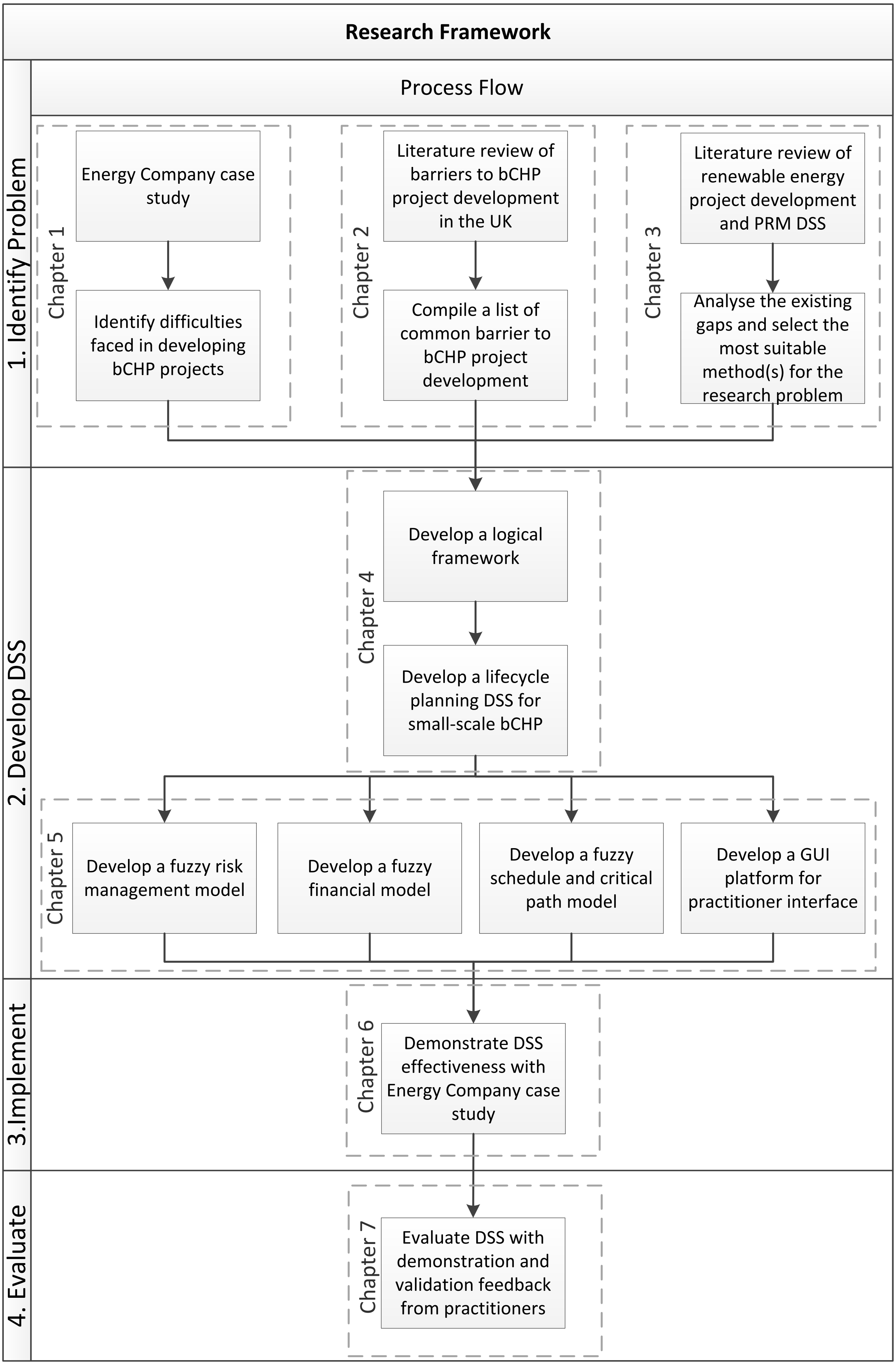

*Figure 4.1 – Research framework*

For the problem identification phase it is important to ensure that the company's problems are representative of wider issues or barriers within the industry (Chapter 2). The barriers highlighted within the second chapter are aligned with the issues of the company and these are covered in greater detail within Chapter 6. A systematic review of the literature further supports the contribution of the research by confirming that there is an existing gap in the current DSS developed for practitioners (Chapter 3). The second phase starts with the development of a logical framework (Section 4.4.1) that methodically links the research objective and purpose to deliverable outputs. Moreover, the logical framework includes the validation methods (Section 4.8) employed to assess whether the research successfully meets the set deliverables and in turn the research objective. The individual models within the support system are then developed and this is covered in detail in Chapter 5. The implementation phase demonstrates the functionality and contribution of the DSS to Energy Company's case study (Chapter 6). The evaluation phase, with the practitioner demonstration, gives an additional validation to the system (Chapter 7).

### 4.4.1 Logical Framework

The logical framework is defined by Schmidt [169] as a set of organised concepts that help to logically design a project. The logical framework (Table 4.1) is a useful and widely adopted project management tool; though some of the matrix headings have been changed to better suit the context of the research. The logical framework aids in linking the project aim and purpose with the deliverables. It also creates clear relationships between the purpose and deliverables with measures and methods for testing whether they have been achieved (validation).

*Table 4.1 – Logical framework*

| **Objectives** | **Success measures** | **Validation** | **Assumptions** |
|---|---|---|---|
| **Aim:** | | | |
| To develop a DSS for small-scale (500 kWe to 10 MWe) biomass combustion CHP project development and risk management | Project feasibility outputs that are useful for Energy Company, project developers and other potential users | Feedback from stakeholders (Energy Company or other potential user groups) | Sufficient similarity between biomass combustion projects to be able to create a generalisable DSS |
| | Test DSS against real project data or other analysis of cases | Results of the validity test(s) | There is an existing case where the outputs are known (e.g. financial models of potential or operational projects) |
| | | Existing case data or notional cases | |
| **Purpose:** | | | |
| To support developers in the early stages of project development with a project objective (financial and schedule) and risk management support system | Is original and supports developers and other potential users of the DSS | Developer and appraisal questionnaire | Participants have some experience of the industry and project development |
| | | | They are able to use the model for a case(s) |
| **Deliverable:** | | | |
| Fuzzy risk management model | A functioning fuzzy risk management model that enables the user to move through all the phases of the process and is able to assess the cost: benefit of risk responses or optimise with limited resources | Case study and practitioner demonstration | Relationships between risks and responses can be simplified to suit feasibility stage decision-making and fuzzy theory |
| | | | The risk management model can be linked to the project objective outputs |
| Fuzzy financial model | A functioning fuzzy financial model that incorporates the commonly used financial metrics (e.g. cash flow analysis, NPV, IRR and LCOE) and terms of project finance. | Case study and practitioner demonstration | Fuzzy sets can be translated into the necessary financial outputs for decision-making |
| Fuzzy schedule model | A functioning fuzzy project scheduling model with critical path analysis | Case study and practitioner demonstration | Users can define fuzzy task functions within the DSS and a method for fuzzy task criticality can be created |
| Graphical user interface (GUI) | A GUI that enables users to independently utilise the system without the need of an expert or technical specialist | Practitioner demonstration | A GUI can be developed that links all the models and this can be utilised by a project developer or similar user |

The logical links between framework tiers show that if the assumptions hold for each tier within the matrix, and the deliverables are achieved then so is the purpose and the overall aim. The research assumptions and purpose within the framework strongly influenced the simplifications and assumptions within the decision support system (Section 4.7). Similarly, the validation measures for each tier led to the applied techniques within the research (Section 4.8).

### 4.4.2 Project Schedule

A project schedule was adhered to and communicated to Energy Company before they failed and to the supervisory team at Aston throughout the research. Table 4.2 gives a description and duration of each task within the research project.

*Table 4.2 – Project work plan*

| # | Task | Description | Duration |
|---|---|---|---|
| 1 | Pre-research project with Energy Company | Worked closely with the company to a further understanding of the industry and the company | Sept 2009 – Jan 2010 |
| 2 | Conceptual and planning phase | Problem defining and preliminary literature review | Jan 2010 |
| 3 | Clarification of the objectives and methodology | Clarification of objectives with Energy Company and supervisory team | Feb – March 2010 |
| 4 | Literature review | Extensive review of the literature | March – June 2010 |
| 5 | Methodology | Extensive development of the methodology to achieve the research aim and objectives | June – Sept 2010 |
| 6 | Qualifying report | Submit qualifying report and work conducted to date | Sept – Nov 2010 |
| **7** | **Report to Energy Company** | **Feedback qualifying report direction and comments before continuing** | **Jan 2011** |
| 8 | OR and DSS experimental research | Develop and compare fuzzy, probability and MCDM models using company data | Feb – April 2011 |
| 9 | Software platform selection and develop programming skills | Select software platform and learn computer programming language and database design | May – Sept 2012 |
| **10** | **Report to Energy Company** | **Progress feedstock before continuing** | **Sept 2012** |
| 11 | Finance model | Develop crisp and then fuzzy financial models | Oct 2011 – Jan 2012 |
| 12 | Energy Company starts dissolution process | Made aware of the issues with Energy Company | Jan – Feb 2012 |
| 13 | Risk management model | Develop crisp and fuzzy risk management models | Feb – March 2012 |
| 14 | Scheduling model | Develop crisp and fuzzy scheduling models | March – April 2012 |
| 15 | DSS coding (GUI) | Transfer to MS Visual Studio and then integrate the model functionality | March – Aug 2011 |
| 16 | Final verification | Run multiple tests throughout the DSS | July 2012 |
| 17 | Energy Company validation | Apply the DSS to the Energy Company case study and support with analysis | July – Aug 2012 |
| 18 | DSS demonstration | Demonstrate the DSS to industry practitioners | Aug 2011 – Jan 2013 |
| 19 | Prepare thesis for submission | Compile work to date and submit thesis | Sept 2011 – Jan 2013 |
| **Lateral tasks:** | | | |
| - | Book chapter (F-PRM) | A chapter on the application of fuzzy sets and logic to project risk management | May – June 2012 |
| - | Journal paper (F-LCOE) | A journal paper on applying the developed fuzzy levelised energy cost method within the research | June – Jan 2013 |

|  |  |  |  |
|---|---|---|---|
| - | Journal paper (F-CPM) | A journal paper on applying the developed fuzzy scheduling and critical path method within the research | June – Feb 2013 |

The research slightly overran the three year target of the end of December 2012. This is a relatively insignificant overrun given the nature of research and the issues faced with the company partner.

After the qualifying report (6) defence, there was a significant change to the research project to its current focus. Formally reporting to the company in January and September 2012 (7, 10) ensured that the project direction and progress remained beneficial to the company before the abandonment of their first development site in late 2011. The experimentation with different decision support techniques (8) also supported the chosen methodology when demonstrated at the September 2012 meeting. As the functioning financial (11) and risk management (13) models were under development when the company informed the research project of the issues (12), it was not possible to demonstrate models in the final functioning form. The DSS was available for demonstration five months after this time (16) and could have been utilised by the company if they had not ceased operation by this point. A greater emphasis was then placed on Energy Company as a validation case study (17) and supported with industry practitioner assessment (18). The validation and verification process applied is covered in greater detail in Section 4.8. Finally, the research also conducted lateral activities and publications to support the research quality.

## 4.5 Paradigm

This research is exploratory and this is defined as “research that aims to seek new insights into phenomena, to ask questions, and to assess the phenomena in a new light” [170:670]. Although, as stated by Lee and Lings [171], it is often difficult to disentangle the explorative and explanative approaches as they form reinforcing cycles that lead to knowledge creation. The research pursues an exploratory approach throughout the applied paradigm and this is shown in the philosophy and research design. Theory or decision support systems on feasibility studies, financial and planning objectives, and risk management exist, but are brought together under the unifying fuzzy set method to induce the ‘general’ case for the purpose of achieving the research aim.

As the purpose of the research has been established, it is important to define the overall research paradigm. It is stated that all of the existing and emerging paradigms are defined by how they attempt to answer these three fundamental questions:

i. *ontological*: what is the nature of the “knowable”? Or, what is the nature of “reality”?

ii. *epistemological*: what is the nature of the relationship between the knower (the inquirer) and the known (or knowable)?

iii. *methodological*: how should the inquirer go about finding out knowledge?

[172:18]

Guba [172:18] also adds that these "...are the starting points or givens that determine what inquiry is and how it is practiced. They cannot be proven or disproven in any foundational sense; if that were possible there would be no doubt about how to practice inquiry".

Typically, DSS research is strongly grounded in the positivistic paradigm with research by Arnott and Pervan [104] finding that of 617 DSS journal papers analysed between 1990 and 2003, 92.2% were positivist. A criticism of their research is the categories were limited to either positivist, interpretive or mixed philosophy. This restricts the inclusion of post-positivistic paradigms such as realism, which Iivari [1991 cited 104] "identified DSS as the only school with strong post-positivist tendencies". It is necessary not to simply accept the typical approach without analysing the important aspects of these main philosophical paradigms as shown in Table 4.3.

*Table 4.3 – Comparison of research philosophies [170:140]*

| | **Positivism** | **Realism** | **Interpretivism** |
|---|---|---|---|
| Ontology | External, objective and independent of social actors | Is objective. Exists independently of human thoughts and beliefs or knowledge of their existence (realist), but is interpreted through social conditioning (critical realist) | Socially constructed, subjective, may change, multiple |
| Epistemology | Only observable phenomena can provide credible data, facts. Focus on causality and law like generalisations, reducing phenomena to simplest elements | Observable phenomena provide credible data, facts. Insufficient data means inaccuracies in sensations (direct realism). Alternatively, phenomena create sensations which are open to misinterpretation (critical realism). Focus on explaining within a context or contexts | Subjective meanings and social phenomena. Focus upon the details of situation, a reality behind these details, subjective meanings motivating actions |
| Axiology | Research is undertaken in a value-free way. The researcher is independent of the data and maintains an objective stance | Research is value laden; the researcher is biased by world views, cultural experiences and upbringing. These will impact on the research | Research is value bound, the researcher is part of what is being researched, cannot be separated and so will be subjective |
| Data collection technique most often used | Highly structured, large samples, measurement, quantitative, but can use qualitative | Methods chosen must fit the subject matter, quantitative or qualitative | Small samples, in-depth investigations, qualitative |

The ontological assumption of this research is realist; in particular critical realist. As Table 4.3 shows, the realist philosophy can be separated into direct or critical realism. Although, the realist paradigm is classed as post-positivistic, critical realism accepts more of the interpretative philosophy than direct realism. Realist ontology is closely aligned with that of classical positivism, sometimes referred to as naive realism [173], which holds the view that reality is what is observable and objective. This classical positivist viewpoint which has traditionally been the 'received view' in social science [172, 174] and is now widely believed to be flawed for this 'objectivity' assumption. Critical realist ontology, is considered as neo-positivism, holding a more critical ontological view that "...there are some things beyond our ability to confirm their existence directly..." [171:31].

An ontological perception influences the research epistemology, as "...ontology is the 'reality' that researchers investigate, epistemology is the relationship between that reality and the researcher..." [175]. By comparing the positivist epistemology where "only directly observable phenomena, with any reference to the intangible or subjective being excluded as being meaningless…" [176:192] against critical realism's view that our perception of the observable is only part of the picture [177] and "sensations which are open to misinterpretation" [178:119]. The epistemological differences between positivism and critical realism become clear. In summation, this means that "realist researchers often seek to offer generalisable explanations but they are less likely (than positivists) to offer predictions" [179:19]. An example of how the critical realist paradigm affects the research method is the selection of fuzzy set theory. Uncertainty in information (subjectivity) is represented in fuzzy sets and with linguistic variables as the research philosophy accepts that there is imperfect knowledge, yet it should not be excluded from the DSS design. This is concordant with Baxter et al. [180:60] who states that "post-positivists argue that we can only know social reality imperfectly and probabilistically. Which objectivity remains an ideal".

## 4.6 Design

There are three key sections to the research design: the bCHP lifecycle planning DSS, the Energy Company case study and a practitioner validation questionnaire. The research design is aligned with the exploratory and critical realist research paradigm. Saunders, Thornhill [170] state that a critical realist philosophy may lead to a multiple or mixed method research design. This is not the case within the employed design as the interpretative or subjective aspects of the research are either accommodated quantitatively by being included in the DSS or discussed in the qualitative parts of the practitioner questionnaire.

The research design is skewed toward the objective ontology and therefore has a largely quantitative design. However, this is not solely the case and qualitative information is present within three sections of the design, such as the use of qualitative linguistic variables within the DSS for the fuzzy set definition and risk analysis. Moreover, the case study requires some interpretation on the motives of Energy Company and the decision-making processes that ultimately led to their failure and the validation questionnaire also has some open questions.

### *DSS Design*

The decision support system incorporates a unifying fuzzy set theory methodology for the financial and schedule viability, and risk management analysis. A DSS is the most suitable method for achieving the research aim as it utilises data and models to facilitate decision processes [101], and has been shown in the myriad of existing support systems covered in the literature review to be suitable to bioenergy and other renewable energy applications. Some of the key issues identified by Arnott and Pervan [111] relate to the research method and paradigm and therefore need to be addressed. They found that the discipline is dominated by a positivistic paradigm and lacked case study research. As stated, the research has a critical realist paradigm and is grounded with a case study linked to practice and therefore avoids these key issues. However, the DSS still suffers from the identified inertia and conservatism issue as a more traditional personal system is designed to achieve the research aim.

Fuzzy set theory also known as possibility theory is utilised within the DSS to incorporate uncertainty, approximate information or subjective assessment of many key bCHP project development variables. This method is more suited to the critical realist philosophy than the probabilistic method applied in some existing support systems covered in the previous chapter. Fuzzy set theory is also preferential as the decision-maker lacks the level of data required to map probabilistic distributions and this was shown in IEA [56] risk quantification method.

### *Case Study Design*

As the DSS is demonstrated with Energy Company as a case study, it is important to define the design. Case study research is more commonly inductive than deductive and is concerned with exploration and understanding [181]. This view conforms to the aim and objectives of the research and the direction influenced from collaboration with Energy Company. A case study is better suited to demonstrating the decision support system as the research is able to utilise a high level of real project development data to explore and induce a new method for conducting project feasibility analysis in bCHP projects within the UK. Alternatively, an experimental design could be employed as it is aligned with the explorative approach [182] and critical realist philosophy but has not been chosen over a case study for several reasons. The foremost is the requirement to verify in a hypothetico-deductive manner or control variables under experimental conditions and establish causality [170]. These would prove difficult to achieve with the complex reality of decision-making in bCHP project development and with the limited sample size. Moreover, due to the company failure an experimentally deductive approach is not possible as pre and post-test measures could not be employed. The developed DSS is applied to the case study to explore the possible reasons for the failure of Energy Company and induce a generalisable support system.

It is stated by Yin [182] that the common concerns with the validity of case studies are the lack of rigour, generalisability and causal relationships (not a true experiment). These are addressed in turn in Table 4.4 through the construct, internal and external validity and reliability tests required for conducting high quality case study research.

*Table 4.4 – Research design quality criteria [182:41]*

| Test | Definition[1] | Yin's requirement | Phase of research | Demonstration |
|---|---|---|---|---|
| Construct validity | Extent to which your measurement questions actually measure the presence of those constructs you intended them to measure | Use multiple sources of evidence | Data collection | There was communication with several stakeholders to the project over a prolonged period and access to project documents |
| | | Establish chains of evidence | Data collection | The chain of evidence in the context of the research is the case study analysis in Chapter 6 |
| | | Have key informants review draft of case study report | Composition | Not possible to get the analysis of the case study reviewed by the company as they ceased operation and communication. However, the case study has been shown to industry practitioners (Chapter 7) |
| Internal validity | Extent to which findings can be attributed to interventions rather than any flaws in your research design | Pattern matching | Data analysis | Not applicable to the research |
| | | Explanation building | Data analysis | Where possible supporting explanations have been given for the analysis of the case |
| | | Address rival explanations | Data analysis | Where possible rival explanations have been sought for the analysis of the case |
| | | Use logic models | Data analysis | Not applicable to the research |
| External validity | The extent to which the research results from a particular study are generalisable to all relevant contexts | Use theory in single case studies | Research design | The theory is demonstrated with the DSS and can be tested on other case studies |
| Reliability | The extent to which data collection technique or techniques will yield consistent findings, similar observations would be made or conclusions reached by other researchers or there is transparency in how sense was made from the raw data | Use case study protocol | Data collection | Not applicable to the type of case study |
| | | Develop a case study database | Data collection | The case study is stored in the DSS and the analysis is held within the thesis |

[1] Taken from [170:668-680]

Where applicable, actions have been taken to ensure that the research is of a high quality and that it achieves the validity and reliability types.

### *Questionnaire Design*

The questionnaire (Annex 3) has nine questions and is semi-structured with a combination of closed, Likert-scale questions and open answers or possibility to add additional comments. The questionnaire survey is given to participants who use the decision support system on a notional case. Furthermore, the questionnaire was delivered electronically through SurveyMonkey.com after the participants have utilised the DSS with or without a site visit by the researcher. As this is a specialised, small, and relatively nascent sector, the research approach is opportunity sampling to maximise the number of participant responses and the overall research impact. The questionnaire supports the development of the DSS and application to Energy Company’s case study by formalising the validation and evaluation of industry practitioners. A large sample size is not pursued for the survey as an empirically deductive analysis is not required for the inductive approach. The five participants have extensive experience in the UK bioenergy industry and are active practitioners (covered in more detail in Chapter 7). A questionnaire survey is the most suitable method for gathering the views of participants as its structured and objective design is more closely aligned with the realist research paradigm than observations and interviews.

## 4.7 Assumptions and Simplifications

Model building always requires simplifications and approximate representations of some aspects of reality [183]. This is the case for the DSS and Table 4.5 covers the main assumptions and simplification along with a rationale for their use. These are defined by Robinson [184] as “assumptions are made either when there are uncertainties or beliefs about the real world being modelled” and “simplifications are incorporated in the model to enable more rapid model development and use, and to improve transparency”.

*Table 4.5 – Assumptions and simplifications*

| Description | Assumption or simplification | Rationale |
|---|---|---|
| **DSS inputs:** | | |
| Project inputs are fixed for the project lifecycle (e.g. plant performance, feedstock energy content, costs, prices, incentives or levels of on or off-site utilisation) and do not increase over the operational period | Simplification | This information is not held by developers at the feasibility stage of project development |
| Variable heat utilisation systems such as in extraction condensing does not affect electrical efficiency | Simplification | No generalisable calculation exists and therefore is required to be entered by the decision-maker |
| Heat demand can be met at all times without the need for a peak load or back up boiler | Simplification | Avoids the added complexity of load mapping and costs of back up boilers. Both are information unlikely to be held or required at the feasibility stage |
| **Finance:** | | |
| Future cash flow projections have not been discounted or in the case of the NPV/IRR a fixed discount rate is utilised | Simplification | Covered in Section 5.10.1 |
| Project finance terms are fixed irrespective of the level of gearing | Assumption | The gearing of a project could influence the terms of finance but this is also ignored in previous work [48, 61, 148] |
| **Scheduling:** | | |
| Project tasks have a start-finish precedence relationship only | Simplification | Reduces the amount of input and better suited for early stage project planning. Dummy tasks may be utilised to circumvent this simplification |
| **Risk management:** | | |
| Risk events and responses are mutually exclusive | Simplification | Covered in Section 5.6.3 |
| Only one response is permitted per risk event | Simplification | Covered in Section 5.6.3 |

The individual model simplifications or assumptions are required to ensure that the assumptions section within the logical framework hold and these are justified within the table or later within the thesis. The most signification simplification is that the project inputs are static over the operational lifecycle of the project, this greatly reduces the amount of information required by developers or users of the DSS that would unlikely be available at the feasibility stage. Fuzzy sets account for a range of possible expected outcomes and can closely map the possibility of changes over the operational period of the project within the fuzzy financial outputs. The fuzzy sets also show the effect of uncertainty or changes to project task durations within the fuzzy schedule outputs. Possible methods for avoiding these assumptions and simplifications in future work are given in Section 8.4 and 8.5.

## 4.8 Validation and Verification

Validation and verification are essential to ensure that the DSS is functioning correctly and that the research satisfies the aim and objectives. The systematically reviewed literature performed poorly at explicitly covering these important aspects within the journal publications. A few of the DSS referred to either validation or verification [124, 126, 131, 134, 136, 138, 185] with only Hong, Koo [141] addressing both through a case study application. A case study application is the most common method of validation or verification [131, 136, 185] within the reviewed research. Case studies are featured in a larger number of DSS but there is not an explicit reference to either term. Moreover, as the reviewed literature highlights the terms are often used interchangeably or with verification being considered a sub-set within validation [186, 187]. However, they are treated differently within the research and are analysed in turn.

Verification is defined as "…the testing and debugging of programs" [187:185]. It is stated by Sojda [188] that verification is an iterative process that should be performed prior to completing or delivering the final system. Similarly to Sojda [188], component verification within the DSS was conducted throughout development to ensure that the individual model code (e.g. finance, scheduling and risk management) was functioning correctly and the support system as a whole. This process utilised cases from others sources where possible and fabricated tests during the development process. The financial model was verified against the de Jager and Rathmann [48] case for levelised costs and the sensitivity analysis. Furthermore, the fuzzy levelised energy cost model has been submitted to *Energy Policy Journal* to seek peer reviewed verification. In addition, the fuzzy scheduling model utilised the conceptual network from Chanas and Zieliński [189] and applied in later papers [190], along with an oil pipeline project development case study[24]. Verification of the risk management model and resource constrained optimisation model were not able to utilise an existing case study and therefore relied on multiple fabricated risk examples.

Validation is not only an important part of DSS development and continued use but not properly validating can lead to costly errors [191]. Validation is defined by Finlay [187:183] as "…the process of testing the agreement between the behaviour of the DSS and that of the real world system being modelled". Yet, he adds that it is never possible to fully conduct validation and refers to Popper's [Popper, 1959 cited 187] reasoning that it is not possible to prove the conclusive truth of a law or relationship by simple gathering supporting data or information. Therefore, Finlay [187] add that demonstrating that the relationships within the DSS are appropriate is sufficient. The validation of the decision support system within the research is two-fold; it is applied to Energy Company's case study in Chapter 6 and then evaluated by practitioners in Chapter 7. This approach enables the

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[24] Forthcoming journal publication to be published by the author in 2013

outcomes, purpose and overall objective of the logical framework (Table 4.1) to be achieved. Moreover, this validation approach is also applied by Sojda [188] when evaluating their expert system with a 'soft validation' through expert or user input and with the use of a case study historic data set.

Firstly, the case study validation process utilises actual project data and forecasted data by Energy Company when developing their first small-scale bCHP scheme. The main advantage of conducting a case study validation is the use of 'real world' data to test, as much as is possible, the translation into the DSS. The case study also gives a unique insight into the barriers of bCHP project development and a less subjective or bias validation process; it is mostly similar to the systematically reviewed literature with the use of real data case studies. However, as the company neither successfully developed the scheme nor is able to validate the DSS interpretation of the case study, it is necessary to support the validation with practitioner assessment through demonstrating the support system.

Secondly, the survey is designed to not only validate the system at representing the research problem but to also evaluate the DSS, its components and the potential benefit to supporting project development. The principles of the questionnaire design are taken from the widely cited and applied End-User Customer Satisfaction (EUCS) method proposed by Doll and Torkzadeh [192]. EUCS is defined as "…the affective attitude towards a specific computer application by someone who interacts with the application directly" [192], with the overall aim being to assess or measure the utility in decision-making. Their survey based method measures the five components of satisfaction as content, accuracy, format, ease of use and timeliness. Some objectives of the survey design are closely aligned or applied within the research's design, such as a focus on satisfaction, evaluating the ease of use, the application of Likert type scales and in identifying the underlying factors or components of end-user computing satisfaction [192].

The EUCS design is utilised as a template due to the small-sample size inhibiting inferential statistical analysis and the objective of the questionnaire survey not being exactly aligned, as the perception of usefulness is not included, an evaluation of the model components is required and timeliness is not applied in the wider sense. Hung, Ku [193] review 18 studies featuring DSS success measures to assess decision performance and user satisfaction within their research. They highlight the wide range of criteria applied in the studies, this not only emphasises the lack of an accepted methodology but also the possible variables or measures to include within the questionnaire survey. Of these studied papers, Alavi and Joachimsthaler [194] contribute to the questionnaire design as they include performance variables and the attitudes / perceptions of DSS use. Due to the small-sample size of five respondents, the survey is limited to largely descriptive statistics and an interpretation on the qualitative, open-ended questions. The questionnaire issued to practitioners is given in Annex 3.

As the results of the verification and validation tests show (Chapter 6 and 7), the DSS is fully functioning and sufficiently resembles the ‘real world’ and logical relationships modelled.

*Table 4.6 – Model component verification and validation*

| Process | Fuzzy finance model | Fuzzy scheduling model | Fuzzy risk management & optimisation |
|---|---|---|---|
| Verification | i. **Variable Isolation**<br>Variables were isolated in turn to verify that they were performing as expected throughout the model building process | | |
| | ii. **Example Use**<br>Applied to a case utilised within de Jager and Rathmann [48] for levelised costs and sensitivity analysis | ii. **Example Use**<br>Applied to a case network applied within multiple journal papers (Chanas and Zieliński [189] and Chen and Hsueh [190]) | ii. **Example Use**<br>Utilised multiple fabricated risk event examples |
| | iii. **Peer Review**<br>The financial model was sent to Energy Policy Journal for verification | | |
| Validation | i. **Case Study Application**<br>Applied the DSS to Energy Company's failed case study development, utilising actual data where possible | | |
| | ii. **Further Case Study Application**<br>Two of the five practitioners ran their own notional cases through the DSS | | |
| | iii. **Practitioner Survey**<br>Practitioner survey of the DSS functionality and evaluation | | |
| | | iv. **Case Study Application**<br>Applied the fuzzy scheduling model to an oil pipeline case study | |

# 5. Lifecycle Planning and Risk Management DSS Description

## 5.1 Introduction

The purpose of this chapter is to fully explain and justify the model equations and algorithms applied within the DSS. For a description of the model with a worked example and screen shots, please refer to Annex 4. Only the fuzzy membership mode with the ability to incorporate uncertain or approximate inputs and throughout the PRM process is covered in the body of the thesis. It is possible to run the DSS without the fuzzy mode enabled, it operates in a very similar way, but produces only 'crisp' outputs as the fuzzy membership functions and uncertainty are not integrated into the system or calculations.

The chapter starts with an overview of the DSS components (5.2) and then defines fuzzy set theory, α-cuts and L-R / L-L type reference functions (5.3). These underpinning concepts are important as the method is applied throughout the DSS. The chapter then methodically proceeds through the parts of the DSS (5.4 – 5.12), as specified in the DSS overview in Section 5.2. The final section of the chapter gives instruction on the stages required to replicate the individual parts of the developed DSS (5.13).

## 5.2 DSS Overview

Before proceeding through the chapter, it is important to give an overview of the decision support system and its major components, as shown in Figure 5.1. The decision-maker is able to interact with the DSS through the graphical user interface. This enables access to and control in the input and output phases of the system.

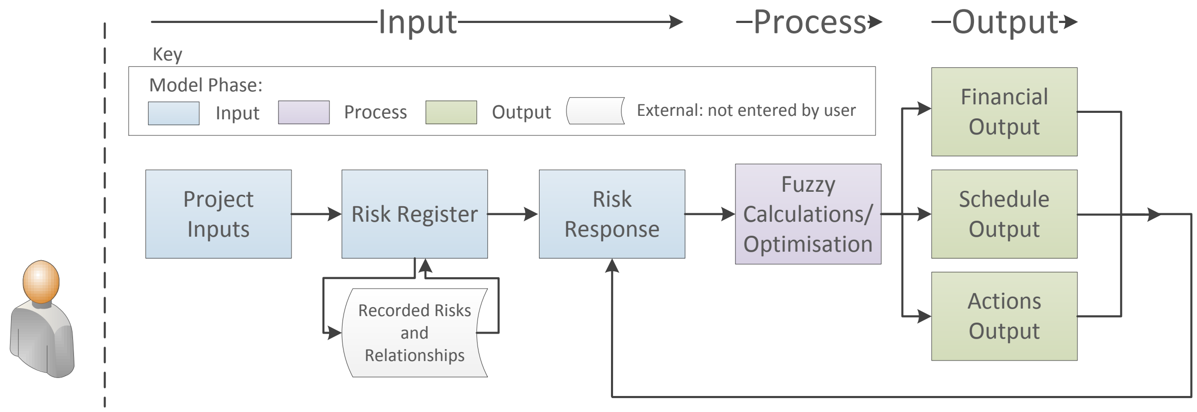

*Figure 5.1 – DSS overview*

The decision-maker is required to enter preliminary information on the project into the project inputs section. For each project, the decision-maker needs to input the technology, feedstock, location, financial and schedule information (5.5) and it is then possible to go through a risk analysis and management phase (5.6, 5.7). The DSS processes the inputs and risk analysis to produce a range of financial analysis outputs (5.9, 5.10), schedule outputs (5.11) and actions (risk response strategy) outputs (5.12).

### 5.2.1 Software Platform

The DSS is an object orientated Windows form deployable application developed on MS Visual Studio 2010. The linear programming models developed for the fuzzy critical path method (Section 5.11) and the optimisation of risk response strategies under limited project resources (Section 5.12) use the MS Foundation Solver software and it is integrated into the application.

## 5.3 Fuzzy Sets

Fuzzy set theory was first proposed in the 1960's by L.A. Zadeh and is conceptually easy to understand and apply. It is especially useful for "…decision-making in an environment of uncertainty and incompleteness of information" [195:ix]. As the theory is different to the traditional probabilistic techniques, it does not require exact values to be attributed to variables. Inputs can be approximate or 'fuzzy', making it ideal for application to future projections of cost and revenue in the early stages of project development and with limited information.

A fuzzy set $\tilde{A}$ is a set of real numbers $\mathbb{R}$ characterised by means of a membership level $\mu_{\tilde{A}}(x), \mathbb{R} \rightarrow [0,1]$. Where the membership to set $\tilde{A}$ for each $x$ within the set $X$ is given as $\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) | x \in X\}$. This can also be expressed as a piecewise function $\tilde{A} = \langle a, b, c, d \rangle$:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, \; for\, a \geq \; x \geq d \\ \dfrac{x-a}{b-a}, \; for\, a \leq \; x \leq b \\ 1, \; for\, b \leq \; x \leq c \\ \dfrac{d-x}{d-c}, \; for\, c \leq \; x \leq d \end{cases} \tag{5.1}$$

Alternatively, it is possible to represent the function in its $\tilde{A} = \langle \underline{m}, \overline{m}, \beta_A, \gamma_A \rangle$ form[25]:

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[25] Traditionally, this is represented as α and β for the left and right hand spread but these have been changed to avoid the use of α as it is used later in the chapter to define α-cuts

$$\mu_{\tilde{A}}(x) = \begin{cases} 0,\ for\ \underline{m} - \beta_A \geq\ x \geq \overline{m} + \gamma \\ \dfrac{1 + (x - \underline{m})}{\beta_A},\ for\ \underline{m} - \beta_A \leq\ x \leq\ \underline{m} \\ 1,\ for\ \underline{m} \leq\ x \leq \overline{m} \\ \dfrac{1 + (\overline{m} - x)}{\gamma_A},\ for\ \overline{m} \leq\ x \leq \overline{m} + \gamma_A \end{cases} \tag{5.2}$$

Where: $\underline{m} = b\ , \overline{m} = c,\ \beta_A = b - a \geq 0,\ \gamma_A = d - c \geq 0.$

As stated in Dubois and Prade [196] the greater the $\beta_A$ and $\gamma_A$ the wider the spread and the fuzzier the number. Within the DSS, the fuzzy trapezoidal membership function is defined by its absolute minimum (abs. min) and maximum (abs. max), and expected lower (exp. lower) and upper (exp. upper) values where:

$\tilde{A} = \langle a, b, c, d \rangle =\ \langle abs.min, exp.lower, exp.upper, abs.max \rangle.$

### 5.3.1 Fuzzy Membership Functions (DSS Context)

Throughout the DSS, the decision-maker can enter fuzzy membership functions where there is uncertainty or only approximate information available. To accommodate uncertainty, an absolute minimum and maximum region and within that the most expected region can be defined. The four inputs create a fuzzy triangular or trapezoidal distribution. The minimum and maximum inputs are the lowest and highest values possible but the least expected to occur, and the expected lower and upper inputs define the range of the most expected values to occur, within which no differentiation of expectation is possible. The expected lower and upper inputs can coincide if a single most expected value can be identified. These inputs affect the final financial, scheduling and risk analysis outputs as they give the possibility of the project being viable under a range of outcomes.

### 5.3.2 α-cut Sets

The extension principle [197] is the underpinning theory for operations of fuzzy numbers. It 'extends' the operations and definitions of ordinary 'crisp' mathematical set-based concepts to fuzzy sets [198]. By taking α-cuts of a fuzzy set, it is possible to produce non-fuzzy numbers that can undergo crisp mathematical arithmetic operations. α-cuts are defined as a crisp set of elements belonging to a fuzzy set $\tilde{A}$ at least to the degree of α [198]:

$$^{\alpha}A = \{x \in X | \mu_{\tilde{A}}(x) \geq \alpha\} \tag{5.3}$$

An example of an α-cut, given in the context of the research, is each $\alpha \in (0,1]$ within the interval $^{\alpha}A = [\,^{\alpha}\underline{m},\ ^{\alpha}\overline{m}\,] = [\inf\{x \in X|\mu_{\tilde{A}}(x) \geq \alpha\}, \sup\{x \in X|\mu_{\tilde{A}}(x) \geq \alpha\}]$ [199] and this is represented graphically in Figure 5.2.

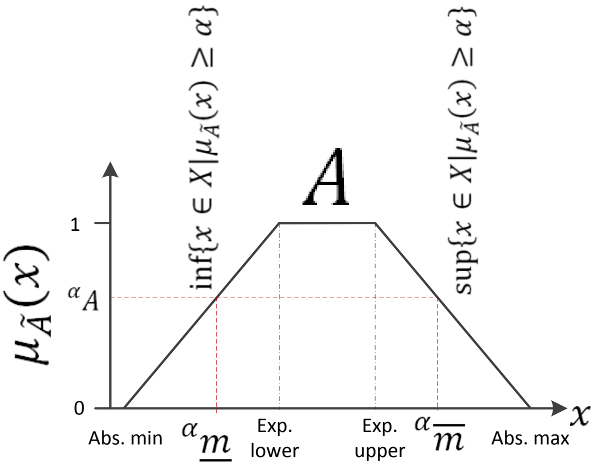

*Figure 5.2 – Fuzzy set α-cut*

Each cut of fuzzy set $\tilde{A}$ produces two crisp outputs ($^{\alpha}\underline{m},\ ^{\alpha}\overline{m}$) that represent the lower and upper bounds of the function. These crisp α-cuts can undergo the necessary mathematical arithmetic operations required to determine approximately the fuzzy output function. The number of α-cuts can be arbitrarily selected depending on the level of precision required in mapping the output function. Within the research, 12 α-cuts are taken at $\alpha = \{.001, .01, .1, .2, .3, \dots, .9, 1\}$ with a greater level of focus on the extremities or tail ends of the fuzzy function, as in previous research [190, 199].

### 5.3.3 L-R and L-L Reference Functions

L-R type representations of fuzzy functions were first defined by Dubois and Prade [196]. As stated by Hanss [200], L-R representations split a fuzzy function $\tilde{A}$ into two bounds left $\mu_L(x)$ and right $\mu_R(x)$ of the model values $(\underline{m}, \overline{m})$. The membership function can then be expressed as reference function in the L-R form:

$$\mu_{\tilde{A}} \begin{cases} \mu_L(x) = L\left[\frac{\underline{m}-x}{\beta_A}\right] for\ x \leq \underline{m} \\ \mu_R(x)\ = R\left[\frac{x-\overline{m}}{\gamma_A}\right] for\ x \leq \overline{m} \\ \quad 1\ for\ x\ \in [\underline{m}, \overline{m}] \end{cases} \tag{5.4}$$

Where L and R are:

- continuous non-increasing functions, defined on [0,+∞);

- strictly decreasing to zero in those subintervals of the interval [0,+ ∞) in which they are positive, and fulfilling the condition L(0) = R(0) =1;
- the parameters $\beta$ and $\gamma$ are non-negative real numbers.

[189]

An L-R type function is classified as being semi-symmetrical if L and R apply the same reference function or fully symmetrical if β and γ are also the same [200]. Within the DSS, the functions can be fully symmetrical if the decision-maker enters a fuzzy function with that characteristic, but are always semi-symmetrical as the same reference function is applied to the L and R bound and are therefore referred to as L-L type.

To map L-R and L-L type functions it is necessary to apply the extension principle. The reference functions are usually in one of the following forms, as first proposed by Dubois and Prade [196] and utilised in [189], with parameter $p$ and their inversed counterparts:

*Linear*

$$RF_p(x) = max(0{,}1 - x) \tag{5.5}$$

$$RF_p^{-1}(\alpha) = 1 - \alpha, \quad \alpha \in (0{,}1] \tag{5.5'}$$

*Exponential*

$$RF_p(x) = e^{-px}\, p \geq 1 \tag{5.6}$$

$$RF_p^{-1}(\alpha) = -(ln\,\alpha)/p\,, \quad \alpha \in (0{,}1] \tag{5.6'}$$

*Power*

$$RF_p(x) = max(0{,}1 - x^p)\; p \geq 1 \tag{5.7}$$

$$RF_p^{-1}(\alpha) = \sqrt[p]{1-\alpha}, \quad \alpha \in (0{,}1] \tag{5.7'}$$

*Exponential Power*

$$RF_p(x) = e^{-x^p} p \geq 1 \tag{5.8}$$

$$RF_p^{-1}(\alpha) = \sqrt[p]{-\,ln\,\alpha}\,, \quad \alpha \in (0{,}1] \tag{5.8'}$$

It is then possible to calculate the reference function from its piecewise function (Eq. 5.4) by determining the membership value of $x$ at a given point on the left bound, such that in a linear example:

$$L_A(x) = ma\,x\left(0{,}1 - \left(\frac{\underline{m}-x}{\beta_A}\right)\right) for\; x \leq \underline{m} \tag{5.9}$$

Alternatively, the inverse reference function equations can be utilised to determine the value of $x$ at a given membership level or α-cut, such that in an the linear example:

$$L_A(\alpha) = \underline{m} - (1 - \alpha) \cdot \beta_A \tag{5.10}$$

Therefore, the α-cuts of a fuzzy set of L-R type ${}^{\alpha}\tilde{A}_{L-R}$ has the following form [189]:

$${}^{\alpha}\tilde{A}_{L-R} = [\underline{m} - L^{-1}(\alpha) \cdot \beta_A, \overline{m} + R^{-1}(\alpha) \cdot \gamma_A\,] \tag{5.11}$$

Finally, as L-L type functions differ in that the same reference function is applied to the left and right bounds of the function, they have the following form:

$${}^{\alpha}\tilde{A}_{L-L} = [\underline{m} - L^{-1}(\alpha)\alpha_A, \overline{m} + L^{-1}(\alpha)\beta_A\,] \tag{5.12}$$

## 5.4 Attitude and Confidence Linguistic Controls

Previous research [189, 190, 199] has assumed that the correct reference functions were already selected and mapped by the decision-maker before proceeding to calculating the fuzzy outputs for the project. Although possible, it is unlikely to be an activity a decision-maker could or would do before proceeding, especially if there are many fuzzy functions to map or multiple iterations or changes to be made. This produces a cumbersome method, so a simplified methodology has been proposed to increase the speed and ease of modifying the fuzzy function inputs with the application of fuzzy linguistic term attitude and confidence levels. The Mon, Cheng [201] fuzzy PERT[26] paper incorporates the typical three-point decision-maker optimism scale (optimistic, most likely, and pessimistic) to model a project task duration., but does not support function mapping with the use of linguistic terms. Their approach does give greater control to the decision-maker but is considered overly simplistic for the research and therefore requires further development.

An alternative and more suitable solution is in the application of fuzzy attitude and confidence levels as proposed by Wang and Poh [202] and later by Fenton and Wang [203] in their papers on fuzzy multi-criteria decision-making. The attitude and confidence level calculations have undergone some modification to be suitable for handling trapezoidal functions and the confidence controls have been adapted to more closely map the reference function options (Section 5.3.3). Furthermore, the DSS

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[26] Program Evaluation and Review Technique

applies these linguistic controls to all the fuzzy functions throughout as a method for quickly adapting the form of any fuzzy cost, demand or risk impact membership functions.

*Table 5.1 – Attitude linguistic terms*

| Linguistic term | Abbr. | Fuzzy function |
|---|---|---|
| Absolutely | AO | $(a, a, b, d)$ |
| Very | VO | $(a, (b+3a)/4, (c+3b)/4, d)$ |
| Optimistic | O | $(a, (b+a)/2, (c+b)/2, d)$ |
| Fairly | FO | $(a, (3b+a)/4, (3c+b)/4, d)$ |
| **Neutral (default)** | **N** | $(\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \boldsymbol{d})$ |
| Fairly | FP | $(a, (3b+c)/4, (3c+d)/4, d)$ |
| Pessimistic | P | $(a, (b+c)/2, (c+d)/2, d)$ |
| Very | VP | $(a, (b+3c)/4, (c+3d)/4, d)$ |
| Absolutely | AP | $(a, c, d, d)$ |

Nine linguistic terms are employed, ranging from absolutely optimistic (AO) which skews the fuzzy function to the lower bound, increasing the possibility of the cost or duration being less than predicted, to the absolutely pessimistic (AP) where the converse is true. The effect of a change in the attitude level is shown in Figure 5.3.

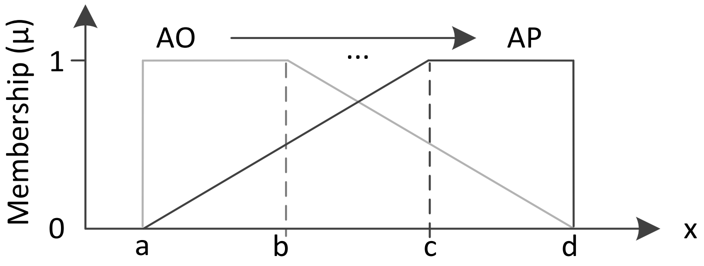

*Figure 5.3 – Fuzzy attitude skew*

L-R reference functions commonly used in previous research [189, 190, 199] were not ideal for linguistically mapping confidence as there are the aforementioned impracticalities in mapping functions. Moreover, further issues exist for the exponential reference type functions (Eq. 5.6) as the tail-ends do not converge to zero. This produces poor results with potentially incorrect negative duration or cost values at lower α-cut levels. Quasi-exponential reference functions [200] could be utilised to avoid infeasible negative durations or costs, but this just shifts the problem with the tail-ends higher up the α-cut spectrum as they are just simply capped.

After entering a risk attitude level, it is necessary to select the confidence level. Increasing confidence increases the possibility of the expected inputs occurring whilst reducing the possibility of the absolute inputs occurring. The opposite is true for a decrease in confidence. Table 5.2 shows the five options for selecting the confidence level for a given set $A$.

*Table 5.2 – Confidence linguistic terms*

| **Linguistic term** | **Abbr.** | **Left** | **Right** |
|---|---|---|---|
| Absolutely | AC | $\underline{m}$ | $\overline{m}$ |
| Very | VC | $\beta_A \cdot \alpha^{1/2} + (\underline{m}\text{-}\beta_A)$ | $(\overline{m} + \gamma_A) - \gamma_A \cdot \alpha^{1/2}$ |
| **Confident (default)** | **C** | $\boldsymbol{\beta_A \cdot \alpha + (\underline{m}\text{-}\beta_A)}$ | $\boldsymbol{(\overline{m} + \gamma_A) - \gamma_A \cdot \alpha}$ |
| Fairly | FC | $\beta_A \cdot \alpha^2 + (\underline{m}\text{-}\beta_A)$ | $(\overline{m} + \gamma_A) - \gamma_A \cdot \alpha^2$ |
| Neutral | N | $\underline{m}\text{-}\beta_A$ | $\overline{m} + \gamma_A$ |

The absolutely confident (AC) term converts the L-L type function to the expected lower and upper bounds $(\underline{m}, \overline{m})$. If a triangular fuzzy function is entered selecting this confidence level produces a fuzzy singleton. Very confident (VC) and fairly confident (FC) linguistic terms convert the original input into a fuzzy function that closely replicates the exponential (Eq. 5.6’) and quadratic (Eq. 5.7’) reference functions respectively without the identified weaknesses. Confident (C) maintains the original linear function (Eq. 5.5’) input and the neutral (N) term converts the function to all values within the abs. min and max bounds being equally possible. The effect of the changes in confidence level is also illustrated graphically in Figure 5.4.

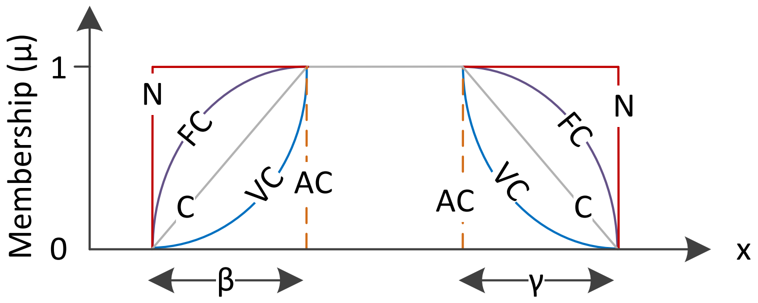

*Figure 5.4 – Fuzzy confidence levels*

The applied method gives greater functionality to the decision-maker in defining the fuzzy membership functions. It is also an improvement on the functions used in previous research, as it is more decision-maker friendly with the use of the linguistic controls. The L-L type linguistic functions adopted for the DSS do slightly reduce the flexibility given with the L-R type reference functions but greatly increase the level of control demonstrated in the fuzzy PERT method [201]. Moreover, they can be quickly applied and changed within the body of the DSS and this is not possible with the existing approaches [189, 190, 199].

## 5.5 Project Inputs

The following sections of this chapter move through the DSS phases (as shown in Figure 5.1). The inputs for the DSS are given in Table 5.3.

*Table 5.3 – Project inputs by type*

| **Technology** | | **Location** | | **Financial** | | | | **Schedule** |
|---|---|---|---|---|---|---|---|---|
| **Plant** | **Fuel** | **Demand** | **Additional** | **CAPEX** | **OPEX** | **Incentive** | **Market** | **Task** |
| Net capacity | Type | Residential electricity | Residential electricity price | Development | Maintenance | ROCs | Tax | Duration |
| Heat to power ratio | Cost | Residential heat | Residential gas price | Plant | Operation | ROC price | PPA limit | Preceding tasks |
| Boiler losses | Energy content | Industrial electricity | Industrial electricity price | EPC | Insurance | RHI price | | |
| Parasitic load | | Industrial heat | Industrial gas price | Other | Land lease | LEC price | | |
| Electrical efficiency | | Annual residential: industrial heat demand ratio | | | Other | Export price | | |
| Availability | | | | | | | | |

Information is required on the technology, feedstock, location, finances and project schedule. Wherever possible, the decision-maker is able to enter approximate or uncertain information in the form of fuzzy membership functions (Section 5.3) with the additional attitude and confidence controls (Section 5.4) for quickly modifying the function shape given the information available. It is not possible to enable fuzzy inputs for all the technology variables within the model as this would violate any interdependencies between them. For example, a fuzzy net capacity function would have an explicit and in turn fuzzy relationship with the other plant variables and this becomes overly complex.

### 5.5.1 CHP Incentive Requirements

There are currently two main options to incentivise renewable power and heat production: the ROC with the ROC uplift or the ROC with the RHI[27]. As the calculation method for the ROC uplift, as assessed under the Combined Heat and Power Quality Assurance (CHPQA) programme, is more complicated it requires some definition and explanation on its translation into the DSS.

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[27] For an introduction to the applicable EU and UK policy for small-scale biomass, please refer to Annex 2

The CHPQA certification (Annex 2 Section A2.5) provides several benefits to bCHP projects. Within the DSS, the CHPQA calculation method for qualifying heat and ROC uplift level is calculated to enable the decision-maker to quickly assess the benefits of each incentive. There are assumptions and simplifications in the calculation method and these are:

- the facility has no initial operating conditions;
- that the facility qualifies for normal operating conditions for maximum heat output hours;
- that there is not variable heat take-off and electrical efficiency as there is insufficient information for calculating the $z$ ratio;
- all CHP Schemes are ≤25 MWe as additional constraints are needed otherwise.

[204]

Moreover, the total fuel input (TFI) has been calculated from the NCV as opposed to the gross calorific value used in the CHPQA. The NCV is used, as it is the input unit form applied throughout the research and for the feedstock input within the DSS.

The CHPQA scheme incentivises a range of feedstock types, with a greater emphasis on wastes without an existing market or those that are emerging and costly to produce such as energy crops. The feedstock types covered are shown in Table 5.4.

*Table 5.4 – QI for CHPQA fuel types [205]*

| **Feedstock**[28] | **Definition**[1] | **Size (TPC)** | **X** | **Y** |
|---|---|---|---|---|
| By-product gases | Products from industrial processes (blast furnace gas, coke oven gas and refinery fuel gas), which may include constituents such as hydrogen, ethane, propane etc. | ≤1 MWe | 294 | 120 |
| | | >1 MWe to ≤25 MWe | 221 | 120 |
| Biogas/ syngas | Gas produced by the anaerobic digestion (AD) of biological materials (such as sewage gas, landfill gas, food processing waste, pharmaceutical waste and municipal waste) | ≤1 MWe | 285 | 120 |
| | | >1 MWe to ≤25 MWe | 251 | 120 |
| Waste gas or heat | Waste gases (such as carbon monoxide or volatile organic compounds), or waste heat (such as the exhaust gas from high temperature processes, or as a product of exothermic chemical reactions) | ≤1 MWe | 329 | 120 |
| | | >1 MWe to ≤25 MWe | 299 | 120 |
| Liquid biofuels | Manufactured liquid biofuels (such as biodiesel, bioethanol rapeseed oil, etc.) | ≤1 MWe | 275 | 120 |
| | | >1 MWe to ≤25 MWe | 191 | 120 |
| Liquid waste | Material of biological or non-biological origin from domestic and industrial activity (such as Tallow, Fats and biological oils, solvents, recycled used vegetable oil) | ≤1 MWe | 275 | 120 |
| | | >1 MWe to ≤25 MWe | 260 | 120 |
| Biomass or solid waste | Energy crops, waste wood, municipal solid waste, hospital waste, agricultural residues, straw, and sewage treatment residues | ≤1 MWe | 370 | 120 |
| | | >1 MWe to ≤25 MWe | 370 | 120 |
| Wood fuels | Commercial-grade wood fuels (such as clean woodchips, logs, and wood pellets) | ≤1 MWe | 329 | 120 |
| | | >1 MWe to ≤25 MWe | 315 | 120 |

[1] Abu-Ebid [206]

CHP schemes are also not required to meet the power efficiency threshold of 20% [204] and this is factored into the calculation method by calculating the qualifying power output (QPO) of the total power output (TPO). The quality index (QI) threshold for obtaining the full ROC uplift is 100 under normal operating conditions [207] and the calculation method applied is given below:

1. CALCULATE

   Power efficiency:

   $${}^{\alpha}\eta_{power} = {}^{\alpha}CHP_{TPO} / {}^{\alpha}CHP_{TFI}$$

   Heat efficiency:

   $${}^{\alpha}\eta_{heat} = {}^{\alpha}CHP_{QHO} / {}^{\alpha}CHP_{TFI}$$

2. DETERMINE THE CORRECT X AND Y FACTORS

   (refer to Table 5.4.)

3. CALCULATE QUALITY INDEX (QI)

   $${}^{\alpha}QI = \left( {}^{\alpha}\eta_{power} \cdot X \right) + \left( {}^{\alpha}\eta_{heat} \cdot Y \right)$$

4. IF QI <100 GO TO Step 5

---

[28] Fuel types need to go through the combustion boiler for the model calculations to be correct

```
    Else GO TO Step 6 as full uplift accredited
5. CALCULATE Qualifying Power Output (QPO)
        ${}^{\alpha}CHP_{QPO} = {}^{\alpha}CHP_{QHO}/(100 - ({}^{\alpha}\eta_{power} \cdot X))/Y$
6. END
```

The heat efficiency $\eta_{heat}$ is calculated as the qualifying heat output $CHP_{QHO}$ (MWhth/yr) divided by the total fuel input $CHP_{TFI}$ (MWhe/yr) based on the NCV. The $CHP_{QHO}$ only includes heat used to displace heat demand that would have been supplied from other sources. It does not include heat rejection or parasitic heat loads as qualifying sources. A similar method is applied for calculating the power efficiency $\eta_{power}$, with the total power output $CHP_{TPO}$ (MWhe/yr) divided by $CHP_{TFI}$. Once the efficiencies have been calculated along with the relevant X and Y factors, it is possible to calculate the QI. If the QI is less than the required target of 100 for normal operating conditions, then only a portion of the $CHP_{TPO}$ qualifies for 'Good Quality CHP' and this qualifying power output $CHP_{QPO}$ is awarded the ROC uplift. As with the other calculations within the decision support system, it is necessary to calculate the level of ROC uplift at each α-cut.

The CHPQA uplift calculation is given fully in the non-fuzzy mode of the DSS, in the calculation of the levelised cost of heat and electricity outputs as well as the NPV and IRR outputs (as shown in Annex 5-7). In the fuzzy version, the partial calculation (QI score and uplift) are given when calculating the fuzzy levelised cost of heat and electricity outputs only.

### 5.5.2 Corporation Tax Rate and Enhanced Capital Allowance

The rate of corporation tax for RET schemes is subjective to policy and the rates set by the HMRC (Her Majesty's Revenue & Customs). Small-scale projects could potentially fall under one of the two corporate tax rates depending on the size of the plant and the total annual taxable revenue. The two rates shown in Table 5.5 are the small profits rate up to £300,000 and the main rate for anything greater. To support a company's transition from one rate to another there is a marginal relief system that reimburses a proportion of their taxable revenue as long as they do not exceed the upper limit of £1.5 million. There has been a trend over the past four years of reducing the main rate of tax [208] and this may be in response to the current UK recession.

*Table 5.5 – Corporation tax rates 2010 to 2013 [209]*

| Rate | 2010 | 2011 | 2012 | 2013[1] |
|---|---|---|---|---|
| Small profits rate | 21% | 20% | 20% | 20% |
| Small profits rate limit (≤ pa) | £300,000 | £300,000 | £300,000 | £300,000 |
| Marginal relief lower limit | £300,000 | £300,000 | £300,000 | £300,000 |
| Marginal relief upper limit | £1,500,000 | £1,500,000 | £1,500,000 | £1,500,000 |
| Standard fraction | 7/400 | 3/200 | 1/100 | 1/80 |
| Main rate of corporation tax | 28% | 26% | 24% | 24% |

[1] Taken from the consultation rates [210]

A company's tax exposure is subject to change as policy changes. Currently, the rates are low to help support companies in the UK. However, it is possible that as the economic situation improves, there will be higher rates of tax payable, as historically shown in HMRC [208]. In the context of the case study, a change in the rate of tax from 28% to 20% over the lifetime of the project results in a LCOE change of c. £2 per MWhe. Due to the subjectivity of the variable tax rate and the standard fraction, the research assumes that the tax rate is fixed for the project lifecycle. It is possible to enter a fuzzy membership range for the tax rate as a change on the main tax input value and this could be used to better model any uncertainty over the duration of the project.

Under the 'energy-saving plant and machinery' tranche of the Enhanced Capital Allowance (ECA) scheme (see Section A2.5), it is possible to reduce the taxable profits in a year by the amount spent qualifying on plant and machinery. This provides another incentive to CHP schemes but does require certification under the CHPQA scheme. However, it is only applicable if the plant is providing the majority of the produced heat and power to known users and not exporting it to the grid [211]. This incentive is not accounted for in the DSS, but may be applicable when assessing a project's viability.

## 5.6 Risk Register

The risk register compiles the possible lifecycle risks of the project. At this point in the DSS, the decision-maker enters possible risk event information to be later used in the risk response and analysis process (Section 5.7). There are several inputs for the risk register and these are to be covered in turn.

### 5.6.1 Lifecycle Phase

Lifecycle phases are utilised to define where in the project lifecycle a risk event is expected to occur. This is applied later within the actions output (Section 5.12) to group together risk events for further analysis and use. The phases of the project lifecycle are:

- Pre-development
- Development

- Construction
- Operation

These lifecycle stages were taken from the commonly used project lifecycle terminology [47] and those defined in Chapter 2. The decommissioning lifecycle phase is not included as this is an early stage project development model and unlikely to be analysed for risk other than the possible capital cost. Furthermore, the Renewable Energy Roadmap [6] does not include a decommission phase in its analysis of non-domestic heat only biomass power station lifecycle[29].

### 5.6.2 Project Impact

The project impact is a qualitative measure of a risk event's impact on the project achieving its wider objectives. Likelihood and severity are categorised on a six-point scale, as shown in Table 5.6.

*Table 5.6 – Likelihood and severity terms*

| **Likelihood** | **Severity** | **Abbr.** |
|---|---|---|
| Very Low | Very Low | VL |
| Low | Low | L |
| Moderate | Moderate | M |
| High | High | H |
| Very High | Very High | VH |
| Certain | Critical | C |

Likelihood is defined as the possibility of the risk event occurring and, upon occurrence, the severity is defined as the possibility of the risk event impeding the project's overall objectives. These inputs are utilised to rank the risk events in the risk response phase (Section 5.7.1).

### 5.6.3 Risk Cause and Effect

The 'risk cause' is the reason for the risk event occurring and the effect is the impact upon occurrence. The risk causes at the highest level are categorised as political, environmental, social, technological, legal, and economical (PESTLE). A PESTLE categorisation method is the highly suitable as it is applied in practice and in the literature [56, 155, 212][30]. By creating a sub-level of risk causes, the decision-maker is not limited to only the PESTLE class and can add additional risk causes in the settings menu of the DSS. Whereas, the risk effects (Table 5.7) function differently as every effect requires a link to an input variable from the project inputs to enable quantitative modelling.

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[29] They do not have biomass CHP only giving a heat or power analysis of biomass project development

[30] IEA-RETD utilises PEST

*Table 5.7 – Risk effect hierarchy*

| **Category** | **Sub-cat.** | **Second sub-cat.**[1] | **Notes** |
|---|---|---|---|
| Technological | Plant | Availability (%) | Technological effects such as net capacity, heat: power ratio, boiler thermal losses, electrical efficiency could not be used as fuzzy effects as this would ignore any real world interdependencies between the variables (Section 5.5) |
| | Feedstock | Cost (£/ODT)<br>Energy Content (MWh/ODT) | |
| Locational | Demand | Res Electric (wkday)<br>Res Electric (wkend)<br>Res Heat (wkday)<br>Res Heat (wkend)<br>Ind Electric (wkday)<br>Ind Electric (wkend)<br>Ind Heat (wkday)<br>Ind Heat (wkend) | The demand risk unit is kWh per day |
| Financial | CAPEX | Development Cost<br>Plant Cost<br>EPC Cost<br>Other CAPEX Cost | The capital and operating expenditure (CAPEX and OPEX) cost risk unit is pounds (£) |
| | OPEX | Maintenance Cost<br>Operations Cost<br>Insurance Cost<br>Lease Cost<br>Other OPEX Cost | |
| | Incentive(s) | ROC Band<br>ROC Price<br>RHI Price<br>LEC | The incentive ROC band is measured in ROCs/MWhe and the prices for the ROC, RHI and LECs are in pounds (£) |
| | Market | Tax | The corporate tax rate, this is an absolute change in % |
| Schedule | Task | Task Ref. | Each project task is referred to by their unique reference identification and task risk unit is months |

[1] Residential (res), Industrial (ind), weekday (wkday), weekend (wkend)

Risk effect impact range is the same as described in Section 5.3.1 and given by its abs. min and max and expected points. Additionally, the decision-maker can also input the defined attitude and confidence inputs (Section 5.4).The risks events can only be quantitative or quantifiable in the form of one or more of the risk effects given within the hierarchy. Furthermore, a risk event can only have one impact and risk events were mutually exclusive, this logic also applies to the risk responses. This simplification is applied in other decision support models [56] as it becomes overly complex to map networks of risk effects and interdependencies.

## 5.7 Risk Response

The purpose of the risk response register is to manage or mitigate the possible risk events. The response register calculates the effectiveness of responding to a risk event and the overall change in the financial and schedule goals. Multiple parts to this phase of risk management exist and they are covered in turn.

### 5.7.1 Risk Criticality

The risk criticality output utilises the risk impact likelihood and severity input given for each risk in the risk register (Section 5.6.2). Each likelihood and severity input is given a value, as shown in Table 5.8.

*Table 5.8 – Risk likelihood and severity matrix*

| | | | **Severity** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Linguistic label** | | **Very Low** | **Low** | **Moderate** | **High** | **Very High** | **Critical** |
| | | **Score** | **1** | **2** | **4** | **6** | **8** | **10** |
| **Likelihood** | **Very Low** | **1** | 2 | 3 | 5 | 7 | 9 | 11 |
| | **Low** | **2** | 3 | 4 | 6 | 8 | 10 | 12 |
| | **Moderate** | **3** | 4 | 5 | 7 | 9 | 11 | 13 |
| | **High** | **4** | 5 | 6 | 8 | 10 | 12 | 14 |
| | **Very High** | **5** | 6 | 7 | 9 | 11 | 13 | 15 |
| | **Certain** | **6** | 7 | 8 | 10 | 12 | 14 | 16 |

An individual risk's criticality is given as a rank within the total number of risks and colour coded to express the overall impact of the risk in impeding the project's objectives. The colour coding of risk impact levels is similar to the existing research [56] covered in Section 3.3. Within the table, the severity scale scores more highly than the likelihood scale as the severity of a risk has a greater effect on impeding the project's objectives. This is similar to the risk severity matrices of IEA-RETD [56]. If there are two or more risk events of the same score they would get the same number i.e. two risks with certain likelihood and critical severity would both score a rank of 1 and the next risk in descending order would score a rank of 2.

### 5.7.2 Response Strategy

The response strategy is not only a key component to risk management but also closely reviewed by potential lenders to assess a sponsor's ability to effectively manage the project [63]. Four possible risk response actions or strategies were possible within the DSS and these are as defined in previous work [46, 56, 212]:

- Reduce

  Take action to reduce the impact of the risk event. An example of this would be to implement a control process or procedure.

- Retain

  Tolerate or accept the risk event. This response is usually sufficient for low likelihood and severity risks.

- Transfer

Transfer the risk event to another party. An example of this would be to pass the risk event to another stakeholder or have it insured.

- Avoid

  Avoid the risk event. This response is reserved for critical risks with very high likelihood and severity. An example of this would be to change a process to completely avoid the risk event or, failing that, abandon the project.

Risk mitigation actions are applied in the IEA-RETD [56] model to respond to risk events but are not defined in this structured manner. A risk response consists of an action that has a level of effectiveness and a cost to the project. Similarly, the response cost can be any one of the effect variables in Table 5.7 and mutual exclusivity is maintained between risk responses.

### 5.7.3 Response Cost: Benefit Analysis

Cost: benefit analysis is commonly applied in project risk management [52, 154, 213] and has been applied within the research for assessing risk response strategies within bioenergy projects. There are two outputs for the cost: benefit analysis of the risk response strategy or strategies. The first output calculates the effect of each selected risk response on the final minimum levelised cost of electricity. This could be a decrease in the LCOE if the response action is beneficial to not having a risk response action for the selected risk or an increase if opposite is true. The second output calculates the effect of each selected risk response on the project duration. If the risk event or the cost of the risk response affects a project task then the output shows a decrease or increase in the overall project duration. The pseudo-code algorithm for the cost: benefit calculations is as follows:

```
1. CALCULATE (without response)
   Run the residual risk scenario[31] without the risk response for that particular risk
      a. Project LCOE ( $^{\alpha}LCOE_e$)
      b. Project Duration ( $^{\alpha}D_e$)
2. CALCULATE (for each response strategy)
   Run the residual risk scenario with each risk response action benefit and cost accounted for
         Project LCOE ( $^{\alpha}LCOE_a$)
   GO TO Step 3
         Project Duration ( $^{\alpha}D_a$)
   GO TO Step 4
```

---

[31] The risk scenarios are defined in Section 5.8

```
3. CALCULATE LCOE Change ( $^{\alpha}LCOE_{ea}$)
   For each α-cut
       $^{\alpha}LCOE_{ea} = {}^{\alpha}LCOE_{a} - {}^{\alpha}LCOE_{e}$
   Next
   $\overline{LCOE}_{ea} = \frac{\sum_{\alpha=0.001}^{1} {}^{\alpha}LCOE_{ea}}{24}$
4. CALCULATE Duration Change ( $^{\alpha}D_{ea}$)
   $^{\alpha}D_{ea} = {}^{\alpha}D_{a} - {}^{\alpha}D_{e}$
5. END
```

The algorithm essentially calculates the LCOE (Section 5.9) with the risk occurring but no response $LCOE_e$ and then with each risk response applied $LCOE_a$ at each α-cut to determine approximately the fuzzy change. This also applies to the project duration (Section 5.11.2) without a response $D_e$ and with a risk response $D_a$. A positive mean LCOE change ($\overline{LCOE}_{ea}$) implies that the risk response strategy effectiveness or benefit does not justify the cost of responding. Whereas, a negative $\overline{LCOE}_{ea}$ implies that the risk response strategy effectiveness or benefit does warrant the cost of responding and would reduce the project LCOE. If multiple possible risk responses are available then the greater the reduction in levelised unit cost the more effective the response. However, the decision-maker would have to assess the best strategy given the trade-off between time and cost goals if a risk event or response affects both the levelised unit cost and project duration. Given graphically as outputs within the DSS, it is necessary for the decision-maker to select an optimal risk response. In cases where there are many risks with responses and limited resources for the project to respond to risk, there is the option to select 'undecided' within the model and use the actions output optimisation method, as covered in Section 5.12.

## 5.8 DSS Scenarios

Three scenarios exist within the DSS to give the decision-maker greater control throughout the project analysis process and these are defined as the initial, inherent, and residual scenarios. The initial scenario calculates the project financial and schedule outputs without the effect and cost of any risk events or any responses. Therefore, it shows the project in its original form without any risk exposure, and represents the 'base case' or initial version of the project. Whereas, the inherent scenario includes the risk event effects, with all risks occurring to their fuzzy degree, in the project output calculations but not the benefit and cost of any risk response(s). Finally, the residual scenario is the same as the inherent scenario in determining the possible total exposure to risk but also calculates the benefit and cost of the chosen risk response strategies. The initial scenario is utilised throughout the case study analysis of Chapter 6.

## 5.9 Levelised Unit Cost

As introduced in Chapter 1, the discounting levelised unit cost calculation is utilised in the project financial outputs section to assess the viability of a project. However, as the original method is crisp and not fuzzy, it requires some adaption to achieve the research objective for developing a mechanism for handling limited or approximate information (see Objective O$_3$). If each variable in the discounting LCOE is no longer crisp but a fuzzy set, the fuzzy LCOE ($\widetilde{LCOE}$) equation becomes:

$$\widetilde{LCOE} = \widetilde{P_e} = \frac{\sum_t ((\widetilde{I_t} + \widetilde{O\&M_t} + \widetilde{F_t} + \widetilde{C_t} + \widetilde{D_t}) \cdot (1+\tilde{r})^{-t})}{\sum_t (\widetilde{E_t} \cdot (1+\tilde{r})^{-t})} \tag{5.13}$$

The problem with Equation 5.12 is that it is not possible for the $\widetilde{\mathrm{LCOE}}$ calculation to be solved directly for the reasons covered in Section 5.3.2. Although, as also covered, this can be overcome with the use of α-cuts and approximately calculated as:

$$^{\alpha}LCOE = {}^{\alpha}P_e = \frac{\sum_t (({}^{\alpha}I_t + {}^{\alpha}O\&M_t + {}^{\alpha}F_t + {}^{\alpha}C_t + {}^{\alpha}D_t) \cdot {}^{\alpha}(1+r)^{-t})}{\sum_t ({}^{\alpha}E_t \cdot {}^{\alpha}(1+r)^{-t})} \tag{5.14}$$

Within the DSS when determining the levelised unit cost there is no rate of inflation (justified in Section 5.10.1). This removes the discount rate from the numerator and denominator within the LCOE calculation as the discount rate $r$ equals zero. Furthermore, this levelised unit cost measure does not include the cost and terms of financing a RET project which to a sponsor of a potential project is vital for determining viability. Earlier work has addressed this issue to produce a crisp LCOE [48, 61, 148] and this research applies it to the developed fuzzy methodology.

The minimum fuzzy levelised cost of electricity (F-LCOE) to meet the finance terms including the minimum DSC and ROE is determined with the following pseudo-code algorithm:

```
1. INITIALISE
   ($^{\alpha}I$, $^{\alpha}O\&M$, $^{\alpha}F$, $^{\alpha}D$, $^{\alpha}E$, $^{\alpha}P_e = £0.01$)
   GENERATE Cash Flow Projection (Section 5.10)
2. CALCULATE DSC/DSCR
   If $^{\alpha}DSCR_t < DSCR_t^T$ Then
         $^{\alpha}P_e = ((a_t \cdot DSCR_t^T) - ({}^{\alpha}O\&M_t + {}^{\alpha}F_t - {}^{\alpha}R_t)) / {}^{\alpha}E_t$
```

```
    Else
3.  CALCULATE ROE
    If $^{\alpha}ROE < ROE^{T}$ Then
            $E_d = 1/\exp(\ ^{\alpha}ROE - ROE^{T} - 0.01\%)\text{^}(15 \cdot (ROE^{T} -\ ^{\alpha}ROE + 0.01\%))$
            $^{\alpha}P_{e+1} =\ ^{\alpha}P_e \cdot E_d$
    Repeat 2
    Else
            $^{\alpha}LCOE =\ ^{\alpha}P_e$
4.  END
```

The cash flow projection initialises with the α-cuts of each of the fuzzy input variables and the price of electricity $P_e$ set at £0.01. It is necessary to set $P_e$ at a value greater than zero so that it can be exponentially multiplied if an increase in the ROE is required. However, if a more simplistic linear and incremental $P_e$ is adopted then the starting value can be set to zero, but this method performs very slowly computationally and is likely to greatly exceed the necessary minimum value. The conditional DSCR (Step 2) and ROE loop (Step 3) are required within the algorithm to incorporate the finance terms and all possible configurations of debt and equity funding for the project.

If the DSCR for the year $t$ is less than the target $DSCR_t^T$, the price of electricity is recalculated to meet the minimum threshold utilising the debt annuity $a_t$ (Eq. 5.16) and the DSCR (Eq. 5.17) equations. Step 2 produces the minimum unit cost for electricity to achieve the debt financial covenants. The level of debt service cover must be at least at the level required by the lender, any less than this amount the lender will be unlikely to fund the project. Dependent on the level of gearing, the minimum price for electricity to meet the debt terms may be sufficient to also produce the required level of equity return. However, if the electricity price $P_e$ does not produce enough revenue to achieve the specified level of return, the unit price has to be increased further through Step 3.

The return on equity $ROE_T$ is then approximately calculated using the Newton-Raphson method (Section 5.10.4). If the $ROE$ is less than the target $ROE^T$, the price $P_{e+1}$ is multiplied by an exponential decay factor $E_d$ with the process being repeated until $ROE \geq ROE^T$. $E_d$ is designed to take exponentially reducing increments the closer the $ROE$ gets to the target. This saves computational processing time (Section 5.9.1) but in some cases could be replaced with a simple linear multiplier in place of the exponential multiplier applied in the algorithm. Upon satisfying this stage, the price $P_e$ is at least equal to the lowest LCOE for the project to be viable in achieving the terms of finance.

### 5.9.1 Exponential Multiplier

The exponential decay factor applied in the research is the most suitable method for increasing the levelised unit costs of those tested. Exponential decay is a function of the difference between the ROE target and the ROE achieved. It is loosely based on the concept of the cooling function within Simulated Annealing. The original exponential decay equation, which most closely resembles the simulated annealing method, is shown in Equation 1, and Equation 2 is the function finally adopted within the DSS.

1. $1/\exp(ROE - ROE^T - 0.01\%)$
2. $1/\exp(ROE - ROE^T - 0.01\%)\text{^}(15 \cdot (ROE^T - ROE + 0.01\%))$

The rate at which the two equations decay, as the ROE achieved approaches the target, is also shown graphically in Figure 5.5.

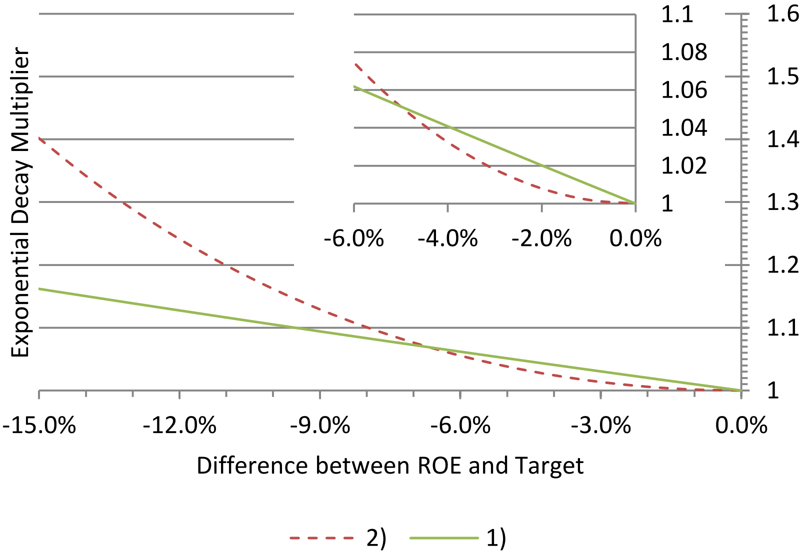

*Figure 5.5 – Exponential decay equations*

As the difference between the ROE target and that achieved decreases, so does the exponential decay multiplier, taking much smaller steps and greater iterations toward achieving the target solution. The first equation tended to perform slowly when there is a large difference between the ROE and the target and this sometimes causes the DSS to ‘hang’ when running more complicated operations. Equation 1, also performs slowly in the time tests and any increase in the exponent, in an effort to increase the computational speed, led to the target ROE being significantly exceeded. Whereas, the second equation has a variable exponent that changes as the ROE increased toward the target, it increases the $E_d$ at higher levels of disparity and reduces the rate at lower levels. This greatly improves the calculation duration whilst also reducing the possibility of significantly exceeding the target $ROE^T$. Furthermore, the second equation is considered more accurate as it does not exceed the ROE target level as much as the first equation. A test on the accuracy of the second exponential equation showed that the maximum error for exceeding the ROE target for the levelised unit cost of electricity for the case study is no greater than $+6 \cdot 10^{-7}$over the range of α-cuts.

## 5.10 Financial Outputs

The following section defines the equations and algorithms used to generate the financial outputs. Examples of the cash flow projections used within the DSS are given in Annexes 5-7. This section methodically moves through the individual calculation methods and, where applicable, justifies the chosen method. Key project viability measures used by developers and financiers such as NPV, IRR [56, 63] and levelised unit costs [48, 59, 61, 148] are covered within this section. As there are fuzzy functions for many of the input variables, there are fuzzy cash flow calculations and these variables are denoted by the usual left-superscript α characters.

### 5.10.1 Inflation

A financial model in the latter stages of project development would include predictions on the inflation rates of the various revenue and cost variables for the project. These forecasts tend to require the project sponsor to purchase forecasts from a consultancy firm. They are projected from historic data and forecasting of future events that may influence the project or wider market. Within the DSS, the future revenues or costs are not inflated for the following reasons:

- forecasts are highly subjective and unlikely to be information a sponsor would possess in the early stages of project development;
- individual variables within the cash flow projection would require variable inflation rate forecasts and this would incur a cost to the sponsor;
- the timing and duration of risk events and response strategy would then become highly time sensitive and ultimately confusing.

This level of depth is also not concordant with the research objective and its aim to support the decision-maker in the early project lifecycle. It is possible to assess the sensitivity of a variable's value, such as feedstock cost by defining a fuzzy range within the risk analysis section of the DSS.

This is also the way in which highly uncertain variables such as ROC price are modelled. Other DSS employ the same approach to not inflating future cash flows, such as the UK industry-adopted NNFCC AD Calculator, for supporting development and economic viability assessment of anaerobic digestion (AD) projects [214] (Section 3.7).

For the NPV calculation measure within the DSS there is a fixed discount on the future values. Fixed discount rates are used commonly utilised within the systematically review literature (e.g. [131, 137, 185]). However, in the DSS, it is applied only to the EBITDA[32] and free cash flow streams, not the individual variables within the cash flow. This simplifies the time value of money issue but assumes that a relative disparity between the revenue and costs steams is maintained over the life of the project.

### 5.10.2 Depreciation

Straight-line depreciation is a simple and accepted from of depreciation [215]. A 10 year straight-line depreciation, calculated on a yearly basis $d_t$ for the plant costs $Pc$ portion of the investment is assumed and calculated as:

$$ {}^{\alpha}d_t = {}^{\alpha}Pc \cdot \left(\frac{1}{10}\right) \tag{5.15} $$

There are several possible methods and periods (e.g. 5 or 15 years) of depreciation and these have been shown to have some influence on the levelised unit costs [48], but they are not included within the DSS.

### 5.10.3 Debt and Interest Rates

Debt, referred to as total debt $T_d$, is repaid over the debt term $d_T$ in the form of a debt service payment. This is the principle and interest paid annually in the form of the debt service annuity $a_t$:

$$ {}^{\alpha}a_t = {}^{\alpha}T_d / \frac{1-(1+r)^{-d_T}}{r} \tag{5.16} $$

It is assumed that the debt interest rate $r$ is fixed over the debt term. Financial coverage ratios are also typically included within the loan agreement [63] with the debt provider typically stipulating

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[32] Earnings before Interest Tax Depreciation and Amortisation

that there should be additional revenue over the debt term to protect the debt service payment against unforeseen risks. Often referred to as the debt service cover and is calculated as a ratio (DSCR) of net operating income divided the debt service annuity $a_t$:

$$^{\alpha}DSCR_t = (\,^{\alpha}R_t - \,^{\alpha}O\&M_t \; - \,^{\alpha}F_t)/\,^{\alpha}a_t \quad if\ t\ \leq d_T \tag{5.17}$$

Where:
$R_t$ is the revenue in year t

The DSCR can typically range from 1.3 to 2, depending on the risk or uncertainty for the RET [48] and it is required to be maintained for the debt term.

### 5.10.4 Equity Finance

Equity is capital invested into the project by investors who are typically paid in return in dividends from the free cash flow. Sometimes referred to as the equity IRR, as it includes the cost of servicing debt and tax, the IRR at this point is equal to the return on equity with the free cash flow being entirely paid to the equity investor and not retained by the project for other purposes. Moreover, this IRR is also the largest possible equity investor return from the future yearly project cash flows for the project to break-even, such that the project net present value for its lifecycle is equal to zero. When there are greater than two cash flow amounts there is not a method for directly calculating the IRR [216], so it becomes necessary to rely on an iterative methods such as the Newton-Raphson and Secant methods. The Newton-Raphson method is the most widely adopted as it is the applied method in MS Excel to solve IRR equations. Named after Sir Isaac Newton and Joseph Raphson, the method was originally proposed as a better approximation method for finding the root of an equation. In the case of the research, the root is the point at which the NPV equals zero. The calculation method is not been included as the research utilises the Newton-Raphson method within Visual Studio to determine the solution.

There can be difficulties in calculating the IRR if there is non-convergence on the root, a poor estimate on the IRR or irregular cash flows to the project. Within the DSS, the initial outflow in year 0 and a series of returns over the 20-year operational life of the scheme help to mitigate irregular cash flows and non or multiple root convergence.

### 5.10.5 Production

The production of electricity and heat is important as it is the source of revenue generation through onsite and export sales or the applicable generation incentives. The total annual production of electricity $E_t$ is calculated as:

$$ {}^{\alpha}E_t = N_c \cdot (8760 \cdot {}^{\alpha}A_t) \tag{5.18} $$

The total electricity production $E_t$ is a function of the net capacity $N_c$ of the bCHP plant multiplied by the annual availability $A_t$.

Within the financial cash flow analysis the total heat utilisation is given instead of the total heat produced by the bCHP scheme. The rationale being that it is unlikely that a scheme of this size would be able to fully match the heat demand and therefore a proportion of the heat produced will be lost. The total heat utilisation for given year $H_t$ is the sum of the total residential $Trh_t$ and industrial $Tih_t$ demand (MWhth):

$$ {}^{\alpha}H_t = {}^{\alpha}Trh_t + {}^{\alpha}Tih_t \tag{5.19} $$

### 5.10.6 Revenue

Revenue is derived from electricity, heat sales and supporting energy generation and use incentives. The electricity revenue $er_t$ is calculated from onsite sales (MWhe/yr) to residential $Tre_t$ or industrial $Tie_t$ consumers and the remaining power is exported to the grid with an export contract:

$$ {}^{\alpha}er_t = \left({}^{\alpha}Tre_t \cdot Re_p\right) + \left({}^{\alpha}Tie_t \cdot Ie_p\right) + ({}^{\alpha}E_t - ({}^{\alpha}Tre_t + {}^{\alpha}Tie_t) \cdot PPA_p) \tag{5.20} $$

It is also assumed that the project could achieve the market equivalent prices for residential $Re_p$ and industrial $Ie_p$ electricity. As bCHP plants of this size often possess grid connections to benefit from a PPA and ROCs, there is the assumption that all excess electricity production could be exported. However, it is possible within the DSS to remove this option and only generate revenue from onsite sales.

In the case of heat production, it is not possible to export any unused heat and it is therefore considered wasted or ‘dumped’ onsite. The heat revenue for the plant $hr_t$ is calculated in largely the same way with the total annual residential $Trh_t$ or industrial $Tih_t$ sales (MWhth/yr), except there is not the possibility to export any heat that cannot be utilised on site:

$$hr_t = \left(Trh_t \cdot Rg_p\right) + \left(Tih_t \cdot Ig_p\right) \tag{5.21}$$

Similarly, it is assumed that the heat utilised on site could be sold competitively with residential $Rg_p$ and industrial $Ig_p$ gas prices (£/MWhth).

Already covered partially throughout this chapter, the Climate Change Levy (CCL) and RO schemes provide LECs and ROCs respectively to the generator. One LEC is awarded per kWhe, and the number of ROCs per MWhe is subject to the generator's banding under the scheme (Annex 2 Section A2.5). The level of uplift for CHP generation under the RO for renewable heat utilisation has been covered in Section 5.5.1. The alternative to the RO uplift is the RHI and this is awarded per kWhth of utilised heat.

### 5.10.7 Costs

For most biomass schemes the largest operational expenditure is the feedstock cost. Within the DSS, the amount of feedstock required is determined from the information given in the project inputs section:

$${}^{\alpha}F_t = \left(\frac{\left(\frac{C_{pn}}{(1-Pl)\cdot\eta_{power}}\right)\cdot\left(2-\eta_{boiler}\right)\cdot\left(8760\cdot{}^{\alpha}A_t\right)}{f_{NCV}}\right)\cdot{}^{\alpha}F_p \tag{5.22}$$

The annual feedstock cost $F_t$ is calculated from the plant net capacity $C_{pn}$ with its power conversion efficiency $\eta_{power}$, parasitic losses $Pl$ and boiler efficiency $\eta_{boiler}$ to determine the required gross feedstock energy required per full load operational hour. This is multiplied by the total number of operational hours available $A_t$ and then divided by the feedstock net calorific value $f_{NCV}$ (MWh/ODT) to give the total number of oven dry tonnes required. Finally, this is multiplied by the feedstock price per ODT $F_p$ to arrive at the solution.

The remaining costs are separated, within the DSS, into the capital (CAPEX) and operating (OPEX) expenditures. The CAPEX inputs include the development, plant, EPC and other costs. The CAPEX costs are incurred in year 0 of the project and could be fuzzy if there is any uncertainty. For the OPEX inputs there are maintenance, operations (excluding feedstock costs), insurance, land lease and other costs. OPEX costs can also be fuzzy functions and are incurred per annum for the life of the project (year 1 to 20).

### 5.10.8 Levelised Unit Costs (LCOE and LCOH)

In the DSS, the LCOE follows the algorithm of Section 5.9 but assumes that the electricity revenue (Eq. 5.14) is the minimum price $P_e$ multiplied by the total production of electricity $E_t$ at each α-cut. The same is applied to the LCOH except that the denominator of the LCOE equation (Eq. 5.14) is the total heat utilisation in a given year $H_t$. Furthermore, it is possible to account for the heat revenue from onsite sales and associated incentives within the LCOE calculation and the same is true for the electricity revenue and incentives within the LCOH. It is important to include this, as it is a particular benefit to CHP schemes and can contribute significantly to reducing the levelised unit cost of a scheme. IEA [26] in their report adopt the same method with the use of 'heat credit' to reduce the levelised unit cost for CHP.

### 5.10.9 Project Capital Structure

The capital structure method calculates the possible configurations of debt to equity, at the terms specified, to find the lowest levelised unit cost for the project whilst still adhering to the financial covenants. It is similar to a calculation of the WACC (weighted average cost of capital) but accounts for the necessary coverage ratio terms to be also met. An optimal capital structure for a project has been demonstrated in earlier work on RET financing [48, 61, 148] but only in the crisp form and not able to show the fuzzy membership range given approximate information or the effect of the project risk exposure. The adopted method applies the same algorithm to calculate the minimum fuzzy LCOE and calculates over the range on 0% debt to 100% at 1% intervals. The output of this is shown graphically within the DSS. It is useful in quickly ascertaining the optimal debt to equity for the given finance terms. The inclusion of uncertainty can further support developers when negotiating the project terms of finance and capital structure or to assess the viability of possible financing options. However, there are some real world factors that may need to be considered, such as finance terms are likely to vary as the proportions of debt and equity do, and that the debt interest rate may be variable. These factors are not dealt with in the DSS, but should be considered by the decision-maker and if necessary, the terms should be adjusted to reflect any additional information or restrictions.

### 5.10.10 Sensitivity Analysis

There is also the functionality to assess the sensitivity of a ±10% change in nine key project variables, these are:

- equity share;
- ROE;
- tax;
- debt interest;

- DSCR;
- project cost (total CAPEX);
- O&M costs (total OPEX);
- electricity production;
- feedstock price (per ODT).

Each variable is changed ±10% on the original input, except for ROE, tax and debt interest where the variable changes a per cent of the original relative value (e.g. 6% ±10% = 6.4% to 6.6%). The sensitivity of a variable is also measured as a function of the change in the levelised unit cost of electricity. The input variables change at 1% intervals and run through the LCOE algorithm in Section 5.8. This produces a graphical representation of the sensitivity analysis with or without the fuzzy membership functionality.

### 5.10.11 Variable Heat Utilisation (Levelised Cost and PPA)

The variable heat utilisation and PPA output highlights the effect of increasing heat utilisation on-site on the viability of the project. Both produce the minimum levelised cost of heat or export price of electricity as the amount of heat utilised on-site increased. The purpose of these outputs is twofold by highlighting the current project viability under the given assumptions and showing the possible effect of greater heat utilisation.

For the variable LCOH output, the levelised cost of heat is a function of the break-even deficit over the total units of heat utilised. The minimum LCOH for the project to break-even and be viable is calculated with the levelised unit cost algorithm (Section 5.9). However, to express the underpinning principle and explain the produced output, it could be defined as followed. The total free cash flow target $TFC_T^T$ over its total operation life $T$ is the minimum cash flow required for the project to break-even. If this target is met or exceeded then the levelised unit cost of heat could be zero and the heat given at no charge to the consumer. The break-even deficit is the difference between the target and the achieved level of total free cash flow $(TFC_t^T - TFC_t)$ over the total units of heat utilised in a year $Th_t$ (MWhth):

$$^{\alpha}LCOH = \sum_{t=1}^{n}(^{\alpha}TFC_t^T - {}^{\alpha}TFC_t)/\sum_{t=1}^{n}{}^{\alpha}Th_t \tag{5.23}$$

If the future values are to be discounted then Equation 5.23 would need to apply the discounting formula as shown earlier in Equation 5.14. With increasing levels of heat utilisation, excluding the price of heat sales, there would be a greater amount of incentive support and revenue (ROC uplift or RHI). This reduces the deficit numerator and increases the total heat denominator $Th_t$ in the equation, this produces an exponentially reducing $LCOH$. Within the DSS, this output is expressed as a graph of the LCOH for a range of possible levels of onsite heat utilisation ranging from 0% to 100% of annual heat production. As an increasing percentage of heat is utilised onsite, the LCOH price required to make the project viable decreases. For the project to be viable and competitive with gas, the amount of LCOH for the heat utilised is required to be below the gas price (MWhth) equivalent. Furthermore, if the owner of the scheme were also the owner of the heat load source(s), the output would show the marginal saving on avoiding fossil fuel generated heat.

For the PPA output, the cost of heat is fixed at the residential $Rg_p$ and industrial $Ig_p$ gas price equivalents, with the annual utilisation of heat $Th_t$ in their respective proportions, e.g. 3:1 ratio of residential to industrial demand. The minimum PPA price is the minimum price required for the exportable portion of the electricity produced to make the project viable:

$$ {}^{\alpha}PPA = \sum_{t=1}^{n}\left({}^{\alpha}TFC_t^T - {}^{\alpha}TFC_t\right)/\sum_{t=1}^{n}{}^{\alpha}e_n - \left({}^{\alpha}Tre_t + {}^{\alpha}Tie_t\right) \qquad (5.24) $$

As only the numerator of the calculation varies at a given α-cut point and the denominator of exportable power does not change at increasing levels of heat utilisation, the output is linearly reducing unlike the variable LCOH. Within the DSS, this output is also expressed as a graph that illustrates the minimum power purchasing agreement (£/MWhe) price for exportable electricity when the onsite price and demand for electricity, and the onsite price for heat are all fixed, but the amount of heat utilised can vary from 0% to 100%. In this case, the amount of heat utilised must be large enough to allow the PPA price to be less than the PPA price obtainable for the project to be viable.

### 5.10.12 Project NPV and IRR

The NPV and IRR outputs calculate the performance of the project under the current assumptions, including the assumed value and demand for heat and power sales. This differs from all the other outputs (5.9.8 – 5.9.11) as it does not calculate the minimum value necessary to make the project viable and meet the terms of finance. This output assumes that the project can only achieve the expected onsite heat demand, and prices for on and offsite utility sales. It is therefore possible that the coverage ratio for debt and amount of free cash flow for equity investor dividends will not meet the financial covenants.

Two outputs for the NPV and IRR are given in the DSS, as they are both useful to decision-makers and serve different purposes. The EBITDA is important as it is used to measure cash flow to service debt [63]. Whereas, the free cash flow is the available earnings after all liabilities have been deducted. This is also, where the equity investor would receive their dividend and determine whether the project is a suitable investment opportunity. Discount rates are required for the future EBITDA and free cash flows for calculating their respective NPVs and the decision-maker enters this. As there is no prediction of future cost or revenue stream changes over the project lifecycle and relative revenue and cost disparity is assumed, they should be considered when selecting the applicable rate of discount.

## 5.11 Schedule Outputs

The schedule outputs within the DSS support the decision-maker in the analysis of the total duration and task criticality through the project lifecycle up to the operational phase. This is achieved by utilising a novel fuzzy critical path method (F-CPM) along with the already applied α-cut method (Section 5.3.2) and attitude and confidence level linguistic inputs (Section 5.4). A humanistic view is applied in the research to further developing the earlier work on F-CPM [189, 190, 199, 217]. The current body of F-CPM research is limited in that it is not feasible for a project manager to manually map individual reference functions for tasks, this is an important point raised by Chen [199] but not addressed in his work or similar papers (as covered in Section 5.4).

The DSS applies the existing F-CPM method with an original technique for mapping L-L type reference functions for the task duration by utilising linguistic terms to improve decision-maker familiarity and ease in modification. Furthermore, the critical path is solved by using linear programming formulations to calculate the left and right bounds [190, 199] at 12 α-cut intervals of possibility. At each α-cut point on the upper and lower bound of the network, the critical path and total duration is calculated, and from this the task duration criticality is determined [adapted from 217].

### 5.11.1 Critical Path Method (CPM)

In the traditional critical path method, a network $N = \langle V, A, T \rangle$ has a finite set of nodes $\mathrm{V} = \{1,2,3 \dots n\}$ and a set of activities $A \subset \mathrm{V} \times \mathrm{V}$ with a crisp duration that is defined by $T: A \rightarrow \mathbb{R}^{+}$

where $\mathbb{R}^{+}$ are non-negative real numbers, for which $t$ is the vector of task times. The total duration of the network $T_{1n}$, from the starting node 1 to the last $n$, is a function of the individual task durations $T_{ij}$ and their precedence relationships.

The purpose of the CPM is to determine the shortest time in which the project can be completed and to identify the 'critical path' upon which all activities have no slack [46]. To be able to calculate the slack $T_{ij}^{S}$ of each task $a$, it is necessary to calculate the earliest start time $T_{ij}^{EST}$ and the latest start time $T_{ij}^{LST}$, where $T_{ij}^{S} = T_{ij}^{LST} - T_{ij}^{EST}$. A task is critical, meaning that its duration is critical, when the slack equals zero $T_{ij}^{EST} = T_{ij}^{LST}$ [151, 217]. The critical path(s), from the start to the end of the network, are likely part of a wider number of possible 'non-critical' paths $p_c \in P$. Therefore, $p_c$ is the minimum time in which the project can be completed $T_{1n}$. It is useful for a decision-maker to identify the critical path as any reduction or extension of the activities along this path will affect the total project duration.

### 5.11.2 Fuzzy CPM Linear Programming (LP) Models

The fuzzy critical path method (F-CPM) has one significant change to the original, crisp CPM method, as the network $N_f = \langle V, A, \tilde{T} \rangle$ now has a fuzzy duration $\tilde{T}$ defined as $\tilde{T}: A \to \tilde{\mathbb{R}}^{+}$ where the fuzzy duration $\tilde{T}$ is the mapping of the activities to a set of fuzzy non-negative real numbers $\tilde{\mathbb{R}}^{+}$. As each task has a membership function at the point $t_{ij}$ that is $\mu_{\tilde{T}_{ij}}(t_{ij})$ where: $\tilde{T}_{ij} = \{(t_{ij}, \mu_{\tilde{T}_{ij}}(t_{ij})) | t_{ij} \in N(\tilde{T}_{ij})\}$. As with the applied fuzzy LCOE (Section 5.9), it is not possible to calculate the fuzzy CPM directly or exactly, and it is therefore necessary to take α-cuts to determine the solution approximately. By applying the extension principle [198] as demonstrated in Chen [199], α-cuts of a task duration $\tilde{T}_{ij}$ are given as:

$$ {}^{\alpha}T_{ij} = \{ t_{ij} \in N(\tilde{T}_{ij}) | \mu_{\tilde{T}}(t_{ij}) \geq \alpha \} \tag{5.25} $$

$$ \begin{aligned} {}^{\alpha}T_{ij} &= [\, {}^{\alpha}(T_{ij})_L, \, {}^{\alpha}(T_{ij})_U ] \\ &= [\inf_{t_{ij}} \{ t_{ij} \in N(\tilde{T}_{ij}) | \mu_{\tilde{T}}(t_{ij}) \geq \alpha \}, \sup_{t_{ij}} \{ t_{ij} \in N(\tilde{T}_{ij}) | \mu_{\tilde{T}}(t_{ij}) \geq \alpha \}] \end{aligned} \tag{5.26} $$

Where: ${}^{\alpha}(T_{ij})_L$ is the shortest duration and ${}^{\alpha}(T_{ij})_U$ is the longest duration in the set at a given α-cut respectively.

There are two methods for determining the critical path of a network, the first of these is the forward and backward pass method to determine the path of activities with a total of zero slack time. The second method, and the method applied in this research, is to determine the critical path with the formulation of linear programming models, as utilised in Chen [199]. By using the extension principle and α-cuts Chen [199] show that it is possible to convert the F-CPM problem into two parametric crisp LP problems.

Returning to the fuzzy network $N_f = \langle V, A, \tilde{T} \rangle$, the objective is to maximise the total duration time to ascertain the critical path. The maximal objective value $\widetilde{D}$ for the network is not a real but fuzzy number as the task durations are fuzzy. The F-CPM linear programming model is formulated as:

$$\widetilde{D} = \begin{array}{ll} max & \sum_{i=1}^{n}\sum_{j=1}^{n} \tilde{T}_{ij} x_{ij} \\ s.t. & \sum_{j=1}^{n} x_{1j} = 1, \\ & \sum_{j=1}^{n} x_{ij} = \sum_{k=1}^{n} x_{ki}, \qquad i = 2, \dots, n-1, \\ & \sum_{k=1}^{n} x_{kn} = 1 \\ & x_{ij} \geq 0, \qquad (i,j) \in A. \end{array} \tag{5.27}$$

Where: 1 is the first node and $n$ is the last node in the network and $x_{ij}$ is the binary integer flow in $(i,j) \in A$.

However, it is not possible to solve this linear programming model directly, without the application of α-cuts to determine the $\mu_{\widetilde{D}}(d)$, as applied for the fuzzy LCOE method. Utilising the extension principle, the membership function is defined as:

$$\mu_{\widetilde{D}}(d) = \sup_{t_{ij \in \mathbb{R}^+, (i,j) \in A}} \min_{(i,j) \in A} \{ \mu_{\tilde{T}}(t_{ij}) \, | d = D(t) \} \tag{5.28}$$

As Chen [199] states, to be able to calculate the membership value where $\mu_{\widetilde{D}}(d)$ is the minimum of $\mu_{\tilde{T}}(t_{ij}) \forall (i,j) \in A$. It is necessary to have at least one $\mu_{\tilde{T}}(t_{ij})$ equal to α such that $d = D(t)$ and satisfy $\mu_{\widetilde{D}}(d) = \alpha$ and this can be achieved by mapping the left (lower) and right (upper) sides of $\mu_{\widetilde{D}}(d)$:

$$ {}^{\alpha}D_L = \min\{D(t) \mid {}^{\alpha}(T_{ij})_L \le t_{ij} \le {}^{\alpha}(T_{ij})_U \, \forall (i,j) \in A\} \tag{5.29} $$

$$ {}^{\alpha}D_U = \max\{D(t) \mid {}^{\alpha}(T_{ij})_L \le t_{ij} \le {}^{\alpha}(T_{ij})_U \, \forall (i,j) \in A\} \tag{5.30} $$

As also shown in Chen [199], these can be reformulated into two linear programming problems for the lower and upper bounds where the objective is to find the minimum duration in which the project can be completed and all precedent relationships are satisfied. The lower bound LP model is shown below:

$$ {}^{\alpha}D_L = \begin{array}{ll} \min & y_n - y_1 \\ \text{s.t.} & y_j \ge y_i + {}^{\alpha}(T_{ij})_L, \quad (i,j) \in A, \\ & y_i, y_j \text{unrestricted in sign} \ \forall (i,j) \in A. \end{array} \tag{5.31} $$

Where $y$ is the occurrence of a node at a specific time and $y_n - y_1$ is the duration of the network from start to finish. The model is constrained to also adhere to the precedence relationships within the network and to find the minimum duration to complete the project at each possibility level $\alpha$. The upper bound formulation of the LP is still given as a maximisation problem, as it is important to find the longest duration through the network of activities:

$$ {}^{\alpha}D_U = \begin{array}{ll} max & \sum_{i=1}^{n} \sum_{j=1}^{n} {}^{\alpha}(T_{ij})_U \, x_{ij} \\ s.t. & \sum_{j=1}^{n} x_{1j} = 1, \\ & \sum_{j=1}^{n} x_{ij} = \sum_{k=1}^{n} x_{ki}, \qquad i = 2, \ldots, n-1 \\ & \sum_{k=1}^{n} x_{kn} = 1 \\ & x_{ij} \ge 0, \qquad (i,j) \in A. \end{array} \tag{5.32} $$

The model is subject to their being a logical flow from the first $x_{1j}$ and the last $x_{kn}$ task in the network and there being a path in and out of each task according to the precedence relationships. As the lower and upper LP formulations of the model give $t_{ij}$ as the lower and upper bounds of their α-cuts so that $\mu_{\tilde{T}}(t_{ij}) = \alpha$ it assures that $\mu_{\tilde{D}}(d) = \alpha$ as required by (Eq. 5.28) [199].

The overall project duration $\widetilde{D}$ could be approximated by the optimal solutions at ${}^{\alpha}D_L$ and ${}^{\alpha}D_U$ (critical path) for each α-cut. As the α-cut increases in size, the lower duration ${}^{\alpha}D_L$ is non-decreasing and the upper duration ${}^{\alpha}D_U$ is non-increasing, this ensures that a convex fuzzy membership function for the overall project duration.

### 5.11.3 Task Duration Criticality

The method chosen for calculating the task duration criticality is adapted from Zareei, Zaerpour [217]. In their method, the slack time for a node as opposed to a task is calculated. This serves the purpose of their paper in analysing the criticality of different paths through a network and improving on the method suggested by Chen [199], but has been converted for the needs of the research so that a task's slack $T_{ij}^S$ is a function of the slack between adjoining nodes $y_i^S$ and $y_j^S$ .

The pair of LP formulations (Eq. 5.31, 5.32), enable the calculation of the total network duration but not the amount of slack and in turn criticality of nodes within the network. The original LP formulations only calculate the earliest start time (EST) of the lower bound for the shortest overall duration and the latest start time (LST) of the upper bound for the longest overall duration. However, the EST and LST of the upper and lower bounds respectively are also required to determine the slack. For Equations 5.33 – 5.36, $y_i = e_i = l_i$ is used to aid in expressing the relationship between the models. The EST LP formulations for the lower and upper bounds of the model are:

$$
{}^{\alpha}D_L^{EST} = \begin{array}{ll} \min & \left({}^{\alpha}(e_1)_L + {}^{\alpha}(e_2)_L + \ldots + {}^{\alpha}(e_n)_L\right) \\ \text{s.t.} & {}^{\alpha}\left(e_j\right)_L \geq {}^{\alpha}(e_i)_L + {}^{\alpha}\left(T_{ij}\right)_L, \quad (i,j) \in A, \\ & e_i, e_j \text{unrestricted in sign } \forall (i,j) \in A. \end{array} \tag{5.33}
$$

$$
{}^{\alpha}D_U^{EST} = \begin{array}{ll} \min & \left({}^{\alpha}(e_1)_U + {}^{\alpha}(e_2)_U + \ldots + {}^{\alpha}(e_n)_U\right) \\ \text{s.t.} & {}^{\alpha}\left(e_j\right)_U \geq {}^{\alpha}(e_i)_U + {}^{\alpha}\left(T_{ij}\right)_U, \quad (i,j) \in A, \\ & e_i, e_j \text{unrestricted in sign } \forall (i,j) \in A. \end{array} \tag{5.34}
$$

Equation 5.33 is the same as Equation 5.31 with a rearranged objective function that arrives at the same solution. Whereas, Equation 5.34 calculates the possible EST of the upper bound. Moreover, the LST LP formulations for the lower and upper bounds are calculated as:

$$
{}^{\alpha}D_L^{LST} = \begin{array}{ll} \max & \left( {}^{\alpha}(l_1)_L + {}^{\alpha}(l_2)_L + \dots + {}^{\alpha}(l_{n-1})_L \right) \\ \text{s.t.} & {}^{\alpha}(l_j)_L \geq {}^{\alpha}(l_i)_L + {}^{\alpha}(T_{ij})_L, \quad (i,j) \in A, \\ & {}^{\alpha}(l_n)_L = {}^{\alpha}(e_n)_L \\ & \quad l_i, l_j \text{unrestricted in sign } \forall (i,j) \in A. \end{array} \qquad (5.35)
$$

$$
{}^{\alpha}D_U^{LST} = \begin{array}{ll} \max & \left( {}^{\alpha}(l_1)_U + {}^{\alpha}(l_2)_U + \dots + {}^{\alpha}(l_{n-1})_U \right) \\ \text{s.t.} & {}^{\alpha}(l_j)_U \geq {}^{\alpha}(l_i)_U + {}^{\alpha}(T_{ij})_U, \quad (i,j) \in A, \\ & {}^{\alpha}(l_n)_U = {}^{\alpha}(e_n)_U \\ & \quad l_i, l_j \text{unrestricted in sign } \forall (i,j) \in A. \end{array} \qquad (5.36)
$$

For the LST formulations of the linear programming model, it is necessary to have a constraining or bounding relationship between the two models and this is given as ${}^{\alpha}(l_n)_U = {}^{\alpha}(e_n)_U$.

As in the Zareei, Zaerpour [217] method, the total slack of a node $y_i^S$, is given by the sum of the slack for the upper and lower bound at each α-cut:

$$
y_i^S = \sum_{\alpha=0.001}^{1} \left( {}^{\alpha}(l_i)_U - {}^{\alpha}(e_i)_U \right) + \left( {}^{\alpha}(l_i)_L - {}^{\alpha}(e_i)_L \right), \quad i = 1,2,\dots,n. \qquad (5.37)
$$

The relative degree of criticality of a node is then given as:

$$
R\deg(i) = 1 - \frac{y_i^S}{\max\{y_i^S, i = 1,2,\dots,n\}} \qquad (5.38)
$$

Where: 1 is the most critical and 0 is the least, and a path degree of criticality is obtained by the minimum $R\deg(i)$ for each task on the path $P_k$:

$$
P\deg(P_k) = \min(R\deg(i)) \qquad (5.39)
$$

The Yager method, as demonstrated in Chen [199], calculates the sum of a path by totalling the centre of sum for each fuzzy task on the path. The criticality of a path is then determined in a similar way to Equation 5.38, with the duration of the critical path divided by the maximum of all path durations. The Zareei, Zaerpour [217] method is more suitable as it calculates criticality from the amount of slack for a node $y_i^S$ without having to reduce a fuzzy number to a crisp number for calculation.

The previous research [189, 199, 217] is concerned with the application of their respective criticality method to analysing the criticality of paths within the network $p_c \in P$. However, the method differs within the DSS at this point, the rationale being that a decision-maker is more concerned with the identification of the critical path and the criticality of individual tasks within the network rather than all paths $P$ with varying degrees of criticality. The criticality of a task is obtained from:

$$T_{ij}^C = \min\{R\deg(i), R\deg(j)\} \tag{5.40}$$

In the research adaption of the method, the criticality of a task $T_{ij}^C$ is the minimum of the preceding $R\deg(i)$ or proceeding node $R\deg(j)$. It is then possible for a decision-maker to calculate the criticality of any or all paths within the network by using Equation 5.38 from the DSS outputs.

## 5.12 Actions Output

The actions output is a risk response optimisation tool that enables a decision-maker to optimise the risk response strategies to maximise risk mitigation with limited money and time resources. This section of the DSS is beneficial as it is possible to manage risk from a project holistic level as opposed to the individual risk response analysis given in Section 5.7.

The objective function of the LP model is to maximise the mean LCOE saving for the project. Each risk event and response action $x_{ea}$ pair has an effect on the overall mean levelised unit cost $\overline{LCOE}_{ea}$ and project duration $\overline{D}_{ea}$. These two effects are gathered by utilising the same algorithmic approach covered in the response cost: benefit strategy (Section 5.7.3). This is subject to not exceeding the available time $A_T$ and money $A_M$ resources, and only possible to have one response action chosen for each risk event. The optimisation equation employed in the DSS is given as:

$$S = \begin{cases} max \ \sum_{e=1}^{n} \overline{LCOE}_{ea} \cdot x_{ea} \\ s.t. \ \sum_{e=1}^{n} (\overline{LCOE}_{ea} \cdot x_{ea}) - A_M \leq 0, \\ \sum_{e=1}^{n} (\overline{D}_{ea} \cdot x_{ea}) - A_T \leq 0, \\ \sum_{e=1}^{n} x_{ea} \leq 1, \ for \ a = 1, \dots, m \\ x_{ea} \geq 0. \end{cases} \tag{5.41}$$

The mean levelised unit cost $\overline{LCOE}_{ea}$ is taken otherwise an optimal configuration of risk response actions is given at each α-cut and this is overly confusing. It is also important to acknowledge that it is possible that not all the $x_{ea}$ are beneficial in reducing the levelised unit cost. It this case, the DSS recommends that no response action should be taken for that risk event. Furthermore, the optimised risk response strategy to meet the resource constraints of the project can then be quickly applied to the residual risk scenario for further analysis in the finance and schedule outputs.

The linear programming model only maximises the LCOE saving and not the project duration saving, which in some cases may be the desired objective function for a decision-maker. It also does not have resources allocated to individual tasks as suggested by Long and Ohsato [218], but this level of information granularity would unlikely be available to decision-maker at such an early stage of project development.

## 5.13 Model Component Development

To develop individual components, such as the fuzzy financial, scheduling or risk management model of the fuzzy system developed within the research, it is necessary to follow stages as given in Table 5.9.

*Table 5.9 – Model component development stages*

| Common elements | Fuzzy finance model | Fuzzy scheduling model | Fuzzy risk management & optimisation |
|---|---|---|---|
| i. **Linguistic functions**<br>Define the fuzzy confidence and attitude linguistic terms as given in Section 5.4 | iii. **Input variables**<br>Define the required technological, locational and financial variables given in Table 5.3 in Section 5.5 | iii. **Input variables**<br>Define the schedules variables given in Table 5.3 in Section 5.5 | iii. **Risk register**<br>Define the project lifecycle stages and impact groups for categorisation (5.6.1, 5.6.3, 5.7.1) |
| ii. **α-cut number**<br>Determine the number of α-cut points as given in Section 5.3.2 | iv. **Production incentives and tax**<br>If the financial model utilises current UK production incentives such as the CHPQA for good quality heat utilisation, and taxation then Section 5.5.1 and 5.5.2 are also required | iv. **Critical path**<br>Convert the project network into the linear programming models given in Section 5.11.2 | iv. **Risk cause and effect hierarchy**<br>Define a risk cause and effect hierarchy (5.6.3) utilising the applied input variables given in Table 5.3 in Section 5.5 |
| | v. **Cash flow variables**<br>The calculation method required for each financial variable within cash flow analysis is given in Sections 5.10.1 – 7 | v. **Task duration criticality**<br>Calculate the task duration slack with the additional set of linear programming models and task criticality scoring method given in Section 5.11.3 | v. **Risk response strategy**<br>Define the possible risk response strategies as given in Section 5.7.2 |
| | vi. **Levelised energy cost**<br>The fuzzy levelised cost can then be approximately calculated by utilising the algorithm in Section 5.9 for each α-cut (ii) | | vi. **Response cost: benefit analysis**<br>Determine the most effective risk response strategy with the application of the algorithm of Section 5.7.3 and this draws on the fuzzy levelised cost (5.9) and fuzzy scheduling (5.11.2) algorithms |
| | vii. **Additional financial analysis**<br>Project capital structuring (5.10.9), sensitivity analysis (5.10.10), variable heat utilisation levelised energy cost (5.10.11) and project NPV and IRR (5.10.12) can also be applied | | vii. **Risk response actions optimisation**<br>Utilise the linear programming formulation given in Section 5.12 to maximise the risk mitigation impact on the LCOE with limited resources |

# 6. Model Demonstration

## 6.1 Introduction

This chapter demonstrates the functionality and validity of the DSS by applying it to the Energy Company case study. In addition to analysing the case study with the DSS, it was also demonstrated to several industry professionals for their evaluation and this is shown in Chapter 7.

The chapter introduces the case study in more detail (6.2), using the location, technology and feedstock data given by the company where possible. An initial analysis of the case on an 'as was' basis is given (6.3) and then the major barriers or challenges faced in the developmental stages are covered in more detail and supported by the DSS (6.4). This is followed by a demonstration of the possible risk management processes that could have been employed within the case study (6.5). The final section of the chapter (6.6) gives a short conclusion on how the project could have adapted to increase its viability.

## 6.2 Energy Company Case Study

The case study is of a recently failed (2011) small-scale biomass CHP project in the UK as introduced in Chapter 1. If successful, the bCHP plant would have supplied onsite heat and power to residential and light-industrial properties, and exported any additional power to the grid. Although the project received planning permission, it was unable to leave the developmental stage by securing finance also known as 'financially closing' the project. There were several potentially contributing risk factors and challenges over the project's duration of development, such as:

1. capital structure;
2. contract length and bankability;
3. incentive changes for biomass CHP;
4. feedstock type and price uncertainty;
5. plant oversizing.

This section of the thesis, where possible, uses the company's forecasted data to highlight the application and benefits of using the DSS. To maintain confidentiality for Energy Company, the information given is an approximate estimation of their data. In order to demonstrate the fuzzy application of the model with the estimated ranges, it is necessary to give hypothetical ranges around the case study data. Ideally, the company would have given information on the fuzzy ranges but this was not possible due to the failure of the project and company. Due to the failure of the company, it was also only possible to apply the risk exposure and mitigation impact excluded scenario, referred to as the 'initial' scenario (Section 5.8), throughout the analysis in this chapter.

### 6.2.1 Technology

A 1.5MWe net capacity, virgin wood chip fired bCHP combustion plant with an extraction-condensing turbine was proposed for the site. Table 6.1 shows the key performance metrics for the chosen CHP technology.

*Table 6.1 – Technology and feedstock characteristics*

| **Technology** | **Unit** | **Value** |
|---|---|---|
| Net Capacity | MWe | 1.5 |
| Heat to power ratio | H:P | 3.5:1 |
| Thermal losses (boiler) | % | 15 |
| Parasitic Load | % | 12 |
| Electrical Efficiency | % | 20 |
| Availability | % | 90 |
| **Feedstock** | | |
| Cost | £/ODT | 50 |
| Energy Content | MWh/ODT | 4.8 |

The heat to power ratio implies that 3.5 units of heat are produced for every unit of electricity produced. There would have also been losses in the efficiency of the boiler and a parasitic load of electricity, set at 15% and 12% respectively. Plant availability was estimated at 90%, resulting in approximately 7800 operational hours per annum.

The virgin woodchip was the bi-product of an industrial wood processing plant in the UK. This was not commercial grade wood chip, as this would have a significantly higher cost. The feedstock cost of £50/ODT was correct at the time of project development, however the current price for this feedstock is more likely to be c. £70/ODT[33].

### 6.2.2 Location

The site had a mixture of residential and light industrial premises. It was possible to gain a grid connection for the site, but it would have been necessary to retrofit a district heating network to provide heat for hot water and space heating purposes.

---

[33] Telephone conversation with a Biomass Procurement Manager (September 2012)

*Table 6.2 – Residential and industrial demand*

| | | Certain | | Total | Uncertain (kWh/d) | | |
|---|---|---|---|---|---|---|---|
| **Residential[3]** | **Unit** | **Potential** | **Achieved[1,2]** | **(MWh/pa[6])** | **Abs. min** | **Exp.** | **Abs. max** |
| Electricity | kWh/d | 1967 | 983 | 358 | 800 | 983 | 1100 |
| Heat | kWh/d | 7597 | 3799 | 1383 | 3000 | 3799 | 4000 |
| **Industrial** | | **Potential** | **Achieved[4,5]** | | | | |
| Electricity | kWh/d | 6606 | 686 | 178 | 600 | 686 | 760 |
| Heat | kWh/d | 11736 | 1220 | 317 | 1000 | 1220 | 1320 |

[1] Assumed at 50% of total residential capacity; [2] Total demand divided by 365 days as insufficient information available to calculate weekend demands; [3] Residential electricity demand assumed at 4,174 kWh/per dwelling/pa and gas demand assumed at 15,698 kWh/ per dwelling /pa [219]; [4] Typical open plan office electricity consumption set at 85 kWh/m$^{2/}$pa and heat demand set at 151 kWh/m$^{2}$/pa [220]; [5] Based on the inhabited non-domestic properties ; [6] per annum

Table 6.2, shows that if the site was fully occupied the onsite heat and power demand potential for the scheme was high. However, this was not the case and it was expected to take a significant number of years to reach this target. The annual industrial to residential heat demand ratio was approximately 1:3. Furthermore, the onsite price of heat and power was to be set competitively with the fossil fuel generated equivalents and these are shown in Table 6.3.

*Table 6.3 – Residential and industrial fossil fuel equivalent prices*

| | **Unit** | **Electricity** | **Gas** |
|---|---|---|---|
| Residential | £/MWh | 120 | 50 |
| Industrial | £/MWh | 60 | 30 |

### 6.2.3 Finance

The project CAPEX and OPEX were estimated in the actual project and these estimates are given in the ‘certain’ column of Table 6.4. However, as the model could accommodate uncertain or approximate inputs for project costs these are the shown in the ‘uncertain’ columns of the same table. Furthermore, limited recourse project financing was to be pursued as it was not possible to have corporate ‘on-balance sheet’ financing due to insufficient funds and the sponsor lacking the ‘track record’ to secure additional funding through the company.

*Table 6.4 – Project costs*

| | | **Certain** | **Uncertain** | | |
|---|---|---|---|---|---|
| **CAPEX** | **Unit** | **Value** | **Abs. min** | **Expected** | **Abs. max** |
| Development | £000s | 100 | 80 | 100 | 130 |
| Plant | £000s | 4000 | 3700 | 4000 | 4500 |
| EPC | £000s | 500 | 500 | 500 | 700 |
| Other (DHN) | £000s | 200 | 190 | 200 | 230 |
| **OPEX** | | | | | |
| Maintenance | £000s/pa | 50 | 35 | 50 | 70 |
| Operations | £000s/pa | 200 | 190 | 200 | 250 |
| Insurance | £000s/pa | 5 | 5 | 5 | 10 |
| Land Lease | £000s/pa | 250 | 250 | 250 | 250 |
| Other | £000s/pa | 0 | 0 | 0 | 0 |

The total development cost for the project, to bring it to the point of financial close, was estimated at £100,000. The uncertain, fuzzy distribution for the same development costs estimates that the absolute minimum is £80,000, the most expected cost remains £100,000 and the absolute maximum is £130,000. There is also a tendency for the difference between the expected value and abs. max to be greater than the expected and abs. min as there is a greater possibility that costs would overrun. The same method of fuzzifying the certain values was applied to the rest of the CAPEX and OPEX costs, with the exception of the EPC, insurance and land lease costs. In the case of the EPC and insurance costs, it was assumed that the abs. min and expected price were the same to show that the price was not going to reduce on the expected but could possibly increase. In addition, the project would have benefited from the Government incentives for renewable energy (Annex 2 Section A2.5) and the rates for these are shown in Table 6.5.

*Table 6.5 – Incentive information*

| | **Unit** | **Value** |
|---|---|---|
| ROCs | ROC/MWhe | 1.5 |
| ROC Price | £/MWhe | 47 |
| LEC Price | £/MWhe | 4.7 |
| RHI | £/MWhth | 10 |

A biomass CHP combustion plant running on dedicated biomass receives 1.5 ROCs/MWhe and the ROC price modelled by Energy Company was £47/MWhe. However, as the ROC is a market based incentive, the price can vary greatly (as shown in Annex 2 Fig. A2.1) and is currently closer to £40/MWhe [221]. Accredited bCHP plants are also exempt from the CCL and receive LECs that had a resale value of c. £4.70/MWhe, but is currently £5.09/MWh [222]. Furthermore, the project was to be financed from debt and equity sources, and the assumed terms of finance for the company from consultation with potential financiers is shown in Table 6.6.

*Table 6.6 – Finance terms*

| Variable | Unit | Value |
|---|---|---|
| Debt Term | Yrs | 10 |
| Debt Interest | % | 6 |
| Debt Service Cover Ratio | | 1.35 |
| Return on Equity | % | 15 |
| Tax | % | 28 |

The term for equity return was assumed to be over the operational duration of the project and as covered in Section 5.5.2, the tax rate is correct for the 2010 financial year.

### 6.2.4 Schedule

There was limited information on the scheduling of the project. To accommodate this, a high-level interpretation of the project schedule tasks and dependencies has been created (Table 6.7) to demonstrate how it could have been applied in the DSS.

*Table 6.7 – Project schedule*

| | | | Duration (Months) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Certain | Uncertain | | | |
| ID | Details | Prerequisite task(s) | Value | Abs. min | Exp. Lower | Exp. Upper | Abs. max |
| A | Pre-feasibility | - | 3 | 1.5 | 2 | 3 | 4 |
| B | Site acquisition | A | 2 | 1 | 2 | 2 | 2.5 |
| C | Concept design | B | 2 | 1 | 1 | 2 | 3 |
| D | Financial modelling | B | 3 | 2 | 3 | 3 | 4 |
| E | Planning permission | C,D | 2 | 2 | 2 | 3 | 3 |
| F | Find investors | E | 1 | 0 | 0.5 | 1 | 1 |
| G | Detailed design | E | 5 | 4 | 4 | 5 | 6 |
| H | Component tender and HOT[1] | G | 4 | 3 | 4 | 4 | 5 |
| I | Feedstock tender and HOT | G | 3 | 2.5 | 3 | 3.5 | 5 |
| J | EPC tender and HOT | G | 4 | 2.5 | 3 | 4 | 5 |
| K | Grid connection HOT | G | 2 | 1 | 2 | 2 | 3 |
| L | PPA HOT | G | 2 | 1 | 2 | 2 | 3 |
| M | Due diligence | F,H,I,J,K,L | 4 | 2.5 | 3 | 4 | 4 |
| N | Financial close | M | 1 | 0.25 | 0.5 | 0.5 | 1 |
| O | Award contracts | N | 2 | 1 | 2 | 2 | 3 |
| P | Ground work | O | 4 | 3 | 3 | 4 | 5 |
| Q | Construction | O | 12 | 10 | 11 | 12 | 13 |
| R | CHP installation | O | 4 | 4 | 4 | 5 | 6 |
| S | Handover | P,Q,R | 0 | 0 | 0 | 0 | 0 |

[1] Heads of terms

The project schedule tasks were given unique identifiers (in this case alphabetic characters), dependencies in the form of precedent relationships and fixed or approximate durations.

### 6.2.5 Project Risks

Possible project development risks have been interpreted from discussions with the company and from the section on barriers to biomass development (Chapter 2) to demonstrate the efficacy of the risk management section of the DSS. The quantification of the risk events (Table 6.8) is for demonstration purposes only.

*Table 6.8 – Project risks*

| **#** | | **Description** | | **Project impact** | | **Unit** | **Certain** | **Uncertain** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Risk event** | **Cause** | **Effect** | **Likelihood** | **Severity** | | **Impact** | **Abs. min** | **Exp.** | **Abs. max** |
| | **Development** | | | | | | | | | |
| 1 | Planning permission (PP) | PP requires community consultation | Community consultation may be required | Moderate | High | Cost (£000s) | £10 | £8 | £10 | £12 |
| 2 | Planning permission (PP) | PP takes longer to achieve | Duration overrun | Low | Low | Duration (months) | 0.5 | 0.5 | 0.5 | 1 |
| 3 | Underestimated cost | Under estimation of the development cost | Cost increase | Moderate | Low | Cost (£000s) | £5 | £0 | £5 | £10 |
| | **Construction** | | | | | | | | | |
| 4 | Construction | Stakeholder communication causes delay | Construction duration overrun | High | Moderate | Duration (months) | 1.5 | 0.5 | 1.5 | 2 |
| | **Operation** | | | | | | | | | |
| 5 | Feedstock cost | Volatility in feedstock prices increases price when contract is signed | Price increase per ODT | High | High | £/ODT | £10 | £0 | £10 | £15 |
| 6 | Fire | Poor feedstock flow and management | A fire in an area of the plant | Moderate | Very High | Availability | 5% | 5% | 5% | 10% |
| 7 | ROC value | Market price for ROC falls or transaction costs increase | Decreased obtainable value per MWhe | High | Moderate | ROC value | £5 (c. 10%) | £0 | £5 | £10 |
| 8 | Feedstock quality | Variance in energy content | Price increase per ODT | High | High | MW/ODT | .5 | 0.0 | 0.5 | 0.7 |
| 9 | Equipment failure | Minimal maintenance regime | Risk of reduced plant availability | High | High | Availability | 5% | 0% | 5% | 5% |
| 10 | Onsite residential heat demand | Inaccuracies in estimates of industrial demand and improved energy efficiency in properties | Demand is lower than forecasted | High | High | Heat demand (kWhth/d) | 250 | 0 | 250 | 500 |

Each risk was recorded along with the cause and effect with fixed or approximate quantitative implications. The risks are analysed further with the DSS in Section 6.5.

## 6.3 Case Study Results ('as was' basis)

This section of the chapter gives an initial analysis of the project with the given forecasted inputs to assess its viability. The 20-year cash flow projections without any uncertainty in the inputs or any risk events (initial scenario) are given in Annex 5-7.

### *Levelised Energy Cost*

Utilising the extension principle (Section 5.3.2) and the fuzzy LCOE algorithm (Section 5.9), it is possible to calculate the minimum levelised unit cost required for the project to be viable. Under the original assumptions modelled by the company, at a maximum debt gearing of 60% and supported by the ROC incentive with ROC uplift for heat, the unit cost of electricity was £86.60 per MWhe over the life of the project. This is shown as the dashed red line within Figure 6.1.

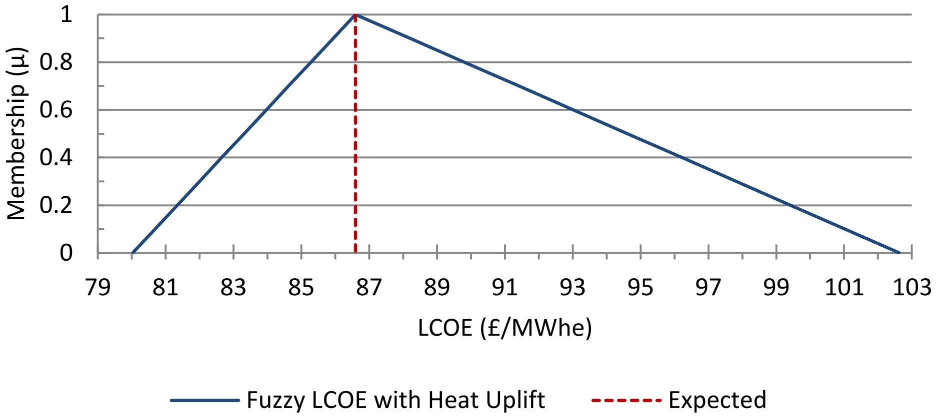

*Figure 6.1 – LCOE with ROC heat uplift*

The fuzzy LCOE range covers the possible uncertain or approximate costs and demand outcomes. If the project CAPEX and OPEX costs were at the absolute minimum and the onsite demand of heat was at the absolute maximum then a LCOE of £80.04 would have been required, and in the worst case the converse would lead to a LCOE of £102.62. These values were the absolute minimum and maximum LCOE given that the input assumptions held. They were also the least expected to occur with the confidence increasing as the level of membership increases, with the most expected value being £86.60.

The crisp or fuzzy values accounted for the revenue generated from production incentives (LEC, ROC, ROC uplift) and the sale of onsite heat charged at the gas equivalent price. It would therefore be necessary for the levelised unit cost of electricity to be met from onsite or exported energy sales. If the project, in the expected case, could not generate on average £86.60 per MWhe over the lifecycle of the project from electricity sales then it was not viable under the current assumptions. As the current short-term PPA price for exported electricity is c. £40/MWhe and significantly less than the levelised unit cost required for the project to break-even, it is unlikely that this unit rate could have been achieved.

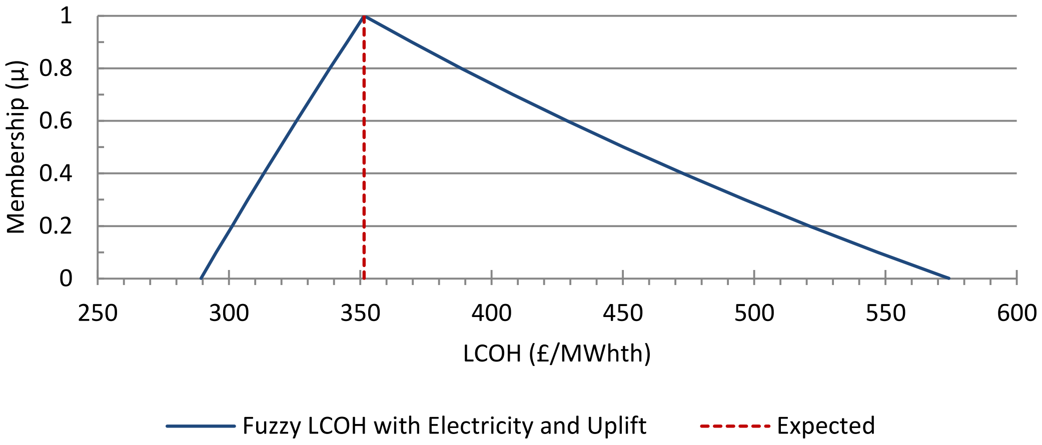

*Figure 6.2 – LCOH with ROC heat uplift*

By assuming the onsite electricity sales could have been sold at the market equivalents, £120/MWhe for residential and £60/MWhe for industrial, and assuming the export price to £40/MWhe, it was possible to calculate the LCOH for the onsite demand of heat, as shown in Figure 6.2. The additional revenue required to make the project viable was the same as in the LCOE example but as there were far fewer units to distribute the deficit across (c. 1700 MWhth/yr) the unit cost is expected to be £351.51/MWhth with the absolute min and max being £289.36 and £574.17 MWhth respectively. Heat could not be sold at this unit price, and this indicates that the project was not viable in its current state.

### *Project EBITDA NPV and IRR*

If the project was only able to achieve the range of utilisation for onsite and exported heat and power, the project EBITDA NPV at a discount rate of 10% would be as is shown in Figure 6.3.

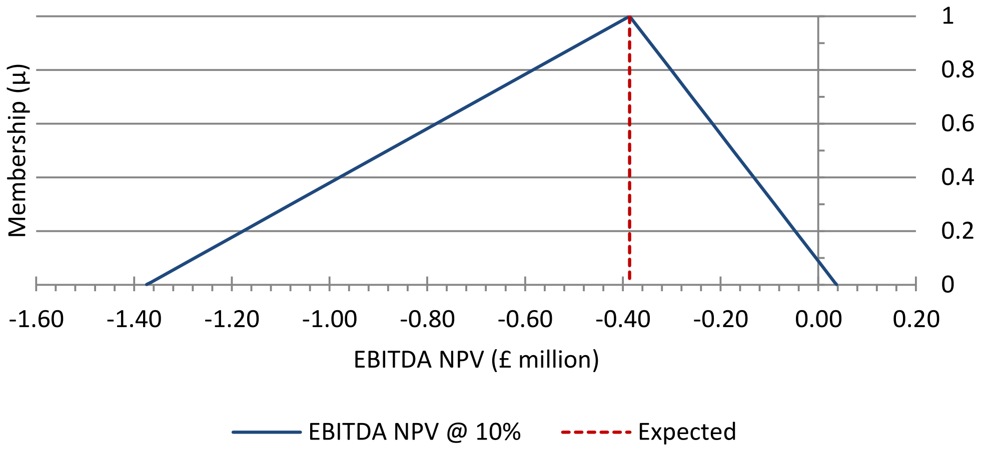

*Figure 6.3 – Project EBITDA NPV*

The fuzzy distribution in the figure only passes the breakeven point under the most favourable and least expected current assumptions. The abs. min and max NPV for the project were -£1.37 million and £0.04 million respectively, with the most expected outcome of -£0.39 million. As to be expected, this was also reflected in the IRR for the project with a range of -0.01% to 10.3% with a most expected EBITDA IRR of 6.93%. Furthermore, as the EBITDA value excludes interest, tax, depreciation and amortisation it is more favourable than the free cash flow calculation, which also generated a greater negative NPV and IRR. This further supports the other analysis with the DSS and implies that the project was not financially viable under the current assumptions or discount rate.

### *Project Duration*

The project's total fuzzy duration (Eq. 5.31, 5.32), to the point of operation, given the fuzzy task durations and precedence relationships in Table 6.7 is shown in Figure 6.4.

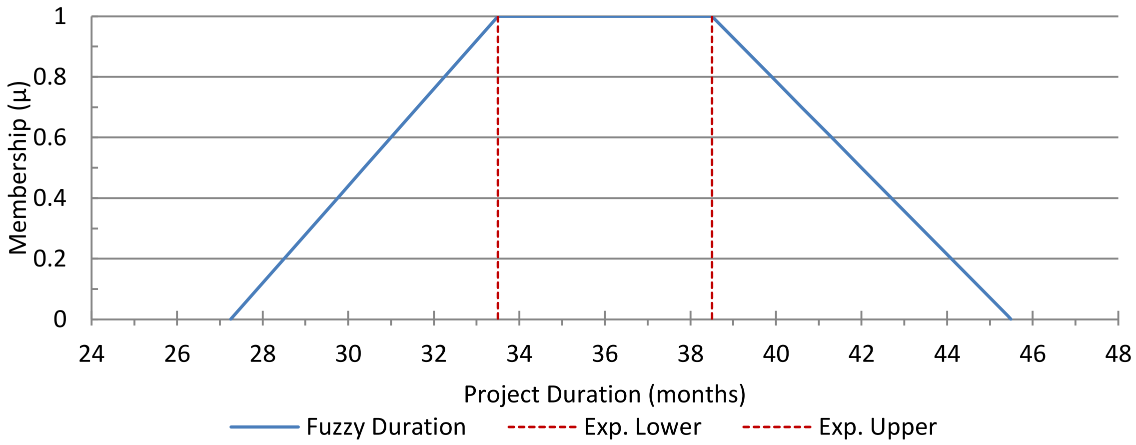

*Figure 6.4 – Fuzzy project duration*

The project was expected to take between 33.5 to 38.5 months to complete with the abs. min duration being 27.3 months and the abs. max being 45.5 months. The lower and upper expected region in this figure, denoted by the dashed red lines, is the possible range in which the project duration was equally expected to occur. As actual task duration estimates and precedence relationships were not obtainable from the case study sponsor, it was not possible to assess whether this was an acceptable duration. Furthermore, the DSS is also able to calculate the path and critical tasks over the project given the fuzzy durations and this is shown in Table 6.9.

*Table 6.9 – Project critical path and task duration criticality*

| **Task** | **Pre-feasibility** | **Site acquisition** | **Concept design** | **Financial modelling** | **Planning permission** | **Find investors** | **Detailed design** | **Component tender and HOT** | **Feedstock tender and HOT** | **EPC tender and HOT** | **Grid connection HOT** | **PPA HOT** | **Due diligence** | **Financial close** | **Award contracts** | **Ground work** | **Construction** | **CHP installation** | **Handover** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | **A** | **B** | C | **D** | **E** | F | **G** | **H** | I | J | K | L | **M** | **N** | **O** | P | **Q** | R | **S** |
| **Crit.** | 1 | 1 | .85 | 1 | 1 | 0 | 1 | 1 | .94 | .96 | .75 | .75 | 1 | 1 | 1 | .05 | 1 | .17 | 1 |

The case study's critical path was calculated at the 12 α-cuts on the lower and upper duration bounds of each task membership function. It is possible for there to be multiple critical paths in the fuzzy calculation of the CPM, but in this example there was only one critical path: ABDEMNOQS (shown in bold in the table). The task duration criticality was calculated from the slack of the LST and EST at each α-cut (Eq. 5.33 – 5.40). The tasks with values equal to 1 were the most critical and would have needed to be closely monitored as any increase in their duration would increase the total duration of the project. Moreover, if the sponsor was trying to crash the project duration these critical tasks should have been targeted first. The tasks that scored zero or close to zero were the least critical and any small variance in duration beyond that estimated within the DSS would likely not change the overall project duration as there was slack present.

## 6.4 Further Analysis

This section of the chapter further analyses the known barriers and challenges for the project. With the aid of the DSS, these were addressed in turn along with possible solutions that could have improved the viability of the case study.

### 6.4.1 Capital Structure

For the case study, it was estimated that the project financed capital structure would be 50%-60% debt geared with the remaining capital being generated from equity sources. During the financial closing phase, the debt provider produces a term sheet for the sponsor that stipulates the terms of the loan. As debt is less costly than equity a sponsor will try to maximise the proportion of debt. However, at higher levels of debt the DSCR (Eq. 5.17) can significantly increase the levelised unit cost. Given the terms of finance or estimated in the early stages from market analysis, it was possible to calculate the effect of the capital structure (Section 5.10.9) on the LCOE as represented in Figure 6.5.

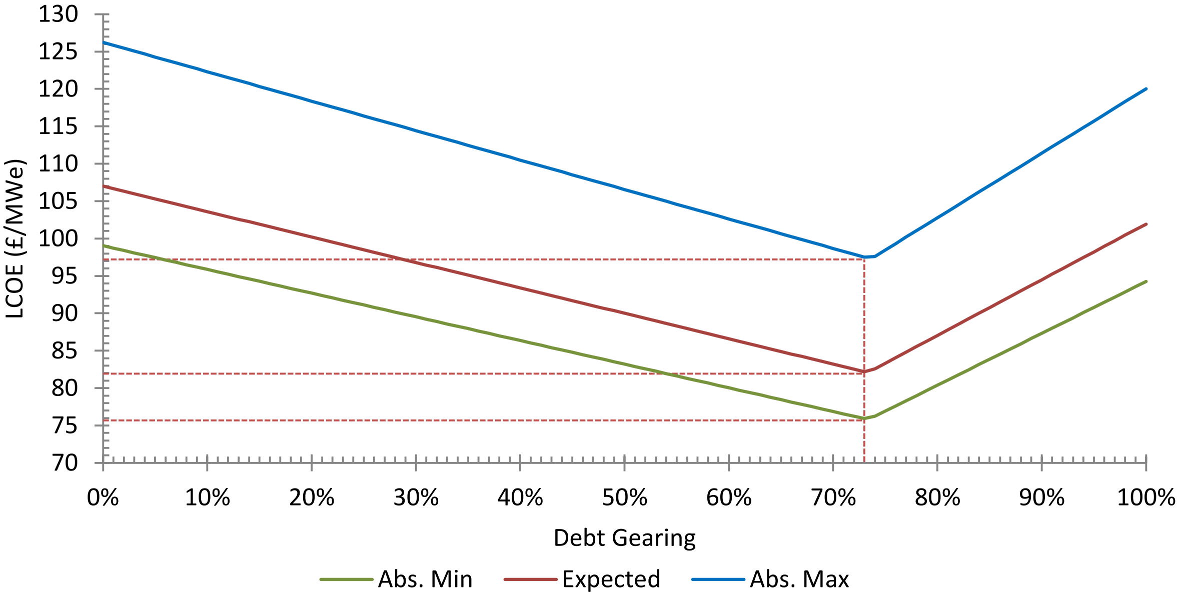

*Figure 6.5 – Fuzzy capital structure*

A 50% to 60% debt gearing resulted in an expected LCOE of £90 to £86.60 respectively. A cross-section of this figure at a gearing of 60% reproduces Figure 6.1. However, as shown in Figure 6.5 and Table 6.10, the optimal gearing for the project was c. 73%, as at this point the LCOE would have been reduced to £82.18 per MWhe. Ideally, the sponsor would try to achieve a gearing at or close to the lowest possible range of fuzzy unit costs. This optimal point may however be subject to change depending on the terms of finance and the rate of tax.

*Table 6.10 – Capital structure table (LCOE £/MWhe)*

| **Debt:** | 50% | 60% | 65% | 70% | 71% | 72% | **73%** | 74% | 75% |
|---|---|---|---|---|---|---|---|---|---|
| **Abs. Min** | 83.20 | 80.04 | 78.45 | 76.87 | 76.55 | 76.24 | **75.92** | 76.22 | 76.92 |
| **Expected** | 90.00 | 86.60 | 84.90 | 83.20 | 82.86 | 82.52 | **82.18** | 82.58 | 83.32 |
| **Abs. Max** | 106.55 | 102.62 | 100.65 | 98.68 | 98.28 | 97.89 | **97.50** | 97.60 | 98.46 |

At 73% debt and 27% equity, the 20-year cash flow projection produced the lowest levelised unit cost. Any increase in the share of debt, increased the required DSC for the DSCR and any increase toward equity increased the LCOE to meet the required rate of return.

The project finance terms shown in Table 6.6 are the assumed terms of finance for the case study. It is however, unlikely that these were achievable as the wake of the financial downturn reduced funding and created greater competition between projects as financiers became more risk adverse. A drive to the financing of larger scale or, perceived to be, less risky RET projects such as wind has made the market for small-scale biomass project finance increasingly difficult. From initial talks with potential debt providers, Energy Company could achieve a maximum debt gearing of 50-60% with the rest of the project being financed from equity sources. However, it later became evident that the debt and equity proportions of the finance did not constitute the entire capital required to fund the project. Before the project and ultimately company failed, the sponsors were considering utilising subordinate debt (mezzanine finance) (as covered in Section 2.4.1). The DSS does not have the option of entering subordinate debt, but as stated by Fabozzi and de Nahlik [63] it may be considered as equity for calculating the debt to equity ratio. As the subordinate debt is of a higher rate of return it would not improve the cost of capital to be more favourable than without it.

### 6.4.2 Contract Length and Bankability

As covered in Section 2.4, it is often necessary to have contracts or at least heads of terms for feedstock supply and heat and power revenues in place to secure finance. For the case study, this issue created the most significant difficulties for the onsite sale of heat. As the company was not able to present a long term heat supply contract (as also identified by [84]) and could not guarantee the demand of the DHN supplied heat to the occupied residential and light industrial premises. It was not considered by the lenders they approached as a secure enough revenue stream.

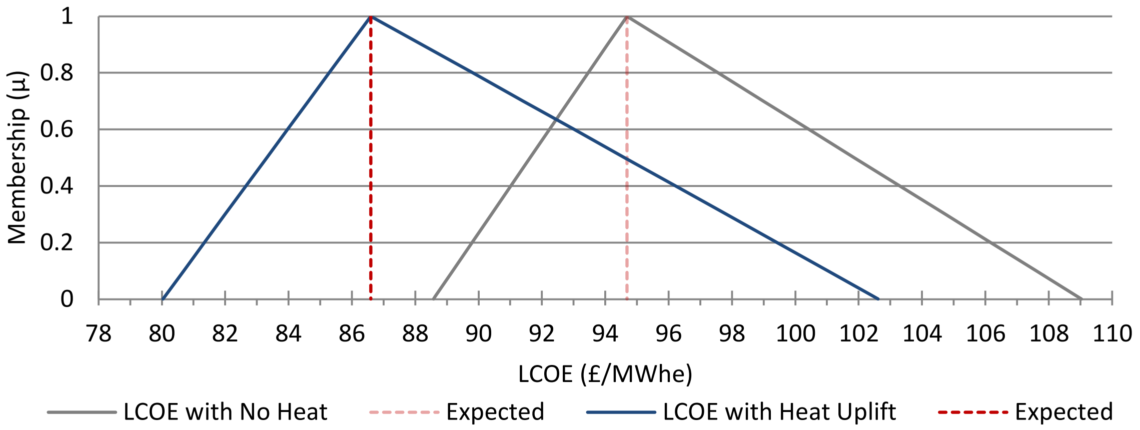

*Figure 6.6 – The effect of onsite heat revenue on the LCOE*

By removing the additional revenue of onsite heat sales from the LCOE (Fig. 6.6), there was an increase in the unit cost of c. £8 per MWhe. This significantly disadvantaged the project and at higher levels of onsite heat utilisation the benefit of the additional heat credit could ultimately have decided if the project was viable or not. This can was also shown in the project from the PPA output Figure 6.7.

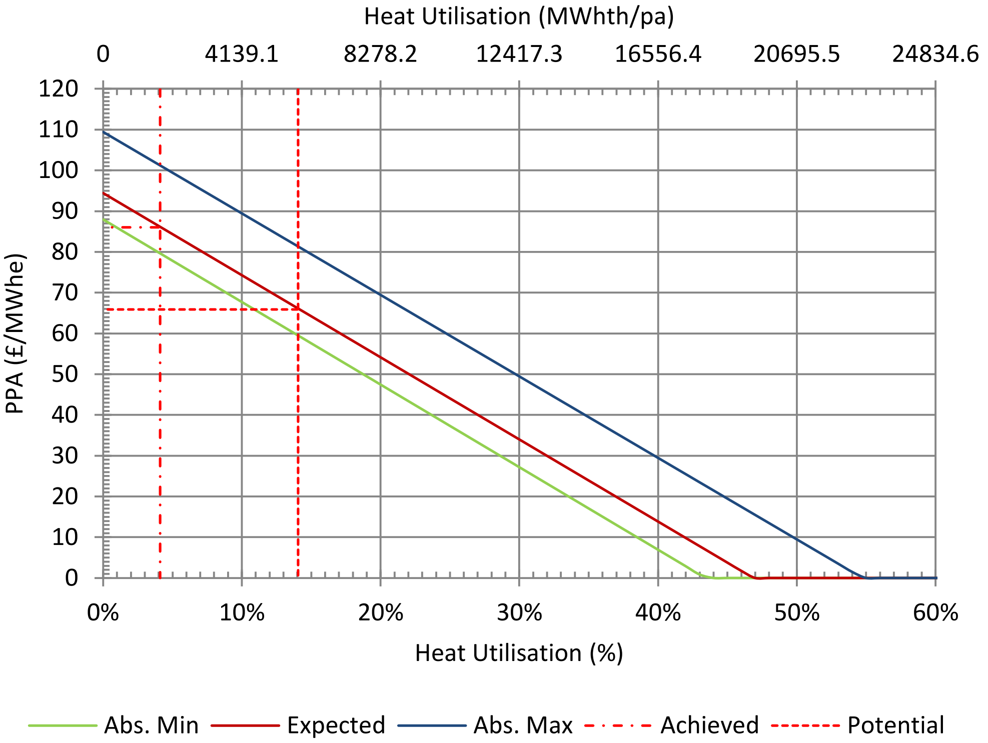

*Figure 6.7 – Minimum PPA unit price with ROC uplift*

At higher levels of annual heat utilisation the minimum unit cost per MWhe exported to the grid fell. At approximately the achieved onsite heat demand the minimum expected unit cost is £86.37 per

MWhe and, this was reduced to £66.22 if the site could reach its potential heat load. Assuming that the current PPA contract value was c. £40 MWhe, the project could be expected to be viable at 28% annual heat utilisation (Table 6.11) if heat revenue was considered secure enough for investment purposes.

*Table 6.11 – Minimum PPA contract price at different heat utilisation levels*

| | **Heat utilisation (MWth):** | **Achieved[1] 1656 (4%)** | **Potential[2] 5794 (14%)** | | **PPA (£/MWhe) < £40** |
|---|---|---|---|---|---|
| **PPA (£/MWhe)** | Abs. Min | £79.86 | £59.6 | **Heat utilisation (MWhth/pa)** | 9934 (24%) |
| | Expected | £86.37 | £66.22 | | 11589 (28%) |
| | Abs. Max | £101.43 | £81.44 | | 14487 (35%) |

[1] Closest DSS output to actual of 1700 MWhth/pa; [2] Closest DSS output to potential of 5817 MWhth/pa

The company was considering the possibility of entering into a contract with an ESCO (Energy Services Company) type entity, but this third party would also need the financial credibility and track-record to ensure that the revenue stream was bankable in the eyes of the financier and such a third party proved difficult to find.

### 6.4.3 Incentive Changes for Biomass CHP

As covered in the annex on policy (Section A2.5), the RO has been through several transformations over the past decade with the next changes to be implemented in April 2013 with the scheme to be ceased in 2017. Furthermore, during the development of the case study project, the FiT tariff and RHI were introduced. Continual changes in policy create difficulties for sponsors and, most likely, financiers as there is reduced confidence and clarity in the policy [7]. It is important for there to be clarity for these parties on areas such as incentives, as project development may take a couple of years to progress from concept to financial close [6].

Presently, there are two options for incentivising CHP in the UK: ROC with ROC uplift for good quality CHP (under the CHPQA scheme) or the ROC (1.5/MWe) and RHI for the utilised heat. During the development phase of the project (2010) the ROC with uplift was the only incentive for CHP although the RHI had been announced[34] it was not to be introduced until April 2011 but was subsequently delayed until November 2011.

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[34] Energy Act 2008

During the company's financial modelling of the case study, the ROC was the only available incentive, which also happened to be at a high and relatively stable price of £47 MWhe (Fig. A2.1). An analysis, with the aid of the DSS, compared the benefit of the ROC uplift at £47 MWhe and the subsequently announced RHI value of £10 MWhth over the range of heat utilisation scenarios for the project, as shown in Figure 6.8.

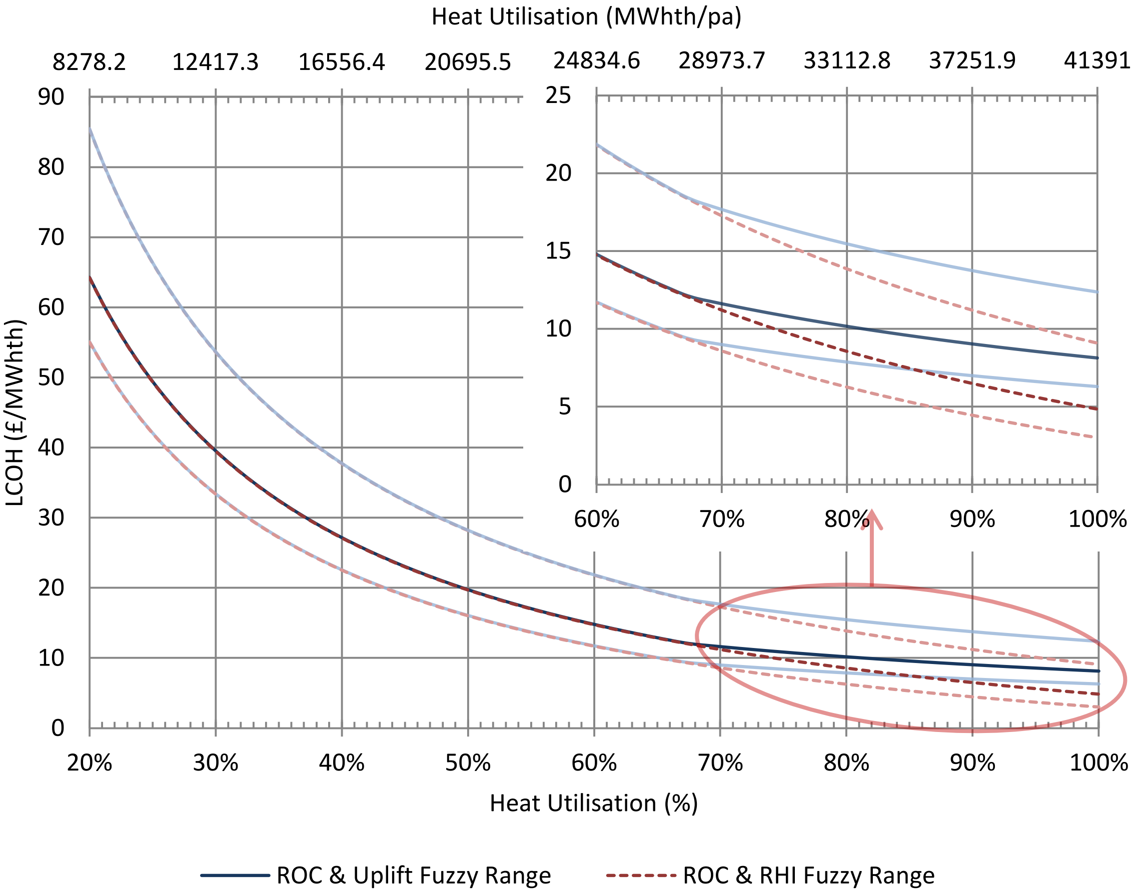

*Figure 6.8 – Comparison of the fuzzy LCOH with ROC uplift or RHI*

Under the CHPQA ROC uplift scheme, the amount of 'uplift' toward a possible 0.5 ROC/MWhe is calculated by the overall efficiency of the plant and the feedstock used (Section 5.5.1). The revenue generated for the qualifying heat output under the CHPQA ROC uplift scheme amounted to an £0.05 increased LCOH over the RHI for the life of the project. This output in the DSS suggests that the RHI was marginally beneficial to the ROC at these rates as it resulted in a lower LCOH. At 68% annual heat utilisation, the LCOH under the RHI became more attractive as it produced a significantly lower levelised unit cost. This change occurred because the ROC uplift reached the maximum of 0.5 ROCs/MWhe at this point (QI ≥ 100). At the current ROC price of £40.17 (August 2012 [221]), the RHI option is much more attractive to a sponsor and financier, as shown in Table 6.12. However, if the ROC value returns to the previous highs of greater than £50 MWhe then the converse would be true.

*Table 6.12 – Tariff comparison calculation*

| | | ROC value at £47 | | ROC value at £40 | |
|---|---|---|---|---|---|
| **ROC Uplift** | **Unit** | **Actual** | **Potential**[1] | **Actual** | **Potential**[1] |
| Heat Utilised | MWhth/pa | 1700 | 5816.67 | 1700 | 5816.67 |
| Heat Utilised | % of total | 4.11% | 14.05% | 4.11% | 14.05% |
| Power Efficiency | % | 15% | 15% | 15% | 15% |
| Heat Efficiency | % | 2% | 8% | 2% | 8% |
| Quality Index (QI) | | 59.27 | 65.66 | 59.27 | 65.66 |
| ROC Uplift | £/MWhe | 0.03043 | 0.10413 | 0.03043 | 0.10413 |
| ROC Value | £/MWhe | 47 | 47 | 40 | 40 |
| Uplift | £/MWhe | 1.43021 | 4.89411 | 1.2172 | 4.1652 |
| Annual Total | £ | 16913.66 | 57877.74 | 14394.61 | 49257.66 |
| **RHI** | | | | | |
| RHI Value | £/MWhth | 10 | 10 | 10 | 10 |
| Annual Total | £/pa | 17000 | 58166.68 | 17000 | 58166.68 |
| RHI - ROC Value | £/pa | 86.34 | 288.94 | 2605.39 | 8909.02 |
| | **Most Suitable:** | **RHI** | **RHI** | **RHI** | **RHI** |

[1] Values taken from estimated potential for the site (Table 6.2)

The ROC value is indexed linked to the Retail Price Index (RPI) but market-based and therefore subject to fluctuations in price over the lifecycle of the project. As shown in Figure A2.1, over the past five years (08-13) the ROC value has fluctuated from £53.28 to £40.17 (August 2012, [221]). This makes long-term cash flow projections difficult to predict and often leads to highly discounted future projections of the ROC value price to give a 'worst case' project viability projection. ROC buyout and recycling revenue, as discussed in Section A2.5, may slightly increase the value through the ROC scheme, but is still subject to the same transaction costs so their true value is rarely realised by the sponsor. This is not the case with the RHI as it is also index linked but not market-based and therefore does not suffer the same transaction costs, making it a much more secure revenue stream.

As there is not a specific tariff for CHP under the RHI yet there are additional costs associated with utilising heat (such as a DHN). DECC has indicated that a higher rate is required to incentivise CHP especially when the RO uplift finishes at the end of 2015 [43]. Furthermore, the consultation document suggests an increase in the RHI rate from 1p/kWh to 4.1p/kWh [43]. Although this rate is subject to change, DECC's estimation that a greater than 400% increase in the current rate is required to stimulate the sector may somewhat explain the lack of growth.

### 6.4.4 Feedstock Type and Price Uncertainty

The largest operating expenditure for biomass plants, not using a waste feedstock, is the feedstock cost. The case study project was highly susceptible to feedstock price volatility and uncertainty over supply. As shown with the aid of the DSS sensitivity analysis in Figure 6.9, a 1% increase in the feedstock price resulted in approximately a 1% increase in the levelised unit cost for the plant.

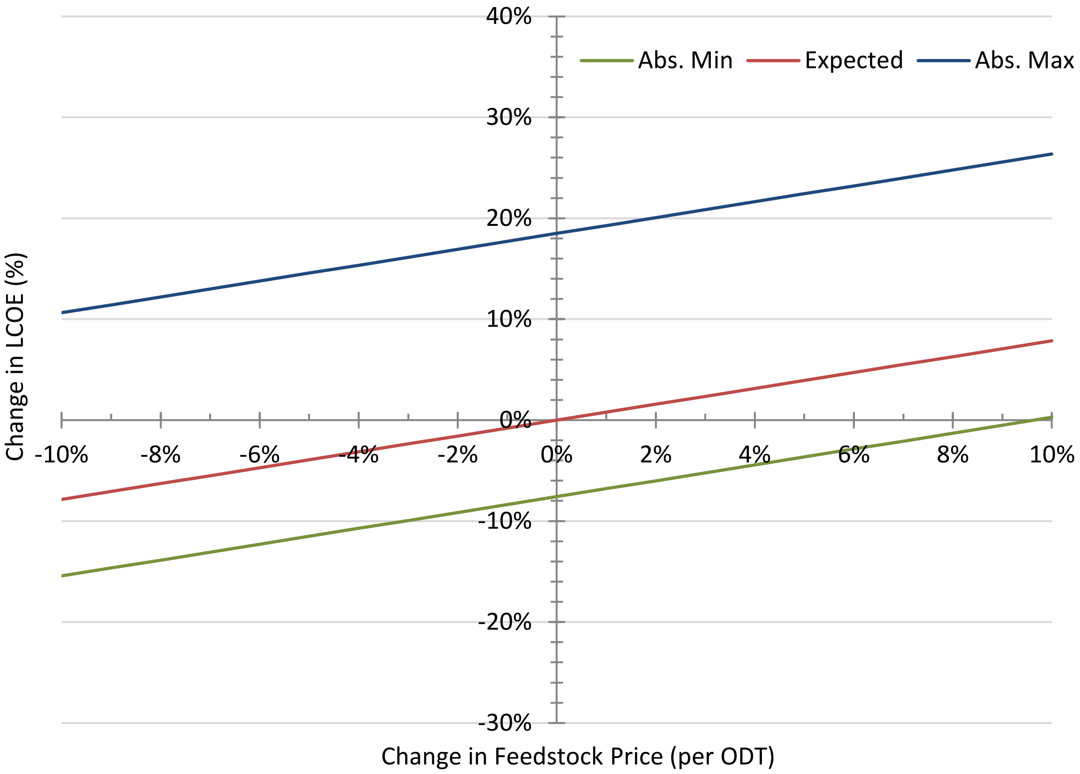

*Figure 6.9 – Fuzzy sensitivity analysis of feedstock prices with ROC uplift*

If the project could have secured an alternative feedstock at a lower cost, the viability and in turn attractiveness to investors could have been increased. It is possible to change the feedstock type and properties within the DSS to assess the viability of the project with different feedstocks. The energy content and price of some alternative feedstocks are given in Table 6.13.

*Table 6.13 – Feedstock energy content and current (2010) prices*

| | **Energy density by mass (oven dry)** | | | **Price estimations £/GJ (2010)** | | | **Modelled[9]** |
|---|---|---|---|---|---|---|---|
| **Feedstock type** | **GJ/t** | **MWh/t** | **Source** | **Low** | **Mid** | **High** | **£/ODT** |
| Wood Chips[1] | 19 | 5.282 | E4tech[5] | 1.5 | 2.6 | 3.4 | 49.4 |
| Waste Wood[2] | 18.8 | 5.22 | AEA[6] | -2 | 1 | 3 | 18.8 |
| Straw[1] | 18 | 5 | AEA[7] | - | 2.5 | 4.5 | 45 |
| Chicken Litter[3] | 15 | 4.167 | AEA[8] | - | 0.5 | - | 7.5 |
| MSW[4] | 9 | 2.5 | AEA[4] | -12 | -8 | -4 | -36 |

[1] Taken from [223] ; [2] Taken from [224] ID#1989 ; [3] Taken from [224] ID#3196 ; [4] Taken from [225] and [WRAP, 2010 cited in 225]; [5] Domestic price estimations (30,50,65 £/t) taken from [85] ; [6] Dependent on the grade/level of contamination ; [7] Mid-price is for unprocessed and high is for pelletised [225] ; [8] Taken from [225] ; [9] The cost applied within the DSS are from the mid-price

The energy content and price estimations modelled by the company (4.8 MWh/t and £50t) slightly differed from the secondary data for wood chip (5.282 MWh/t and £49.4t), which had a higher energy content and lower cost. For a fairer comparison with the other feedstock data the secondary source estimation for wood chip was chosen over that modelled by the company. This slightly improved the economic viability of the wood chip case as the feedstock characteristics had improved. Each feedstock with its central price and energy content was entered into the DSS in turn to record the effect on the LCOE and NPV.

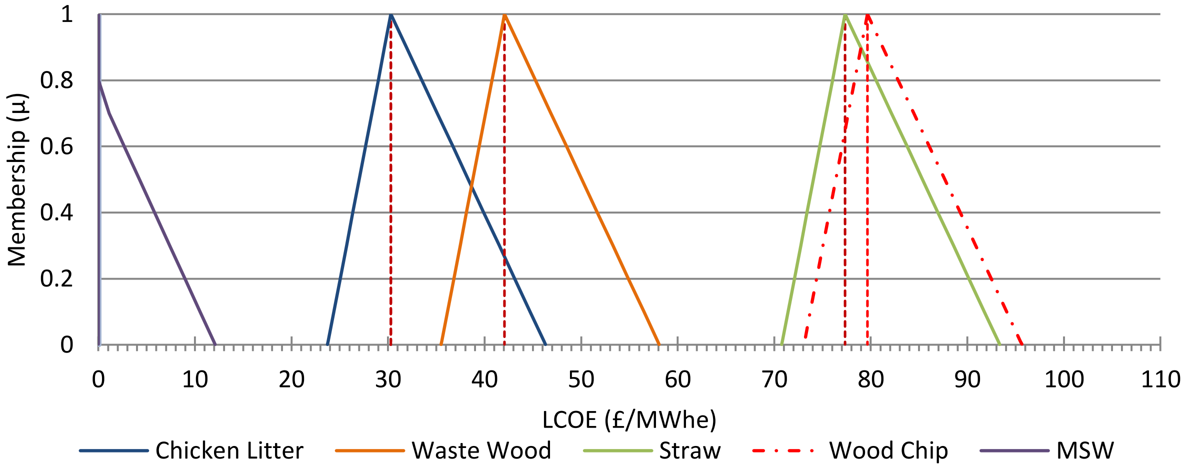

*Figure 6.10 – Comparison of the LCOE (inc. heat revenue) with different feedstocks*

It is likely that in the case of the MSW and contaminated wood waste that there would need to be some increased additional flue gas cleaning equipment or waste disposal (fly ash) costs and these were not been accounted for. It was also assumed that that the level of contamination in the waste wood was minimal and it therefore still qualified for the ROC with sufficiently high biomass content by energy. In the case of MSW, it is possible to gain up to 1 ROC uplift for MSW with CHP for the biomass proportion of the QHO [204] and under the RHI (assessed by Ofgem)[83]. However, it was assumed that there was no ROC or RHI eligibility as it cannot be easily entered into the DSS. The performance of the alternative feedstock types is shown as the EBITDA NPV discounted at 10% in Figure 6.11.

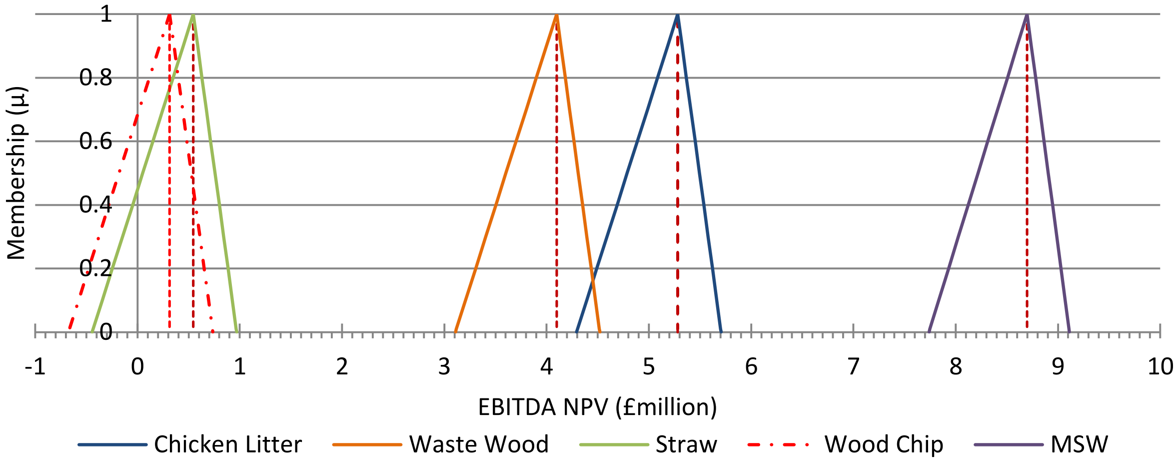

*Figure 6.11 – Comparison of the EBITDA NPV (inc. heat revenue) with different feedstocks*

From the DSS analysis highlighted in figures (6.10 and 6.11), it was clear that the waste feedstocks result in the lowest LCOE. In some instances, the MSW plant would be viable without needing to charge for the electricity produced. This levelised unit cost would likely increase if additional operational and waste incineration directive (WID) compliance costs were added to handle the waste, but it would still be a very viable project. Evidence of small-scale MSW plants in the UK such as NewLincs[35] 3 MWe EfW CHP Plant supports the analysis of the benefits of community-scale schemes [226]. The feedstock with the second lowest LCOE range is chicken litter. This feedstock is eligible for ROCs but does not acquire a gate fee. The low cost and relative abundance of chicken litter in the UK [9] has also led to several plants being developed and operated by EPR [227]. The worst performing feedstock was the wood chip with a LCOE and EBITDA NPV very similar to that shown in Section 6.3.

### 6.4.5 Plant Oversizing

The proposed plant size changed in the early stages of development from sub 1 MWe to 1.5 MWe net capacity. A larger plant size of 1.5MWe was finally pursued by Energy Company as they believed that it was more profitable to oversize the plant than match the heat demand. Furthermore, the company believed that they could also cover additional, non-project related, land lease expenses from the additional revenue generated with a larger plant.

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[35] Site visit and semi-structured interviews with the Operations Director and Plant Manager (November 2012)

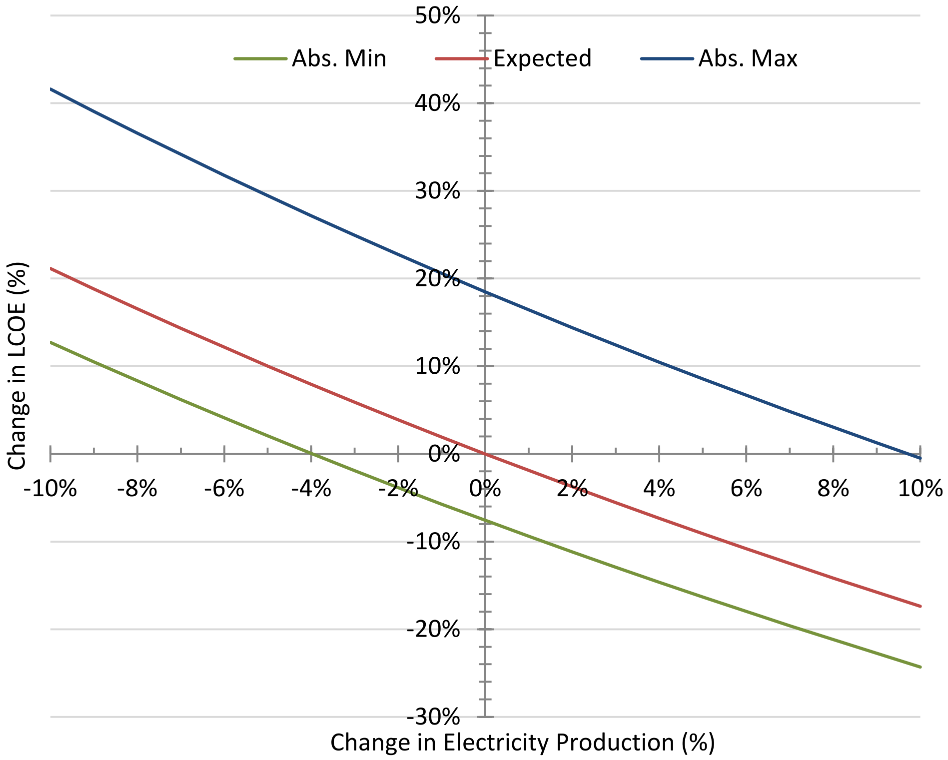

*Figure 6.12 – Fuzzy sensitivity analysis of electricity production with ROC uplift*

The figure highlights the sensitivity of electricity production on the project's levelised unit cost but does not show the effect of more efficiently matching the plant size to the heat load. However, it is also possible with the DSS to analyse the financial viability of smaller scale CHP schemes. Moreover, to test Energy Company's hypothesis that oversizing is more profitable or viable than matching the heat load for this type of investment. For comparison three Turboden ORC plants were selected: TD6, TD7 and TD10 and these are shown in Table 6.14.

*Table 6.14 – Turboden ORC systems*

| | Units | TD 6 CHP[1] | TD 7 CHP[1] | TD 10 CHP[1] |
|---|---|---|---|---|
| Overall thermal power input | kW | 3340 | 3895 | 5140 |
| **Output – hot water** | | | | |
| Hot water temperature (in/out) | °C | 60/80 | 60/80 | 60/80 |
| Thermal power to hot water circuit | kWth | 2664 | 3117 | 4081 |
| **Performance** | | | | |
| Gross active electric power | kWe | 643 | 739 | 1016 |
| Gross electric efficiency | % | 19.3 | 19 | 19.8 |
| Captive power consumption (parasitic load) | 32 | 32 | 37 | 48 |
| Net active electric power | kWe | 611 | 702 | 968 |
| Net electric efficiency | % | 18.3 | 18 | 18.8 |
| **DSS inputs:** | | | | |
| Net capacity | MWe | .611 | .702 | .968 |
| Heat to power[2] | | 4.36:1 | 4.44 | 4.22 |
| Thermal losses (boiler)[3] | % | 15 | 15 | 15 |
| Parasitic load[4] | % | 5.24 | 5.27 | 4.96 |
| Electrical efficiency | % | 18.3 | 18 | 18.8 |
| Availability | % | 90 | 90 | 90 |
| CAPEX[5] | £000s | 3000 | 3200 | 4000 |
| OPEX[6] | £000s | 30 | 32 | 40 |

[1] Standard (not split) Turboden ORC units. Taken from [20]; [2] Calculated as thermal power to hot water circuit / net active power efficiency ; [3] Boiler is independent from the ORC system so subject to the same inefficiencies ; [4] Calculated as captive power consumption / net active electric power ; [5] Total assumed CAPEX with ±10%, excluding £100k of additional developmental costs ; [6] Total assumed OPEX at 5% of plant CAPEX excluding land lease at £50k

The table shows the performance of each Turboden system along with the conversion of each system into the DSS inputs. It was then possible to input these systems into the Energy Company case study to analyse the change in the levelised unit cost.

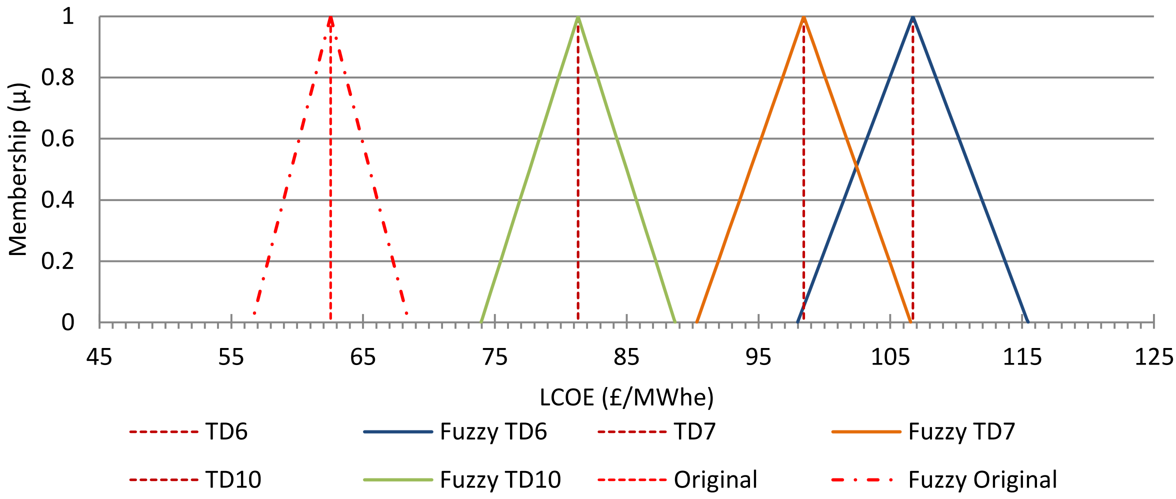

*Figure 6.13 – Minimum LCOE comparison of three Turboden ORC systems*

Figure 6.13 shows that even though the smaller CHP schemes would improve the percentage of heat utilisation and ROC CHP uplift, it did not sufficiently compensate for the reduction in electricity production and sales or incentive revenues. This finding implies that the rates for renewable electricity production are either too high or the rate for renewable heat production is too low. It is likely that the latter, especially in the case of CHP where there are additional costs such as DHN that are not accounted for in the RHI or ROC uplift rates. The RHI incentive does not have a specific rate for CHP schemes, but this is something that is currently under consultation (covered in Section 6.4.3). It also implies that there is little incentive for a sponsor of bCHP schemes to be more efficient or environmentally sustainable, under the current policy, if they are in the pursuit of profit over any other objective.

The DSS also showed that if the company had been simply able to reduce the land lease for the project from £250,000 to £50,000pa[36], this would have led to an expected LCOE of £69.69 or £48.37 if the site could meet its potential on-site heat demand. If the reduced land lease rate were possible or any significant reduction on the originally modelled cost then there would have been a significant reduction in the levelised unit cost and greatly increased project viability.

## 6.5 Risk Analysis and Mitigation

To demonstrate the risk analysis and response mechanism within the DSS, the risk events from Table 6.8 have been applied to the case study. Each risk event was applied in turn and the effect on the levelised unit cost or project duration was recorded, as shown in Table 6.15.

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[36] This is the only change made to the default case

*Table 6.15 – Risk event impact on the LCOE or project duration*

| # | | | **Uncertain effect** | | | **LCOE or duration impact** | | |
|---|---|---|---|---|---|---|---|---|
| | **Risk event** | | **Abs. min** | **Exp.** | **Abs. max** | **Abs. min** | **Exp.** | **Abs. max** |
| | **Development** | | | | | | | |
| 1 | Planning permission (PP) | Development cost | £8,000 | £10,000 | £12,000 | £0.12 | £0.15 | £0.17 |
| 2 | Planning permission (PP) | Duration task E (months) | 0.5 | 0.5 | 1 | 0.5 | 0.5 | 1 |
| 3 | Underestimated cost | Development Cost | £0 | £5,000 | £10,000 | £0.00 | £0.07 | £0.15 |
| | **Construction** | | | | | | | |
| 4 | Construction | Duration task Q (months) | 0.5 | 1.5 | 2 | 0.5 | 1.5 | 2 |
| | **Operation** | | | | | | | |
| 5 | Feedstock cost | Feedstock cost (ODT) | £0 | £10 | £15 | £0.00 | £13.61 | £20.41 |
| 6 | Fire | Availability | 5% | 5% | 10% | £5.13 | £5.51 | £13.71 |
| 7 | ROC value | ROC value | £0 | £5 | £10 | £0.00 | £7.65 | £15.23 |
| 8 | Feedstock quality | MWh/ODT | 0.0 | 0.5 | 0.7 | £0.00 | £7.91 | £11.62 |
| 9 | Equipment failure | Availability | 0% | 5% | 5% | £0.00 | £5.51 | £6.46 |
| 10 | Onsite residential heat demand | Heat demand (kWhth/d) | 0 | 250 | 500 | £0.00 | £0.22 | £0.44 |

As there are multiple risk events, a table was chosen as the most suitable method for giving an overview of the impact on the project finance and schedule goals. Within the DSS, the output is given graphically to fully capture the possible non-linear relationships between fuzzy distribution function points.

Of the risk events that impacted on the LCOE, the feedstock (5, 8) and the ROC value (7) risks impacted most significantly. The sensitivity of feedstock cost per oven dry tonne and energy content changes to the levelised unit costs supports the analysis of Section 6.4.4. As this was the largest operating expenditure for the case study, any negative change per tonne of feedstock significantly affected the financial outputs. Similarly, the ROC value change also had a significant effect on the financial outputs but for a different reason. The ROC value risk, approximately matched what has occurred since the period of development to the current ROC rate. As the RO remains the main renewable generation incentive for schemes of this type, any market value reduction greatly impeded the plant's ability to maximise its revenue, as shown in Section 6.4.5. Additionally, there were two risks that impacted on the project duration (2, 4). Both risks affected tasks on the critical path and therefore resulted in the overall project duration being increased by an equal amount. The risks events did also cause changes to the criticality of events within the task network but not the critical path, as shown in Table 6.16.

*Table 6.16 – Risk event effect on the project critical path and task duration criticality*

| **Task** | **Pre-feasibility** | **Site acquisition** | **Concept design** | **Financial modelling** | **Planning permission** | **Find investors** | **Detailed design** | **Component tender and HOT** | **Feedstock tender and HOT** | **EPC tender and HOT** | **Grid connection HOT** | **PPA HOT** | **Due diligence** | **Financial close** | **Award contracts** | **Ground work** | **Construction** | **CHP installation** | **Handover** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | **A** | **B** | C | **D** | **E** | F | **G** | **H** | I | J | K | L | **M** | **N** | **O** | P | **Q** | R | **S** |
| **Orig.** | 1 | 1 | .85 | 1 | 1 | 0 | 1 | 1 | .94 | .96 | .75 | .75 | 1 | 1 | 1 | .05 | 1 | .17 | 1 |
| **Risk 2** | 1 | 1 | .85 | 1 | 1 | 0 | 1 | 1 | .94 | .96 | .75 | .75 | 1 | 1 | 1 | .05 | 1 | .17 | 1 |
| **Risk 4** | 1 | 1 | .86 | 1 | 1 | .1 | 1 | 1 | .95 | .96 | .78 | .78 | 1 | 1 | 1 | 0 | 1 | .11 | 1 |

The effect of risk 2, with the extension of task E did not change the criticality of individual tasks. However, this was different for risk 4 as the extension of task Q caused some changes to the network task criticality scores. This was particularly evident with the changes in the find investors (F), ground work (P) and CHP installation (R) tasks, with a small but significant change in their respective criticality scores as P became the task with the largest amount of slack instead of F (Eq. 5.38).

To demonstrate the risk mitigation strategy application, an individual risk was selected along with three viable strategies for its reduction (Table 6.17).

*Table 6.17 – Risk event response strategies*

| **Action** | **Details** | **Effective** | **Response effect** | **Unit** | **Value** |
|---|---|---|---|---|---|
| Reduce | Purchase fire suppression equipment and monitoring safeguards | 80% | CAPEX: Plant cost | Cost (£000s) | 20 |
| Retain | Set aside risk funds | 60% | CAPEX: Other | Cost (£000s) | 20 |
| Transfer | Insure against the cost of a fire | 95% | OPEX: Insurance | Cost (£000s/pa) | 5 |
| Avoid | N/A | | | | |

As the operational risk of a biomass storage fire is an ever present danger for biomass power stations [11, 228, 229][37], it has been chosen to demonstrate the risk response strategy functionality within the DSS. As it was only possible to apply one risk effect to an event, an impact on the plant's availability is taken as the most suitable as this directly covers the downtime of the plant and the associated impacts to energy production and production incentives.

Three of the four possible risk response strategies were available to the decision-maker at this point as it was not conceivable that the risk of a fire could ever be completely avoided. A possible reduction strategy would be to purchase additional fire suppression and monitoring equipment, which was considered to be 80% effective in reducing the cost of a fire but would cost an additional £20,000. Alternatively, a strategy could be to remain reactive to a fire yet set aside additional capital, also £20,000, to cover the cost of the event if it occurs. This 'retain' strategy is less effective as there will possibly be additional, unforeseen costs related to the event of a fire: downtime, lost production and incentive costs etc. The final risk response strategy available to cover the risk of a fire was to obtain insurance, which would be highly effective and cover most of the cost of the event. However, the transfer strategy was estimated to cost £5,000 pa and be 95% effective in mitigating the risk event as there may be a policy excess or uninsured related costs.

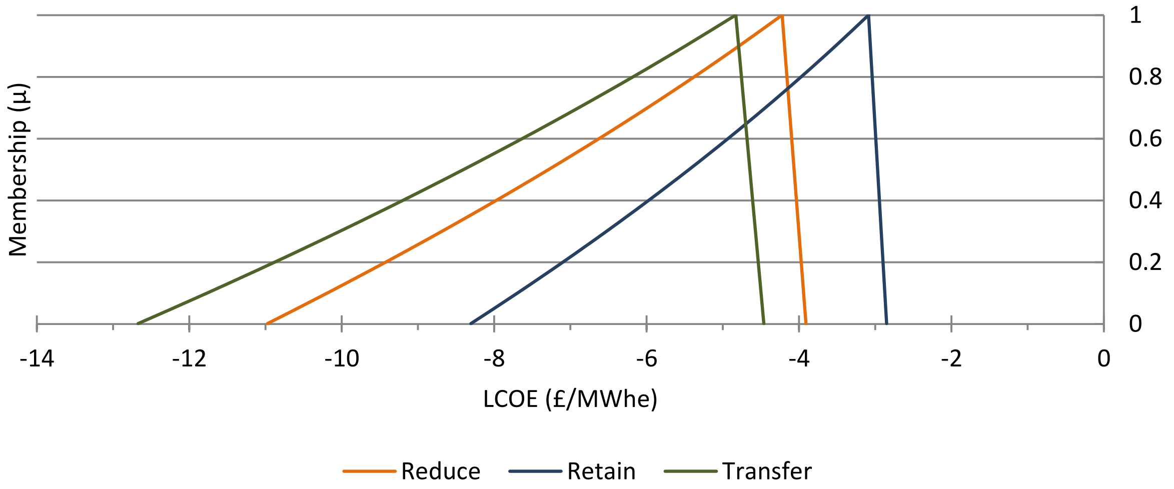

*Figure 6.14 – Response strategy reduction in the LCOE*

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[37] The April 2012 fire at RWE Tilbury Power Station started in the biomass pellet storage hoppers and was largely believed to have been caused by insufficient biomass storage and monitoring controls. This fire also follows the cited October 2011 Port of Tyne biomass fire

Figure 6.14 shows the reduction of each risk response strategy on the LCOE without a risk response and the occurrence of the fire. Of the three possible risk response strategies, the retention strategies was least effective lead to the lowest reduction in levelised unit cost against not having a response strategy in place. Despite the transfer strategy cost being five times larger than the total reduction strategy, the higher effectiveness justified the cost if a fire of this nature were to occur over the lifecycle of the project.

The advantages of this proactive risk response action are predicated on the occurrence of a fire that is insured by the plant's policy, at the specified cost and effectiveness. Within the DSS, it is also possible to assess the viability of a risk response strategy if the risk event does not occur. If the project purchased fire liability insurance at £5,000 pa and there was not a fire there would be a £0.42 increase in the levelised cost for the plant on the original base case. However, if the fire were to occur when the insurance was in place this would lead to a £0.26 increase in the LCOE as opposed to a £5.51 increase without insurance. Therefore an implemented risk response action for this risk event only marginally changed the LCOE and if the event occurs it greatly reduced the impact of not having a strategy in place. By modelling risk events within the DSS the decision-maker is quickly able to make informed decisions on the effect of risk or response actions on the viability of the plant.

## 6.6 Conclusion

In conclusion, the analysis with the aid of the DSS has shown that the project was not viable under the modelled assumptions and terms of finance. The analysis of the 'as was' case confirmed this with an unachievable levelised unit cost and largely negative EBITDA. Ultimately, the further analysis highlighted that there could have been some modification to the proposed scheme that may have improved its viability. These were namely:

- the possible change of feedstock type to a less costly waste or residue;
- a reduction in the operating expenditure, especially a reduction in the land lease cost;
- an increase in the amount of heat utilisation on site or securing a financier that would consider heat sales as a bankable revenue stream.

Additionally, the issue of contracts and supplying a portfolio or wide range of small heat users not giving the same amount of security as a large heat user such as an industrial plant, public leisure centre or social housing development. This may be a possible explanation for a complete lack of community scale projects in the UK that have successfully circumvented this barrier. Moreover, this view also aligns with the barriers covered with the heat off-take contracts barrier section within Section 2.10.

The further analysis explicitly showed the weakness of the RO in incentivising small-scale, decentralised generation, especially in the case of CHP. However, the proposed consultation rates for CHP under the RHI could potentially offer a lifeline to the nascent industry and may change the associated issues identified with the tendency to oversize under the ROC and the lack of community-scale CHP plants and DHNs. Although, as the rate is under consultation and therefore not guaranteed, there is likely to be a hiatus on projects in the early stages of development pursuing CHP. If successful, the changes could be implemented in summer 2013 [43] but a formal review of the RHI in 2014 may change the tariff rates again. As there is a long development lifecycle for bioenergy schemes [6], this may only potentially leave a small window of clear policy for potential and early stage sponsors.

Uncertainty was applied throughout the DSS with the use of the fuzzy functionality defined in the previous chapter, but it was not possible to validate its use and benefits by Energy Company. The project financing variables within the DSS, such as the required rate of return for debt and equity and the DSCR were not fuzzy inputs but incorporated uncertainty within the sensitivity analysis outputs. Fuzzy functions could also be applied to these variables if it is desired by the decision-maker. Any uncertainty here would have a significant effect on the break-even output variables such as the levelised cost of heat or power as the break-even price is largely driven by reaching the financial covenants.

Energy Company was not able to utilise the DSS when developing the case study project, but the analysis has shown how it could have been applied and the clear benefits upon application. In addressing the forth research question ($Q_4$), if the DSS had been available to Energy Company during the early stages of project development, the highlighted issues may have been avoided and the company could have been successful in developing their first project and remained in operation. However, due to their dissolution this can only be speculated and never truly measured. The most similar method for trying to replicate this is by demonstrating the DSS to other practitioners for their evaluation and validation, as covered in Chapter 7.

# 7. Practitioner Evaluation and Validation

## 7.1 Introduction

This chapter analyses the questionnaire survey results from demonstrating the DSS to industry professionals. The chapter further supports the case study application (Chapter 6) with practitioner evaluation and validation. An overview of the questionnaire design and the structuring of individual questions for the purposes of evaluation and validation are covered in Section 4.6 and 4.8 respectively. For reference, the questionnaire is given in Annex 3. Five industry practitioners participated in the survey and an introduction to their positions and experience is given in Section 7.2. The participant introduction is followed by a detailed analysis of the DSS functionality (7.3), evaluation (7.4) and, finally, an overview of the strengths and weaknesses (7.5). The chapter concludes (7.6) with a discussion on the implications of the survey.

## 7.2 Categorisation and Demonstration

The categorisation of participants is given in Table 7.1. A range of stakeholders to bioenergy project development were surveyed with the company sizes varying from small to multinational enterprises.

*Table 7.1 – Participant categorisation*

| **Sector** | **#** | **Experience in industry** | **#** | **Number of employees** | **#** | **Current position** | **Ref.** |
|---|---|---|---|---|---|---|---|
| Consultancy | 3 | ≤ 5 | 1 | ≤ 10 | 2 | Energy Consultant | 1 |
| Utility | 2 | ≤ 10 | 2 | ≤ 10k | 1 | Biomass Procurement Manager | 2 |
| | | > 10 | 2 | ≤ 100k | 2 | Anonymous | 3 |
| | | | | | | Director | 4 |
| | | | | | | Director | 5 |

It was not possible to secure a ‘bioenergy project developer’ as a survey participant and this is possibly due to the relatively small number of developers in the UK. However, the five participants have extensive and direct industry experience, and currently are key stakeholders to the development of bioenergy projects. Within the table, the participant positions (of those who agreed to be referred to) are given along with a unique reference identifier. This identifier is utilised throughout the chapter when quoting or referring to comments or opinions. As the third respondent declined to be referred to within the thesis, their current position is not disclosed but their responses are included in the analysis.

Of the five participants, three were sent the software in advance along with the user guide (Annex 4). Two of these (Ref. 1 & 2) were able to apply their own notional cases within the system. The remaining participants only utilised the DSS with the supporting case study, as analysed in the previous chapter. Demonstrations with the case study were conducted during site visits lasting approximately 1 to 1.5 hours.

## 7.3 Functionality

It is vitally important to confirm that the DSS functionality is not only useful in addressing the issues within project development but also to confirm the translation of the functions into the DSS is sufficient. To achieve this analysis, Question 5 is separated into two parts: '*for each of the following: (A) how useful is it to have this function; and, (B) how would you rate the model in achieving this function*', with the possible responses being given on two five-point Likert-style scales (Table 7.2).

*Table 7.2 – Response scales*

| Useful scale | Achieved scale | # |
|---|---|---|
| Not | Very low | 1 |
| Slightly | Low | 2 |
| Moderately | Moderate | 3 |
| Very | High | 4 |
| Extremely | Very high | 5 |

The survey results are shown as two 'spider web' diagrams for the perceived usefulness of the project development functions (Fig. 7.1) and the level of achievement in modelling these functions within the DSS (Fig. 7.2).

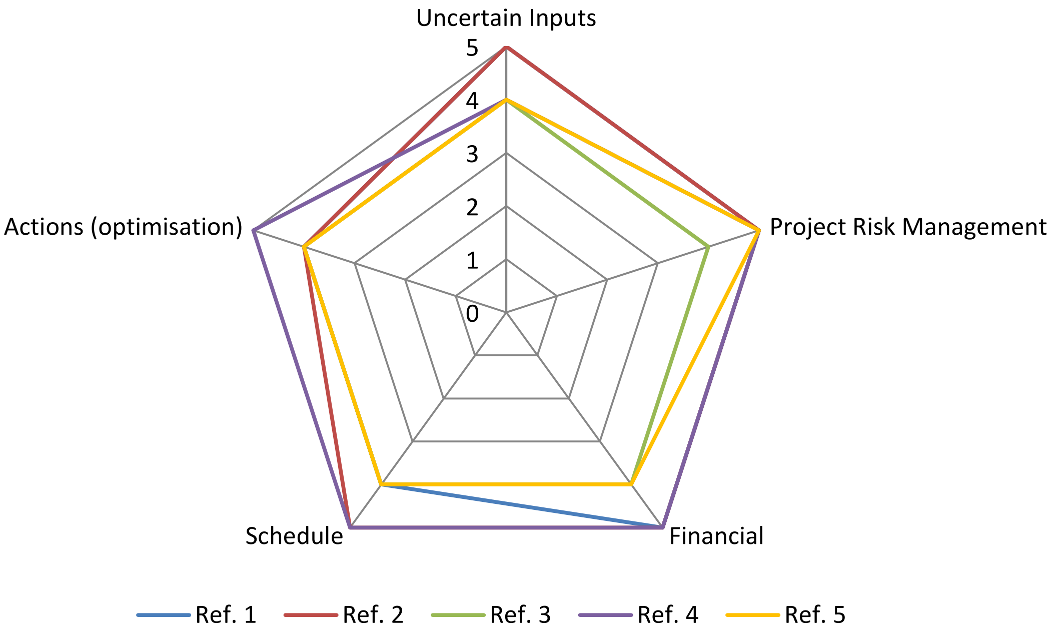

*Figure 7.1 – Perceived usefulness of the project development functions*

The project risk management function was rated as the most useful and this was followed by the financial function. Project scheduling and uncertain input functions were rated equally with the response optimisation model scoring the lowest. It is important to also note that although the project risk management function scored the highest, the risk response optimisation scored the lowest overall.

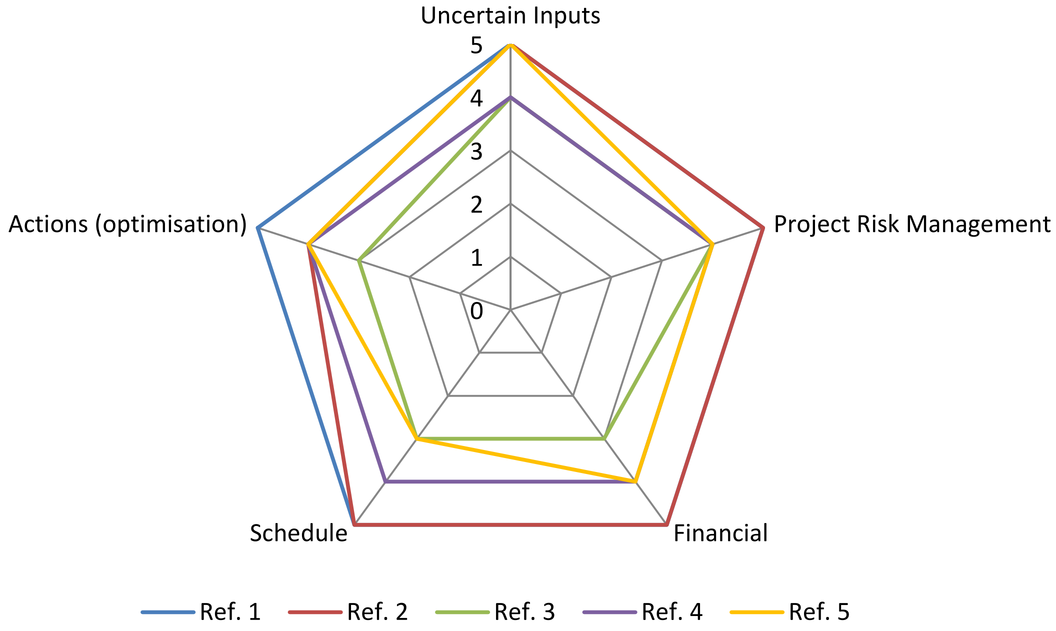

*Figure 7.2 – Achievement level of the modelling project development functions*

As shown in Figure 7.2, the participants rated the uncertain inputs, PRM and financial functionality as the top three achieved functions within the DSS. Furthermore, a higher level of agreement was maintained between the participants for rating the useful functions with a maximum range or 1 (e.g. extremely to very) than in the assessment of the DSS in modelling each function. Ref. 3 scored the DSS lowest overall.

The sixth question asked the participants to rate the DSS functionality as a whole and in addressing the problems faced by developers, the question is *‘overall, how well does the model functionality represent the difficulties faced by developers in the early stages of project development?’*. All participants stated that the model functionality represents the difficulties faced by developers in the early stages of project development very well despite their differences in rating the individual functions. Additional comments could be optionally added by the participants to this question, with Participant 1 stating that “yes, although I have no direct experience as a developer, I expect that the functionality covers the issues faced”. Similarly, Participant 2 added that “this is a very useful model and it would be very useful for anyone starting out as a project developer or even for those experienced in the industry". However, the view of Participant 4 expressed a more conservative opinion on the DSS by stating that "I understand the model had been produced for a particular end user / scheme and this was reflected in the available inputs". Participant 2 and 4 felt that the functionality could be improved with additional feedstock (Ref. 2 & 4) and heat and power inputs for mapping load types and timings (Ref. 4).

## 7.4 Evaluation

The seventh question is designed to evaluate the DSS on seven possible evaluation factors. The first two factors are cost and time effectiveness in adopting the DSS. These are important DSS evaluating factors for achieving the research aim that are not included in the EUCS survey designed by Doll and Torkzadeh [192]. The EUCS survey does include a timeliness criterion but this is in the context of system performance, not in comparison to the existing non-support system process. However, Alavi and Joachimsthaler [194] apply both performance and attitudes/perception variables to assess DSS implementation success, with decision-making time and cost or profits being key evaluation variables. Usability is featured in both the 'ease of use' EUCS criterion and under the 'perceived usefulness of the system' in Alavi and Joachimsthaler [194]. A system is required to not only be useable by the targeted decision-maker but they also require confidence (featured in [192, 194]) in the decision outputs and satisfaction (featured in [194]) in the system meeting expectations upon use. It is also important to measure the system's originality for the participants and its contribution to practitioners. The originality criterion is not featured in either of the methods utilised to build the questionnaire nor any of the 18 reviewed papers in Hung, Ku [193], but adds further evidence to the reviewed literature in Chapter 3. Finally, contribution to practitioners is indirectly covered with the content criterion in Doll and Torkzadeh [192] and meeting the needs of the user.

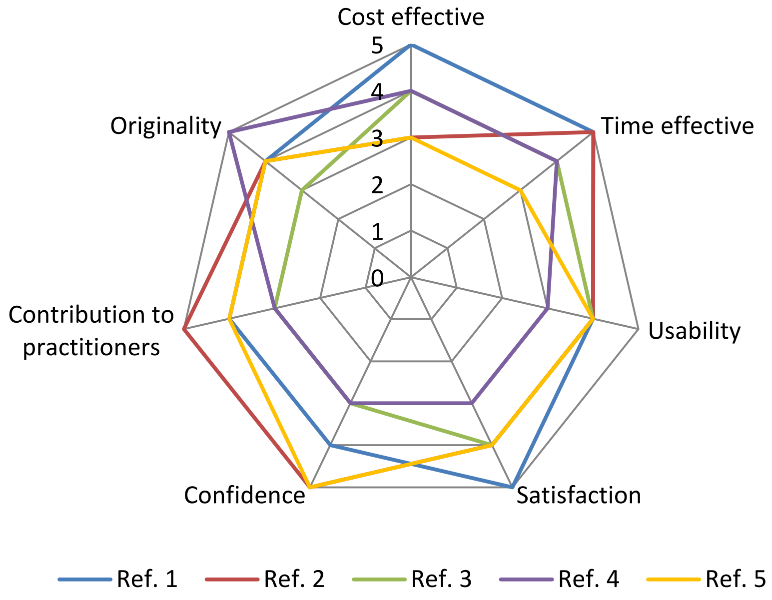

*Figure 7.3 – DSS evaluation criteria performance*

As shown in Figure 7.3, decision support system time effectiveness and confidence scored the most 'very high' ratings, with the usability receiving the most consistent rating of high. None of the individual evaluation functions scored below a 'moderate' rating and all evaluation criteria scored at least one 'very high' with the exception of the most consistently scored, usability.

Similarly to Question 6, Question 8 asks the participants to evaluate the benefit of the DSS as a whole and is given as '*overall, how beneficial is the model in supporting project developers in the early stages of project development'*. Scored on the same scale as applied in the 'useful' scale (Table 7.2), the responses ranged from moderate (Ref. 3) to extremely beneficial (Ref. 5), with the forth participant stating that "the model would score 'extremely beneficial' with the additional development to allow for more varied inputs as noted earlier" (Ref. 4). As the third participant did not give any additional comments, it is not possible to completely assess their viewpoint but it may be partially due to the low scores given for the achieved functionality question. The second participant states that:

> "while many factors of a potential development can be modelled already these are often done on complex spreadsheets which are often so complex only the original author can understand them. This tool would allow potential developers to run quick analysis of potential projects at an early stage and could then be used to plan the more detailed project execution as a project moves through from concept stage. Overall a very useful tool" (Ref. 2)

Participant 5 scored the time and cost effectiveness lowest out the participants but explained that the rationale for this was "…it is difficult to assess from the demonstration what costs would be involved in running the model, or how long it might take to amass the information required to run it". With regard to the system usability they added that the "…model appears to be very straightforward for a suitably trained operator to use…". Finally, Participant 5 added that "…confidence in the model is based on the understanding that its limitations (e.g. the risks highlighted, estimates made etc.) are an intrinsic part of the work itself and so as long as these are suitably taken into account, confidence would nonetheless be very high".

## 7.5 Strengths and Weaknesses

The ninth and final question in the survey asks for the participants to '*please provide and comments on the strengths and weaknesses of the model and/or any thoughts for improving the model*'. Most participants gave a positive comment in this open-ended question. Participant 2 gives the strengths of the DSS as "it covers almost all of the key considerations for a UK CHP plant developer" and "[the use of] default values throughout allow for quick analysis to be run" (Ref. 2). They add to this that "the model overall is very good and has a logical flow" (Ref. 2).

The DSS functions are noted by the first participant as a particular strength, as "…the model features some very interesting outputs such as the effect on debt gearing on the LCOE, the choice between ROC uplift and RHI, and effect of heat utilisation on PPA" (Ref. 1). Although "…a decision support tool for such projects might not in itself be "new", the way that the model includes probabilities, risks, confidence & "Fuzzy" logic IS innovative and gives, if not a definitive decision indicator in each case, at the very least a much more sophisticated range and direction for those undertaking the early stages of such a project" (Ref. 5). Adding to this, Participant 2 states that there is the "potential to use [the DSS] globally" (Ref. 2), but caveated this by emphasising that there should be less focus on the UK policy if that is the overall goal.

Some weaknesses were also commented on, with the second participant adding that the DSS could be more generally applied by reducing the UK specific policy. Furthermore, Participant 3 adds in their only comment that the model would benefit from having more input options for the technology and feedstock. Finally, it was stated by Participant 4 that they would prefer to see the inputs for project scheduling given in a way that is more familiar to project stakeholders or developers, such as a linked bar or Gantt chart.

Several possible improvements for the system were suggested by the respondents. Participant 2, with their experience as a biomass procurement manager, would like to see a greater number of feedstock options, such as virgin wood, recovered wood and commercial wood pellets. Furthermore, they add that feedstock availability and sustainability, and environmental impact (e.g. carbon per MWh), would also be a very useful addition for feedstock in the risk analysis section as these are the main risks weighed up alongside the (DSS included) price risk. Moreover, Participant 5 would like the ability to combine risk responses within the risk response section (e.g. to partially reduce and transfer a risk event). Additionally, suggestions were made for some minor improvements or changes to the conversion units so that they are given in Gj/t not MWh/t (Ref. 2) and for greater heat and power usage classes for the locational inputs (Ref. 5). Finally, an automated knowledge base for the technology and feedstock inputs was also suggested by Participant 2, such that, decision-maker selections within the technology inputs automatically create approximate financial costs (e.g. £3million per MWe net capacity input) and similarly for the feedstock characteristics.

## 7.6 Conclusion

In conclusion, the participant responses support that the chosen financial, schedule and risk management functions are not only important to practitioners but are also effectively translated into the DSS with significant benefits to utilising the software, principally for saving time (as this scored the highest in the evaluation results). The systematically reviewed literature confirmed that the project scheduling objective is not included in the majority of existing DSS but it was rated as equally as useful as the finance functionality by four of the five participants. Project risk management was rated as the most useful overall, scoring higher than the project finance function. A possible explanation for this may be the perceived or actual riskiness of bioenergy projects (Chapter 2) or the more general applicability of risk management to the five participants' respective current positions. For example, the Biomass Procurement Manager (Ref. 2) is more likely to be involved in risk management activities than bioenergy project scheduling and financial analysis. The optimisation of risk response measures with limited resources scored the lowest out of the perceived functions but this still only amounted to one moderate response across the two parts of the functionality question and five participants. Fuzzy set theory was well received by the participants, as the uncertain or approximate input functionality scored the highest for being achieved within the DSS. This confirms that the fuzzy method applied throughout is suitable for handling limited and approximate information held by developers at the early stages of project development ($O_3$).

The DSS also performed highly in the evaluation section (7.4). Time effectiveness and confidence scored the most 'very high' ratings, with the usability receiving the most consistent rating of high.

This supports the validation of the DSS in achieving the research aim of being utilised by non-expert opportunist developers at Energy Company or other similar SMEs. The information within the DSS was also confirmed to be in a format that is useable by developers (Ref. 1 & 2). In response to Participant 5, it is expected that the level of training required for a non-expert developer or decision-maker to use the DSS is significantly shorter than training without the system. Moreover, further clarification could have been given to the time and cost effectiveness when demonstrating the DSS to improve the ratings given by Participant 5 and with the other participants. In addition to the other evaluation criteria, the assessment for 'contribution practitioner' evaluation also supports the research aim of being adopted by developers in practice. The five practitioner responses to the questionnaire survey clearly show that those surveyed evaluate the DSS as successful in achieving the research objectives ($O_5$).

Allowing participants the option to independently operate the software and, if desired, their own cases further validates the support system applicability. As stated by Finlay [187:183], validation is "…the process of testing the agreement between the behaviour of the DSS and that of the real world system being modelled". Participant 1 and 2 both ran notional cases of their own through the system and their positive responses, particularly from Participant 2, confirm that the DSS operated as expected and satisfied their needs.

For the model to be generalisable, in a commercial sense, it is necessary to address the concerns of the participants. A greater number of technologies (Ref. 3 & 4), feedstocks (Ref. 2, 3 & 4) and locational inputs (Ref. 4) would improve the DSS by appealing to a wider range of end users (Ref. 4). These changes in some instances are fairly superficial (e.g. feedstock unit form) and easily changed or are outside the research aim but could help the DSS to potentially be used more widely (Ref. 2). A change to the scheduling interface within the DSS to be more familiar to users of typical project scheduling software (Ref. 4) could be applied to improve the software and is within the remit of the aim. Moreover, as suggested by Participant 5, improvements to the PRM method with regard to the mutual exclusivity simplification (Section 6.7.3) and possible combination of risk responses could be incorporated in further research. These changes are discussed further in Section 8.5.

# 8. Conclusion

## 8.1 Introduction

Section 8.2 starts with a sequential summary of the research and finishes with the main outcomes and conclusion. This is followed by a review of the research aim and objectives (8.3), and its limitations (8.4). The conclusion chapter finishes with some recommendations for further research (8.5).

## 8.2 Summary and Conclusions

Energy Company's problem statement (Section 1.4.1) highlighted that there was a need for a decision support system that would help non-expert opportunist developers or trainee members of staff analyse the viability and risk in potential bCHP projects in the early stages of development. A wider search of the barriers faced by project stakeholders in Chapter 2 confirmed that the problems facing Energy Company are also representative of the industry, which may offer some explanation to the high number of RET projects failing [4] and the very low rate of CHP capacity growth in 2011 [9]. Not addressing these barriers greatly inhibits biomass reaching approximately half of the new energy production needed to meet the 15% primary energy generation target by 2020 [6].

Several stakeholders are vital to the successful development of a biomass CHP scheme (as shown in Fig. 2.2), with each stakeholder or the contract required presenting a unique set of challenges for either party. Importantly, the heat user and the heat off-take contract (Section 2.10) barriers are unique to CHP or heat only schemes, but likely more important to former as there are increased capital costs and therefore a longer payback period. Moreover, longer investment return is shown in the second chapter to act as a disincentive to potential financiers [28].

In project financed bioenergy schemes, the lender is the primary enforcer of contracts with the key stakeholders [49]. Lenders attempt to de-risk investments where possible [49, 61] and desire set of key characteristics in project sponsors and a thorough feasibility study, financial and risk management plan [63] are targeted with the designed DSS. As project success or viability is determined from the critically important cost and duration objectives [56], yet as these are still prone to overruns [53, 54], it was necessary to systematically search the literature to determine the current methods and approaches to supporting developers for these objectives and for risk management. Furthermore, modelling these three objectives could aid bioenergy project developers as a significant number of the barriers covered in Chapter 2 and summarised in Table 2.4 could be quantified wholly or partially quantified within the DSS.

The critical review of the academic and grey literature confirmed that clear gaps are present in the existing DSS developed to support decision-makers in achieving the project development and risk management objectives. Project scheduling and risk management are the least covered and supported aspects within the literature, with often only a passive reference to or deterministic sensitivity analysis respectively. Financing is the most covered objective but often only covered as the objective function within linear programming type optimisation models. Only a limited number of academic papers include the cost and terms of project financing within their analysis [136-138], but this is more common in the grey literature and commercial software. Furthermore, the grey literature is more focused on the pragmatic problems faced in project development than the academic DSS.

The largely deterministic DSS reviewed would not support the research in developing a mechanism for handling limited or approximate information held by developers ($O_3$), therefore a stochastic or similar method is required. The IEA [56] risk quantification method is the closest single DSS to the research aim with the project financial and scheduling objectives and the complete risk management process, however its probabilistic method is less appropriate than the applied fuzzy method for supporting decision-makers in the feasibility stage and with limited information.

The original fuzzy method defined in Chapter 5 is followed throughout the entire DSS in each objective from the initial inputs to the outputs. As demonstrated in the application to Energy Company's first and failed bCHP development (Chapter 6), the fuzzy methodology enriches the typical deterministic and crisp assessment of the project objectives and risk analysis. The addition of the absolute min and max bounds, and the confidence level over the cost or schedule L-L reference function ranges incorporates the approximate mapping of other variables within DSS. Increasing information certainty held by the decision-maker would reduce the fuzzy range given and in turn increase confidence in achieving the expected levelised cost or schedule value. This is an improvement on the existing reference function method applied before in the fuzzy CPM papers [189, 190, 199, 217], as functions can be designed and altered quickly within the DSS through the use of the attitude and confidence linguistic controls (Section 5.4). At the very least the fuzzy levelised cost method (Section 5.9) can also help to improve the commonly applied traditional sensitivity or capital structuring analysis by incorporating uncertainty and enriching the level of information, as displayed within the case study analysis of Chapter 6.

In achieving the forth objective ($O_4$), with the application of the DSS in Energy Company's case study, it became clear that the case study development was not financially viable under the project design taken forward. A required 'expected' LCOE value of £86.60, when including the achieved heat sales and without the cost of any risk exposure or mitigation, was over twice the market short term PPA price for exported electricity at £40/MWhe. As shown from the analysis (Section 6.3, 6.4), the DSS would have quickly confirmed this issue and some possible modifications to remedy this, with a possible change of feedstock to a waste or residue, addressing the unnecessary land lease cost or attempt to increase heat utilisation onsite. It was also quickly shown with the DSS that a reduction in the size of the plant (Section 6.4.5) would not improve the viability of the scheme. The ability to model these scenarios quickly within the DSS may have resulted in a different outcome for the case study project and the company.

Due to the failure of the company during the development process, it was not possible to gather real data on the case study scheduling and risk exposure. These objectives were also displayed within the case study analysis chapter but relied on notional data. The improved fuzzy scheduling and CPM method (Section 5.11) with the integration of the attitude and confidence linguistic controls and original equation for determining individual task criticality (Eq. 5.40) are demonstrated in Section 6.3. Similarly, the original fuzzy project risk management methodology (Sections 5.6, 5.7, 5.12) applies the same linguistic controls as included in the other project objectives, and is demonstrated in Section 6.5. Furthermore, the benefits to proactive risk management are shown with the notional 'biomass storage fire' risk to greatly reduce the project sensitivity to occurring risk events in LCOE terms. This method could be utilised more holistically within the project to maximise the mean fuzzy LCOE saving with limited time and money resources (Section 5.12), although this is not demonstrated within the case study as the data was not available from the company and it would have only repeated the individual risk management process of Section 6.5. Furthermore, it was only possible to confirm the validity of the scheduling and risk management objectives through the practitioner validation and evaluation survey of Chapter 7, as they relied on notional data.

The practitioner survey not only further supported the validation of the DSS in representing the 'real world' system being modelled, but also the overall usefulness of the model functions and the evaluation of the DSS overall. The project risk management functionality, which was not able to utilise real Energy Company data within the case study application (Chapter 6), is rated the highest overall for perceived usefulness (Fig. 7.1). Project scheduling is widely neglected in the academic literature within Section 3.5.1, but it scored similarly to the financial functionality for perceived usefulness. However, its translation into the DSS is somewhat less successful with it being rated joint lowest with the risk optimisation function, but this may be partially due to the lack of linked bar or Gantt chart type inputs as in MS Project or similar software (Participant 4, Section 7.5). Finally, as somewhat expected from the importance of project finance (Section 2.4) within the project stakeholders and the large number of financial DSS within the literature review (Section 3.4.1); the financial functionality is rated highly by the five participants. They also believed that this is translated very well within the DSS.

The remaining function assessed by the participants was the ability to include uncertain or approximate inputs ($O_3$). Probability or fuzzy distributions are the two methods demonstrated within the literature review that are able to handle these types of inputs. Fuzzy distributions were selected as the more suitable for achieving the research objective and research aim of producing a DSS to be utilised in the early stages of project development where there would likely be a lack of detailed information or data. The case in point is the IEA [56] risk quantification method (Section 3.6.2) in utilising probability distributions but in lacking the necessary data to create detailed distributions, they simplify the method to triangular distributions within their case study. As argued, it is better to accept the level of approximation and apply fuzzy distributions as they are conceptually easier to understand and are better suited to solving problems with approximate or imprecise information. As the participants within the survey rated this function as the highest achieved within the DSS, this part of the third objective ($O_3$) is considered successfully achieved.

Within the survey, all evaluation factors received positive ratings from the practitioners and this confirms that the aim of the research was achieved. Time effectiveness and confidence within the DSS are rated highest of the evaluation factors surveyed. These two factors are also closely aligned with the problem statement (Section 1.4.1), as Energy Company or a similar SME developer would be able to give the DSS to a non-expert trainee with confidence that the system produces valid analysis and outputs that would be time effective to the same process of decision-making without the system. Additionally, as also specified in the problem statement, it can support competent employees or experienced practitioners by reducing the reliance on complex spreadsheets (Ref. 2, Section 7.4).

The research has been successful in achieving the aim, as originally specified from collaboration with Energy Company. However, due to the difficulties faced by the company over the duration of the research project, they were not able to receive the DSS output in time to fully benefit from the decision support and analysis demonstrated in Chapter 6. Collaboration with Energy Company has led to a greater insight into the issues and challenges of developing small-scale bCHP schemes in the UK and the unfortunate but not uncommon project and company failures (as also highlighted in Annex 1). It has also led to the development of an original, and potentially commercially deployable, project development and risk management decision support system for small-scale (500 kWe to 10 MWe) biomass combustion CHP schemes in the UK, to be utilised by developers, in the early stages of a potential project's lifecycle. Energy Company is, for obvious reasons, not able to utilise the research output, but the researcher's involvement in BioenNW [230], a large EU funded project to develop small-scale emerging bioenergy technologies (e.g. combined pyrolysis and AD) in North West Europe means that the DSS is to be deployed either wholly or partially for use in supporting practice. The option to transfer the novel methodology developed to support UK developers in small-scale bCHP combustion project to a wider array of bioenergy technologies in North West Europe confirms that the DSS can be generalised and applied in practice. This ensures that the research aim is achieved with the DSS helping to realise increased bioenergy deployment.

## 8.3 Research Aim and Objective Review

To support the chapter conclusions (8.2) a review of the research aim and objectives is given:

### *$O_1$) analyse the current barriers to small-scale project financed bCHP schemes in the UK*

The current barriers to small-scale project financed bCHP in the UK ($Q_4$) are analysed in Chapter 2. The barriers identified throughout the chapter are given in the context of a project developer and the necessary stakeholders and contracts required for successfully developing bioenergy schemes of this type. The majority of the project development barriers can be quantified within project cost, duration and risk management functionality proposed for the support system.

### *$O_2$) review the current body of decision support system literature aimed at addressing the barriers of bCHP project development and risk management*

A systematic literature review is applied in Chapter 3, to specifically answer the third research question ($Q_2$) for evidence of project finance, scheduling or risk management developed DSS for feasibility stage or project development of bioenergy or renewable energy projects. 31 academic papers were fully reviewed after the second inclusion stage (Section 3.3.2), and these are supported with relevant grey literature and some commercially available software. From conducting the review, it became clear that there are significant gaps in the literature and no single DSS addressing the research aim.

*$O_3$) develop a decision support system for small-scale bCHP developers at an early stage of project development with a mechanism for handling the uncertain or approximate information*

The configuration of the developed decision support system ($Q_3$) and the calculation methods and logic utilised are given in Chapter 5. It includes an original fuzzy method for handling uncertain or approximate information that is applied throughout the project finance, scheduling and risk management objectives. The validation of the system through the case study application ($O_4$) and practitioner evaluation ($O_5$) confirmed that the objective is achieved and the DSS is suitable for its intended purpose.

*$O_4$) implement the resulting decision support system in Energy Company's case study*

To achieve the forth objective, the DSS was applied to Energy Company's first and failed project in Chapter 6. In addressing Question 4, it is shown how the DSS could have supported their decision-making in the early stages of the project's development to improve the financial viability and approach to project scheduling and risk management (Section 6.6).

*$O_5$) seek further evaluation of the decision support system from industry practitioners*

The research question ($Q_5$) for achieving the fifth objective required practitioners to evaluate the DSS as successful in achieving the research aim. The survey results given in Chapter 7 conclusively show that the practitioners rate the DSS highly overall.

*Logical Framework Review*

Four deliverables are given in the logical framework (Section 4.4.1), each with a success measure objective measured through the validation process (Section 4.8). The first deliverable is the fuzzy risk management model, which is successfully demonstrated in Sections 6.5 within the case study application and rated highly within the practitioner evaluation. As discussed the mutually exclusive risk events and responses assumption is not ideal for some of the practitioners and this is proposed to be addressed in further research (Section 8.5.4). The second and third deliverables are the fuzzy finance and scheduling models respectively. The fuzzy finance deliverable is positively evaluated within the survey (Chapter 7), and is able to benefit from Energy Company's actual data to highlight viability issues in the case study (Section 6.5). The fuzzy project scheduling could only utilise notional data within the case study, with the exception of the user interface weakness (Section 8.5.3), it is also evaluated highly by the practitioners. The final deliverable, the GUI is measured as successful if users can independently utilise the DSS without the need for experts or technical specialists. The independent installation of the system and use on their own notional cases by two of the participants confirms that this success measure is achieved. However, as Participant 5 states that some training may be required to use the DSS (Section 7.4), this may not be universal and some training may be required or a greater level of help within the system could be added. The purpose is also achieved as the DSS is deemed original by the participants and to offer support to practitioners, namely for saving time. Finally, as the purpose and deliverables within the logical framework are achieved, the aim to develop a DSS for small-scale (500 kWe to 10 MWe) biomass combustion CHP project development and risk management in the early stages of a potential project's lifecycle is also accomplished.

### 8.3.1 Contribution

Three methodological contributions and one practical contribution are targeted for the research and demonstrated within the body of the thesis. These are reviewed in turn with reference to their demonstration within the thesis, validation and, in the case of the practical contribution, the demonstrable contribution and implication of the research output.

1. *development of the fuzzy LCOE method*

The original fuzzy LCOE method (Section 5.9) is developed from the original LCOE discounting method introduced in Section 1.3.2. It is then demonstrated through the case study financial analysis within Chapter 6, enhancing the level of output information given in the traditional financial analysis by incorporating uncertain or approximate inputs from the decision-maker. Further validation from the surveyed practitioners confirmed that the fuzzy method is not only a suitable addition to the levelised cost method but also an important function that is modelled well within the DSS.

The fuzzy LCOE method is demonstrated as a method applicable to a wide range of energy project viability decisions, such as project development or for informing policy. The method is not restricted to solely bioenergy or RET project and, as with the original method, can be applied to all types of energy project. As shown in the project work plan (Section 4.4.2) and referred to in the verification section (4.8), the proposed method was sent to *Energy Policy Journal*.

2. *adaption of the existing fuzzy critical path method (F-CPM) research by improving the reference function inputs to further support the practitioner with linguistic terms*

As there is an existing body of research into the application of fuzzy theory to project scheduling through the critical path method (Section 5.11), the research contributes by improving the weaknesses identified in the existing body of research, namely the difficultly in decision-makers mapping reference functions (Section 5.3.3) or exponential or quasi-exponential functions producing potentially incorrect negative task durations at lower α-cuts (Section 5.4). Rapid function mapping is shown to be possible with the attitude and confidence linguistic controls developed. This adaption also addresses the mapping problems of the existing research. The F-CPM method is further adapted to incorporate the Zareei, Zaerpour [217] calculation method for determining criticality without the requirement to defuzzify tasks or nodes, as demonstrated in Chen [199] (Section 5.11.3). It is not possible to fully validate this functionality in the case study application due to Energy Company's failure. However, it is possible to confirm the contribution of the method through practitioner validation in Chapter 7.

The adaptions to the existing body of F-CPM research are applied within the DSS for supporting bioenergy project development, although, as with the existing body of research, the new method is applicable to a wide range of project management or planning decision-making situations. A possible further development to this method, as suggested by Participant 4 (Section 7.5) and as proposed in the further research (Section 8.5.3), is the incorporation of a graphical stacked bar or Gantt chart. To support this research contribution, a journal paper around the improved method is to be completed in the coming months and sent to a project or operations management centric journal (Table 4.2).

3. *development of a fuzzy risk management method for bioenergy projects*

The third methodological contribution is the development of a fuzzy risk management method for bioenergy projects, as defined in (Section 5.6, 5.7 & 5.12) and demonstrated in the case study (Section 6.5). The systematically reviewed academic literature (Section 3.6.1) does not apply a risk management methodology nor do they incorporate the additional cost of risk management or mitigation within their DSS. However, risk analysis through sensitivity analysis quantification is present in a large number of the academic research. This confirms the importance of risk or uncertainty within their research and calculations but paradoxically they neglected the management aspects of the identified and 'analysed' uncertainty. The grey literature DSS (Section 3.6.2) include a complete project risk management process similar to the ISO 31000 [153] standard (Table 3.8). Of these, the recent IEA-RETD [56] report is the closest method to the fuzzy approach developed within the research. Their probabilistic Monte Carlo PRM method is limited to either assumed Gaussian type or triangular distribution functions as there is insufficient information held by developers for a true stochastic analysis. Furthermore, within their case demonstration, only three point triangular (min, most likely, max) or discrete risk events are utilised and this is likely for the same limited data reason.

The development of the fuzzy risk management method contributes to the existing methods as it is an alternative approach to analysing risk with uncertainty or only approximate information. If there is limited data, it is better suited than the probabilistic method defined by the IEA-RETD [56], as the attitude and confidence linguistic controls (Section 5.4) allow the decision-maker the option to further define the function beyond a triangular or trapezoidal distribution without the need for the same level of data. Notionally demonstrated within the case study (Section 6.5), the proactive response to a risk event is shown to increase the resilience of the project. An additional contribution of this method is the functionality to maximise the risk response benefit at a project level with limited resources (Section 5.12). This method was not demonstrated within the case study but was demonstrated to the project participants though it did not score as highly as the fuzzy PRM methodology which scored highest in the achieved functionality (Section 7.3). Despite the high rating given by the project participants, the fuzzy PRM method can be developed further to incorporate not mutually exclusive risk events or responses (Participant 5), as discussed in Section 8.5.4.

### *Practical Contribution / Implications*

As stated in Section 4.2.1, the research aimed to generate a practical contribution with the DSS being utilised in practice or applied in further research. Although the failure of Energy Company means it is not possible to deploy the DSS within the company it was original intended for, their problems as defined in the problem statement (Section 1.4.1) are representative of the wider industry (Chapter 2). The research achieves the practical contribution as the DSS produced from this research is likely to form a part of the BioenNW project's deployment of a DSS for emerging bioenergy technology in North West Europe.

### *Theoretical Contribution*

The research aim and contributions are largely practical and methodological. However, it is important to pay attention to the important body of work that supported the development of this research or to which it contributes. The fuzzy application to the LCOE method builds upon the earliest application of the method to RETs by Wiser and Kahn [148] and Wiser and Pickle [61] by incorporating a method handling uncertainty. The methodological improvements within the fuzzy CPM build on the body of work of several authors in this area [189, 190, 199, 217] and the attitude and confidence function mapping method of Wang and Poh [202] and Fenton and Wang [203]. Finally, the fuzzy risk management method for bioenergy projects developed within the research contributes, to the growing body of literature and theory of fuzzy set and fuzzy logic to support risk and reward decision making, such as Tah and Carr [231-233] and Lam, So [234].

## 8.4 Research Limitations

Actions were taken wherever possible to avoid or mitigate any limiting factors but, as with any research project, this is not possible in all cases. This section of the thesis is intended to support the further application of the research by explicitly stating and responding to the key limiting factors of the research project.

Due to the failure of Energy Company, it was not possible to have 'closed loop' validation of the case study application and in achieving the problem statement originally set out by the company. This meant that the fuzzy application to the financial projections generated by the Managing Director within Energy Company could not be also be validated by the same person. A closed loop type of validation would have also been beneficial with the project scheduling and risk management sections within the project development DSS, where there was less data available. The research compensated for the unexpected failure of the company with the use of bioenergy practitioner validation (Chapter 7). However, an alternative to this would be to have secured access to either a complete or nearly complete bioenergy project within the UK where there existed sufficient information to capture the analysis of these aspects at around the pre-feasibility stage of the project's development.

The research is also limited by the number of participants able to utilise the software within the research project's timeframe. This was partially due to the unexpected failure of Energy Company, but also due to difficulty in securing practitioners within this relatively emerging industry. It was also necessary to secure access to the software and install the application on an often company protected laptop or computer before participating in the research. This reduced the number of respondents able to run their own notional cases which is shown in Chapter 7 with only two of the five respondents being able to successfully achieve this. If the DSS were deployed as a web-enabled application, so that it was not limited by these issues, it would have enabled not only quicker but also much wider access to the software. Furthermore, it would then be possible to update the system with any changes in UK policy and incentives for bioenergy projects.

There are four significant DSS functionality limitations, with the first being the user ability to conduct heat load mapping within the software for CHP sizing. During development and with the guidance of Energy Company, it was indicated that there would be limited information on the heat load characteristics of a potential site. The functionality within the DSS reflects this, with only the option to set the week or weekend day demand. This also excludes the seasonality of demand and some additional costs with the simplification that the heat demand can be met by the CHP system without the need for peak load or back-up boilers. Within the DSS, the base load fulfilled by the CHP could be entered to partially circumvent this simplification but this does not incorporate the cost of the additional boiler(s). Greater functionality around heat load mapping, with the possible use of building type estimates as utilised within the case study (Table 6.2) with the inclusion of seasonal variation could reduce this limitation. Furthermore, although the DSS is robust and able to handle a wide array of project scenario inputs, such as varying CHP size, feedstock and financing options, it is not able to optimally select a CHP size for a given scenario. This functionality was not defined within the problem statement or referred to by the project participants but would be a useful and time saving function in future work. This is currently an issue for the longevity of the support system.

Secondly, the project inputs and performance are fixed over the generation of the project lifespan. This simplification greatly reduces the amount of information required and unlikely held by the developer in the early stages of project development. However, it does also limit the functionality within the financial outputs if there is expected partial or varying operation within a year due to the timing of the bCHP scheme completion or due to a possible risk event impacting on a cost in this manner.

Thirdly, risk events within the risk management function are simplified to be mutually exclusive with that only one risk response is allowed per risk event. Discussed in greater detail in Section 8.5.3, this limiting factor was also identified by the validating practitioners within Chapter 7. Finally, there is no link between the financial and scheduling objectives within the DSS outputs. The decision-maker is able to assess the combined financial or scheduling risk effect or responses within the risk response section and the risk response optimisation section, but there is not a relationship beyond this. It is possible improve this limiting factor by possibly attributing a fixed day rate change to an increase or decrease in the project development time within a financial cost line within the cash flow projection.

## 8.5 Recommendations for Further Research

There are several possible recommendations for further research and further development of the DSS. These recommendations were considered in light of the feedback from the participants in the survey (Chapter 7) and the assumptions and simplifications of Section 4.7.

### 8.5.1 Contract Lengths and Financing Methods

The necessary feedstock [6] and heat off-take [84] contract lengths required to secure finance are cited as barriers to bioenergy project development. Committing to a long-term feedstock contract is not only difficult to achieve with the limited number of suppliers offering this option [85], but also restricting for the operator to benefit from favourable changes in the feedstock market or through securing potentially cheaper spot market prices. Similarly, a secure and long-term heat off-take contract or contracts are needed but heat users are generally unwilling to commit to these with a lack of trust in the heat supplier [84]. Competition with low-cost incumbent of natural gas is also cited as a barrier by Element Energy [29]. However, shorter term heat contracts may make it easier for a heat supplier to offer price guaranteed or gas price relative off-take contracts. Although not directly cited as a barrier to development, shorter PPA contracts could reduce the transaction costs charged by the supplier, which are shown to be up to 10% of the market value of the electricity or associated incentives [93]. It is also assumed that for project financing the required capital is wholly structured from debt or equity sources. This excluded the other commonly applied method of corporate financing and some other forms of finance such as subordinate debt (mezzanine finance). Further research will evaluate the effect of corporate financing or alternative financing methods and more easily obtainable contract types or relationships with the key stakeholders.

### 8.5.2 Construction Risk Allocation

EPC contracts are employed in most if not all of the small-scale RET schemes in the UK. As covered within Section 2.7, the primary reason for this is the financiers' desire to offset risk [6] with the EPC contractor being allocated most of the common risk within the project [76]. Typically, this leads to a large contingency premium that as shown within previous research to often be an arbitrarily selected [53] or overestimated [87] amount. The failed case of the ARBRE gasifier project (2002) and the high construction cost barrier to market energy for RETs [5] show that EPC contracts do not guarantee success and in some instances can be a barrier to project development. Furthermore, the allocation of risk to one party without the consideration of competency in handling the risk event(s) or value for money is not aligned with the risk management methodology employed within the research and DSS. The recommendation for further research would therefore be to research in more detail the barriers to and advantages of a different contract form with a more optimal distribution of risk between the project developer / sponsor and the contractor(s).

### 8.5.3 Fuzzy Critical Path Method Interface and Dependency Relationships

A further improvement to the F-CPM method adaptations, suggested within the research and within the forthcoming research journal publication, is the integration of a visualisation method and possible task relationships. Firstly, project scheduling is most commonly conducted by practitioners with the use of MS Project or similar linked bar or Gantt chart interface. Participant 4 stated that they would prefer to see the input interface within the DSS in this form as it is more familiar (Section 7.5). The user interface does not affect the contribution of the method but would be beneficial to the existing interface utilised if the proposed method is to be successful as a commercially utilisable method. Secondly, as it arose during the development of the journal paper when utilising an oil pipeline project given by an experienced industry practitioner, the task relationships within the model are limited to finish-start relationships and this restricts the use of offset activities or other dependency relationships, such as finish-finish dependencies. Dummy tasks can be used to offset tasks, and these were adopted within the journal paper case study, but it is not possible to handle the other dependency relationships and this is not addressed within the existing research utilised to improve the method [189, 190, 199, 217].

### 8.5.4 Multiple Risk Event and Responses

Mutually exclusive risk events and responses are applied within the DSS (Section 5.6.3) to avoid the risk management method becoming overly complex or confusing for the decision-maker, with a network of intertwined possible outcomes. The dominance of deterministic DSS within the systematically reviewed literature (Section 3.6.1), typically applying only a sensitivity analysis emphasises the simplicity of the current risk and uncertainty analysis practice. These DSS are therefore limited to one variable being changed at a time and the effect being measured. The proposed fuzzy risk management method is already far more complicated than the vast majority of the literature reviewed, with the exception of the IEA [56] risk quantification method (Section 3.6.2) that also applies the same simplification. To establish relationships between fuzzy risk events, heuristic rules could be developed if there is sufficient information held by decision-makers, for example: *IF risk event $A$ occurs AND risk event $B$ occurs THEN consequence $X$*.

Similarly, within the developed methodology, the risk responses are mutually exclusive between risk events with only one risk response applied to a risk event. The effectiveness of a risk response is given as a percentage (Section 5.7.2), if multiple risk responses are to be considered then a method for calculating the cumulative effect of multiple responses or the effect of risk response combinations needs to be clarified within the proposed method and for the understanding of decision-makers. Further research into these issues would improve the method or similar methods to be more representative of actual practitioner risk management (Participant 5). The design of this method with a limited level of complexity for practitioner validation is the desired approach for conducting further research into this area.

## Glossary

This glossary is given to clarify the use of terms within the supporting DSS. A greater explanation of each term utilised within the DSS is given within the information tab in each section of the system.

| Section | Term | Definition |
|---|---|---|
| **Input Glossary** | | |
| Plant Inputs | Availability (%) | operational hours expected per annum |
| | Boiler losses (%) | inefficiency of the boiler in converting the biomass to the thermal output |
| | Electrical efficiency (%) | efficiency of converting the thermal input into electricity |
| | Heat to power ratio (H:P) | number of heat units produced for each unit of electricity |
| | Parasitic load (%) | load of the CHP system and the difference between the gross and the net capacity of the system |
| Feedstock Inputs | Cost | delivered cost incurred |
| | Energy content | feedstock net calorific value |
| | Type | feedstock category |
| Location Inputs | Heat demand (residential or industrial) | daily demand of heat by the total residential or industrial users onsite |
| | Electricity demand (residential or industrial) | daily demand of electricity by the total residential or industrial users onsite |
| | Electricity price (residential or industrial) | expected electricity price incurred by the residential or industrial user |
| | Gas [heat] price (residential or industrial) | expected heat price incurred by the residential or industrial user |
| | Grid connection | can electricity generated be exported |
| Financial Inputs | Development costs (CAPEX) | the cost incurred to develop the project |
| | EPC costs (CAPEX) | the lump sum incurred from the EPC contractor |
| | Export price (£/MWhe) | value for electricity exported to the grid |
| | Insurance (OPEX) | project insurance cost (cost incurred annually) |
| | Land lease (OPEX) | project land lease cost (cost incurred annually) |
| | LEC price (£/MWhe) | value of electricity levy exemption |
| | Maintenance cost (OPEX) | the cost of maintaining the facility (cost incurred annually) |
| | Operation costs (OPEX) | all costs of operation excluding the maintenance costs (cost incurred annually) |
| | Other cost (CAPEX or OPEX) | any additional costs not included in either the CAPEX or OPEX inputs |
| | Plant costs (CAPEX) | cost of the plant |
| | PPA limit (£/MWhe) | highest possible rate obtainable for exported power to the grid |
| | RHI price (£/MWhth) | value of heat per MWhth utilised |
| | ROC price (£/MWhe) | value of ROC per MWhe utilised |
| | ROCs (banding) | number of ROCs given per MWhe utilised |
| | Tax | rate of corporation tax payable |
| Schedule Inputs | Duration (months) | amount of time taken to complete the task |
| | Preceding tasks | tasks that need to be completed before this task |
| Risk Register Inputs | Likelihood | possibility of the risk event occurring |
| | Project lifecycle phase | phase in which the risk event is expected to occur in |
| | Risk cause and risk effect category, sub- and sub-sub category | hierarchy of a risk cause or effect, useful to navigate around the levels or risk causes and effects |
| | Severity | upon the risk occurring the severity of the risk in impeding the project objectives |

| | | |
|---|---|---|
| Response Register Inputs | Avoid | avoid the risk event |
| | Reduce | take action to reduce the impact of the risk event |
| | Retain | tolerate or accept the risk event |
| | Risk criticality | the rank importance of the risk (number) and the severity (colour) |
| | Transfer | transfer the risk event to another party |
| **Output Glossary** | | |
| Finance Outputs | Calculate LCOE | levelised cost of electricity for the project to break-even over the project lifecycle |
| | Calculate LCOH | levelised cost of heat for the project to break-even over the project lifecycle |
| | Calculate NPV/IRR | expected net present value or rate or return for the project under the assumptions without the need to break-even |
| | Debt int (%) | debt interest payable annually |
| | Debt term (yrs) | number of years the debt is paid back over |
| | DSCR | a required coverage ratio and term for debt, expressed as annual EBITDA/Debt payment |
| | Graph LCOH | calculates the minimum LCOH (break-even) under variable heat utilisation onsite |
| | Graph PPA | calculates the minimum LCOE (break-even) for exportable power under variable heat utilisation onsite |
| | ROE(%) | return on equity for the equity investment over the life of the project |
| Schedule Outputs | Critical Path(s) | longest path of tasks to complete the project |
| | Task Criticality | duration importance of a task within the project development network; 1 is the most important and 0 is the least |

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## Annex 1 – Small-scale bCHP Schemes (1 to 10 MWe) Recently in Development or Operational in the UK

| Plant | Company | Location | Net Cap (MWe) | Technology | Feedstock | Use for Heat | Additional Information |
|---|---|---|---|---|---|---|---|
| **Operational** | | | | | | | |
| Balcas Timber Biomass CHP[1] | Balcas Bioenergy Limited | County Fermanagh, Northern Ireland | 2.7 | Combustion | Bi-product wood chip | Production of wood pellets for boilers | - |
| Bentwaters CHP[2] | REG Bio-Power | Suffolk | 4.8 | Engine | Vegetable oil | - | - |
| Merthyr Biomass CHP[3] | Merthyr Industrial Services | Glamorgan, Wales | 1 | Gasification | Waste wood | - | - |
| Newry[4] | Kedco plc | County Down, Northern Ireland | 2 | Gasification | Waste wood | - | Plans to increase to 4 MWe |
| UEA[5] | University of East Anglia | Norfolk | 1.4 | Gasification | Wood chip | Heat and Power demand on site | - |
| **Construction** | | | | | | | |
| Heathrow airport CHP[6] | BAA Airports | London | 1.8 | ORC | Wood chip | Heating and Cooling to the airport terminals | - |
| BskyB[7] | BSkyB | London | 1 | ORC | Wood chip | BSkyB premises | - |
| **Development** | | | | | | | |
| REG Bio-Power Leeds North[2] | REG Bio-Power | Yorkshire | 2 | Engine | Vegetable oil | - | Commissioned 2011 |
| R Plevin & Sons[8] | R Plevin & Sons | Nottinghamshire | 1.6 | Combustion | Waste wood | Utilised on site | - |
| Twinwoods[9] | Twinwoods Heat and Power Ltd | Bedfordshire | 2.5 | Gasification | Waste wood | Export opportunities mentioned | Partner dissolved (status unclear)[10] |
| RedHill Road Biomass[11] | Barnes Wallis Heat & Power Ltd. | Surrey | 2.5 | Gasification | Waste wood | - | Partner dissolved (status unclear)[10] |
| Enfield[4] | Kedco plc | Greater London | 12 | Gasification | Waste wood | - | Achieved planning permission |
| **Failed** | | | | | | | |
| Georgemas CHP[12] | Georgemas Biomass CHP Limited | Surrey | 6.3 | Gasification | Forestry arising | - | Dissolution notice in Gazette Aug 2012[13] |

[1] Taken from [235]; [2] Taken from [236] ; [3] Taken from [237]; [4] Taken from [238] ; [5] Taken from [239] ; [6] Taken from [240] ; [7] Taken from [241] ; [8] Taken from [242] ; [9] Taken from [243] ; [10] Bioflame Ltd. [244]; [11] Taken from [245] ; [12] Taken from [246] ; [13] Notice from [244]

## Annex 2 – Policy specific to Small-scale bCHP Project Development in the UK

Policy is a fundamental driver to the commercial deployment of renewable energy technologies. It is clear that current policy is inextricably linked to renewable energy deployment, but future policy or the perception of future policy by industry stakeholders also plays an important role. As the typical life of a bioenergy project is 20 years, there needs to be confidence in both future regulation and incentives. The policy covered in the annex is applicable to bioenergy and CHP.

### A2.1 Kyoto Protocol 1997

The Kyoto Protocol to the United Nations Framework Convention on Climate Change set global greenhouse gas emissions targets. The Protocol, once ratified, became the first international legally binding emission reduction targets for developed countries. The Protocol which came into effect in 2005 would collectively result in a greenhouse gas emissions reduction of 5.2% below 1990 level during the first “commitment period” (2008 - 2012). The target set for the UK is a 12.5% reduction on the 1990 emission levels.

### A2.2 EU Directives

*EU Renewables Directive 2001 (Directive 2001/77/EC) [247]*

The 2001 package was for promoting renewable electricity production. National targets were set for each of the Member States, with the UK having a target of 10% of electricity production from renewable sources. This target was subsequently missed [248]. The Directive was repealed by the 2009 EU Renewables Directive (Directive 2009/28/EC).

*Combined Heat and Power (CHP) Directive 2001 (Directive 2001/77/EC) [249]*

The Directive’s purpose is to promote the installation and operation of CHP plants as a more efficient approach to heat and energy production and ultimately combating climate change. The UK signed up to the directive and established the Combined Heat and Power Quality Assurance Scheme (CHPQA) which is overseen by DECC. The CHPQA incentives are covered in more detail in Section A2.5.

*EU Climate-Energy Package 2009*

This package includes the 2009 EU Renewables Directive (Directive 2009/28/EC) [3] and is widely known for the ‘20-20-20’ targets. Binding national renewable energy targets for each Member State collectively result in 20% of the total energy consumption in 2020 being generated from renewable sources. The UK is committed to achieving a 15% target, which is the largest relative percentage increase of all the Member States.

### A2.3 White Papers

*Energy White Paper 2007*

The 2007 White Paper [250] contained four main policy goals: aim to reduce CO2 emissions by 60% by 2050, with significant progress by 2020; maintain the reliability of energy supplies; promote competitive energy markets and ensure that every home can be heated adequately and affordably.

*Electricity Market Reform (EMR) White Paper 2011*

The Electricity Market Reform (EMR) [5] proposes a Carbon Floor Price to reduce investor uncertainty. An Emissions Performance Standard (EPS) that ensures no new coal-fired power stations are built and to encourage short-term investment in gas. Proposed changes to the FiT scheme with the introduction of Contracts for Difference (CfD) ensure greater stability and control over returns on investment (see A1.5). Finally, the EMR proposes changes to how the Grid is operated with the introduction of a new Capacity Market mechanism that rewards generators for reliable generation when required.

### A2.4 Acts

*Electricity Act 1989*

The Energy Act 1989 [91] privatised the electricity supply market in the UK and required suppliers to be licensed by an industry regulator, currently OFGEM. Schedule 3 of the Electricity Order 2001 [89] stipulates license exemptions to the Electricity Act 1989 for small-scale distributors of domestic electricity up to 2.5 MWe (net cap) and exemptions for on-site and non-domestic distribution.

*Climate Change Act 2008*

The Act [251] set legally binding targets and a framework for the UK to guarantee that the net UK carbon account for the year 2050 is at least 80% lower and an intermediate target that by the year 2020 $C0_2$ emissions are at least 26% lower than the 1990 baseline. A carbon budgeting system was also introduced to ensure that the 2050 target is achieved.

*Energy Act 2008*

The Energy Act 2008 [252] implements the legislative aspects of the 2007 Energy White Paper [250]. This introduces ROC banding under the ROO (Renewables Obligation Order) for different renewable energy technology types and, in the case of biomass, feedstocks. The act also enables the

Government to introduce a Feed-in-Tariff for small-scale renewable electricity production and to encourage renewable heat production with the introduction of a Renewable Heat Incentive.

## A2.5 Current Incentives and Regulations

### *Climate Change Levy (CCL) 2001*

The Climate Change Levy (CCL) was introduced in April 2001 under the Finance Act 2000 [253], with the purpose of encouraging commercial and industrial businesses to be more energy efficient. The CCL charges all non-domestic consumers of energy a carbon-tax on the energy consumed. Energy produced from renewable energy sources are exempt from the scheme by acquiring Levy Exemption Certificates (LECs) for each MWhe generate, currently valued at £5.09/MWh for 2012/13 [222]. CHP is liable under the CCL unless they are accredited under the CHPQA scheme (see CHPQA A2.5).

### *Renewables Obligation (RO)*

The Renewables Obligation (RO) was first introduced as a market based incentive in 2002 [254] and for a significant period was the UK's main incentive policy for encouraging renewable energy. Biomass schemes, to qualify under the RO require the feedstock to be at least 90% biomass by energy content and this has some implications for waste feedstock sources. The RO requires electricity suppliers to purchase a quota of Renewable Obligation Certificates (ROCs) from renewable energy generators, dependent on the supplier's total energy sales and the target generation growth for the renewable energy sector for that year. If a supplier is unable to fill their quota, they are penalised by Ofgem for each ROC not fulfilled at an index linked (RPI) buy-out fee. This is set at £40.71 per ROC for 2012/13 [255]. Buy-out pool proceeds are then distributed between the suppliers proportionate to their level of conformance. Buy-out pool recycling effectively raises the value of a generator's ROC as a supplier or trader will pay an additional price to increase their holding of certificates to then receive a greater proportion of the buy-out pool. This causes the ROC value to have a limited float, as shown in figure A2.1.

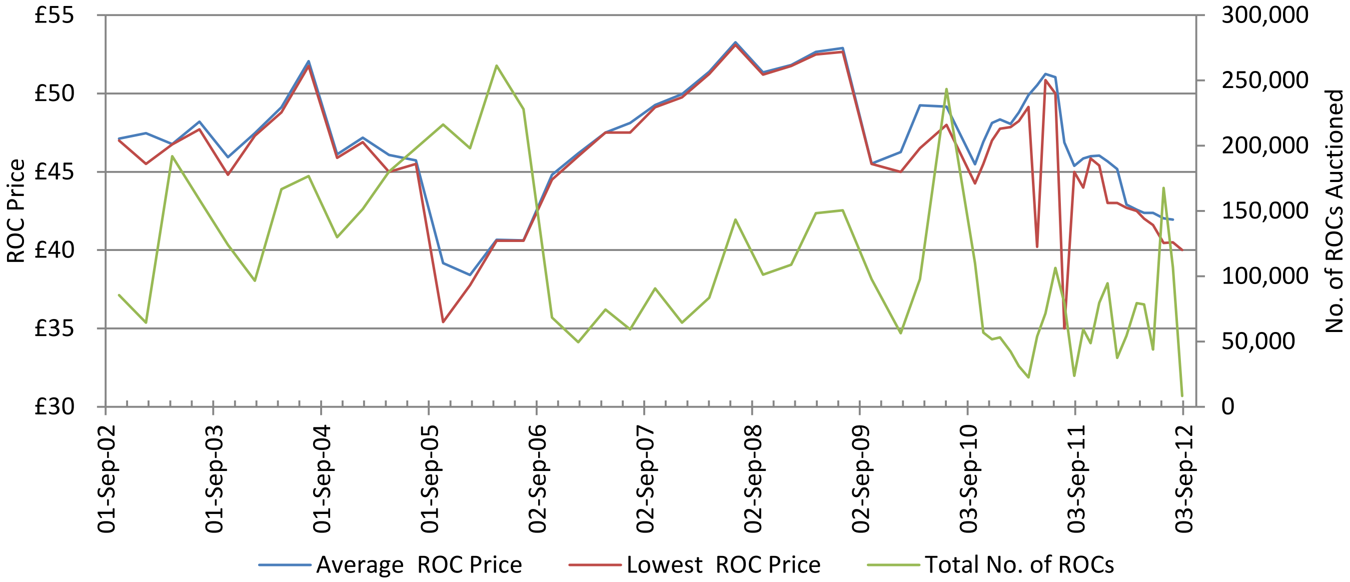

*Fig. A2.1 – Historical ROC prices and number traded [221]*

As it is a market based incentive that involves suppliers and traders, there is limited information on the value of ROCs at a given time. Figure A2.1 shows historic data taken from the E-ROC trading website [221]. Over the period from the incentives inception, the ROC rate has reached a highest value of £53.27 in July 2008 and a lowest of £40.17 in August 2012.

In its original form, the RO attributed 1 ROC/MWh to all forms of renewable energy generation, in an attempt to not select preferential technologies and allow the forces of the market to decide. This approach did not have the desired effect and investment went to the generation technology with the lowest cost per MWh, typically existing landfill gas or large-scale co-fired coal power stations. This led to wide criticism for over-subsidising established technologies and under-subsidising newer ones.

Excluding the minor adjustments to the ROO with the 2004 amendment order [256], the first significant change came to the Order came in 2009 [257]. In an attempt to improve the scheme and encourage newer RE technology development, RO banding is introduced. Set out in the Energy Review 2006 [258] then the Energy Act 2008 [252] it was introduced in April 2009, ROC bandings give varying levels of support for different RETs and, in the case of biomass, feedstock types. Typically, the closer a RET is to market the smaller the level of support (ROC/MWh). CHP schemes under the RO may receive an 'uplift' of ROCs per MWhe for utilising heat and this is assessed under the CHPQA (see CHPQA Section A2.5).

The RO is currently under consultation and the next proposed changes are to come into force in April 2013. The Government response to the consultation [15] makes several changes to the bandings of technologies and possible digression over the period of 2013 to 2017, when the scheme will be vintaged and replaced with the FiT Contracts for Difference (FiT CfD) as proposed in the 2011 Electricity Market Reform White Paper [5].

### *CHPQA*

'Good Quality' CHP certification under the Combined Heat and Power Quality Assurance Scheme (CHPQA) provides generators with several benefits. Two tax breaks are available to certified generators through the business rates exemption [259] and the first year reduction in corporation tax under the ECA [260] for qualifying machinery expenditure. Certified generators are also exempt from the Climate Change Levy and issued with tradable Levy Exemption Certificates (see Section CCL) [261]. If the scheme is a combustion plant larger than >20 MWth input then it is liable to pay for carbon credits under the EU Emissions Trading System (EU-ETS). However, certification enables the generator to access the New Entrant Reserve (NER) carbon allocation [262] for the qualifying power capacity. Finally, the CHPQA scheme enables ROC allocation uplift for the certified qualifying power output of a plant (covered in detail in Section 5.5.1). The ROC uplift is to be vintaged in 2015, and replaced with the RHI  and a rate specifically for CHP is under consultation [43].

### *European Union – Emissions Trading System (EU-ETS)*

The European Union - Emissions Trading System (EU-ETS) was introduced in 2005. The 'cap and trade' system for reducing greenhouse gas emissions within the EU was adopted with the (2003/87/EC) [263] to achieve the targets of the Kyoto Protocol (Section A2.1). The ETS is currently in its second phase that ends at the same time as the first commitment period under the Kyoto Protocol. The third phase of the system will last for seven years, from 2013 – 2020, with the aim of further reducing GHG emissions and extending the scheme to a greater remit of GHG emitting sectors and gas types. Combustion installations with a thermal input exceeding 20 MW except hazardous or municipal waste installations are required to participate in the scheme [263]. However, exemption under the CHPQA can be achieved for CHP schemes [262].

### *Feed-in-Tariff (FiT) 2010 / EMR Reforms*

The Feed-in-Tariff (FiT) specified in the Energy Act 2008 [252] was introduced in April 2010. The FiT is based on similar successful 'generation' tariffs used in other European countries such as Germany. This financial support scheme is targeted at small-scale (<5 MWe) renewable electricity production. It was felt that the RO, although successful, was not the right incentive for stimulating growth in small-scale renewables [4][38]. The FiT tariff is comprised of two parts: the generation and export tariffs. The generation tariff is paid for every kWhe generated, with an optional minimum export tariff paid for every kWhe exported to the grid. The generator can accept the minimum export tariff 'opt-in' or 'opt-out' and enter into a PPA with a licensed supplier for the exported electricity [264][39]. The FiT, in its current form, does not include small-scale biomass or CHP schemes.

As specified in the Electricity Market Reform (EMR) White Paper [5], the proposed FiT CfD aims to stabilise the production incentive revenue to yield predictable and secure return on investment for project generators and investors. The FiT, in this form, acts as a variable top-up payment to reach a given 'strike price' (minimum levelised unit cost per MWh) required to secure investment in a given technology. As it is not planned to be introduced until 2014, there is limited information on the exact conditions of the incentive, including: eligibility, strike price setting and accounting for biomass, with its highly variable feedstock costs [265].

### *Renewable Heat Incentive (RHI) 2011*

The Renewable Heat Incentive (RHI) was also specified in the Energy Act 2008 [252] but not introduced for non-domestic generation schemes until November 2011. It operates in a similar manner to the FiT by being administered by Ofgem and issuing a fixed, index-linked payment system but for the generation of utilised heat. However, the RHI supports the production of renewable heat at all sizes. Unlike under the RO, it does not require certification under the CHPQA scheme and is not linked to the production of electricity. There are multiple rates for biomass depending on the size of the installation and in the small and medium scale biomass combustion systems two incentive rate tiers for different levels of utilisation are given [83]. Finally, the incentive scheme does not currently have a rate specific to CHP generated heat but this is currently under consultation [43].

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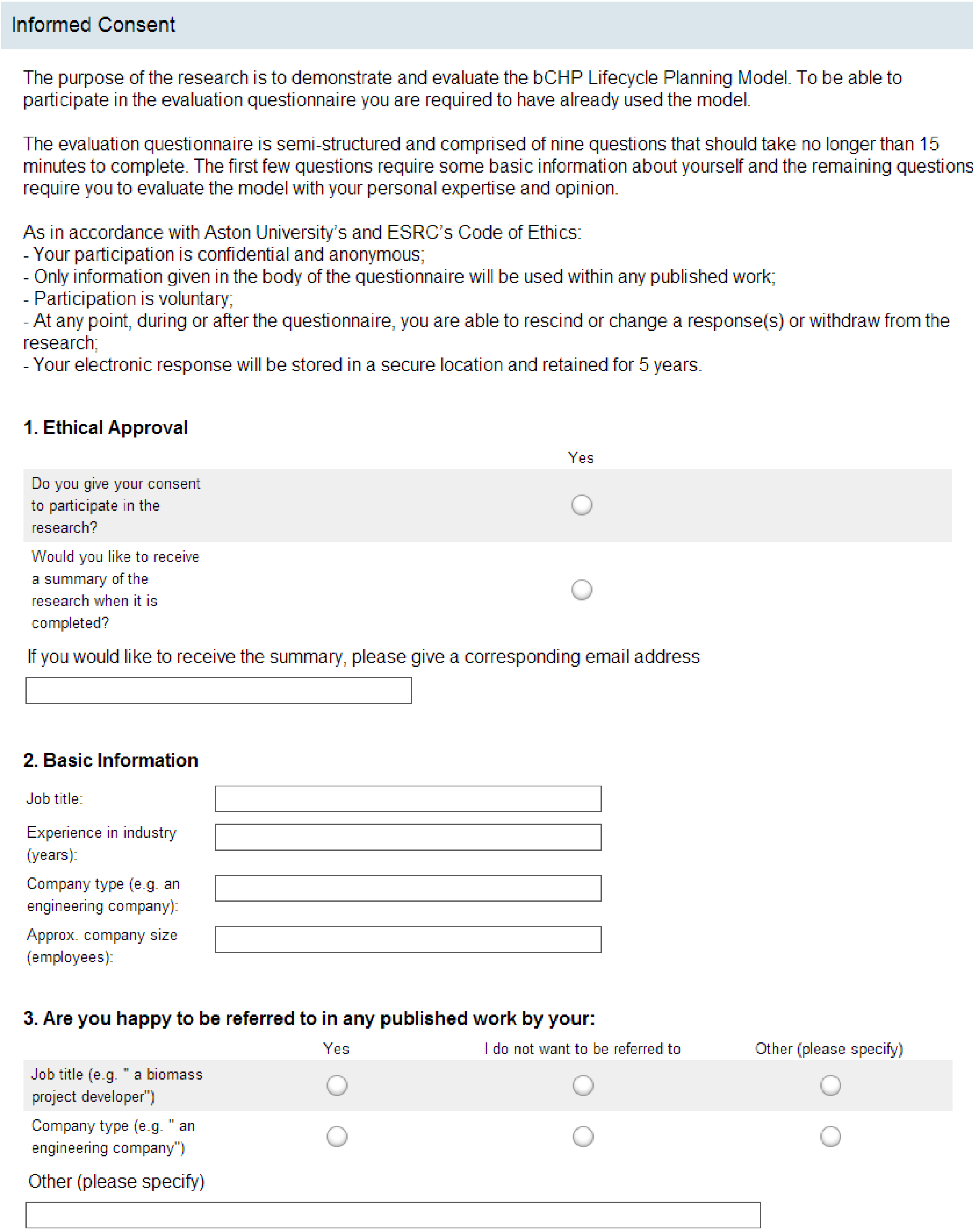
[38] Paragraph 3.32
[39] Paragraph 3.49

## Annex 3 – Practitioner Validation Questionnaire



### Informed Consent

The purpose of the research is to demonstrate and evaluate the bCHP Lifecycle Planning Model. To be able to participate in the evaluation questionnaire you are required to have already used the model.

The evaluation questionnaire is semi-structured and comprised of nine questions that should take no longer than 15 minutes to complete. The first few questions require some basic information about yourself and the remaining questions require you to evaluate the model with your personal expertise and opinion.

As in accordance with Aston University's and ESRC's Code of Ethics:
- Your participation is confidential and anonymous;
- Only information given in the body of the questionnaire will be used within any published work;
- Participation is voluntary;
- At any point, during or after the questionnaire, you are able to rescind or change a response(s) or withdraw from the research;
- Your electronic response will be stored in a secure location and retained for 5 years.

**1. Ethical Approval**

| | Yes |
|---|---|
| Do you give your consent to participate in the research? | ○ |
| Would you like to receive a summary of the research when it is completed? | ○ |

If you would like to receive the summary, please give a corresponding email address

**2. Basic Information**

Job title:

Experience in industry (years):

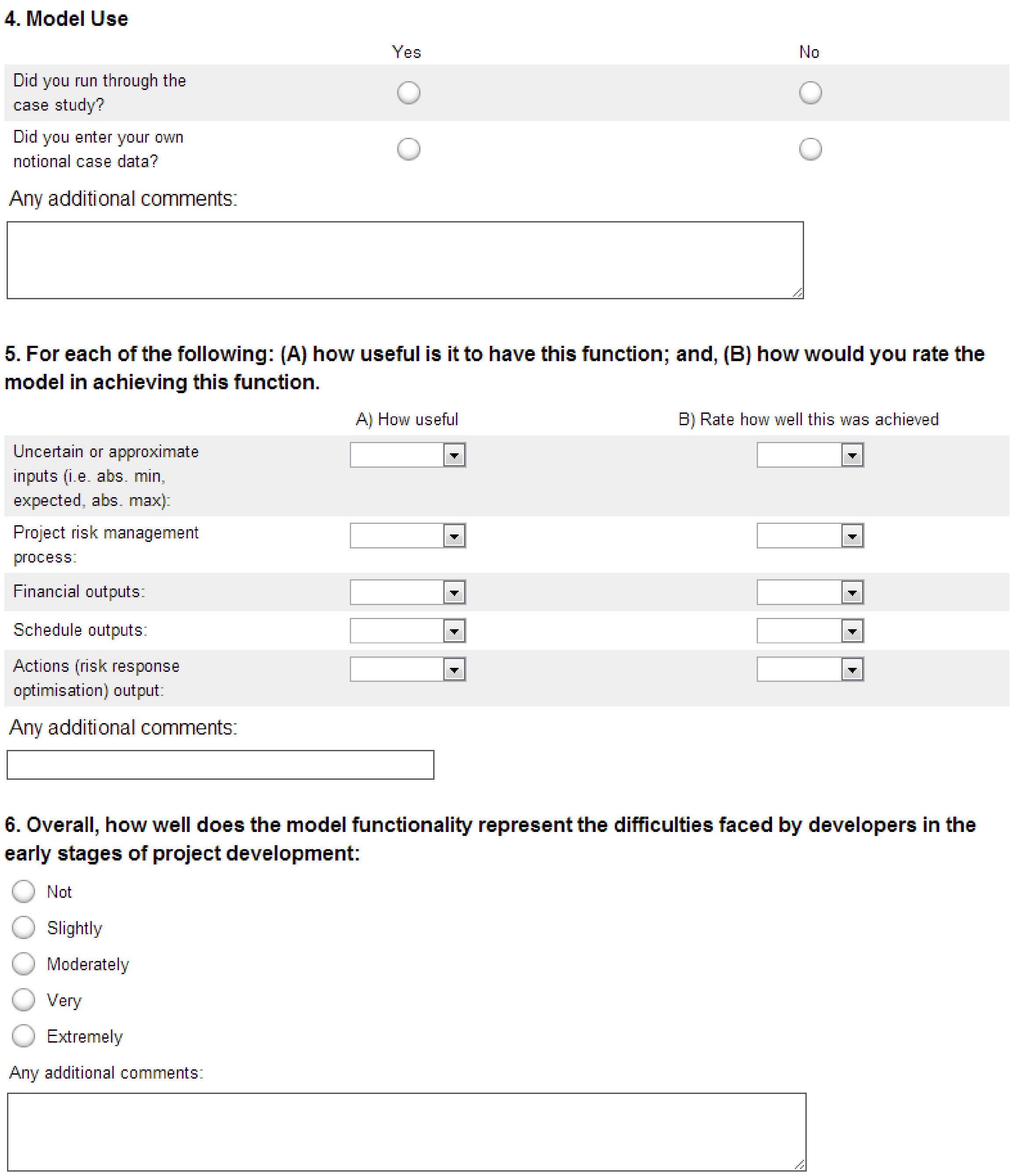
Company type (e.g. an engineering company):

Approx. company size (employees):

**3. Are you happy to be referred to in any published work by your:**

| | Yes | I do not want to be referred to | Other (please specify) |
|---|---|---|---|
| Job title (e.g. " a biomass project developer") | ○ | ○ | ○ |
| Company type (e.g. " an engineering company") | ○ | ○ | ○ |

Other (please specify)



### 4. Model Use

| | Yes | No |
|---|---|---|
| Did you run through the case study? | ○ | ○ |
| Did you enter your own notional case data? | ○ | ○ |

Any additional comments:

### 5. For each of the following: (A) how useful is it to have this function; and, (B) how would you rate the model in achieving this function.

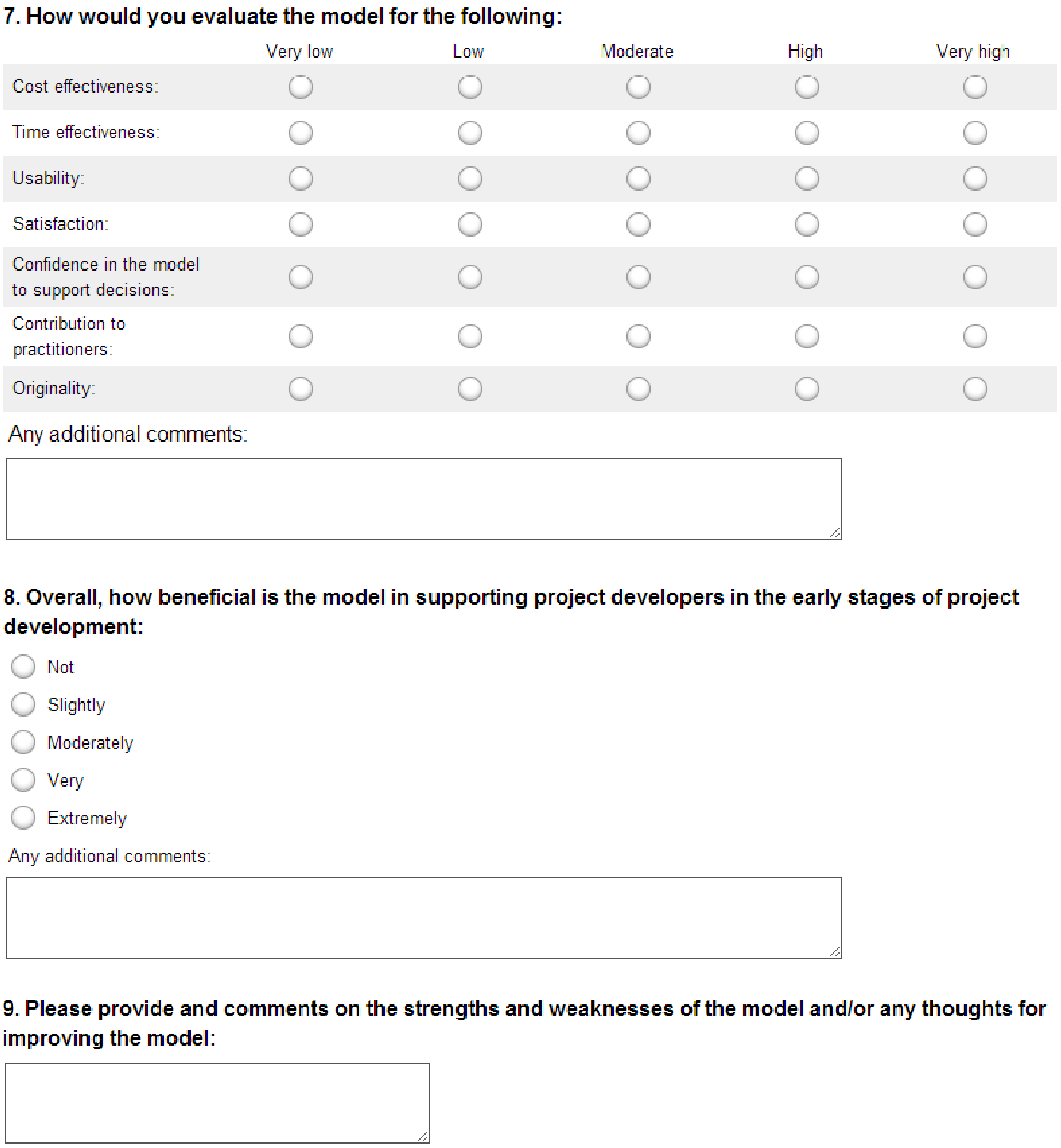
| | A) How useful | B) Rate how well this was achieved |
|---|---|---|
| Uncertain or approximate inputs (i.e. abs. min, expected, abs. max): | ▾ | ▾ |
| Project risk management process: | ▾ | ▾ |
| Financial outputs: | ▾ | ▾ |
| Schedule outputs: | ▾ | ▾ |
| Actions (risk response optimisation) output: | ▾ | ▾ |

Any additional comments:

### 6. Overall, how well does the model functionality represent the difficulties faced by developers in the early stages of project development:

- ○ Not
- ○ Slightly
- ○ Moderately
- ○ Very
- ○ Extremely

Any additional comments:



**7. How would you evaluate the model for the following:**

| | Very low | Low | Moderate | High | Very high |
|---|---|---|---|---|---|
| Cost effectiveness: | ○ | ○ | ○ | ○ | ○ |
| Time effectiveness: | ○ | ○ | ○ | ○ | ○ |
| Usability: | ○ | ○ | ○ | ○ | ○ |
| Satisfaction: | ○ | ○ | ○ | ○ | ○ |
| Confidence in the model to support decisions: | ○ | ○ | ○ | ○ | ○ |
| Contribution to practitioners: | ○ | ○ | ○ | ○ | ○ |
| Originality: | ○ | ○ | ○ | ○ | ○ |

Any additional comments:

**8. Overall, how beneficial is the model in supporting project developers in the early stages of project development:**

- ○ Not
- ○ Slightly
- ○ Moderately
- ○ Very
- ○ Extremely

Any additional comments:

**9. Please provide and comments on the strengths and weaknesses of the model and/or any thoughts for improving the model:**

# bCHP Lifecycle Planning and Project Risk Management DSS

Daniel Wright

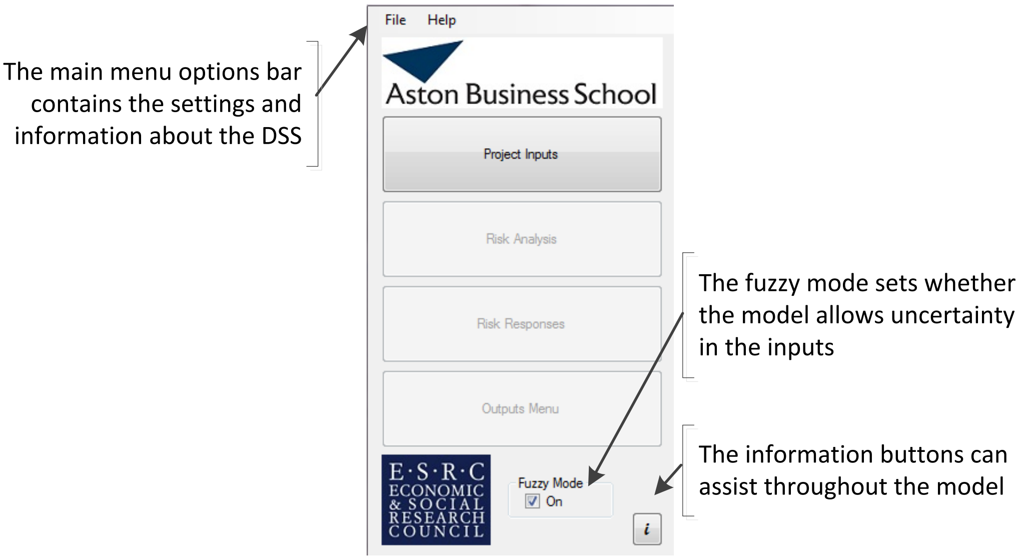
Aston University, Birmingham, UK

E-mail: Wrightd1@Aston.ac.uk

**Overview:** A small-scale biomass combined heat and power (bCHP) project development and risk management decision support system (DSS). The DSS is for use in the early stages of project development to aid in quickly and cost effectively assessing project viability and possible risk exposure over the project lifecycle. The DSS is a fuzzy logic based model that can accommodate uncertainty and vagueness in information to produce a suite of metrics that show the possibility of a project achieving financial return and schedule targets.

## *Main Menu*

The main menu has four options, with the additional option to turn off the fuzzy logic mode if the user would like to limit the *DSS* to fixed (certain) inputs. The user is required to enter project inputs before it is possible to advance to the risk analysis, response, and output stages.



The main menu options bar contains the settings and information about the DSS

The fuzzy mode sets whether the model allows uncertainty in the inputs

The information buttons can assist throughout the model

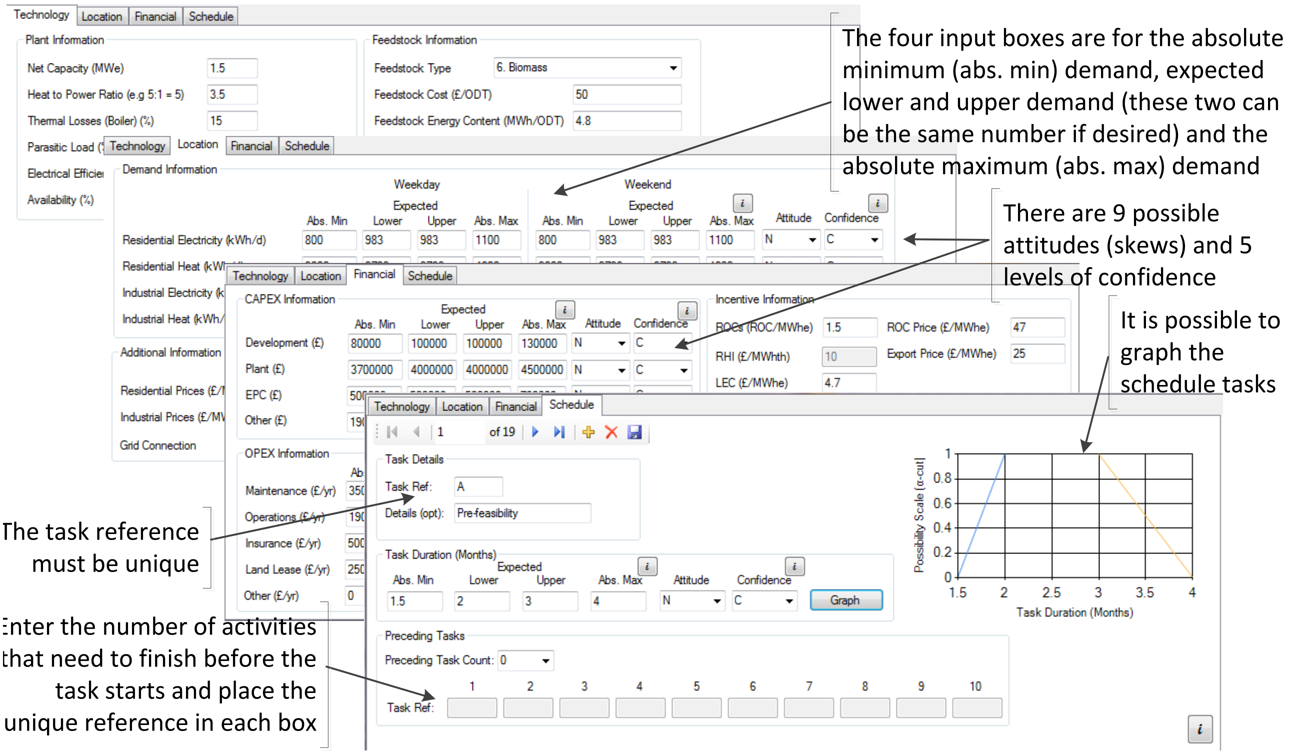
*Fig. 2. Main Menu*

Case Instructions:

Ensure that the fuzzy (uncertainty) mode is selected, and then click the project inputs button.

*Project Input Form*

The project inputs form has four main tabs: technology, location, financial and schedule. With the fuzzy logic mode enabled (as shown in Fig. 2), it is also possible for the user to specify possible ranges (fuzzy sets), with varying attitude and confidence levels for some input variables to gain greater control over mapping uncertainty.



Net Capacity (MWe): 1.5
Heat to Power Ratio (e.g 5:1 = 5): 3.5
Thermal Losses (Boiler) (%): 15
Feedstock Type: 6. Biomass
Feedstock Cost (£/ODT): 50
Feedstock Energy Content (MWh/ODT): 4.8

| | Weekday Abs. Min | Weekday Expected Lower | Weekday Expected Upper | Weekday Abs. Max | Weekend Abs. Min | Weekend Expected Lower | Weekend Expected Upper | Weekend Abs. Max | Attitude | Confidence |
|---|---|---|---|---|---|---|---|---|---|---|
| Residential Electricity (kWh/d) | 800 | 983 | 983 | 1100 | 800 | 983 | 983 | 1100 | N | C |

| | Abs. Min | Expected Lower | Expected Upper | Abs. Max | Attitude | Confidence |
|---|---|---|---|---|---|---|
| Development (£) | 80000 | 100000 | 100000 | 130000 | N | C |
| Plant (£) | 3700000 | 4000000 | 4000000 | 4500000 | N | C |

ROCs (ROC/MWhe): 1.5
ROC Price (£/MWhe): 47
RHI (£/MWhth): 10
Export Price (£/MWhe): 25
LEC (£/MWhe): 4.7

Task Ref: A
Details (opt): Pre-feasibility

| Abs. Min | Expected Lower | Expected Upper | Abs. Max | Attitude | Confidence |
|---|---|---|---|---|---|
| 1.5 | 2 | 3 | 4 | N | C |

Preceding Task Count: 0

The four input boxes are for the absolute minimum (abs. min) demand, expected lower and upper demand (these two can be the same number if desired) and the absolute maximum (abs. max) demand

There are 9 possible attitudes (skews) and 5 levels of confidence

It is possible to graph the schedule tasks

The task reference must be unique

Enter the number of activities that need to finish before the task starts and place the unique reference in each box

*Fig. 3. Project Input Form*

Case Instructions:

On the technology tab, press the 'load default values' to load the default case study. It is now possible to cycle through the four tabs and, if desired, make changes. On the location and financial tabs, the onsite heat and power demand, CAPEX and OPEX inputs have multiple input boxes and two multiple-choice boxes labelled 'attitude' and 'confidence':

**Uncertain Input Range:**

The four inputs create a triangular or trapezoidal distribution of expected demand. The minimum and maximum inputs are the lowest and highest values possible but are the least expected to occur, and the expected lower and upper inputs are the most expected values to occur. The expected lower and upper inputs can be the same if a fixed value is the most possible, but if not the range between these two inputs is the uncertain region over which you cannot differentiate.

**Attitude and Confidence:**

Changes in attitude and confidence influence the original distribution inputs. For the case, the attitude and confidence values are set to the default.

### *Attitudes*

The default for this is 'neutral'. This alters the skew of the distribution with varying degrees of optimism (skew to the left) or pessimism (skew to the right). These can be useful for quickly adjusting inputs without needing to re-enter them. The possible options are:
Absolutely Optimistic (AO)
Very Optimistic (VO)
Optimistic (O)
Fairly Optimistic (FO)
Neutral (N)
Fairly Pessimistic (FP)
Pessimistic (P)
Very Pessimistic (VP)
Absolutely Pessimistic (AP)

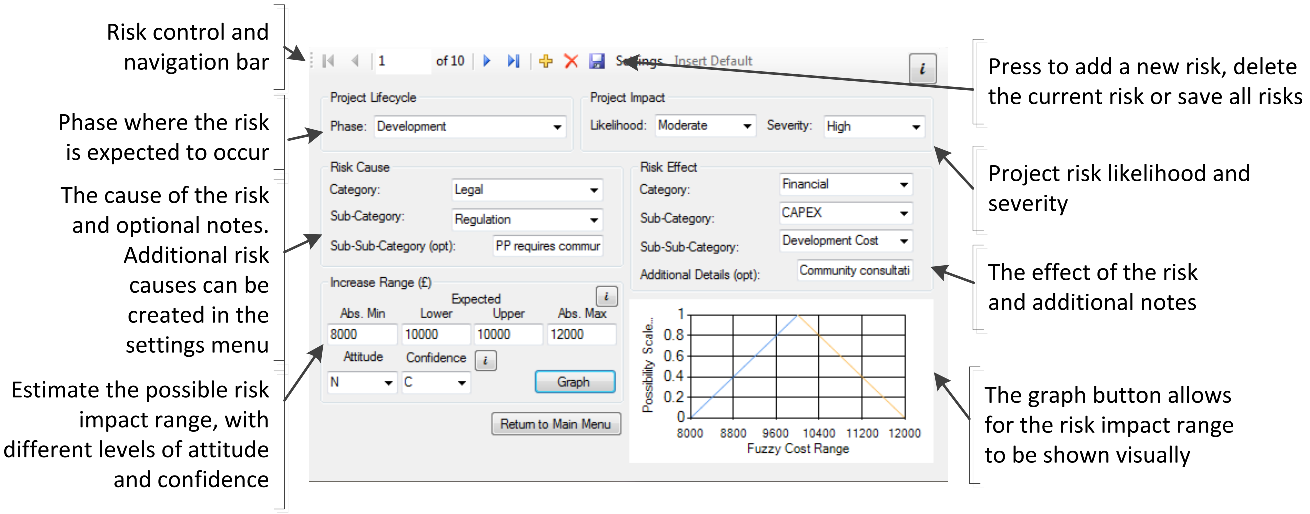
### *Confidence*

The default for this is 'confident'. Increasing confidence reduces the possibility of the absolute min and max inputs occurring, and the opposite is true for a decrease in confidence. The possible options are:
Absolutely Confident (AC)
Very Confident (VC)
Confident (C)
Fairly Confident (FC)
Neutral (N)

The schedule tab contains the tasks required to develop the case study scheme and the dependencies between tasks (also shown in Appendix 1). It functions in a similar way to a traditional project scheduling tools except it is able to accommodate uncertainty in task duration times. When you are ready to progress, return to the technology tab and press the 'save and continue' button.

### *Risk Register*

The risk register is the next stage in the process. This stage defines and maps possible risks for the project from a library of possible risk causes and effects. With the fuzzy logic mode enabled, the user is also able to control and visually map the risk's possible impact range.



Risk control and navigation bar

Phase where the risk is expected to occur

The cause of the risk and optional notes. Additional risk causes can be created in the settings menu

Estimate the possible risk impact range, with different levels of attitude and confidence

Press to add a new risk, delete the current risk or save all risks

Project risk likelihood and severity

The effect of the risk and additional notes

The graph button allows for the risk impact range to be shown visually

1 of 10

Project Lifecycle

Phase: Development

Project Impact

Likelihood: Moderate

Severity: High

Risk Cause

Category: Legal

Sub-Category: Regulation

Sub-Sub-Category (opt): PP requires commur

Risk Effect

Category: Financial

Sub-Category: CAPEX

Sub-Sub-Category: Development Cost

Additional Details (opt): Community consultati

Increase Range (£)

| Abs. Min | Expected Lower | Expected Upper | Abs. Max |
|---|---|---|---|
| 8000 | 10000 | 10000 | 12000 |

Attitude: N

Confidence: C

*Fig. 4. Risk Analysis*

Case Instructions:

To enter the default risks for the case study, it is necessary to click the 'insert default' button on the navigation bar. It is then possible to cycle through these risks by using the navigation buttons on the top bar and add a new risk by pressing the '+' button. If you would like to add a new risk go to Appendix 2.

**IMPORTANT: Save any changes before returning to the main menu or proceeding.**

### *Risk Responses*

The risk response is the next phase in the risk management process. The user is given possible risk mitigation strategies and is able to assess the benefit of individual risk responses in reducing the risk's impact and the improvement on the project cost and duration overall.

The risk has a rank (number) and a criticality (colour)

Recaps the current risk

There are four possible response actions, each having a benefit and a cost

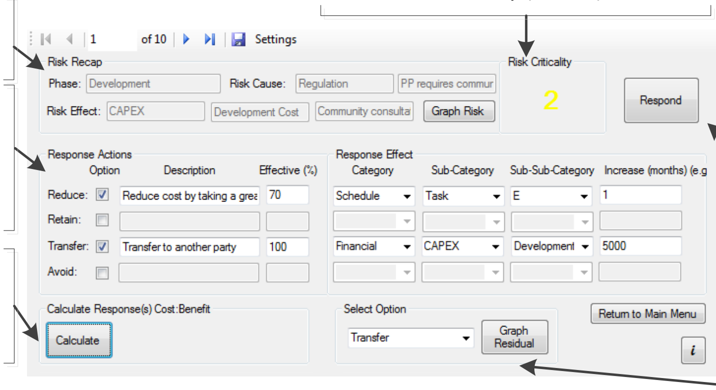
Calculates overall project change in LCOE and schedule

The settings menu allows access to the finance terms for calculating response effectiveness

Press the respond button when want to enter risk responses

Response effect and cost

Graphs the residual risk for the selected option



Risk Recap

Phase: Development

Risk Cause: Regulation

PP requires commur

Risk Effect: CAPEX

Development Cost

Community consulta

Risk Criticality: 2

| Response Actions |  |  |  | Response Effect |  |  |  |
|---|---|---|---|---|---|---|---|
|  | Option | Description | Effective (%) | Category | Sub-Category | Sub-Sub-Category | Increase (months) (e.g |
| Reduce: | ☑ | Reduce cost by taking a grea | 70 | Schedule | Task | E | 1 |
| Retain: | ☐ |  |  |  |  |  |  |
| Transfer: | ☑ | Transfer to another party | 100 | Financial | CAPEX | Development | 5000 |
| Avoid: | ☐ |  |  |  |  |  |  |

Calculate Response(s) Cost:Benefit

Select Option: Transfer

*Fig. 5. Risk Responses Menu*

Case Instructions:

The navigation bar is populated with all the risks entered in to the risk register. It is possible to quickly cycle through and recap each risk before deciding whether to enter a risk response. Each risk has a criticality score and colour. The risk shown in fig. 4 is a community consultation risk in the development phase that will increase the development cost of the project. It is possible to see the impact range for the risk by clicking on the 'graph' button.

**Responding to Risks:**

To insert possible risk response strategies for each risk, it is necessary to click the 'respond' button and this enables the response tick boxes. The four possible options are to reduce, retain, transfer, and avoid the risk event.

In this example, a possible strategy would be consult with the community over a greater period to reduce the cost by 70%, but this increases the duration of the planning permission task (task E) by 1 month. Alternatively, the risk could be transferred to another party who will handle the community consultation costs for £5000, and this is 100% effective in controlling the risk. It is possible to enter up to four risk response strategies, but is not possible to have multiple responses selected for a single risk.

Once the response inputs are entered, the next stage is to calculate the overall benefit of each risk response strategy on the project by pressing the 'calculate' button. This is shown in two ways: change in levelised cost of electricity (LCOE) and change in total project duration on not responding to that risk (Fig. 5 & Fig. 6).

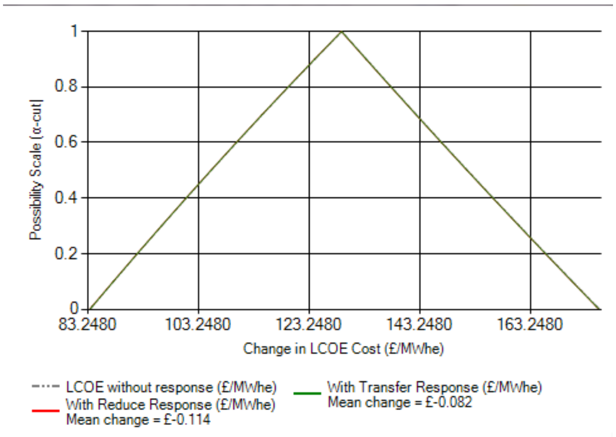


*Fig. 6. LCOE*

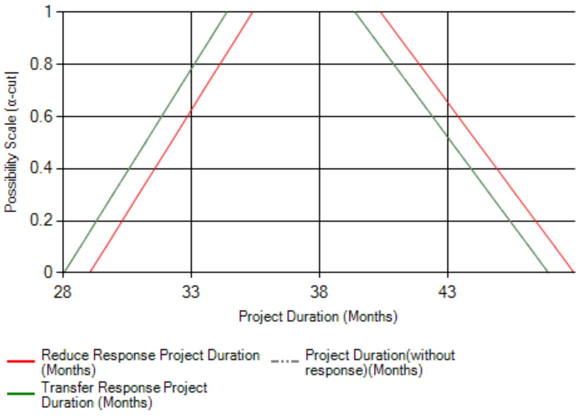


*Fig. 7. Schedule*

Case Instructions (cont.):

LCOE is the minimum price (£/MWhe) required for the project to meet the terms of finance. The finance terms can be changed in the settings menu (Appendix 3) on the form. Fig. 5 and 6 show the two risk strategies entered into the risk response form for that particular risk, with the reduce strategy (red) and the transfer strategy (green). The retain strategy, if enacted, would result in a possible mean LCOE reduction of £0.114 or 11.4p for every unit of electricity sold on not acting on the risk but would increase the overall project duration (Fig. 6) by 1 month. Whereas, the transfer strategy would result in a smaller mean LCOE reduction of 8.2p as the cost of the transfer (£5000) is included and no change in the project duration. The developer would then have to decide the optimal response option to take given the effect on the LCOE and project duration.

Finally, it is necessary to select a risk response strategy before proceeding to the next risk in the response register. The ‘select option’ box, in this example, has three options: undecided, reduce or retain. Select the undecided option if you are unsure of which response to select or whether to respond at all – this option is utilised in the actions output to optimise risk responses with limited resources. If a particular risk response strategy is selected (reduce in this example), it is possible to graph the residual risk impact after the response, as shown in Fig. 7.

**IMPORTANT: Save the response input before moving to the next risk, otherwise any input will be lost.**

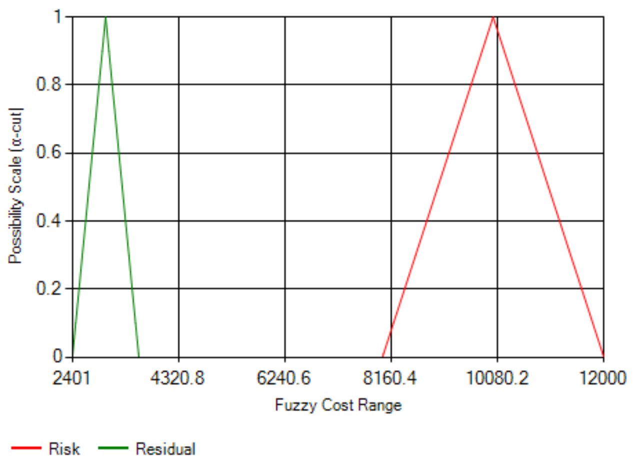
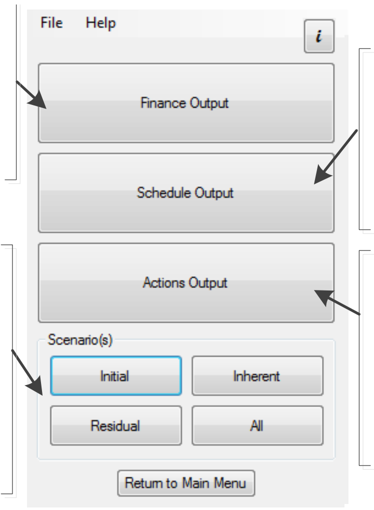


*Fig. 8. Residual Risk Impact Range*

*Outputs*

The final of the four main menu options is the project outputs option. The user is able to select individual project scenarios to model or, alternatively, they are able to model all three scenarios together. The 'initial' scenario is the project's original inputs, without factoring in any project risk or the risk responses. The 'inherent' scenario factors in the risk but not the benefit or cost of the risk mitigation actions. The final of the three scenarios, the 'residual' scenario maps the project outputs with the risks and risk mitigation strategies included.



Access to all finance outputs for the project: LCOE, finance gearing, sensitivity analysis, LCOH and PPA

Calculates the overall project duration, critical path and criticality of scheduling tasks

Select a scenario before proceeding: initial is the project with no risk or responses; inherent is with project risk no responses; and, residual is with risk and responses

Lists the project lifecycle risks and optimises the response actions to maximise benefit with limited time and cost

*Fig. 9. Outputs Menu*

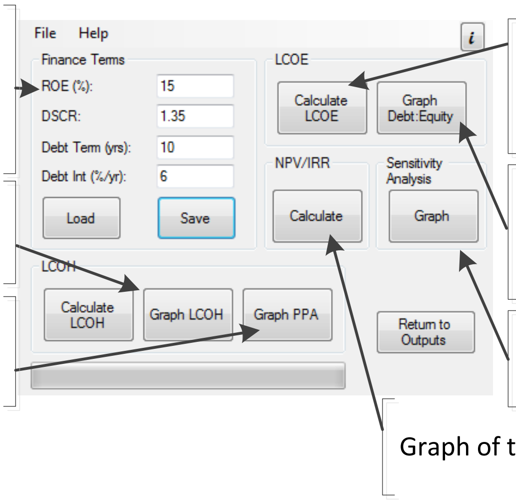
The finance output takes the user to all of the financial outputs for the project. The schedule output maps the project duration (with or without project task uncertainty), the critical path of activities and the importance of tasks within the project. The actions output gives the user an overview of the selected risk response actions to be taken over the project lifecycle and the ability to optimise risk responses with limited time and money resources.

Case Instructions:

Select the ‘initial’ scenario, which is the project without any risk events or risk responses factored in. Then select the ‘finance output’.

*Finance Output*

The finance output form enables the user to map the project over each of the scenarios with or without project uncertainty. There are multiple levelised cost of electricity (LCOE) and levelised cost of heat (LCOH) options for the user, with the additional ability to map individual or multiple variables with a sensitivity analysis.



ROE (%): 15
DSCR: 1.35
Debt Term (yrs): 10
Debt Int (%/yr): 6

Before proceeding to the finance outputs it is necessary to enter and save the finance terms

Graph of the LCOH at varying heat utilisation levels

Graph of the minimum PPA at varying heat utilisation levels

Graph of the minimum LCOE for the project to meet the finance terms

Graph of the minimum LCOE over the possible gearing ratios

Graph of the sensitivity of nine key variables

Graph of the IRR or NPV

*Fig. 10. Finance Output Form*

Case Instructions:

Before proceeding to the individual outputs it is necessary to input some finance terms for the project. The ‘load ’ button inserts the preset finance terms for the project from the settings menu, but it is possible to enter your own if desired. Once the finance terms have been entered, click the ‘save’ button. It is now possible to select multiple finance outputs. Click the ‘Calculate LCOE Graph’ button. An input box requests that the debt to equity ratio is entered, for this example 60% was entered – this implies 60% debt funded and 40% equity funded.

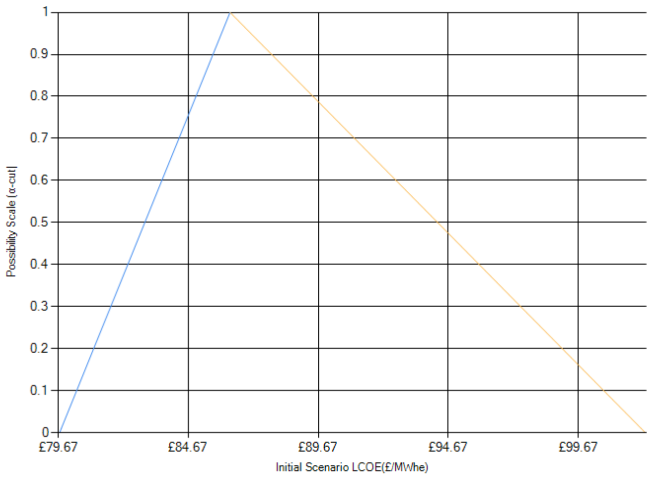


*Fig. 11. Calculate LCOE Graph*

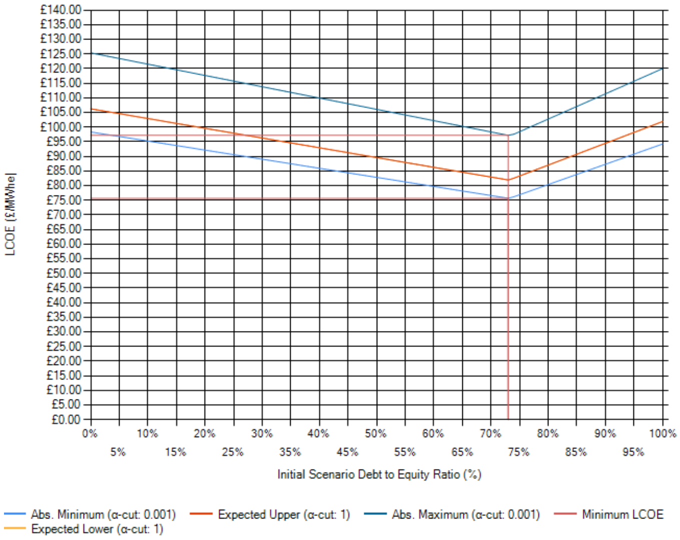
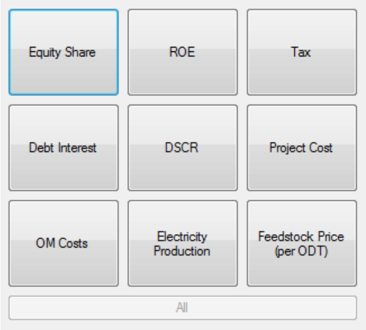


*Fig. 12. Debt to Equity LCOE*

Case Instructions:

Fig. 10 shows the produced graph. This is the range of minimum LCOEs required, given the uncertain or approximate inputs, to meet the finance terms and to be viable. The absolute minimum price is c. £79.7 and the highest is c. £102.2, with the expected unit cost being c. £86.3. If it is possible to achieve the unit price per MWhe from onsite sales or by exporting the power over the life of the project then the project is viable.

Returning to the finance form, now click the ‘graph debt:equity’ button. This is a graph of the minimum LCOE for the project at all possible debt to equity ratio grearing ratios. Fig. 11 shows the output for the worked example. The three lines on the graph represent the abs. min, abs. max and expected unit cost points. For example, if a cross section slice of the graph at 60% debt was taken, it would be the same as Fig. 10. The optimal gearing ratio of debt to equity for the project given the finance terms is c. 73%. Returning to the finance form, now click the ‘Select Variable(s)’ button in the sensitivity analysis group box.



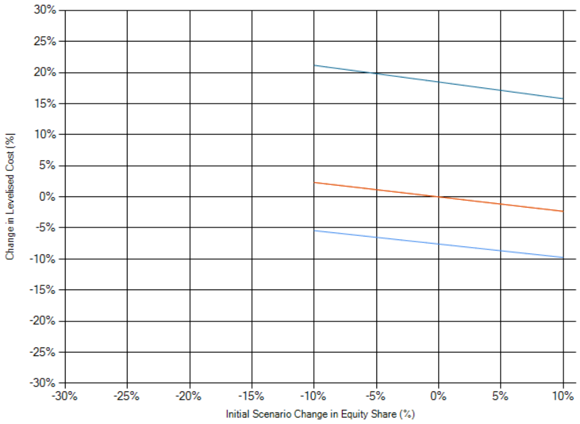


*Fig. 13. Sensitivity Analysis – Select Variable(s)*

*Fig. 14. Sensitivity Analysis – Equity Share*

Case instructions (cont.):

The select variable(s) popup menu has 10 options, nine of which are for modelling the sensitivity of key variables in the project and the tenth is all variables together. In this example, select ‘equity share’ and then click the sensitivity analysis ‘graph’ button. In a traditional (non-uncertain) sensitivity analysis there is one line that assesses the effect of a ±10% change in the selected variable on the change in LCOE (%). However, as this is for the project under uncertainty, there are three lines representing a top-down view as in the debt:equity output. Returning to the finance form, now click the ‘calculate LCOH’ button in the LCOH group box.

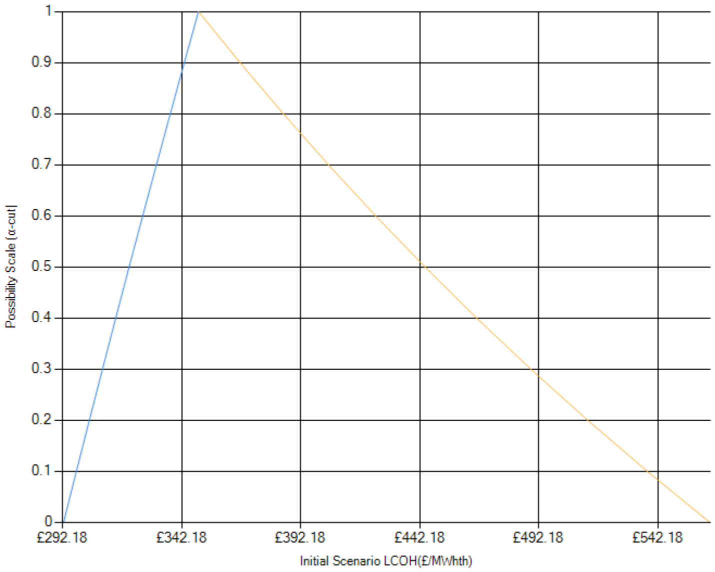


*Fig. 15. Calculate LCOH Graph*

Case instructions (cont.):

This output shows the required unit cost of heat utilised on the site given the original demand inputs to make the project viable. This value assumes that the onsite and offsite sales of power are fixed at the entered brown or fossil fuel energy equivalents. The LCOH range is far in excess of what could be charged per MWhth meaning that the project is not viable under these inputs. Returning to the finance form, now click the ‘LCOH graph’ button in the LCOH group box.

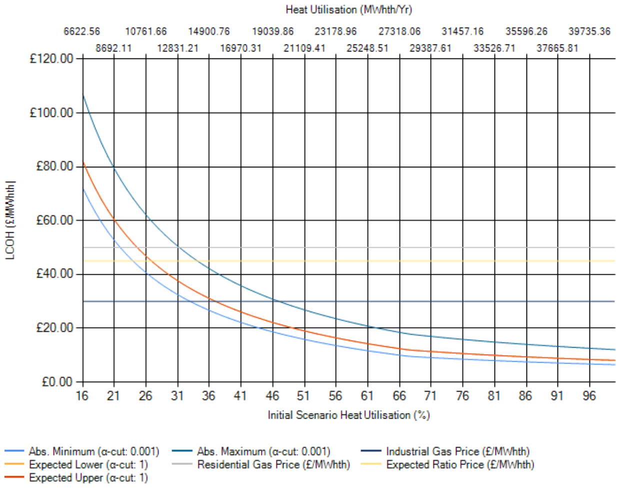


*Fig. 16. LCOH Graph*

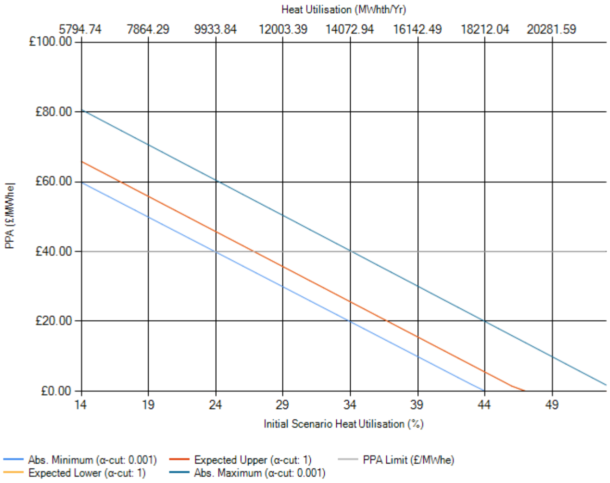


*Fig. 17. PPA Graph*

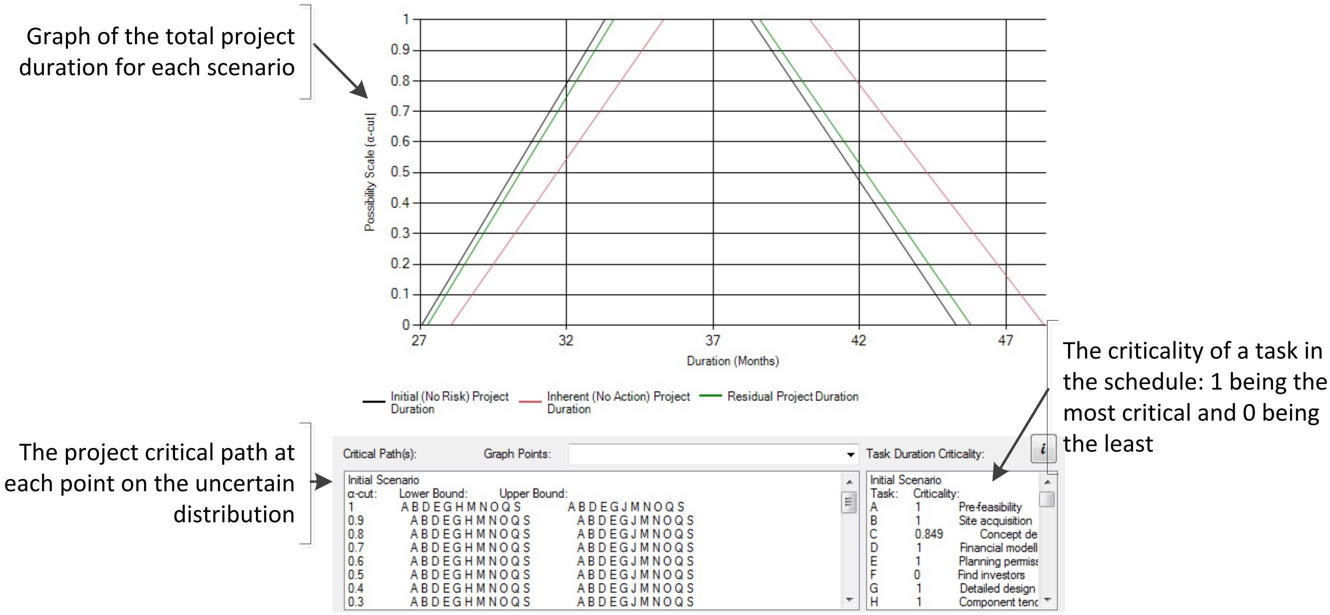
Case Instructions (cont.):

This Graph shows the minimum LCOH at a range of heat utilisation rates with any electricity revenue fixed at market price for onsite and all exported production charged at the export price. The horizontal lines show the residential and industrial equivalent gas prices (£/MWhth) and the yellow line, between these two, represents the projects expected ratio of residential and industrial demand of the site. For the example case to be viable the LCOH range should be at a minimum less than the gas price equivalent price set at £45/MWhth. This would require at least 24% (abs. min) to a maximum of 35% (abs. max) heat utilisation at the site. Returning to the finance form, now click the ‘PPA graph’ button in the LCOH group box.

The PPA graph increases the utilisation rate of heat at the given residential and industrial ratio and restricts the heat price to the gas equivalent. Onsite electricity is fixed at the market price but the price per MWhe for exported electricity is calculated to ensure that the project meets its finance terms. This will likely be contracted out as a Power Purchasing Agreement (PPA), so this price is the minimum price acceptable for the project to be viable. For example, if £40/MWhe was the maximum amount obtainable, the site would again need to utilise at least 24% (abs. min) to a maximum of 35% of the heat produced for the project to be viable.

*Schedule Output*

The schedule output form enables the user to map the total project duration, the critical path(s) and the task duration criticality (importance). It is also possible to see the effect of risks or responses that influence the project duration.



```
Initial Scenario
α-cut:   Lower Bound:          Upper Bound:
1        A B D E G H M N O Q S        A B D E G J M N O Q S
0.9        A B D E G H M N O Q S        A B D E G J M N O Q S
0.8        A B D E G H M N O Q S        A B D E G J M N O Q S
0.7        A B D E G H M N O Q S        A B D E G J M N O Q S
0.6        A B D E G H M N O Q S        A B D E G J M N O Q S
0.5        A B D E G H M N O Q S        A B D E G J M N O Q S
0.4        A B D E G H M N O Q S        A B D E G J M N O Q S
0.3        A B D E G H M N O Q S        A B D E G J M N O Q S
```

```
Initial Scenario
Task:   Criticality:
A       1       Pre-feasibility
B       1       Site acquisition
C       0.849       Concept de
D       1       Financial modell
E       1       Planning permiss
F       0       Find investors
G       1       Detailed design
H       1       Component tenc
```

Graph of the total project duration for each scenario

The project critical path at each point on the uncertain distribution

The criticality of a task in the schedule: 1 being the most critical and 0 being the least

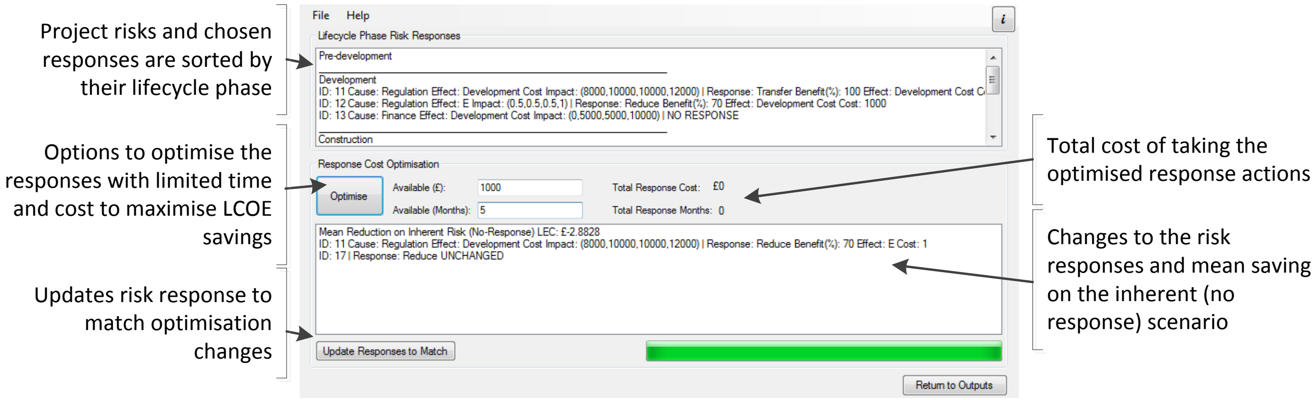
*Fig. 18. Scheduling Output*

Case Instructions:

Before proceeding to the schedule output, select ‘all’ scenarios on the outputs menu. The schedule output graph shows the project duration of the three scenarios. The initial scenario (in black) has the shortest project duration, ranging from 27 to 46 months. The critical path is calculated at 12 points along the upper and lower bounds of the function. The critical path of the project is denoted by the lower and upper bound unique task reference ids. The final output box shows the task duration criticality, this is the importance of a task’s duration in controlling the total project duration, if a task is always critical thus having no slack, it receives the highest score (1), and the converse is true, a task that is never critical with receive the lowest score (0). Having an understanding of the duration criticality of each task and the overall project duration facilitates better project and project risk management.

*Actions Output*

The actions output form, is the final of the output forms and it serves two purposes: to recap the project risks and responses (sorted by lifecycle phase) and to optimise the project risk responses with limited resources.



```
Pre-development

Development
ID: 11 Cause: Regulation Effect: Development Cost Impact: (8000,10000,10000,12000) | Response: Transfer Benefit(%): 100 Effect: Development Cost C
ID: 12 Cause: Regulation Effect: E Impact: (0.5,0.5,0.5,1) | Response: Reduce Benefit(%): 70 Effect: Development Cost Cost: 1000
ID: 13 Cause: Finance Effect: Development Cost Impact: (0,5000,5000,10000) | NO RESPONSE

Construction
```

Available (£): 1000
Available (Months): 5
Total Response Cost: £0
Total Response Months: 0

```
Mean Reduction on Inherent Risk (No-Response) LEC: £-2.8828
ID: 11 Cause: Regulation Effect: Development Cost Impact: (8000,10000,10000,12000) | Response: Reduce Benefit(%): 70 Effect: E Cost: 1
ID: 17 | Response: Reduce UNCHANGED
```

Project risks and chosen responses are sorted by their lifecycle phase

Options to optimise the responses with limited time and cost to maximise LCOE savings

Updates risk response to match optimisation changes

Total cost of taking the optimised response actions

Changes to the risk responses and mean saving on the inherent (no response) scenario

*Fig. 19. Actions Output*

Case Instructions:

In the top box, there are several project risks, sorted by lifecycle phase. If there is a risk response strategy selected in the response form then this is also shown. The second part of the form allows the user to optimise the risk responses to maximise LCOE savings with limited time and money resources. The available time and money for risk responses needs to be entered into the input boxes. When the ‘optimise’ button is pressed, the DSS calculates the possible benefit of each risk response strategy entered for each risk within the model and then maximises the LCOE saving whilst not exceeding the resource limitations. The output shows any changes, along with the cost and time of enacting this risk response strategy. It is then possible to update the risk responses to match the changes.

## *Appendix 1: Project Schedule*

| Ref. | Details | Prerequisite activities | Duration (Months) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Certain | Uncertain | | | |
| | | | Value | a | b | c | d |
| A | Pre-feasibility | - | 3 | 1.5 | 2 | 3 | 4 |
| B | Site acquisition | A | 2 | 1 | 2 | 2 | 2.5 |
| C | Concept design | B | 2 | 1 | 1 | 2 | 3 |
| D | Financial modelling | B | 3 | 2 | 3 | 3 | 4 |
| E | Planning permission | C,D | 2 | 2 | 2 | 3 | 3 |
| F | Find investors | E | 1 | 0 | 0.5 | 1 | 1 |
| G | Detailed design | E | 5 | 4 | 4 | 5 | 6 |
| H | Component tender and HOT | G | 4 | 3 | 4 | 4 | 5 |
| I | Feedstock tender and HOT | G | 3 | 2.5 | 3 | 3.5 | 5 |
| J | EPC tender and HOT | G | 4 | 2.5 | 3 | 4 | 5 |
| K | Grid connection HOT | G | 2 | 1 | 2 | 2 | 3 |
| L | PPA HOT | G | 2 | 1 | 2 | 2 | 3 |
| M | Due diligence | F,H,I,J,K,L | 4 | 2.5 | 3 | 4 | 4 |
| N | Financial close | M | 1 | 0.25 | 0.5 | 0.5 | 1 |
| O | Award contracts | N | 2 | 1 | 2 | 2 | 3 |
| P | Ground work | O | 4 | 3 | 3 | 4 | 5 |
| Q | Construction | O | 12 | 10 | 11 | 12 | 13 |
| R | CHP installation | O | 4 | 4 | 4 | 5 | 6 |
| S | Handover | P,Q,R | 0 | 0 | 0 | 0 | 0 |

## *Appendix 2: Add a New Risk*

*Example Risk:*

| **Risk Event** | **Description** | | **Project Impact** | | | **Uncertain Range** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Operation** | **Cause** | **Effect** | **Likelihood** | **Severity** | **Unit** | **Abs. min** | **Expected** | | Abs. max |
| | | | | | | | Lower | Upper | |
| Tax | Change in the tax rate | Tax rate increases | Moderate | Moderate | Increase (%) | 0 | 0.03 | 0.04 | 0.05 |

1. Press the + button
2. Select the lifecycle phase in which the risk is expected to occur: operation
3. Select the likelihood and severity
4. Select a risk cause and sub-cause from the lists and enter a cause description
5. Do the same for the effect

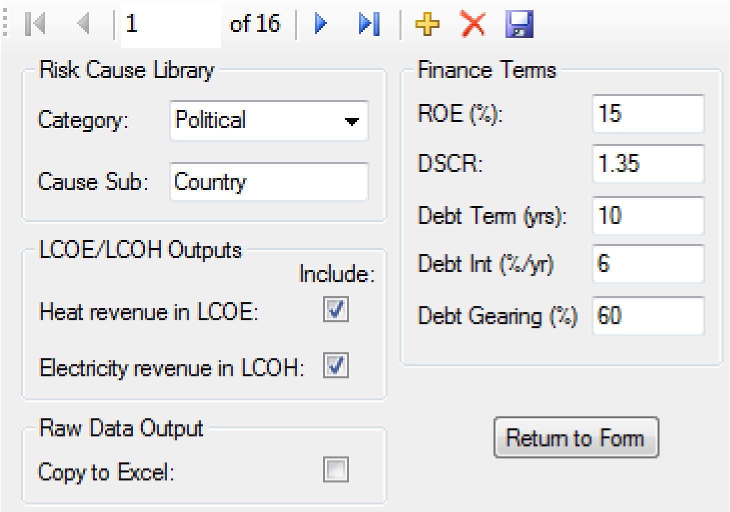
Note: Tax is under ‘finance’ and then ‘market’

6. Enter the range
7. Enter ‘N’ for attitude and ‘C’ for confident

Optional: continue adjusting the attitude and confidence multiple-choice boxes and pressing the graph button to better understand the effect of these inputs on the risk function form.

8. Save changes by clicking the save icon in the navigation bar.

## *Appendix 3: Settings Menu*



Category: Political

Cause Sub: Country

Include:

Heat revenue in LCOE: ☑

Electricity revenue in LCOH: ☑

Copy to Excel: ☐

ROE (%): 15

DSCR: 1.35

Debt Term (yrs): 10

Debt Int (%/yr) 6

Debt Gearing (%) 60

The settings menu has four key functions:

- Risk Cause Library: allow you to develop a library of risk causes to be used in the risk register and management process. The navigation bar can be used to cycle through, add or remove risks from the library;
- LCOE/LCOH Outputs: allow you to choose whether the revenue from onsite heat sales and heat incentives are included in the final levelised electricity unit cost price given in the finance outputs. The same option applies for electricity revenue when calculating the levelised heat unit cost;
- Finance Terms: this is the default finance terms utilised in the risk response register to calculate the LCOE saving of risk mitigation strategies and when optimising the risk mitigation strategies in the actions output;
- Raw Data Output: copies the finance graph outputs to an MS Excel spreadsheet to enable further analysis or use.

## Annex 5 – Initial Scenario Non-Fuzzy LCOE with Heat Revenue Not Included

| **Depreciation** | **Year** | 1 | 2 | 3 | 4 | 5 | … | 9 | 10 | … | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Begin Year | £ | 4000000 | 3600000 | 3200000 | 2800000 | 2400000 | … | 800000 | 400000 | … | 0 | 0 |
| Depreciation | £ | 400000 | 400000 | 400000 | 400000 | 400000 | … | 400000 | 400000 | … | 0 | 0 |
| End of Year | £ | 3600000 | 3200000 | 2800000 | 2400000 | 2000000 | … | 400000 | 0 | … | 0 | 0 |
| | | | | | | | | | | | | |
| Debt | | | | | | | | | | | | |
| Begin Year Debt | £ | 2880000 | 2661500 | 2429891 | 2184384 | 1924148 | … | 717406 | 369150.7 | … | 0 | 0 |
| Debt Service Payment | £ | 391299.7 | 391299.7 | 391299.7 | 391299.7 | 391299.7 | … | 391299.7 | 391299.7 | … | 0 | 0 |
| Interest | £ | 172800 | 159690 | 145793.4 | 131063.1 | 115448.9 | … | 43044.36 | 22149.04 | … | 0 | 0 |
| Principal | £ | 218499.7 | 231609.7 | 245506.3 | 260236.7 | 275850.9 | … | 348255.4 | 369150.7 | … | 0 | 0 |
| End Year Debt | £ | 2661500 | 2429891 | 2184384 | 1924148 | 1648297 | | 369150.7 | 0 | | 0 | 0 |
| | | | | | | | | | | | | |
| Energy Production | | | | | | | | | | | | |
| MWhe/yr | | 11826 | 11826 | 11826 | 11826 | 11826 | … | 11826 | 11826 | … | 11826 | 11826 |
| MWhth/yr | | 0 | 0 | 0 | 0 | 0 | … | 0 | 0 | … | 0 | 0 |
| | | | | | | | | | | | | |
| Revenue | | | | | | | | | | | | |
| Electricity Revenue (PPA/Sales) | £ | 1119720 | 1119720 | 1119720 | 1119720 | 1119720 | … | 1119720 | 1119720 | … | 1119720 | 1119720 |
| Heat Revenue (Sales) | £ | 0 | 0 | 0 | 0 | 0 | … | 0 | 0 | … | 0 | 0 |
| LEC | £ | 55582.2 | 55582.2 | 55582.2 | 55582.2 | 55582.2 | … | 55582.2 | 55582.2 | … | 55582.2 | 55582.2 |
| ROC | £ | 833733 | 833733 | 833733 | 833733 | 833733 | … | 833733 | 833733 | … | 833733 | 833733 |
| RHI | £ | 0 | 0 | 0 | 0 | 0 | … | 0 | 0 | … | 0 | 0 |
| Total Revenue | £ | 2009036 | 2009036 | 2009036 | 2009036 | 2009036 | … | 2009036 | 2009036 | … | 2009036 | 2009036 |
| | | | | | | | | | | | | |
| Costs | | | | | | | | | | | | |
| Feedstock | £ | -804918 | -804918 | -804918 | -804918 | -804918 | … | -804918 | -804918 | … | -804918 | -804918 |
| O&M | £ | -505000 | -505000 | -505000 | -505000 | -505000 | … | -505000 | -505000 | … | -505000 | -505000 |
| | | | | | | | | | | | | |
| EBITDA | £ | 699117.4 | 699117.4 | 699117.4 | 699117.4 | 699117.4 | | 699117.4 | 699117.4 | | 699117.4 | 699117.4 |
| Depreciation | £ | -400000 | -400000 | -400000 | -400000 | -400000 | … | -400000 | -400000 | … | 0 | 0 |
| EBIT | £ | 299117.4 | 299117.4 | 299117.4 | 299117.4 | 299117.4 | … | 299117.4 | 299117.4 | … | 699117.4 | 699117.4 |
| Interest | £ | -172800 | -159690 | -145793 | -131063 | -115449 | … | -43044.4 | -22149 | … | 0 | 0 |
| EBT | £ | 126317.4 | 139427.4 | 153323.9 | 168054.3 | 183668.5 | … | 256073 | 276968.3 | … | 699117.4 | 699117.4 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tax | £ | 35368.86 | 39039.66 | 42930.7 | 47055.21 | 51427.18 | … | 71700.44 | 77551.13 | … | 195752.9 | 195752.9 |
| After Tax | £ | 90948.51 | 100387.7 | 110393.2 | 120999.1 | 132241.3 | … | 184372.6 | 199417.2 | … | 503364.5 | 503364.5 |
| Add back depreciation | £ | 400000 | 400000 | 400000 | 400000 | 400000 | … | 400000 | 400000 | … | 0 | 0 |
| Deduct Principal | £ | -218500 | -231610 | -245506 | -260237 | -275851 | … | -348255 | -369151 | … | 0 | 0 |
| Free Cash Flow (Equity Investment Dividends) | £ | 272448.8 | 268778 | 264886.9 | 260762.4 | 256390.5 | … | 236117.2 | 230266.5 | … | 503364.5 | 503364.5 |
| ROE | % | 15 | | | | | | | | | | |
| DSC | £ | 699117.4 | 699117.4 | 699117.4 | 699117.4 | 699117.4 | | 699117.4 | 699117.4 | | 0 | 0 |
| DSCR | | 1.787 | 1.787 | 1.787 | 1.787 | 1.787 | … | 1.787 | 1.787 | … | 0 | 0 |
| DSCR Minimum LEC | £ | 80.235 | 80.235 | 80.235 | 80.235 | 80.235 | … | 80.235 | 80.235 | … | | |
| LCOE Price | £/MWhe | 94.683 | | | | | | | | | | |
| LCOH Price | £/MWhth | 0 | | | | | | | | | | |

| CHPQA ROC Uplift | |
|---|---|
| X Value | 370 |
| V Value | 120 |
| Power Efficiency | 15% |
| Heat Efficiency | 0 |
| QI | 56.626 |
| ROC Uplift | 0 |

## Annex 6 – Initial Scenario Non-Fuzzy LCOE with Heat Revenue Included and ROC Uplift

| Depreciation | Year | 1 | 2 | 3 | 4 | 5 | … | 9 | 10 | … | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Begin Year | £ | 4000000 | 3600000 | 3200000 | 2800000 | 2400000 | … | 800000 | 400000 | … | 0 | 0 |
| Depreciation | £ | 400000 | 400000 | 400000 | 400000 | 400000 | … | 400000 | 400000 | … | 0 | 0 |
| End of Year | £ | 3600000 | 3200000 | 2800000 | 2400000 | 2000000 | … | 400000 | 0 | … | 0 | 0 |
| | | | | | | | | | | | | |
| Debt | | | | | | | | | | | | |
| Begin Year Debt | £ | 2880000 | 2661500 | 2429891 | 2184384 | 1924148 | … | 717406 | 369150.7 | … | 0 | 0 |
| Debt Service Payment | £ | 391299.7 | 391299.7 | 391299.7 | 391299.7 | 391299.7 | … | 391299.7 | 391299.7 | … | 0 | 0 |
| Interest | £ | 172800 | 159690 | 145793.4 | 131063.1 | 115448.9 | … | 43044.36 | 22149.04 | … | 0 | 0 |
| Principal | £ | 218499.7 | 231609.7 | 245506.3 | 260236.7 | 275850.9 | … | 348255.4 | 369150.7 | … | 0 | 0 |
| End Year Debt | £ | 2661500 | 2429891 | 2184384 | 1924148 | 1648297 | | 369150.7 | 0 | | 0 | 0 |
| | | | | | | | | | | | | |
| Energy Production | | | | | | | | | | | | |
| MWhe/yr | | 11826 | 11826 | 11826 | 11826 | 11826 | … | 11826 | 11826 | … | 11826 | 11826 |
| MWhth/yr | | 1700.036 | 1700.036 | 1700.036 | 1700.036 | 1700.036 | … | 1700.036 | 1700.036 | … | 1700.036 | 1700.036 |
| | | | | | | | | | | | | |
| Revenue | | | | | | | | | | | | |
| Electricity Revenue (PPA/Sales) | £ | 1024147 | 1024147 | 1024147 | 1024147 | 1024147 | … | 1024147 | 1024147 | … | 1024147 | 1024147 |
| Heat Revenue (Sales) | £ | 78657.8 | 78657.8 | 78657.8 | 78657.8 | 78657.8 | … | 78657.8 | 78657.8 | … | 78657.8 | 78657.8 |
| LEC | £ | 55582.2 | 55582.2 | 55582.2 | 55582.2 | 55582.2 | … | 55582.2 | 55582.2 | … | 55582.2 | 55582.2 |
| ROC | £ | 850648.8 | 850648.8 | 850648.8 | 850648.8 | 850648.8 | … | 850648.8 | 850648.8 | … | 850648.8 | 850648.8 |
| RHI | £ | 0 | 0 | 0 | 0 | 0 | … | 0 | 0 | … | 0 | 0 |
| Total Revenue | £ | 2009036 | 2009036 | 2009036 | 2009036 | 2009036 | … | 2009036 | 2009036 | … | 2009036 | 2009036 |
| | | | | | | | | | | | | |
| Costs | | | | | | | | | | | | |
| Feedstock | £ | -804918 | -804918 | -804918 | -804918 | -804918 | … | -804918 | -804918 | … | -804918 | -804918 |
| O&M | £ | -505000 | -505000 | -505000 | -505000 | -505000 | … | -505000 | -505000 | … | -505000 | -505000 |
| | | | | | | | | | | | | |
| EBITDA | £ | 699117.3 | 699117.3 | 699117.3 | 699117.3 | 699117.3 | | 699117.3 | 699117.3 | | 699117.3 | 699117.3 |
| Depreciation | £ | -400000 | -400000 | -400000 | -400000 | -400000 | … | -400000 | -400000 | … | 0 | 0 |
| EBIT | £ | 299117.3 | 299117.3 | 299117.3 | 299117.3 | 299117.3 | … | 299117.3 | 299117.3 | … | 699117.3 | 699117.3 |
| Interest | £ | -172800 | -159690 | -145793 | -131063 | -115449 | … | -43044.4 | -22149 | … | 0 | 0 |
| EBT | £ | 126317.3 | 139427.3 | 153323.8 | 168054.2 | 183668.4 | … | 256072.9 | 276968.2 | … | 699117.3 | 699117.3 |
| Tax | £ | 35368.84 | 39039.63 | 42930.67 | 47055.18 | 51427.16 | … | 71700.41 | 77551.1 | … | 195752.8 | 195752.8 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| After Tax | £ | 90948.44 | 100387.6 | 110393.2 | 120999 | 132241.3 | … | 184372.5 | 199417.1 | … | 503364.4 | 503364.4 |
| Add back depreciation | £ | 400000 | 400000 | 400000 | 400000 | 400000 | … | 400000 | 400000 | … | 0 | 0 |
| Deduct Principal | £ | -218500 | -231610 | -245506 | -260237 | -275851 | … | -348255 | -369151 | … | 0 | 0 |
| Free Cash Flow (Equity Investment Dividends) | £ | 272448.7 | 268777.9 | 264886.9 | 260762.4 | 256390.4 | … | 236117.1 | 230266.4 | … | 503364.4 | 503364.4 |
| ROE | % | 15 |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| DSC | £ | 699117.3 | 699117.3 | 699117.3 | 699117.3 | 699117.3 |  | 699117.3 | 699117.3 |  | 0 | 0 |
| DSCR |  | 1.787 | 1.787 | 1.787 | 1.787 | 1.787 | … | 1.787 | 1.787 | … | 0 | 0 |
| DSCR Minimum LEC | £ | 72.153 | 72.153 | 72.153 | 72.153 | 72.153 | … | 72.153 | 72.153 | … |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| LCOE Price | £/MWhe | 86.601 |  |  |  |  |  |  |  |  |  |  |
| LCOH Price | £/MWhth | 0 |  |  |  |  |  |  |  |  |  |  |

| CHPQA ROC Uplift |  |
|---|---|
| X Value | 370 |
| V Value | 120 |
| Power Efficiency | 15% |
| Heat Efficiency | 2% |
| QI | 59.266 |
| ROC Uplift | 0.03043 |

## Annex 7 – Initial Scenario Non-Fuzzy LCOE with Heat Revenue Included and RHI

| Depreciation | Year | 1 | 2 | 3 | 4 | 5 | … | 9 | 10 | … | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Begin Year | £ | 4000000 | 3600000 | 3200000 | 2800000 | 2400000 | … | 800000 | 400000 | … | 0 | 0 |
| Depreciation | £ | 400000 | 400000 | 400000 | 400000 | 400000 | … | 400000 | 400000 | … | 0 | 0 |
| End of Year | £ | 3600000 | 3200000 | 2800000 | 2400000 | 2000000 | … | 400000 | 0 | … | 0 | 0 |
| | | | | | | | | | | | | |
| Debt | | | | | | | | | | | | |
| Begin Year Debt | £ | 2880000 | 2661500 | 2429891 | 2184384 | 1924148 | … | 717406 | 369150.7 | … | 0 | 0 |
| Debt Service Payment | £ | 391299.7 | 391299.7 | 391299.7 | 391299.7 | 391299.7 | … | 391299.7 | 391299.7 | … | 0 | 0 |
| Interest | £ | 172800 | 159690 | 145793.4 | 131063.1 | 115448.9 | … | 43044.36 | 22149.04 | … | 0 | 0 |
| Principal | £ | 218499.7 | 231609.7 | 245506.3 | 260236.7 | 275850.9 | … | 348255.4 | 369150.7 | … | 0 | 0 |
| End Year Debt | £ | 2661500 | 2429891 | 2184384 | 1924148 | 1648297 | | 369150.7 | 0 | | 0 | 0 |
| | | | | | | | | | | | | |
| Energy Production | | | | | | | | | | | | |
| MWhe/yr | | 11826 | 11826 | 11826 | 11826 | 11826 | … | 11826 | 11826 | … | 11826 | 11826 |
| MWhth/yr | | 1700.036 | 1700.036 | 1700.036 | 1700.036 | 1700.036 | … | 1700.036 | 1700.036 | … | 1700.036 | 1700.036 |
| | | | | | | | | | | | | |
| Revenue | | | | | | | | | | | | |
| Electricity Revenue (PPA/Sales) | £ | 1024062 | 1024062 | 1024062 | 1024062 | 1024062 | … | 1024062 | 1024062 | … | 1024062 | 1024062 |
| Heat Revenue (Sales) | £ | 78657.8 | 78657.8 | 78657.8 | 78657.8 | 78657.8 | … | 78657.8 | 78657.8 | … | 78657.8 | 78657.8 |
| LEC | £ | 55582.2 | 55582.2 | 55582.2 | 55582.2 | 55582.2 | … | 55582.2 | 55582.2 | … | 55582.2 | 55582.2 |
| ROC | £ | 833733 | 833733 | 833733 | 833733 | 833733 | … | 833733 | 833733 | … | 833733 | 833733 |
| RHI | £ | 17000.36 | 17000.36 | 17000.36 | 17000.36 | 17000.36 | … | 17000.36 | 17000.36 | … | 17000.36 | 17000.36 |
| Total Revenue | £ | 2009036 | 2009036 | 2009036 | 2009036 | 2009036 | … | 2009036 | 2009036 | … | 2009036 | 2009036 |
| | | | | | | | | | | | | |
| Costs | | | | | | | | | | | | |
| Feedstock | £ | -804918 | -804918 | -804918 | -804918 | -804918 | … | -804918 | -804918 | … | -804918 | -804918 |
| O&M | £ | -505000 | -505000 | -505000 | -505000 | -505000 | … | -505000 | -505000 | … | -505000 | -505000 |
| | | | | | | | | | | | | |
| EBITDA | £ | 699117.2 | 699117.2 | 699117.2 | 699117.2 | 699117.2 | | 699117.2 | 699117.2 | | 699117.2 | 699117.2 |
| Depreciation | £ | -400000 | -400000 | -400000 | -400000 | -400000 | … | -400000 | -400000 | … | 0 | 0 |
| EBIT | £ | 299117.2 | 299117.2 | 299117.2 | 299117.2 | 299117.2 | … | 299117.2 | 299117.2 | … | 699117.2 | 699117.2 |
| Interest | £ | -172800 | -159690 | -145793 | -131063 | -115449 | … | -43044.4 | -22149 | … | 0 | 0 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EBT | £ | 126317.2 | 139427.2 | 153323.8 | 168054.2 | 183668.4 | … | 256072.9 | 276968.2 | … | 699117.2 | 699117.2 |
| Tax | £ | 35368.83 | 39039.62 | 42930.67 | 47055.17 | 51427.15 | … | 71700.41 | 77551.1 | … | 195752.8 | 195752.8 |
| After Tax | £ | 90948.42 | 100387.6 | 110393.1 | 120999 | 132241.2 | … | 184372.5 | 199417.1 | … | 503364.4 | 503364.4 |
| Add back depreciation | £ | 400000 | 400000 | 400000 | 400000 | 400000 | … | 400000 | 400000 | … | 0 | 0 |
| Deduct Principal | £ | -218500 | -231610 | -245506 | -260237 | -275851 | … | -348255 | -369151 | … | 0 | 0 |
| Free Cash Flow (Equity Investment Dividends) | £ | 272448.7 | 268777.9 | 264886.9 | 260762.4 | 256390.4 | … | 236117.1 | 230266.4 | … | 503364.4 | 503364.4 |
| ROE | % | 15 |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| DSC | £ | 699117.2 | 699117.2 | 699117.2 | 699117.2 | 699117.2 |  | 699117.2 | 699117.2 |  | 0 | 0 |
| DSCR |  | 1.787 | 1.787 | 1.787 | 1.787 | 1.787 | … | 1.787 | 1.787 | … | 0 | 0 |
| DSCR Minimum LEC | £ | 72.146 | 72.146 | 72.146 | 72.146 | 72.146 | … | 72.146 | 72.146 | … |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| LCOE Price | £/MWhe | 86.594 |  |  |  |  |  |  |  |  |  |  |
| LCOH Price | £/MWhth | 0 |  |  |  |  |  |  |  |  |  |  |

## Annex 8 – bCHP DSS Software Installation Instructions

**Step 1:** Before installing the Software it is necessary to update your Microsoft .Net Framework Software and have the latest SQL Software installed. Both are free to update on the Microsoft website and the links are given below:

.Net Framework 4 Client Profile:
http://www.microsoft.com/en-us/download/details.aspx?id=17851

SQL Compact 3.5 SP2:
http://www.microsoft.com/en-us/download/details.aspx?id=5783

**Note:** When running the SQL update there are two options. You will need to install the correct version(s) for your computer: if you have a 64bit operating system install x64 and x86, or just install x86 for a 32bit system.

**Step 2:** Insert the CD and access the 'bCHP DSS Install Files.zip' file.

**Step 3:** Click on the 'bCHPPlanningModelInstall.msi' file and follow the instructions.

**Step 4:** You can now access the bCHP DSS Software from your desktop or programs menu.

**Uninstall the Software:** Locate the Software under the name 'bCHPPlanningModelInstall' within the 'uninstall a program menu' within the Control Panel and follow the instructions.

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