DEVELOPING A DECISION FRAMEWORK FOR THE STRATEGIC SOURCING OF BIOMASS

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Thesis summary

The deployment of bioenergy technologies is a key part of UK and European renewable energy policy. A key barrier to the deployment of bioenergy technologies is the management of biomass supply chains including the evaluation of suppliers and the contracting of biomass. In the undeveloped biomass for energy market buyers of biomass are faced with three major challenges during the development of new bioenergy projects. What characteristics will a certain supply of biomass have, how to evaluate biomass suppliers and which suppliers to contract with in order to provide a portfolio of suppliers that best satisfies the needs of the project and its stakeholder group whilst also satisfying crisp and non-crisp technological constraints. The problem description is taken from the situation faced by the industrial partner in this research, Express Energy Ltd.

This research tackles these three areas separately then combines them to form a decision framework to assist biomass buyers with the strategic sourcing of biomass. The BioSS framework. The BioSS framework consists of three modes which mirror the development stages of bioenergy projects. BioSS.2 mode for early stage development, BioSS.3 mode for financial close stage and BioSS.Op for the operational phase of the project. BioSS is formed of a fuels library, a supplier evaluation module and an order allocation module, a Monte-Carlo analysis module is also included to evaluate the accuracy of the recommended portfolios.

In each mode BioSS can recommend which suppliers should be contracted with and how much material should be purchased from each. The recommended blend should have chemical characteristics within the technological constraints of the conversion technology and also best satisfy the stakeholder group.

The fuels library is made up from a wide variety of sources and contains around 100 unique descriptions of potential biomass sources that a developer may encounter. The library takes a wide data collection approach and has the aim of allowing for estimates to be made of biomass characteristics without expensive and time consuming testing

The supplier evaluation part of BioSS uses a QFD-AHP method to give importance weightings to 27 different evaluating criteria. The evaluating criteria have been compiled from interviews with stakeholders and policy and position documents and the weightings have been assigned using a mixture of workshops and expert interview. The weighted importance scores allow potential suppliers to better tailor their business offering and provides a robust framework for decision makers to better understand the requirements of the bioenergy project stakeholder groups.

The order allocation part of BioSS uses a chance-constrained programming approach to assign orders of material between potential suppliers based on the chemical characteristics of those suppliers and the preference score of those suppliers. The optimisation program finds the portfolio of orders to allocate to suppliers to give the highest performance portfolio in the eyes of the stakeholder group whilst also complying with technological constraints. The technological constraints can be breached if the decision maker requires by setting the constraint as a chance-constraint. This allows a wider range of biomass sources to be procured and allows a greater overall performance to be realised than considering crisp constraints or using deterministic programming approaches.

BioSS is demonstrated against two scenarios faced by UK bioenergy developers. The first is a large scale combustion power project, the second a small scale gasification project. The Bioss is applied in each mode for both scenarios and is shown to adapt the solution to the stakeholder group importance and the different constraints of the different conversion technologies whilst finding a globally optimal portfolio for stakeholder satisfaction.

Key words: Bioenergy; AHP; optimisation; stakeholder; strategic sourcing

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Chapter 1. Introduction

This chapter intended to provide an overview of this thesis titled developing a framework for the strategic sourcing of biomass. The current state of the industry bioenergy and its policy background are discussed in section 1.1. Express Energy Ltd, the industrial partner and their role in this research is discussed in section 1.1.4. Section 1.2 defines the problem being faced by companies such as Express Energy Ltd regarding the strategic sourcing of biomass materials and defines the problem that will be addressed in this thesis. The overall aims of the presented research are stated in section 1.3. Section 1.4 gives an overview of the approach that is used to address the three identified research problems and shows the research objectives and outcomes for each problem. Section 1.5 describes how the thesis is organised according to these objectives.

1.1 Thesis background

This section sets out the industry and policy background against which the presented research is set. Bioenergy is a term used to describe any form of energy that is generated from biomass sources. Political and social interest in this energy resource is centred around the low, zero or negative greenhouse gas emissions released when converting certain types of sustainable biomass to bioenergy. Biomass resources is a broad term covering a massive range of organic materials ranging from specially grown energy crops, through residues from agriculture to organic waste streams that are difficult and expensive to handle and treat. This chapter discusses the nature of the biomass resource and its availability within the UK in section 1.1.1, then the policy background and incentives and the response from UK developers in section 1.1.2 and 1.1.3 respectively. The industrial research partner Express Energy and their role in the industry and the research is defined in section 1.1.4.

1.1.1 Bioenergy and the biomass resource

Bioenergy refers to energy derived from biomass materials. Biomass is a catch-all term referring to organic matter recently alive (CCC, 2011). Biomass sources include solid and liquid wastes through woody forestry crops, agricultural residues to energy crops and grasses grown specifically for energy conversion purposes. There are several technology routes available for the conversion of biomass to electricity as shown in Figure 1.1. Each of which are better suited to different applications, scales and biomass feedstock types. Not all bioenergy production routes are shown but notable others include hydrogen from biomass, composting, biofuels and integrated technologies where the output of one process becomes the input to another.

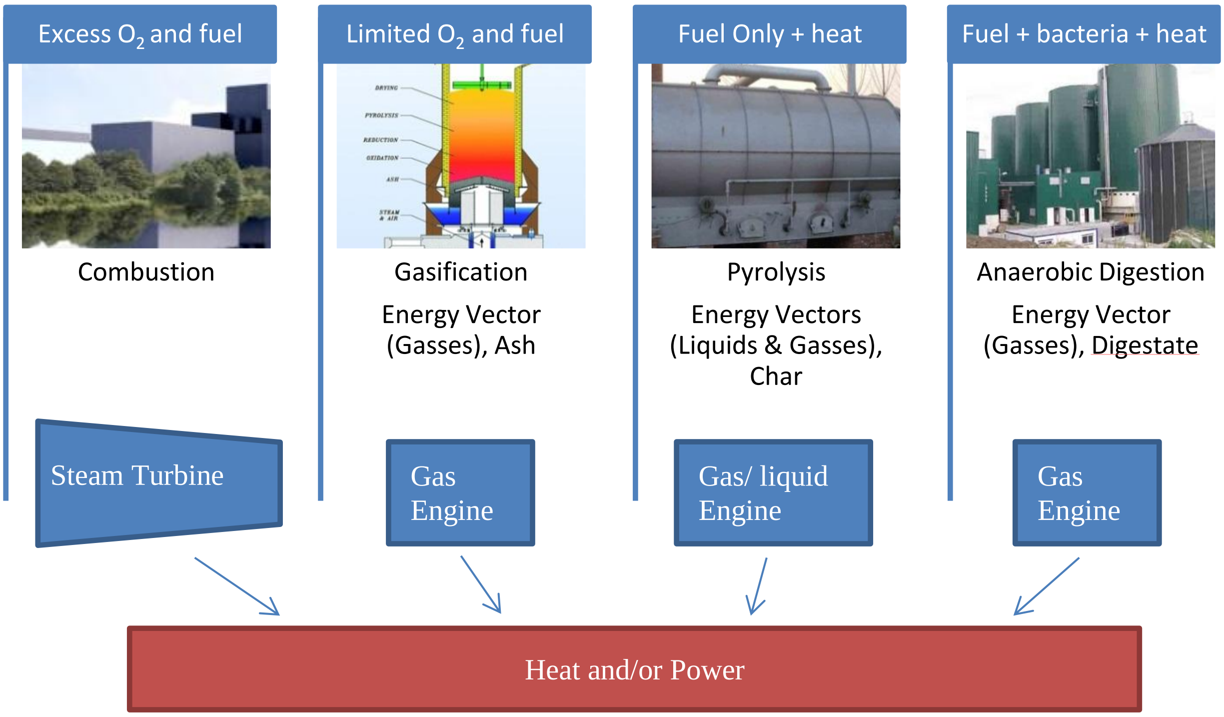

Figure 1.1: Different routes to energy conversion (not including biofuels)

Combustion technologies dominate the current use of biomass both in a global and UK context. High efficiency domestic and small commercial scale boilers have come to the UK market recently and compare economically against fuel oil and delivered gasoline in off-gas-grid areas. At larger scales a small number of large capacity dedicated biomass combustion power stations have been proposed for the UK and biomass is mixed with coal for co-firing at several coal power stations in the UK and Europe. Large utilities are also investigating options to convert coal boilers to biomass boilers (DRAX, 2013).

Anaerobic Digestion (AD) is a biological process has gained popularity for on-farm applications and the technology is well developed in Europe, especially Germany, recently there has been a surge in interest from local councils in AD as a method for dealing with municipal organic wastes and with water companies to deal with sewage wastes. AD produces a biogas rich in methane and a further route to energy is the direct injection into the existing natural gas grid.

Gasification and Pyrolysis processes are classed as advanced conversion technologies (ACT) and have attracted healthy financial incentives from the UK government. Both offer flexibility in both scale and feedstock, able to efficiently process low value waste materials as well as virgin biomass. However reliability issues and development cost appear to have hindered deployment to date (Thornley, 2006, SÖDRA et al., Gill et al., 2005).

The biomass resource available consists of a massive range of materials and mixtures of materials that may be described as biomass. Some examples of biomass sources and products are shown in the pictures in Table 1.1. To convert the sources to products a variety of pre-treatment and conversion technologies and processes exist including dryers, pelletisers, mechanical sorting and biological treatment. The products shown in Table 1.1 are energy vectors that can be converted to heat and electricity depending on the technology being used from Figure 1.1.

Table 1.1: Biomass sources and products suitable for bioenergy. (Images from edie.net, Hadfields wood recycling ltd, letsrecycle.com, the forestry commission, NFU, Shanks Ltd, pellet energy, Coal Products Ltd)

Examples of biomass sources		Biomass products available for purchase	
	Woody energy crops (Short rotation coppice willow)		Refuse derived fuel pellets
	Recycled wood		Wood chips
	Forestry thinning and residue		Wood pellets
	Agricultural residue		Refuse derived fuel (RDF)
	Food waste		Coal substitute (50% blended with fossil fuels)
	Municipal solid waste (MSW) -Organic fraction		Charcoal
	Animal waste		Biogas products

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Many of the biomass sources on the left of Table 1.1 are waste or by-products of other products and processes. The products on the right of Table 1.1 are energy dense products that are available to be converted straight to energy although technical and regulatory restrictions exist for the use of these products. Between the left and the right hand side of Table 1.1 a gulf in value exists, this is demonstrated in Figure 1.2. Residual biomass materials are usually treated as a waste, or sometimes as a by-product. The UK government has had legislation in place for many years to control the disposal of waste, especially to landfill and introduced a landfill tax mechanism to discourage the disposal of waste to landfill, particularly organic wastes. This means that some residual biomass materials such as organic fractions of municipal waste and food waste have a negative cost associated. If this type of material can be upgraded to energy carriers its value increases. Figure 1.2 shows the value chain of bioenergy generated from residual biomass or from biomass fuel products. Biomass fuel products such as the refuse derived fuel (RDF) in Table 1.1 has a positive price whilst residual biomass that is treated as a waste has a negative price due to disposal costs. At the higher end of the value chain is electricity and heat although bio-oils, bio-chemicals, fertilizers and biofuels can also command a high value.

The value adding processes that biomass materials can go through are also shown in Figure 1.2. They are the collection of material, aggregation of material into bulk quantities, purification of material, densification of the energy content, classification of material and finally the conversion into energy.

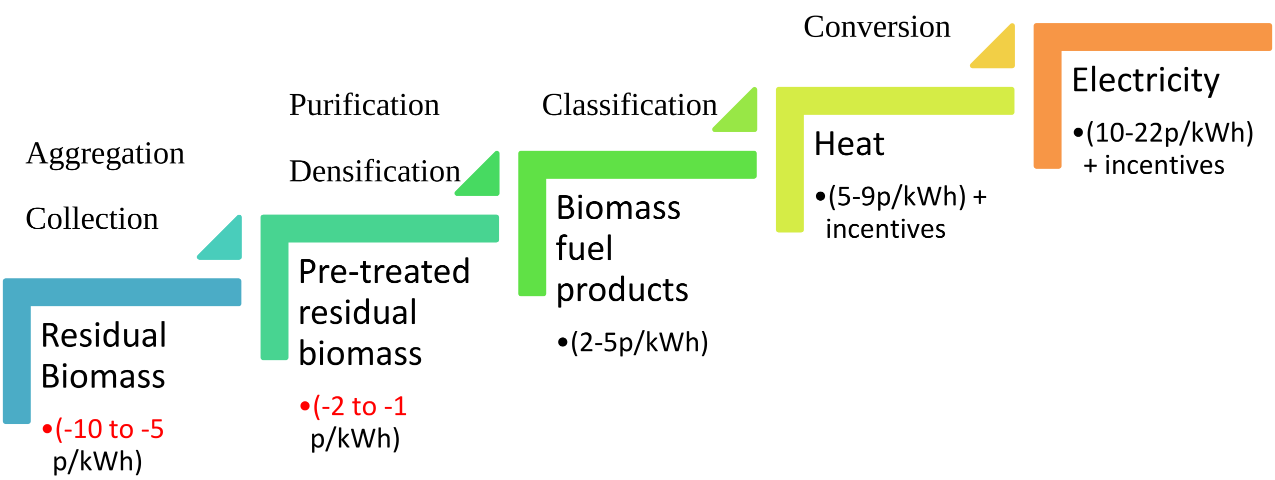

Figure 1.2: Value chain for bioenergy

As with most value chains the residual biomass to energy value chain is influenced by external cost factors. Just as landfill tax influences the beginning of the value chain the price of electricity and heat generation from conventional sources dictates the price of heat and electricity shown in. The cost of pre-treatment dictates the minimum price of biomass fuel products and the selling price of those products is also dictated by the marginal cost against other heating fuels.

Other non-energy centred industries have become involved in the value chain shown in Figure 1.2. Waste sorting and treatment has become a large industry in the UK valued at £13 billion in 2011 (ekogen, 2011) against a background of recycling targets for municipal councils, landfill tax and increasing resource prices such as steel and oil based plastics (defra, 2011). This growth has involved the increased efficiency of waste sorting plants, segregating mixed waste streams into relatively pure fractions of metals, plastics, glass and increasingly organic fractions including wood. The residue or residual waste from this material recovery process depends on both the process and the waste stream but can contain significant proportions of organics suitable for upgrading to biomass fuels. This material is usually sent to landfill or mass incineration under current operating conditions.

1.1.2 Policy background

UK Energy Policy has undergone significant changes over the past 15 years in response to various social, economic, environmental and political drivers. The main factors for change are an increasing public and political requirement to reduce national greenhouse gas emissions in response to evidence on anthropologic impact on climate change and also the need for a secure and affordable supply of energy (DECC, 2012e). In general energy policy has also moved away from the electricity biased legislation associated with the privatisation of UK electricity markets during the 1980s and 1990s. More recent government policy has focused on a transition towards a low carbon economy and the forecast shortage in generation capacity (DTI 2003; DTI 2007). More recent policy also considers energy for heating and transport and secondary energy use in offshore manufacturing as well as electricity generation.

The major strategy document for the EU is the 2020 growth strategy. This consists of five objectives around employment, innovation, education, social inclusion and climate/energy (EC, 2010). This strategy sets key goals for renewable energy to play a greater part in the provision of final energy demand for the EU27 nations. The associated 2009 Renewable Energy Strategy sets the EU overall Renewable Energy target at 20% and also sets the UK a target of 15%. Figure 1.3 shows the current performance against these targets for the UK and the EU27 member states average. Around a threefold increase in renewable energy market penetration is required between 2010 and 2020 for the UK to reach the 15% target, at the time of writing the EuroStat data has not been updated but the UK 2011 figure is reported as 3.8% (DECC, 2012b).

The UK governments most recent response to this challenge is the renewable energy roadmap (DECC, 2011c) which sets out a lead scenario suggesting that 30% or more of electricity generation could come from renewable sources by 2020 compared to 6.7% in 2011 (DECC, 2012e). The committee on Climate Change has also set an ambitious target of an 80% reduction in Greenhouse Gas (GHG) emissions by 2050 (against 1990 levels), although this is not written into statute as the EU 15% 2020 target is. Various other targets exist for renewable transport, heat and electricity production.

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Figure 1.3: EU27 Renewable Energy targets and progress. Source: (EuroStat, 2012)

Figure 1.4 shows the mix of technologies and the amount of energy generated from each that are expected to be developed to meet the 2020 15% target for the UK according to the renewable energy roadmap (DECC, 2011c). The roadmap modelled low and high scenarios of deployment depending on economic growth and the energy intensity of that growth. In both scenarios over half of the renewable energy capacity that will go towards meeting the 2020 target comes from biomass resources as shown in Figure 1.5.

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Figure 1.4: Primary energy mix expected to deliver renewable energy in 2020 (DECC, 2011c)

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Figure 1.5: percentage of 2020 energy mix to come from biomass sources (DECC, 2011c)

At an EU level this situation is repeated, Figure 1.6 shows a similar chart for the 27 EU member states adapted from a report by the European Climate Foundation and industrial partners (SÖDRA et al.).

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Figure 1.6: Growth in Renewable Energy for the European Union under the 2020 Renewable Energy Targets. Adapted from (SÖDRA et al., Capros et al., 2008)

To assist industry in meeting these targets the UK government has implemented three major financial incentive schemes, all operating with slightly different mechanisms and at differing scales and technologies. In 2002 the renewables obligation (RO) came into force, this renewable energy certificate trading scheme is the major UK policy tool to incentivise deployment of renewable electricity generating capacity. From 2010 a Feed In Tariff (FIT(s)) scheme with incentive bands for different technologies and scales was introduced and from 2011 the renewable heat incentive (RHI) was introduced, operating in a similar way to FiTs but for renewable heat generation. Various demand side incentives such as increased public sector uptake schemes for biomass heating, capital grants, streamlined planning application rules, tax breaks and technology acceleration projects have also been introduced. The biomass supply side has not received such interventionist policies, the market has largely left been left to arrange the most efficient deployment of existing technology.

Under the renewables obligation generators claim renewable obligation certificates (ROCs) for electricity generated from renewable sources. Each supplier is obliged to meet an incremental target for renewable electricity generated. The target started at 3% in 2002 and is set to rise to 15.4% by 2015 and beyond (DECC, 2011a). For each unit of renewable electricity generated the generator is awarded of the certificates known as Renewable Obligation Certificates (ROCs), these are then sold to the supplier using an exchange market. There is a financial penalty levied onto suppliers for any shortfall against the yearly target. This arrangement makes the ROC a tradable commodity that can be bought and sold quite independently of the electricity purchased and the ROCs therefore have a market value determined by supply, demand and the cost of the shortfall fine. This process is schematically shown in Figure 1.8. The government has set bands for ROCs to encourage innovation within the generation mix, aiming to increase investment in less commercially competitive technologies. Figure 1.7 shows the ROC price and the number of certificates being traded including those traded for co-firing of biomass with coal. The value of the incentive are converted to show the incentive revenue per unit of energy in Figure 1.9 for electricity from biomass and Figure 1.10 for heat from biomass including biogas to grid injection.

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Figure 1.7: Historical data for ROC market

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Figure 1.8: The structure of the RO renewable energy certificate trading scheme for the UK (source DECC, 2012g)

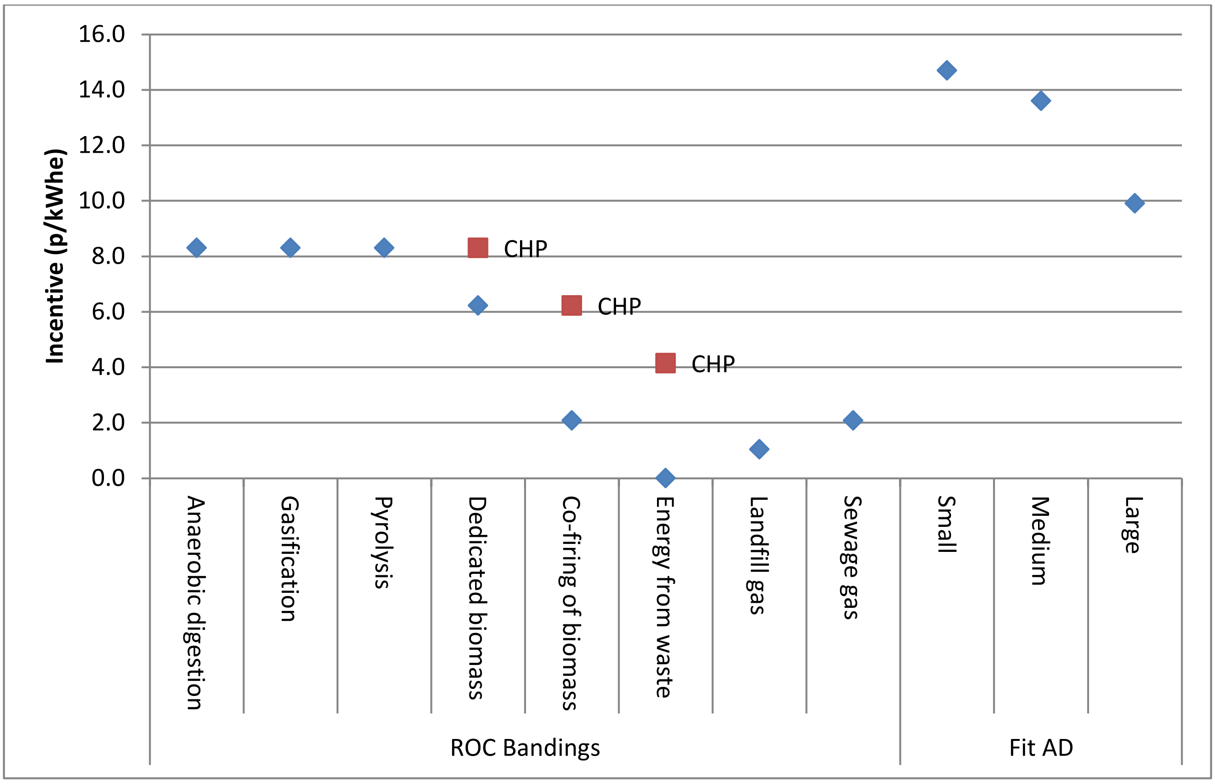

Figure 1.9: Electricity incentives for biomass renewables (calculated from Jan 2013 prices)

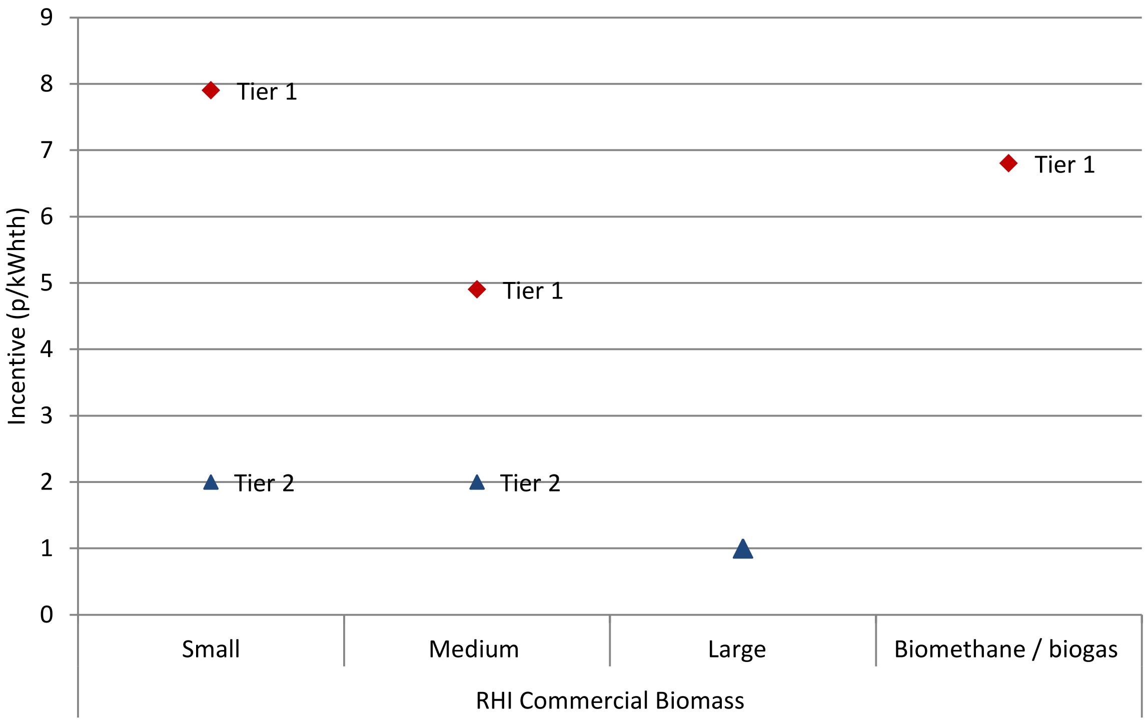

Figure 1.10: Heat incentives for biomass renewables

1.1.3 The UK bioenergy industry

Figure 1.11 shows the relative scale of UK biomass electricity developments compared to other generation technologies. The UK electricity market has traditionally been centralised with few large fossil fuel or nuclear power stations, this appears to be changing with many more smaller generators coming online (although there are still few generating companies in the UK). The fleet of large (circa 2GW) coal power stations shown in Figure 1.11 face a dwindling market in the coming decade as EU air emission restrictions in line with the European Large Combustion Plant Directive (EC, 2001a) reduce their potential operating hours. At least 5 of the coal power stations shown have opted out of the directive and will close by the end of 2015 with the others considering co-firing with biomass or conversion to dedicated biomass schemes.

Figure 1.12 along with Figure 1.13 shows more detail on the current state of UK biomass power developments. Although this picture changes constantly with planning and development decisions made in the industry it provides a telling snapshot of the industry. The red line in Figure 1.12 represents the section 56 planning legislation cut-off. Above 50MW UK legislation classifies developments as being part of strategic infrastructure planning and require a centralised decision making process regarding weather the plant can be built. This requires significantly more investment at the development stage regarding environmental impact assessment and strategic impact assessment making the planning permission process longer and more complex.

According to DECC (2012h) there are 4.8 GW of biomass electricity generation within the development pipeline. According to data collected from the various developers websites and project proposals as well as assistance from Express Energy Ltd these proposed power stations draw from a variety of biomass sources. The exact sources of material to be used are not publically available and the required description for the public planning permission process usually limits the description of fuel to very general statements, for instance ‘recovered wood’, ‘virgin wood’, ‘recycled wood’ or ‘residual biomass’. Figure 1.14 shows an estimate of the type of biomass being used or proposed for use in biomass power schemes. The estimate has been made from developer’s websites, planning information and other sources, including political group websites and biomass opposition websites.

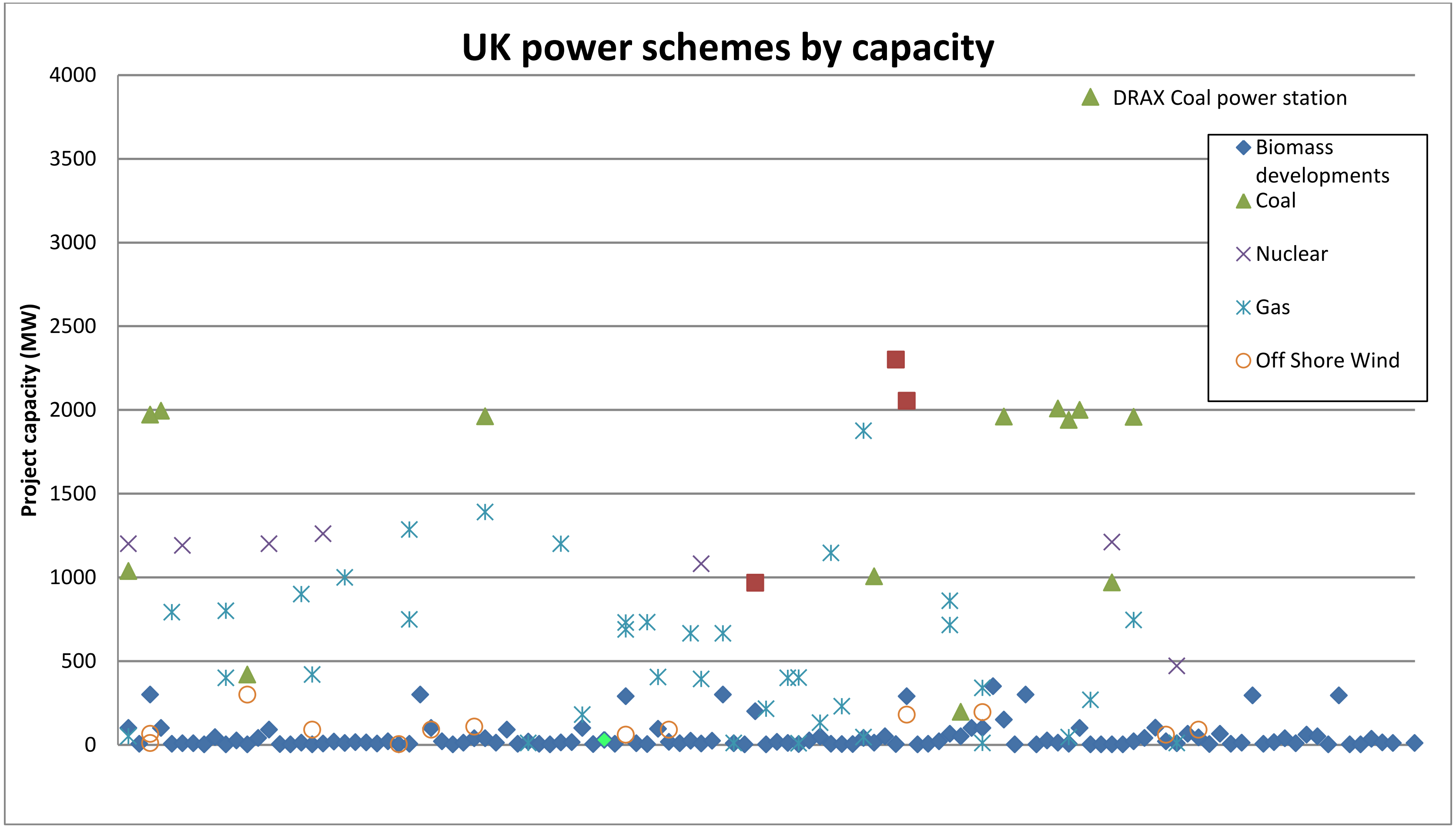

Figure 1.11: UK power projects (existing and proposed) by capacity

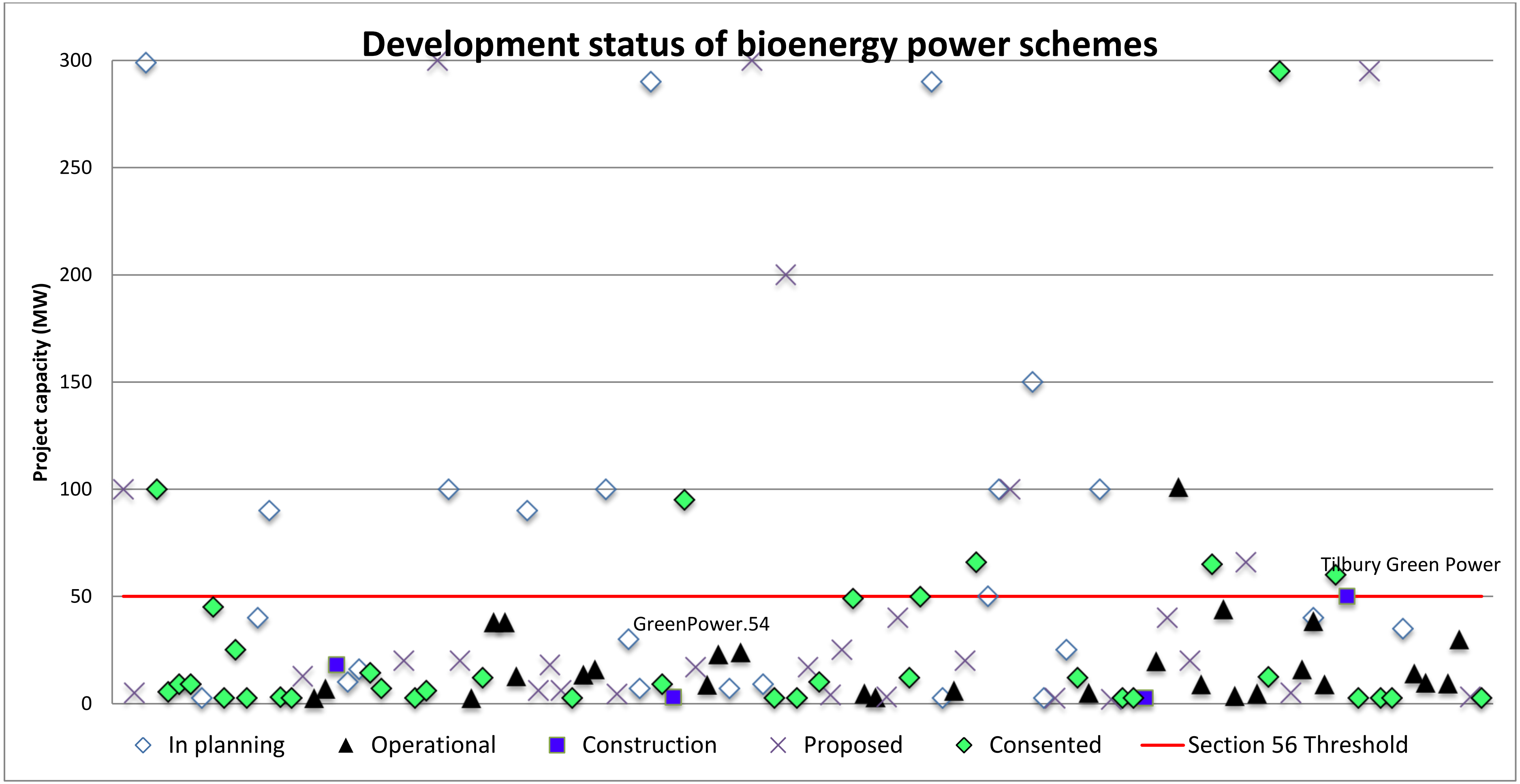

Figure 1.12: UK Biomass developments by capacity and development status

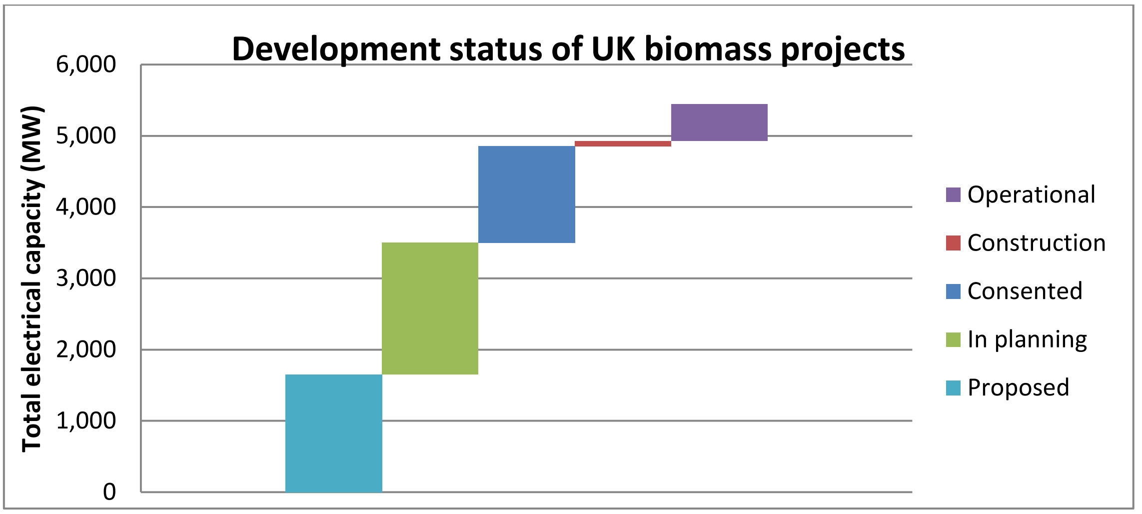

Figure 1.13: UK Biomass projects in various development stages. (Sourced and adapted from DECC, 2012h)

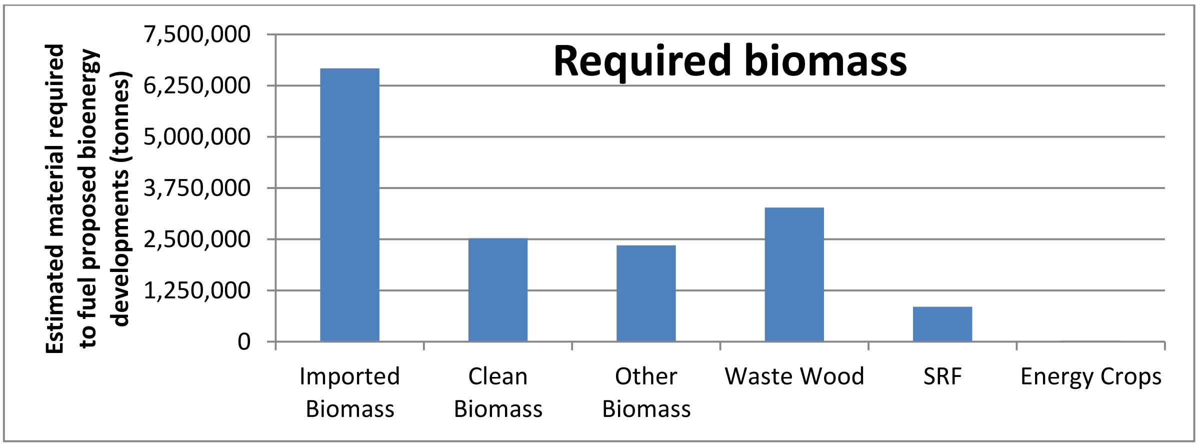

Figure 1.14: Estimate of materials being used by Biomass projects at different development stages. (SRF = Solid recovered fuel, derived from waste). A total of 15.6 million tonnes is represented.

To place Figure 1.14 in some perspective the UK produces a total of 48 million tonnes of waste per year from the commercial and industrial (C&I) sector alone (non-municipal waste), 11.3 million tonnes of which are sent to landfill (Lee and DEFRA, 2010). The total amount of biomass estimated in Figure 1.14 is 15.7 million tonnes. A total of 6.7 million tonnes of biomass is proposed for import under the current proposed schemes, more than double that used from any other source. Much of this demand for import comes from the larger scale combustion only schemes and conversion of coal schemes. Only one coal to dedicated biomass project has been completed in the UK by RWE npower at Tilbury docks which is no longer operating following an industrial fire. Drax power station, the largest coal fired power station in the country, has announced plans to convert its boilers to biomass only before 2015. Other European energy companies are also indicating plans to convert to dedicated biomass including all of the Danish fleet of coal power stations operated by Dong energy.

Such a huge conversion towards biomass fuel sources could have several impacts on the biomass supply chain and market, wood pellets are currently the favoured fuel for conversion projects due to easier handling although issues over indoor storage, ventilation and delivery remain.

1.1.4 Express Energy Ltd

Express Energy is a developer of renewable power stations within the UK. The company receives backing from a Dutch investment group BDI (Nederland) BV along with a minority shareholding by Cargill Inc. a large international company with expertise in so called "massive agriculture". Cargill Inc. were involved with the founding project that Express Energy have been involved with – Tilbury Green Power although for most purposes the company is led by the Dutch main shareholders. Express Energy Ltd are a subsidiary of Express Energy Holdings, the holdings company employs Express Energy Ltd for the development responsibilities of power projects, the holdings company usually then sets up a special purpose vehicle to manage the actual development costs, this de-couples financial risk between different projects and the holdings company. For instance Tilbury Green Power is the special purpose vehicle that is in charge of developing the Tilbury Green biomass power station.

Express Energy Ltd has a public target to develop 450MW of biomass and waste electricity generation capacity by 2015 although progress is well behind meeting this target. The business model for the company is to identify suitable sites and develop projects to a pre-construction stage. Pre-construction means a point where all contracts and details of construction and operation have been clarified, agreed, specified and the projects are effectively ready to build. Importantly the projects must also have full planning permission with all planning conditions discharged and in most cases (depending on the project buyer) a feasible mechanism for financing the project. A project at this stage becomes a very valuable asset and Express Energy can aim to negotiate some on-going shareholding in the final project leaving the company with an on-going income. Alternatively Express may decide to sell the project outright and cash in a large return. Each project is sold or constructed on a case by case basis but the development towards planning permission and pre-construction is managed internally with the assistance of consultants.

Due to the size, capital expenditure and risks involved with this sort of construction project most schemes are financed using some level of debt, therefore Express Energy aim to make their schemes as attractive to banks and financers as possible. Minimising risks to the project in a transparent and clear way is therefore very important during the development process. There are four key elements to a successful project: Technology suitability, location suitability, feedstock suitability and economic viability. Dedicated biomass power schemes are generally viable under the existing set of incentives and policies, unlike other renewable technologies bioenergy schemes can have most of their project cost wrapped up in future costs i.e. the price of fuel, as opposed to wind, solar or geothermal power sources where the fuel is free and the capital is the major expense. This said, dedicated bioenergy power stations are expensive to build, costing between £2m and £3.5m per MW of installed capacity.

Three main components required for a successful biomass project are: The technology to be used, the feedstock or fuel supply and the site location. These aspects are interrelated. Technology selection will depend on the location and feedstock available, the feedstock suitable for the technology will depend on where the facility is located, its size and the technology selection. A good location will depend on the suitability of feedstock for a chosen technology and so forth. This triple approach is summarised in Figure 1.15. Plus, of course, for a project to be built it must convince potential investors that it will make a reasonable profit whilst operating.

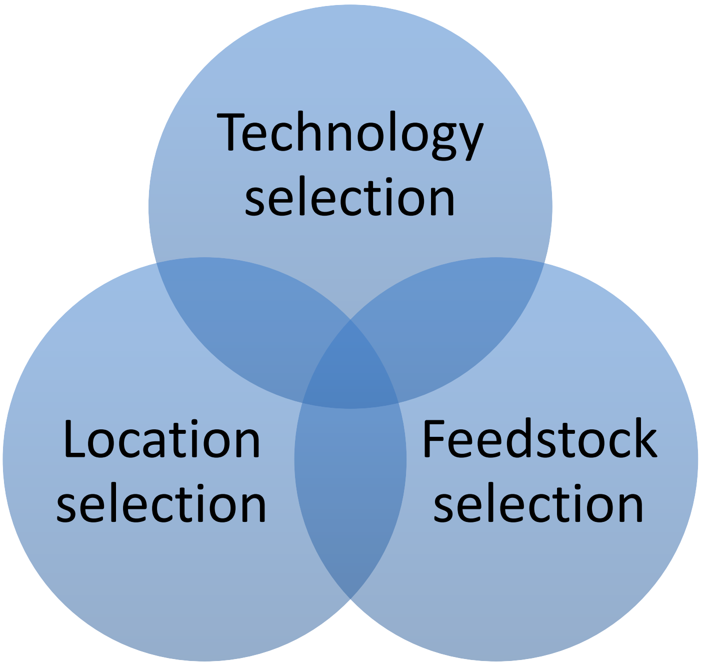

Figure 1.15: Venn diagram showing the three main selection decisions required for a successful bioenergy project

Express Energy Ltd takes a wide-ranging approach to site finding which is typical for developers in general. Guidance from government encourages development of all types on brownfield sites that have been previously developed. Express use a set of screening criteria that developers use when selecting a site, access for construction and fuel, electricity grid connection access and enough area for the plant and fuel storage footprint amongst others are important factors to look for in a good potential biomass site. Beyond these criteria there is a general aim to develop in areas with a good supply of feedstock. Developers will generally deal with land agents and land owners to identify suitable sites.

Technology selection is more straightforward for most developers. Usually previous projects, experience and existing relationships or business deals may partly influence a developers selection of technology provider. All biomass power stations (and power stations in general) are slightly different in their final design and require an extensive detailed engineering design process. The general technology selected however usually follows from a developers particular business strategy, some firms look to develop more advanced technologies such as pyrolysers or gasifiers. Express Energy Ltd choose a more tried and tested combustion technology provider in an effort to give potential investors more confidence through reduced perceived risk of technology failure.

Feedstock selection is a more complex problem and is the focus of this thesis. Investors require the developer to provide evidence of a suitable fuel contract for a large percentage of the fuel that will be required by the power project. From conversations with Express Energy and other developers this percentage is between 70% and 90% of the total fuel required. The type of fuel is also very important. There are two main approaches for developers to take when contracting with suppliers, either they can use a single supplier who they trust and meets the necessary requirements for finance deals to supply all of the material required. Or developers can contract with a number of different suppliers, de-risking themselves from a single supplier being unable to provide material but exposing themselves to mode complex relationships and more complex delivery, quality assurance, certification and contractual arrangements. The second approach appears to be favoured by finance groups and developers in general, however there are disadvantages. The main drawback is that using more, smaller suppliers means that it may be difficult to persuade investors that lost revenue can be recovered through contractual remedies in the event of supply failure. Put simply, if a supplier cannot be fined or sued for the value of at least a years' worth of contracted supply the whole project may become unattractive to investors. Without any fuel, the plant cannot operate.

1.2 Problem description

The problem faced by companies such as Express Energy and their fuel supply chain is to ensure that fuel supply contracts are arranged in such a way that the technical requirements of the conversion plant are met and the project is attractive to the group important stakeholders.

There are many different chemical and physical constraints that are set by the exact type of technology selected, a technology provider may provide a conditional warranty for instance, indicating that the warranty is only valid if a fuel within a particular standard or requirement is used. Typically this warranty requirement is well within the actual operating parameters of the plant. Exceeding the warranty conditions or the operating parameters can have different impacts depending on the type of chemical constraint that is exceeded. Sometimes exceeding a constraint may mean that pollutant emissions are increased, sometimes that efficiency is decreased, sometimes that maintenance costs may increase or plant availability may be reduced.

To further complicate this problem the characteristics of the fuel may vary over time, between deliveries and even within a delivery. This means that the buyer is unsure or uncertain of exactly what the chemical properties of a given batch of material will be, an extensive sampling regime can combat this but even if every kilogram of material was tested there would still be a natural variation of characteristics. For some materials this variation is very wide. From conversations with Express Energy this is currently resolved through clauses within contracts drawn up between suppliers and buyers, the supplier will agree to deliver material within particular constraints specified within the contract. This problem of uncertain characteristics is lessened when material has undergone pre-processing and is more of a homogenised, tradable commodity, however this also pushes up the material price. The cheaper materials tend to have larger variation and less testing or quality control, these tend to be more likely to be described as “waste” or “residual” materials as in Figure 1.2. The challenge is compounded by the buyer not always knowing exactly what the resource is when negotiating for a supply contract. For instance the description of ‘wood waste’ may cover a massive range of sources and materials which may have a wide range of properties.

The challenge facing biomass buyers is made yet more complex when the external requirements placed on the supply of biomass materials are considered. Sustainability is a key consideration for biomass procurement and is partly enshrined in legislation. This element introduces a further raft of concerns and complexity to the strategic sourcing problem. As well as satisfying legal requirements successful projects must also satisfy their stakeholder group. Bioenergy projects are subjected to a range of stakeholder demands and requirements, these can be divided into project site requirements and supply chain requirements. The supply chain of biomass can come into contact with a diverse and influential range of stakeholders who hold different but not always conflicting requirements.

1.3 Aims and objectives

This research aims to develop a framework biomass strategic sourcing (BioSS) to assis biomass buyers address the challenge described in section 1.2. The framework consists of three optimisation models to address three interrelated research problems. The BioSS framework will be demonstrated to operate at three stages of the project development lifecycle over two scenarios that developers currently face in the UK bioenergy industry. The project aims to assist Express Energy and similar companies to be more effective in the design of supply chains for new UK bioenergy projects. This will go towards increasing bioenergy deployment in the UK and meeting the greenhouse gas and renewable energy targets set out by the government.

Towards this aim the research has four main research objectives.

1. To create a fuels library
2. To develop a method to integrate the multi-stakeholder and multi-requirement nature of the bioenergy industry into the strategic sourcing decision
3. Develop a stochastic optimisation model capable of integrating supplier evaluating weightings (derived from objective 2) to determine the optimal allocation of orders between available suppliers

4. Demonstrate the integrated BioSS framework against two different projects typical of the current UK bioenergy industry and over three development stages.

Section 1.4 describes how each of these objectives is achieved and the approach taken for each individual research area and the integrated decision framework.

1.4 Approach

To meet the aims described in section 1.3 a strategic sourcing method has been developed for biomass. The method is referred to as BioSS and comes in 3 distinct operating modes, BioSS.2, BioSS.3 and BioSS.Op which correlate to different stages of the project development and lifecycle. Within BioSS are three key elements that correspond to research problems within the thesis and challenges faced by bioenergy developers. These research problems are addressed in this thesis and come together to make the BioSS:

- Fuels characterisation
- Supplier selection
- Order allocation

Table 1.2 shows the corresponding research objectives and outcomes for each of the three research elements. Sections 1.4.1 to 1.4.3 describe the approach taken for each of these research problems and section 1.4.4 shows how the elements combine to create the BioSS framework.

Table 1.2: Research problem, objective and outcome

Research Problem	Research Objective	Research outcome
Fuels characterisation	Create a fuels library that allows the user to estimate, based on secondary evidence, the salient properties of a feedstock given only the feedstock description	A fuels library
Supplier Selection	Determine the most important factors that should be considered when selecting a supplier of biomass. Determine the most relevant stakeholder groups and their requirements regarding the supply of biomass.	A register of stakeholders and representative actors within each stakeholder group. A list of evaluating factors that can be used to satisfy stakeholder requirements when selecting suppliers of biomass.
Order Allocation	Develop a methodology for assisting with the allocation of orders between the shortlisted suppliers.	An optimisation module that provides a recommended portfolio of suppliers and how much material should be contracted for from each supplier.
BioSS implementation	Demonstrate the BioSS framework against two UK based scenarios over three development stages	A demonstration of BioSS to show application for two scenarios where stakeholder importance and technological constraints change as a project moves through development.

1.4.1 Fuels characterisation

Fuel characterisation and description is a problem in the early phases of project development, when feedstock characteristics are unknown and there is no incentive to test feedstock under laboratory conditions. Usually properties of the more commodity-like fuels can be estimated with reasonable accuracy. However to meet the aim of the research and open up the wider residue and waste biomass resource the BioSS requires some method of making estaimtes for fuel properties.

Estimates are possible based on a fuels library that has been created as one of the outputs of the research. This is a growing library of records collected from both secondary data and user-input data. The BioSS can look-up characteristics of biomass materials from this library to allow the decision maker to quickly assess if further investigation of potential biomass sources is worthwhile.

As more projects are developed and biomass materials are tested the fuels library grows, eventually becoming a valuable repository of information for the developer.

1.4.2 Supplier selection

The problem faced by biomass buyers sits neatly within the existing theoretical structure for supplier selection problems. In the problem being examined biomass is a raw material and the buyer requires some form of collaboration with the supplier and usually a supply contract to ensure that material being purchases is suitable. When selecting between potential suppliers the decision maker must balance the many complex requirements of the stakeholder group against the characteristics of the set of available suppliers.

In BioSS handling this multi-criteria decision process is done using the integrated QFD-AHP method as discussed in chapter 5. The QFD-AHP method allows the usually vague requirements of stakeholders to be translated into more specific factors which each have an importance score. These factors can then be used to compare and rank the available supplies of material that are available. In the case of biomass success in the eyes of the stakeholder group is not just an evaluation of the supplying company but also of the material that they are able to supply. For the material itself (as opposed to the supplying company) these factors are not directly related to quality of the material as this term is essentially redundant given the way that the framework aims to blend different sources together. Instead the factors relate to tacit elements about the material, where it has come from, its wider economic and environmental impact and the use of that material on the risk profile of the project. A preference score is therefore assigned to each available combination of supplier and biomass that can be supplied.

1.4.3 Order allocation

Having established the characteristics of available biomass materials and give each supplier-biomass combination a weighted preference score, orders can be allocated between the available supplier-biomass combinations. Following consultation with industry orders are usually allocated by tonnage of material, especially when arranging strategic supply contracts. This is different to other parts of the energy industry where total energy content is used to determine total price but reflects the way that biomass is usually traded. To ensure that sufficient energy is delivered the buyer aims to procure a blend of material that has sufficient energy content for the conversion plant to operate properly. Energy content is one of 14 identified properties that must be controlled for the final fuel blend. These include impurities such as metals, ash content, moisture content and chemicals that can increase pollution or accelerate corrosion and acid creation such as sulphur and chlorine.

The order allocation model within BioSS uses a chance-constrained programming approach to find a final blend of material that meets the required specification whilst optimising the total stakeholder satisfaction score. The output of the model is a recommended distribution of orders (in tonnage per year) between the available supplier-biomass combinations. The model also has a Monte-Carlo analysis section that allows the user to examine the performance of any input portfolio.

The chance-constrained approach allows the decision maker to set a limit on how frequently each characteristic of the blend is allowed to exceed the corresponding constraint as shown in Figure 1.16. This part of BioSS allows buyers to either enter proposed supply portfolios and examine their performance against both chemical constraints and stakeholder requirements, or to enter available supplies and ask the model to give a recommended portfolio.

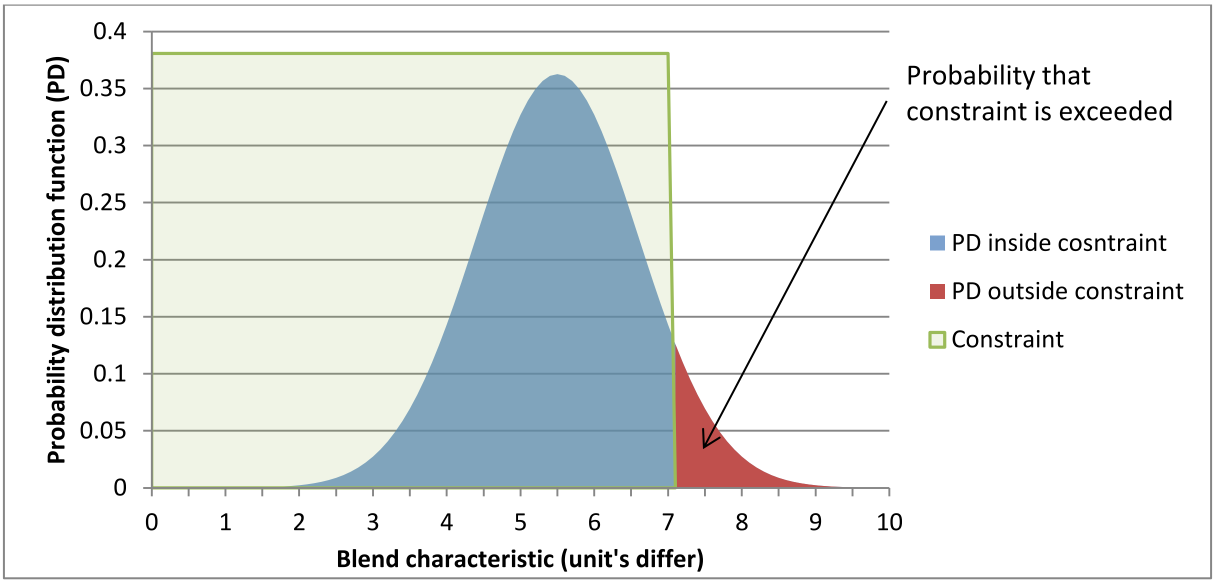

Figure 1.16: A chance constraint.

1.4.4 Contribution and implementation of BioSS

There are several contributions and outcomes from the individual sections of the BioSS and this thesis. The fuels library itself is a unique collection of material descriptions that is integral to BioSS and will be passed directly to Express Energy Ltd and made available for future research projects on biomass decision support schemes and supply chain management. The list of factors that biomass buyers look for and the allocated weightings is also novel, currently no structured research exists on exact factors that buyers look for outside of certification schemes. The application of QFD-AHP to provide weightings is also fairly novel as reflected by the publication of a paper on that part of the thesis (Scott et al., 2013). The optimisation module uses an unusual approach to a well-studied technique (chance constrained programming) in a novel application (bioenergy) to address a classic operations research problem of mixing or blending. The integration with Monte-Carlo analysis makes the model more robust and applicable. BioSS as an entire model running from excel will be passed to Express Energy following the research.

Chapter 7 shows the implementation of BioSS to two scenarios, the framework is demonstrated to operate through the early stage development in BioSS.2 and towards financial close in BioSS.3 mode. The BioSS framework is also demonstrated in the operational phase of the project under BioSS.Op mode.

1.5 Thesis organisation

The thesis is split into chapters that follow the broad structure of introduction and background, literature review, proposed approach, implementation of approach and results then finally a conclusion. A brief description of each chapter is shown in Table 1.2.

Table 1.3: Chapter structure

Chapter	Description of chapter
Chapter 1: Introduction	An overview of the bioenergy industry, the policy background to bioenergy and the problems that are to be addressed in this thesis. A summary of the thesis is also provided.
Chapter 2: Literature Review	A review of the previous literature in the area of bioenergy and multi-criteria decision making.
Chapter 3: BioSS	A full description of the Bioenergy Strategic Sourcing decision support system. Including system architecture, required data and system outputs
Chapter 4: Biomass Fuels Library	A report on the regarding the existing evidence for different types of biomass, its classification and properties. This chapter also contains details of expected constraints as determined by technology providers. Finally a description of the biomass value chain is given and examples of available biomass sources are discussed in the context of the fuels library.
Chapter 5: Supplier Selection	A brief review of existing literature on supplier selection, a theoretical overview and the state of current practice within the bioenergy industry. The QFD-AHP method for supplier selection is applied to identify evaluating factors for bioenergy schemes. This attempts to reconcile opinions of various stakeholders when prioritising between a shortlist of suppliers
Chapter 6: Order Allocation	A brief review of existing resource allocation methods and a description of the main differences in approach. The various methods that have been used in this thesis for optimisation are discussed along with the model formulation including objective functions and constraints. The model is compared to non-chance-constrained alternatives.
Chapter 7: Implementation of BioSS	Two cases are presented, based on real world examples but with some proxy data used where data has been unavailable. The recommended fuel portfolio of the BioSS is shown under various conditions of optimisation, considering the stakeholder opinions salient in both cases. The results are compared to show how BioSS allows for more successful portfolios to be realised and the importance of flexibility in conversion technologies
Chapter 8: Conclusions	The thesis is concluded with a brief review of each research area and the research outcomes, a discussion of the impact and limitations of the BioSS framework and suggestions for future work.

Chapter 2. Literature Review Chapter

2.1 Introduction

This chapter presents a review of previous academic contributions to problems faced by the bioenergy industry in deploying projects. The various reported problem areas or barriers to deployment are identified in section 2.2 and divided into 10 categories. Section 2.3 presents the 95 papers identified as relevant and separates them by the type of problem they address. Section 2.4 discusses the various methods that authors have used in these studies and discusses some of the strengths and weaknesses of the more popular methods. Section 2.5 presents the results of categorising the papers in this way and identifies some trends within the literature. Section 2.8 summarises the findings and discusses the weaknesses in coverage and treatment of the problems identified in section 2.2, highlighting areas that this thesis makes a contribution to the existing body of literature.

2.2 Bioenergy problems identified and addressed by academic literature

Several papers have been identified within the literature that examined various problems with regard to the deployment of bioenergy in the UK and EU. These papers each take a slightly different approach to the identification of barriers with Painuly (2001) taking the most structured approach, classifying the identified issues into 4 barrier levels: Barrier categories (level 1), barriers (level 2), barrier elements (level 3) and barrier dimensions (level 4). The example given is for financial barriers and shows how corresponding descriptions of barrier at each level: Economic and financial (level 1), High cost of capital (level 2), High interest rate (level 3), percentage by which interest rate is over reasonable or acceptable level (level 4).

The other papers identified take a more ad-hoc approach to barrier identification with several using case studies as evidence for particular barriers (Adams et al., 2011, Adams et al., 2008, Mayfield et al., 2007, Reddy and Painuly, 2004). Other studies narrow their field of barrier to specific country contexts, industries or sub-industries within the biomass sector (Sajjakulnukit et al., 2002, Sugathapala, 2002, Stidham and Simon-Brown, 2011, Iakovou et al., 2010). Probably the most relevant paper to this thesis is the most recent publication by Adams et al. (2011) which examines barriers from the perspectives of different stakeholders along the biomass supply chain. Table 2.1 summarises the papers identified and the categories of barrier they each state as significant.

Table 2.1: Literature identifying barriers to biomass deployment

Paper	Notes	Categories of barrier identified		
(Costello and Finnell, 1998)	Barriers specific to biomass	Regulatory		
(Roos et al., 1999)	Presented as critical success factors rather than barriers; specific to the bioenergy sector	Integration	National policy	Competition with different sectors
		Scale effects	Local policy	Competition within sector
(Painuly, 2001)	Presented a framework for assessing and identifying barriers	Market distortions	Social cultural and behavioural	Technical
		Market failures	Environmental	Economic and financial
		Institutional		
(Reddy and Painuly, 2004)	Approached stakeholders to identify which barriers are considered most important regarding the diffusion of renewable technologies	Awareness and information	Institutional and regulatory	Technical
		Financial and economic	Behavioural	Market
(McCormick and Kaberger, 2007)	Identification of barriers using information from bioenergy case studies	Economic conditions	Perceptual	Financial
		Know-how and institutional capacity	Supply chain co-ordination	Infrastructure
(Iakovou et al., 2010)	Literature review examining the waste to energy sector	Collection	Supply and demand contracts	Energy conversion
		Pre-treatment	Fuel sustainability	Network design
		Transportation	Storage	
(Adams et al., 2011)	Specific to the UK Bioenergy industry. Examines the perceived barriers to — *Feedstock supplier*	Competition vs. other investments	Lack of feedstock experience	Physical resource limitations (land availability)
		Negative environmental impacts of feedstock	Limited/uncertain return on investment	Perceptual challenges of feedstock

	deployment from the perspective of different groups within the industry		Resource intensive feedstock	Uncertainties of financial support	Unclear legislative limitations
		Plant developer/ owner	Unsettled bioenergy market (unreliable buyer)	Perceptual challenges of bioenergy plant	Uncertain development and operational costs
			Competition vs. other renewable energy options	Planning and installation Issues	Uncertainty of conversion technology/equipment
			Lack of feedstock supply (resource availability)		
		Primary end-user	Low primary-end-user demand	Possible negative environmental impacts	Unclear and complex legislative issues
			Bioenergy costs vs. fossil-fuel	Low supply of bioenergy	Seasonal effects of bioenergy supply
			Infrastructure and other costs	Perceptual challenges of bioenergy use	Uncertainty of adaptability
			Legislative issues	Preferential over other renewable energy options	Unsettled/changing bioenergy market

From Table 2.1 it can be seen that the identification of barriers does not usually follow the structure laid out by Painuly et al. Painuly (2001), rather authors have reported a mixture of barrier levels within each study. It does appear that in more recent publications authors have identified more level 2 and 3 barriers than the level 1 or 2 barriers found by Costello and Finnell (1998) Roos, Graham et al (1999) and Painuly (2001). This may be a result of the increasing activity in the sector and a better understanding of how these problems affect renewable energy deployment. Recent authors may have moved towards aiming to inform and change development practice rather than looking at interventionist central government policy that was required at the turn of the century due to increased activity following the Kyoto agreement. Policy remains a key driver to the deployment of bioenergy and from the discussion in Chapter 1 the industry is not yet able to survive without government support and incentives.

Table 2.2 shows a synthesis of level 1 barriers identified from Table 2.1 and from the recent bioenergy strategy report by the UK government (DECC, 2012e). The categories in Table 2.2 will be used to classify the reviewed literature in section 2.3, the list aims to cover all possible areas that research contributions may have addressed to date. In this classification some of the identified problems are classified together under sustainability issues, or project planning issues. Project planning indicates all barriers that a potential developer must overcome before a successful project can be built and operated. Sustainability barriers concern the impact that the sourcing, conversion, replenishment and disposal of biomass resources may have on the sustainability of a given system. These two groupings are discussed in section 2.2.1 and 2.2.2.

Table 2.2: Barriers used to classify literature on bioenergy

	Barrier type	Barrier description
	Political/Legislative	Barriers created by the absence or presence of particular legal structures, for instance classification of materials, tax breaks or landfill fees
Sustainability	Economic barriers	General market barriers which prevent deployment, these can range from lack of competition with established energy technologies to variable feedstock costs
	Environmental barriers	Any issue that may prevent deployment due to uncertainty or problems regarding the environmental impact of bioenergy projects. E.g. carbon impact of fuels, sustainability of fuels, impact on the local environment
	Social barriers	Problems regarding the public perception or social impact of bioenergy schemes. E.g. Job creation and safeguarding, perception of pollution or social impact.
Project planning	Logistics and transportation problems	Problems regarding the way that projects or supply chains should operate. E.g. How material and energy vectors should be transported, converted or how schemes should be run, scheduled and operated
	Location selection	Challenges regarding where to locate particular bioenergy facilities. E.g. given the distributed nature of biomass, where should collection and conversion points be located.
	Technology selection barriers	Challenges exist when selecting between technology options, this could be to select between technology types, particular technology suppliers, technology combinations and selecting between competing technology solutions, renewable and non-renewable.
	Capacity	The capacity of bioenergy schemes has a great impact on the success and characteristics of the project. This key decision is represented as a challenge for developers or decision makers.
	Others	

2.2.1 Sustainability

Sustainability is a slippery topic both in the academic literature and in public discourse, the most frequently given explanation indicates that a sustainable system should be sustainable financially, environmentally and socially. This means that the system should be able to operate for ever without failing on any of these three so called pillars of sustainability. In most discussions of sustainability for most contexts the economic sustainability is fairly straightforward to understand, environmental sustainability slightly more abstract with some available metrics and measures, and social sustainability a very difficult concept to quantify and measure. In practice therefore the social impacts of a potential project are estimated in terms of jobs created or safeguarded, improvement in living conditions, and reduction in poverty or some other target metric. These metrics allow for the claim that society will be more sustainable following the project implementation. There are clear problems with measurement and evidence but the principle has stood the test of time in a culture again becoming aware of its social responsibilities. (Gasparatos et al., 2008, Lamberton, 2005, Morrison-Saunders and Retief, 2012)

Sustainability is clearly a key issue for bioenergy. The industry has spent a lot of time and money persuading the general public and policy makers that the carbon cycle is indeed closed when biomass is converted and replaced and therefore that the whole industry be classed as a renewable energy industry. Figure 2.1 is taken from South Yorkshire Wood Fuel (2012) who aim to educate and further the deployment of wood fuels in their region and shows the closed carbon cycle.

Figure 2.1: The carbon cycle for biomass combustion (Source www.wood-fuel.org.uk, 2012)

A further cause for scepticism regarding the sustainable credentials of bioenergy is due to the perceived damage caused by the widespread deployment of biofuels for replacement of gasoline for transport fuel. The biofuels industry grew rapidly in certain parts of the world, especially Brazil, the USA Midwest and the Southern Asian Peninsula. This rapid growth was spurred by rising crude oil prices, increasing demand for petroleum and government incentives. The most recent UK figures for the Renewable Transport Fuels Obligation show that a total of 983.1 million litres of biofuel was delivered to UK cars during 2011, 3.2% of all demand. Of this only 53% met a required environmental standard, well short of the 80% target set by the Department for Transport. 51% of delivered biofuel came with some form of social sustainability standard. (RTFO, 2012)

This dash for biofuels has been difficult for purchasers and governments to properly regulate and several high profile cases of unsustainable practices have been identified in the public media. For instance the UNEP report on deforestation due to biofuel activities in the Borneo jungle endangering the Orangutan population there (Nellemann et al., 2007), or the special issue of national geographic on the failure of US bioethanol production (a failure in economic as well as environmental sustainability) (Geographic, 2007, Gao et al., 2011). This perceived failure to guarantee the sustainability of biofuels has caused governments, including those of the UK and USA to revise targets for biofuel deployment downwards. The solid biomass to energy industry that is the topic of this research is keen to avoid such public relations incidents and therefore places a great emphasis on sustainability of the feedstock used.

2.2.2 Project planning

The problems of selecting a location, a technology type or supplier, facility capacity or the logistics and transportation of biomass materials are all related to the design and project development of bioenergy projects. These important decisions directly relate to the success of the project and can have economic, environmental or social impacts.

The problems encountered in project planning are often complex and related one another. Different constraints come into play for different combinations of technology and context whilst the type of technology selected will affect the type of feedstock that can be used. The location selection problem overlaps with the logistics problem as the cost of feedstock transport will change depending on the location of conversion, pre-treatment facilities and suppliers.

Capacity planning affects the total capital expenditure of the project and is a key decision for all bioenergy projects. Some projects may match the local heat or power demand, others may be sized based on the available feedstock. The important element of this decision is to ensure that the plant is not over-capacity, leaving asset value not fully utilised.

The problem of technology selection is encountered in several contexts. It may refer to selection between energy conversion technologies including fossil fuels, or selection between different technologies for converting biomass to energy, pre-treatment technologies or even transport technologies. For policy makers this problem is of interest when attempting to align incentives and energy strategies with the particular characteristics of the context country. For developers this selection is a balance between efficiency, cost and reliability. Scale is also an important factor, especially for the more advanced conversion technologies.

Arranging transport and logistics operations is a different type of project planning challenge. In this case the decision maker must design a system with several parameters in mind, the cost of the actual transport, the flexibility and reliability of the system, the cost of handling materials and the sensitivity to external cost factors such as fuel price. Transport and logistics problems are further complicated by the properties of the feedstock. This is most evident when considering the effect of moisture content on transport economics. Transporting water by road only to later convert to steam is an expensive and inefficient activity that exposes bioenergy projects to transport fuel price fluctuations.

2.3 Literature search

ScienceDirect, Emerald and ProQuest databases were used to search for academic journal articles published between and including 2000 and the time of writing at the beginning of

2013. Following a number of preliminary searches the broad key topics were identified for both methods used and areas of application. More detailed search strings were then formed for each database to identify all the relevant papers mentioning they key topics. Where possible only the fields of author keywords, abstract and title were searched. This reduced the overall number of results and excluded those papers only mentioning the key literature search terms in the references or literature review sections of papers.

The literature search aimed to identify previous studies that addressed problems faced by the bioenergy industry regarding decisions made either at the project planning and design phase or at a policy level. Table 2.3 shows the search terms that were used. For a paper to appear in the search results it should have at least one term from the decision making terms column and one term from the bioenergy terms column of Table 2.3.

Table 2.3: Search terms

Decision making terms	Bioenergy terms
Multi-criteria, Multi-objective, multi-attribute, MADM, MCDM, optimisation, optimisation, selection, design, development, planning.	Biomass supply chain, biofuel, biomass, bioenergy

Therefore a typical search string may appear as *pub-date > 1999 and ((Multi-criteria) OR (Multi-objective) OR (multi-attribute) OR (MADM) OR (MCDM) OR (Optimisation) (development) OR (Selection) OR (planning) OR (Design) OR (planning)) AND ((Biomass) OR (Bioenergy) OR (Biofuel) or (Biomass supply chain)).*

Using this approach across the various databases a manageable selection of papers was identified. Each paper was then reviewed and those that were irrelevant to the thesis were removed. Irrelevant papers included for instance any papers on the cultivation of bacteria on various substrates, biomass content analysis of forests in fire ecosystems or the assessment of biomass addition potential of various fertilizers. The reference lists of relevant papers were also examined to identify any other papers that may have been missed by the database searches.

Following this search process a total of 95 relevant papers were identified for review. These were a heterogeneous set from authors around the world addressing differing problems under differing contexts. The abstracts and key findings or case studies of these papers were then analysed and notes were made on each paper. From the notes each paper was given a set of keywords which could be used to help with the classification of papers. Keywords were given to each paper describing the area(s) of application and the method being applied to make decisions. For the purposes of classification when a paper applied more than one method the method which provided the greatest contribution or was most relevant to the application being addressed or decision being made is used. When a paper addressed more than one problem area all the problems addressed were recorded. For instance a paper may address the facility location problem and also the capacity problem for that facility using some linear optimisation algorithm. Such a paper would be classified as 'problems with many alternatives' and 'location problem' and also 'capacity problem'.

Based on the dominant problem being addressed the following sections show a brief description of each paper reviewed.

2.3.1 Policy and legal barriers

In a short communication Sourie and Rozakis (2001) reported on a model that allows micro-economic analysis of the biofuel industry using a multiple supply chains or sources. The approach is described as environmental economics and contains several criteria. Multi-criteria analysis is discussed for the approach which is described as environmental economics. This short communication is aimed at informing policy makers on the use of tax as an incentive for biofuel development.

Haralambopoulos and Polatidis (2003) mainly looked at geothermal power for the Greek Island of Chios although biomass is considered as an alternative energy source. This paper used the PROMETHEE II outranking method to evaluate four scenarios against a mixture of three quantitative and two qualitative criteria. These criteria were divided into different aspects or sub-criteria to assist with measurement of the quantitative parts of the problem. The paper aims to recommend the most suitable technology to best satisfy the criteria.

Ulutaş (2005) examined the forthcoming energy scarcity predicted for Turkey. The Analytical Network Process (ANP) method is applied to identify which technologies are most preferable for Turkey to satisfy national energy demand in to the future. The aim of the study was to make recommendations for policy makers when structuring future energy policy. The case study finds that biomass is the most preferable resource and technology for this context allowing a gradual replacement of traditional wood energy towards more modern biomass such as biodiesel and bioethanol.

Thornley (2006) presented a detailed discussion on the use of biomass for power generation in the UK. The paper divides the ‘benefits’; and ‘consequences’ of using biomass for electricity generation into environmental, social and economic categories. The study also discusses how different policies and incentive mechanisms can sit within the bioenergy industry.

Doukas et al. (2006) applied the PROMETHEE II multi-criteria decision making (MCDM) method to select between policy interventions for Greece which intended to introduce greater renewable generation. The technologies considered included fuel cells, biomass gasification and co-firing, wind power, PV and the use of fossil fuels. Several possible future scenarios were then created based on future needs and requirements (Basic, Pessimistic, Optimistic and Unstable depending on various possible domestic and international factors). The criteria identified are categorised under the four dimensions of Economical, Technological, Environmental and Social. The overall conclusions of the

Greek case study were that emphasis should be placed on indigenous resources such as lignite, wind and biomass.

Diakoulaki and Karangelis (2007) examined many policies the Greek government could support to alter energy provision mix in the country. A set of scenarios are assessed in a multi-criteria analysis against social, environmental and economic criteria. Each scenario specifies the blend of new and future total energy mix and makes suggestions as to the impact of supporting different technologies.

Terrados et al. (2007) used a multi-criteria analysis along with a SWOT analysis method to contribute to a report on regional development in Spain. Large biomass resources were identified as one of the major strengths for the region when looking to meet criteria regarding domestic provision of renewable energy.

(Anderson et al., 2008) reported on part 2 of the same scenario modelling exercise by the Tyndall centre. This paper applies multi-criteria analysis to examine the impact of several different demand scenarios. The criteria used cover economic, social and environmental issues and the study finds that the higher demand scenarios have a greater negative impact on climate change.

Mander et al. (2008) reported on part 1 of the Tyndall decarbonisation scenario project and outlines various pathways for the UK to realise a 60% reduction on 1990 greenhouse gas (GHG) levels by 2050. This paper gives a description of the methodology which will be used.

Terrados et al. (2009) too used the PROMETHEE method along with a Delphi method for evaluating policy for planning in a region of Spain. The study aim is to produce a recommendation for the policy measures which will result in the most sustainable development. Criteria used in the analysis were banded under environmental and socio-economic themes. Expert opinion was included through the use of the Delphi method.

Browne et al. (2010) assessed different scenarios as informed by policy on the residential heating and electricity consumption for a city region in Ireland. The NAIADE software was used to complete a multi-criteria decision analysis (MCDA) and a mixture of qualitative and quantitative criteria were used for the assessment. An ecological footprint analysis for the same scenarios was also presented to allow for a comparison. The two methods found the same scenario as most preferable but gave different rankings of the remaining scenarios leading the authors to recommend that several different decision tools should be used when deciding upon policy measures or incentives.

Kalt et al. (2010) used a special simulation model called Green-$X_{Bio\text{-}Austria}$ to inform recommendations for Austrian policy makers regarding policies they should use to improve the carbon efficiency of investments in the bioenergy sector. The study concludes that greater emphasis on heat provision from biomass rather than liquid biofuels would lead to more favourable outcomes for the country.

Theodorou et al. Theodorou et al. (2010) also used multi-criteria decision making to make recommendations to policy makers with the aim of comparing three different decision methods, AHP, PROMETHEE and ELECTRE. Here policies for incentivising PV deployment in Cyprus were assessed against the criteria of maturity, initial investment cost, efficiency, potential and public acceptance. The paper concludes that the multi-stakeholder nature of the government department makes AHP too involved and that the ELECTRE method is preferable given its flexibility.

Turcksin et al. (2011) made a recommendation for the best configuration of biofuel production in Belgium. The recommendation took into account the views of different stakeholders including producers, distributors, NGO's, government and end users. 33 different criteria were identified by the 7 stakeholder groups consulted. The study did not give a final recommendation but a single optimal solution for each stakeholder group.

2.3.2 Economic viability

Chinese and Meneghetti (2005) used two approaches to show where biomass based district heating schemes could be both most profitable and give greatest greenhouse gas savings. For the economic solution a mixed integar linear program was used to calculate profit. For the greenhouse gas solution a linear-programming model was applied. Both methods were applied to a case study in Italy.

Uslu et al. (2008) examined the potential for torrefaction to reduce costs of biomass imported to Europe. The study used an economic model to show that delivered torrefied pellets of biomass could be cost competitive if used to replace coal in a co-firing operation. This is one of the few studies that has seriously considered the global trade of bioenergy as an energy vector and not required that biomass be locally sourced. The study looked at fuel required for transportation and the end cost of electricity finding that final cost could be as competitive as 4.4 €cent/kWhe.

Stanojevic et al. (2010) examined the environmental impact of energy generation from a green accounting perspective. In this context this involves translating the environmental impacts of an energy provision scheme into a monetary penalty for the operator. This paper uses 44 criteria which should either be minimised or maximised to give the best solution, 26 of the 44 criteria are financially focussed. The study finds that biofuel fired combined heat and power (CHP) plants are most favourable and that their advantage increases over fossil fuel equivalents when financial criteria are ignored.

2.3.3 Social impact

Rozakis et al. (2001) developed a multi-criteria model to assist the French government in making choices around the best policy for the French biofuel industry. A multi-level mixed integer linear programme is used to model the 450 participating arable farms. The model is able to predict the impact of different policies on the cost of biofuels.

Shackley and McLachlan (2006) looked at the North West of England using a multi-criteria assessment approach to collect views from stakeholders regarding a set of possible scenarios for future energy supply. The paper reports on the criteria identified by the stakeholders who were interviewed. The nine identified criteria were then grouped under the wider headings of environment, socially focused and business focused criteria.

Raven et al. (2009) mentioned multi-criteria analysis as a suitable method for conflict resolution in established projects where conflict already exists. The paper presents a slightly modified method for avoidance of conflict at the planning phase of an energy project. In this study conflict is discussed in terms of social acceptance by the general and wider public.

Atwell et al. (2010) presented the outcomes of a workshop held with key policy makers on the agricultural sector of the USA. The workshop aimed to discuss how agriculture and governing policy can be used to adapt to the rapid changes taking place due to increased energy crop growth. The aim of policy in this area is to meet the multi-objective social needs of private land owners in the face of this rapid reorganisation.

2.3.4 Logistics and transportation problems

McDowall and Eames (2007) examined the hydrogen economy using a multi-criteria mapping approach to decide between six potential hydrogen energy systems for the UK. The method involves moving through a decision structure from discussion of possible visions for future hydrogen economy through a conversation regarding uncertainty and finally to determine weighted preference ranking of the various different visions. Several of the visions for a hydrogen future economy suggested by the participants of the research involved the use of biomass resources to produce hydrogen. The various visions were given weightings by industry experts and the results vary to a greater or lesser extent across participants.

Dunnett et al. (2007) used a method adapted from batch management in the operations literature to show how with optimisation the price of heat from biomass could be reduced compared to using a simple or intuitive heuristic approach. The harvest, drying and transport of materials was considered as an integrated system for a hypothetical biomass combustion project.

Rentizelas et al. (2009b) presented a decision support system for a multi-biomass system. This is unusual as most studies consider only a single, or two fuel types. The paper aims to assist with decisions around the design of a district heating and cooling network to optimise financial yield within multi-criteria constraints including social and regulatory aspects. The model is tested in a Greek context. Later the model was extended to include cooling services from absorption chillers that use the heat from the CHP plant. (Rentizelas et al., 2009a)

Ayoub et al. (2009) used an evolutionary algorithm in the setting of Japan to identify the solution for a resource assessment of biomass. The created decision support system (DSS) also determines which sources should be sourced from and how much should be taken from each. The DSS combines optimisation algorithms with geospatial information on the location of resources and includes information on supply chain length between raw material and the conversion stage. The system is able to optimise for either energy efficiency, total cost, CO_2 emissions, or to maximise employed labour hours. The authors highlight that further research will look to simultaneously optimise these objectives in a single integrated DSS.

(2009) in a similar field to McDowall and Eames (2007) evaluated different methods for producing hydrogen using different feedstocks including wood chips. The processes were evaluated in terms of exergy, emergy and economic analysis with each method of evaluation recommending a different conversion route.

Huang et al. (2010) presented a model to assist with the planning of a bioethanol supply chain. A mathematical model is presented which is able to consider spatial and temporal information on the supply chain whilst satisfying resource demand and technology constraints and minimising supply cost. The model is applied to a case study in the USA and finds that through careful configuration of the supply chain costs can be significantly reduced.

Pokoo-Atkins et al. (2010) investigated the conversion of fatty-acid wastes into biodiesel. A specialist piece of software called ASPEN plus was used to model the chemical processes involved. A safety index and a set of techno-economic criteria were used to compare different process paths. The results are found to be dependent on the inclusion of safety concerns rather than any other criteria.

Perimenis et al. (2011) presented a simple multi-criteria method for selecting between different potential pathways for converting biomass to biofuels. The user is required to provide opinions and weightings to rank different options. A case is shown for rapeseed to biodiesel in Germany.

Van Dael et al. (2012) showed an extension to the eTransport software that allows the user to consider bioenergy schemes. The extension allows the user to select sites for bioenergy schemes on a macro-screening level, the aim is to allow investors to quickly identify suitable areas where more detailed micro-siting studies can be carried out, focusing development investment. The model is driven by weighting various criteria and applying to a region using GIS.

Čuček et al. (2012) assumed a trade-off existed between economic benefit and social and environmental benefits. The study used an integer linear programming approach to balance this trade off when selecting a biomass energy crop to be grown in a region. The method was tested on a notional region.

Pérez-Fortes et al. Pérez-Fortes et al. (2012) presented one of the more comprehensive attempts at finding suitable sites and logistics solutions for biomass facilities, also incorporating recommendations on the capacity of different types of facility. The study used a multi-objective mixed integer linear programming approach to show a globally optimal solution for biomass supply to give best financial performance, best environmental life cycle performance or greatest job creation potential. These three objectives are used as objective functions to show viable networks at the extreme of each objective.

Yu et al. (2012) used GIS to look at locating storage sites for biomass before it is delivered to a power station. The system used a mathematical optimisation model that was able to reduce costs by between 5% and 18% compared to direct delivery through using satellite storage facilities.

Palander and Voutilainen (2013) showed how a mixed integer programming method could be used to improve the logistics system for a Finish CHP system. The analysis showed that investing in a biomass collection facility could improve operating costs by 14%.

2.3.5 Location problem

Panichelli and Gnansounou (2008) used a GIS (Geographical Information Systems) approach to locating biomass conversion facilities in a region in Spain. The method used was able to select two suitable locations for bioenergy conversion plants in the region and is one of the only GIS-based papers to properly consider issues of competition for biomass resources. The study is also unusual as it considers torrefaction – a pre-treatment method that increases the energy density of biomass making transportation more cost effective. The locations were selected to provide the lowest delivery cost possible.

Ghilardi et al. (2007) used a geospatial information system to identify the locations of supply and demand of wood fuel in Mexico for residential use. The paper identifies hot spots of supply and shortage around the country. In a follow up paper Ghilardi et al. (2009) identified locations for fuel wood use and availability based on a set of six indicators.

López-Rodríguez et al. (2009) also used GIS to make a spatial analysis to select the optimal location for both harvesting/collection points and thermal conversion plants within a region of Spain. The approach takes consideration of difficulties in removing residual forestry material from dense forests and makes an estimate of the viable yield from the regions forestry.

Bastin and Longden (2009) also used Geospatial Information Systems (GIS) to model the location of biomass resources within a region. This study models waste arisings using data from the UK census and uses the results of that analysis to identify suitable locations for Energy from Waste (EfW) plants. The GIS system is also then used to allocate each domestic waste source (household level) to a particular waste treatment facility. The allocation is done by distance alone and a set of social, economic and environmental criteria taken from Longden, Brammer et al. Longden et al. (2007) are given weightings in the multi-criteria analysis which impacts on the selection of suitable locations.

Velazquez-Marti and Fernandez-Gonzalez (2010) proposed a particular method for combining GIS data such as maps with linear programming (LP) techniques. This required the various potential locations in space to be converted using a mathematical algorithm. Although this is the main contribution of the work the method is successfully applied a bioenergy problem that allowed for the optimisation of plant location. Although the case data used is slightly unrealistic the approach is unique in integrating GIS and LP.

Vera et al. (2010) solved the problem of where to locate a conversion facility using a binary honey bee foraging method. This determines the optimal location, where the supply area should be and the size of the plant to give the maximum profitability. The study also compared with genetic algorithm and particle swarm optimisation approaches.

Singh et al. (2011) also used a GIS approach to locate a combustion power plant based on transport costs and resource availability and price in the Punjab area of India. The study was able to identify enough resources for 20MW(electrical) of power capacity with a fuel catchment area of 20km.

Ebadian, Sowlati et al. (2011) extended a previously developed model (IBSAL) and applied the new logistics model to an area of British Columbia, Canada. The model was used to analyse the supply and demand balance of an ethanol plant. The model was able to predict the cost of logistics of straw to the plant and the capacity of on-farm and on-plant storage required. Of all the papers reviewed this was amongst the most in depth, robust and detailed approach found for the logistics problem although it does not have features other studies include such as multi-biomass sources, multi-objective analysis or the location of possible pre-treatment facilities.

In two papers Zhu et al. described a method for optimising biomass supply chains (Zhu et al., 2011), using mixed integer linear programming (MILP) then demonstrated the impact of logistics optimisation for a particular feedstock (Switchgrass) and a particular application (biofuel production) (Zhu and Yao, 2011). The model was able to handle warehouse sizing problems and temporal variations in harvest when optimising the supply chain design for logistics costs.

Kurka, Jefferies et al (2012) used a GIS-based approach to identify the 10 most suitable location for bioenergy CHP plants in a Scottish region. The location ranking is based on available feedstock and proximity to heat demand. The study went further than just to identify potential sites but also allowed allocation of biomass from supplier to conversion facility, estimating environmental impact of the logistics operations for each site-supplier combination. The criteria used for the ranking are utilisation and logistics cost.

Zubaryeva et al. (2012) Also used GIS and combined with results from an AHP method was able to recommend suitable locations for biogas production based on the availability of feedstock.

2.3.6 Technology selection problem

Suganthi and Williams (2000) looked at ways to determine the optimal blend of renewable energy provision considering differing end users in the context of 2020 India. The study identifies critical parameters from which policy should be formed, and then uses an optimisation model to compare various different 2020 scenarios.

Afgan and Carvalho (2003) compared various new and renewable technology options against a set of sustainability indicators. The result of the paper is a relative rating for each technology option with regards to sustainability. The study shows how the most sustainable choice will change when emphasis is placed on different sustainability criteria. The technologies compared are coal, solar thermal, geothermal, biomass, nuclear, solar photovoltaic (PV), wind, ocean, hydro and natural gas. Afgan and Carvalho (2008) used indicators for environmental, economic and social impacts to deal with the sustainability evaluation of different combinations of renewable technologies including biomass. The method allows the most sustainable hybrid combination of technologies.

Beccali et al. (2003) used a multi-criteria decision making methodology to make assessments of which low carbon energy sources should be pursued for the island of Sardinia. The ELECTRE III decision support system is used and is combined with a built-in fuzzy approach for dealing with linguistic values. This method is used to prioritise between 14 different options based on either an "economy-orientated" scenario, an "environmental-orientated" scenario or an "Energy saving and rationalisation" scenario. The aim of the paper is to recommend a suitable renewable energy technology deployment strategy. The study recommends that the robustness of each solution could be assessed using a sensitivity analysis.

Begic and Afgan (2007) also used environmental, economic and social indicators for a multi-criteria assessment, this time for the renovation of a thermal power facility in Bosnia & Herzegovina. This study compared the rank of preference when using either a sustainability index to select the preferred technology or using an investment biased selection criteria.

Buchholz et al. (2007) examined how a DSS could be used to decide on the most suitable technology to satisfy sustainability criteria as determined by the stakeholders in the system. The authors discuss combining a multi-criteria analysis with systems thinking to provide the basis of a holistic decision tool. The study used results from stakeholder workshops to feed into an optimisation DSS, allowing stakeholders to partly define their own definition of sustainability. The proposed DSS is intended to assist at the planning stage helping to select locations and technologies to best encourage sustainable development.

Cherni et al. (2007) presented a multi-criteria decision support system called SURE DSS (SUstainable Rural Energy decision support system) to select between eight different energy supply technologies . Using this method the technology options are scored against the categories of Physical, Financial, Human, Social and Natural impact. SURE DSS allows decision makers to examine the impact of installing different energy options on the livelihoods of local communities. The presented case study is set in a rural Columbian community.

Upham et al. (2007) looked at policy issues around biofuel use in a UK context at a regional level. The study collects the opinions of key stakeholders within the bioenergy industry and government as well as members of the public. The findings show that overall stakeholders preferred the option of combined heat and power (CHP) plants run on biofuel due to higher overall efficiency and perceived improvement in local employment.

Zhou et al. (2007) presented a method to select between several fuel types including bioethanol and blends using biofuels. The multi-criteria analysis used life cycle cost, global warming potential, net energy yield and the potential for non-renewable resource depletion. The method used an aggregating function known to combine relative weightings of each criterion against the impacts of each fuel type. The study explored the impact of changing the relative weightings of each criterion.

Afgan and Carvalho (2008) used a multi criteria method based on a measuring parameter described as a *general index of sustainability*. The general index method requires the formation of an aggregate function using the weighting of different indicators. This method was used to evaluate the sustainability of different renewable energy technologies when used together, for instance PV with Wind technologies. The evaluation uses an economic, environmental and a social indicator set to evaluate sustainability. The study compares five contrasting energy systems which are evaluated in seven different cases where different coefficients are given different weightings. The coefficients used are electricity cost, investment cost, NO_x emissions, CO_2 emissions, efficiency and electricity cost.

Herran and Nakata (2008) used four attributes, electricity cost, employment, land use and CO_2 emissions to make a decision on the optimal system configuration to meet electricity demand in an off-grid rural location. A goal programming algorithm is used to select the most suitable technologies to be used in this context.

Frombo et al. (2009) showed how an environmental decision support system (EDSS) could be used to assist with bioenergy project planning. The DSS allows users to manipulate GIS data to show the impact of using different conversion technologies in different locations. The DSS allows a rapid and high level analysis of expected economic factors and constraints associated with sustainable forest management.

Ren et al. (2009) gave a recommendation for the optimal energy system that could be used in Japanese residential buildings. The study used a multi-criteria analysis combined with linear programming techniques to make the decision along with the application of PROMETHEE and AHP to select between options. The study also includes a sensitivity analysis using 10 different scenarios and is able to examine four assessment criteria.

Karagiannidis and Perkoulidis (2009) combined the ELECTRE III decision method with fuzzy set logic to select between several different anaerobic digestion (AD) technology choices. The criteria used for the selection were greenhouse gas (GHG) emissions, recovered energy per tonne, recovered material per tonne and operating cost per tonne of feedstock. The study was completed for a case study waste stream identified in Greece.

Mohamadabadi et al. (2009) also used the PROMETHEE method but this time to make a selection for fuels to be used in vehicles. Non renewable fuels were considered along with biofuels, electric-hybrid and compressed gas. Different criteria were then weighted against either an environmental scenario where more emphasis is placed on environmental outputs, or a cost scenario. The authors found that biodiesel fuel followed only the hybrid electrical choice for the environmental scenario. This paper also included a sensitivity analysis allowing the authors to identify which criteria were most important for the output ranking.

Buchholz et al. (2009) reported on a comparative review of several decision support systems when applied to a case study in Uganda. The study had a focus on multi-stakeholders and their roles in the decision making process. The multi-criteria decision tools used were SuperDecisions, DecideIT, Decision Lab and NAIADE. The study aimed to make a decision which would result in the most sustainable choice being made and found large variation of results from the various tools used. However social criteria were, in this case, always identified as being decisive to the outcome of each process.

Evans et al. (2010) compared three technology types using either dedicated or residual biomass to determine which combination of biomass and technology is considered most sustainable for electricity generation. The criteria used for sustainability were categorised as CO_2, availability, limitations, land and water use and social impacts. The paper concludes that using hardy crops on marginal or unusable land performs best against the sustainability criteria defined. The use of fertiliser is also highlighted as having negative sustainability impacts.

Jovanovic et al. (2010) examined a district heating application in Serbia with regards to using a blend of technology choices including biomass with either solar or natural gas for hot water provision. The analysis focused on five technologies and compared against a complex set of sub-criteria in a multi-criteria analysis. The approach taken avoids allowing the definition of ‘sustainability’ to be determined by the analysts involved and rather uses a set of energy indicators. This has the advantage that the decision would be consistent across similar schemes regardless of the personnel involved in decision making.

Münster and Lund (2010) selected a suitable energy from waste (EfW) technology for biogas and biofuel production including gasification technologies. The paper uses a so called energy system analysis which allows a direct comparison between technologies based on the focus of the decision maker. The focus could be CO_2, sustainability metrics, cost or efficiency amongst others as defined by the decision maker. The authors propose that the outputs from this method would be suitable for use in other decision tools such as cost-benefit or MCDA.

Oberschmidt et al. (2010) also applied the PROMETHEE method for technology selection. In this study various alternatives for provision of heat and power in a municipality in Germany were compared. The findings report that when considered over the lifetime of the plant using a lifecycle analysis approach renewable technologies can compete with fossil fuel technologies for this application.

Giarola, et al. (2011) tackled the problem of optimal location and logistics operations for a biofuel supply chain over several time periods and for multi-feedstocks. This approach was shown to optimise the location of pre-treatment facilities and allocation of feedstock and final energy to demand centres. The authors found that existing first generation biofuels were unable to meet the requirements of European regulations on environmental and economic performance. The development of second and third biofuels is therefore required.

San Cristóbal (2011) applied the VIKOR method to select between renewable energy technologies in Spain. The VIKOR method attempts to select a solution as close to the "ideal" as possible, the authors also used the AHP to allow decision makers to assign weightings to criteria. The study found that the expert group consulted preferred co-combustion of coal and biomass over other renewable technologies.

In one of three papers on the subject of biofuels in Italy Giarola et al. (2012) presented a mixed integar linear programing model that was used to assess the different designs of upstream bioethanol supply chains, making a recommendation between several technology options. The model was unusual in that it was able to handle changes over time. Giarola et al. (2011) had used a similar model to evaluate environmental and economic impacts over the same case study data.

Steubing et al. (2012) utilised several individual models that examine different problems along the biomass supply chain to create an optimisation strategy for choosing the best technology, capacity and location. Capacity is considered as a continuous variable whilst technology and location are selected from a finite set. This is one of the few studies to attempt to properly integrate the location, technology and capacity[1] problems in one global optimisation approach.

[1] Capacity problem could also be considered as selecting a feedstock problem, the size of the plant will depend on how much feedstock is available.

Baris and Kucukali (2012) made a recommendation for Turkey that the country should deploy more biomass over solar photovoltaic and wind for renewable electricity generation. The study favoured biomass only because of the positive social impact associated with the supply chain and the technology.

De Lange et al. (2012) made a selection between different possible configurations of biomass pre-treatment and conversion facilities that could use particular invasive plants as feedstocks. The method used incorporated stakeholder opinion to determine the best combination and the results showed that local solutions give more favourable outcomes than centralised systems. Six criteria were used for the AHP analysis used.

Jing et al. (2012) presented a two teir set of criteria for the selection of combined cooling, heating and power systems (CCHP). The criteria were split under technology, economy, environment and society. The authors used an integrated fuzzy grey relationship analysis to determine that for the Chinese case examined gas fired CCHP systems were the most desirable.

Mourmouris and Potolias (2013) used a multi-criteria analysis to make a recommendation on how much energy the nation of Greece should use to meet its renewable energy targets. The paper is unusual as it allows for a mixture of energy sources although only looks at wind, solar photovoltaic (PV) and biomass. The study used the previously developed REGIME MCDA software and found that a mixture of biomass and wind would give the most efficient investment against performance as determined by the REGIME software.

Fazlollahi and Maréchal (2013) presented a complex multi-criteria analysis of different configurations of technologies that could provide heat and electricity including several options for the conversion of biomass. The method applied used a mixed integar linear programming and evolutionary algorithm, the study is unusual as it considers more than one time period whilst also accepting multiple objectives.

Keirstead et al. (2012) looked at the future development of eco-towns in the UK and examined various bioenergy conversion options for providing the required 80% reduction in CO_2 emissions. The preferred solution is a combination of gas engines burning biogas and organic rankine cycle (ORC) plants, both operating as combined heat and power schemes.

2.3.7 Capacity selection

In a study related to Ren et al. (2009), Ren et al. (2010) used a linear programming model to help with the design and evaluation of a biomass combined cooling, heat and power (CCHP) system. The model is able to optimise for the capacity of plant that will be required depending on demand side characteristics of the heat load. This model is tested in a Japanese building as a case study.

Yagi and Nakata (2011) used GIS information on resources to calculate the economic case for biomass conversion facilities in the Miyagi region of Japan. The calculation of economic value lead to recommendations for the capacity and number of plants to be built, along with their location.

Parker et al. (2010) used a mixed integer linear programing (MILP) approach to optimise profit from a biofuel supply chain by selecting the locations for new refineries. The system required existing and potential locations and transport routes as an input. The output also gave information on optimal capacity for each refinery. A year later Dal-Mas et al. (2011) used a very similar approach for Northern Italy on the same biomass based ethanol industry. However Dal-Mas et al. focused on finding the optimal location from an infinite selection of potential sites whilst also recommending optimal capacity of each facility. Kim et al. (2011) also took a very similar MILP approach to optimise for capacity and logistics structure (or order allocation) between sources of biomass and buyers. A further paper by Marvin et al. (2012) again looked at this problem for the USA adding a sensitivity analysis that used a Monte-Carlo sampling method.

Uhlemair et al. (2012) used MILP to select a suitable size biomass CHP for a village of a given size. The model required the number of heat users to be given and allowed different operating scenarios to be produced at the planning stage. The model is especially powerful as it allows for the connection map to be drawn up using each heat user as a node in the MILP.

2.3.8 Sustainability issues

Elghali et al. (2007) took a slightly different approach to many other researchers in the field by moving away from assuming a single decision maker analysis and absolute objectivity with common scales and typically heavy data requirements. Instead a paradigm from Rosenhead and Mingers (2001) is used which works towards seeking alternative solutions that are acceptable without demonstrating trade-offs and accepting that uncertainty will exist. This approach seeks a solution rather than an optimal and the Elghali et al. (2007) study used the approach to model a life-cycle perspective of the supply chain of willow for energy. The study concludes that the created framework can be used as guidance to development of supply chains recognising social and environmental impacts as well as socio-economic barriers to development.

Madlener et al. (2007) used PROMETHEE to compare five different scenarios which assumed different proportions of electricity and heat produced by various mixtures of renewable technologies. One scenario was described as “Extensive use of Biomass”. A mixture of qualitative and quantitative criteria is used to define the preferable scenario with expert opinion used to give each scenario a final score.

Sultana and Kumar (2012) made a straightforward but effective multi-criteria comparison of biomass pellets manufactured from different feedstocks. The criteria used a mixture of explicit chemical and qualitative indicators upon which the selection is based. The PROMETHEE I and II methods were found to both recommend wood pellets followed by switchgrass pellets as the most favourable feedstock apart from for maximising the economic benefits when straw is favoured over switchgrass.

2.3.9 Others

Jablonski et al. (2008) treated the qualitative assessment of market segments as a multi-criteria analysis. The study examines the interactions between market segments through a qualitative score code. The paper proposes a framework involving dividing the heat market into segments based on fuel supply options, identifying key factors affecting the uptake of bioenergy for each segment, classifying those factors to identify barriers and finally identifying those which can be overcome. The results show a massive variation in market potential but that the most suitable heat market segment would be the residential segment.

Beck et al. (2008) used optimisation methods to set a target for energy planners and policy makers by choosing a preferred pathway of biomass conversion. The optimisation method used techno-economic, environmental and social criteria and looks at the behaviour of different agents within the network influencing the final energy mix. The method is tested in a South African case study.

Briceno-Elizondo et al. (2008) used a multi-criteria analysis model to simulate the Boreal Forrest over 100 years. This study uses stochastic input data and a stochastic treatment of alternatives to produce a measure of utility as defined by a previous model. A Monte-Carlo analysis is used to evaluate eight different Forrest treatment programmes against the objectives leading to utility, including Timber production, CO_2 and biodiversity.

Tenerelli and Carver (2012) used a spatial GIS approach to estimate the potential for different types of energy crops for a region in the UK. The assessment used several different criteria to determine the potential for energy crops such as rainfall, PH, slope and depth of soil.

In one of the few studies that addresses the feedstock supply problem from a purchasing strategy approach (Prasertsan and Krukanont) presented a mathematical model to find the maximum acceptable fuel cost that can be withstood by the a project prior to the engineering part of the development. The model shows that the maximum affordable fuel cost is sensitive to various factors including moisture content, electricity sale price and capital expenditure.

Balezentiene et al. (2013) used a fuzzy multi-objective approach to help decision makers select between different energy crops. The decision is influenced by carbon sequestration ability, erosion control, water and nitrogen consumption as well as two economic indicators; dry-matter and energy yield per hectare. Giant Reed was found to be the most favourable energy crop for a case study on Lithuania.

2.4 Methods applied within the academic literature

A general typology of the different methods that are used in the reviewed literature is shown in Table 2.4. The categories have been made from typologies presented in Zopounidis and Doumpos (2002) and in a less systematic and less focused review on decision methods for renewable energy by Pohekar and Ramachandran (2004).

Table 2.4: General division of methods, typologies of method and the corresponding problem or approach. (adapted from: Pohekar and Ramachandran, 2004, Zopounidis and Doumpos, 2002)

Problem type/approach	Method type	Examples of method
Choice between few or finite alternatives	Outranking methods	ELECTRE; PROMETHEE; TOPSIS; VIKOR; Weighted sum models AHP; MACBETH.
Choice between many or infinite alternatives	Optimisation methods	Stochastic programming; linear programming; integer programming; mixed integer programming; multi-objective linear programming.
	Heuristic methods	Swarming/bees method; evolutionary/genetic algorithms; hill climbing; simulating annealing; tabu search.
Predicting the future	Simulation methods	Simulation; predictive/temporal mathematical modelling.
Qualitative analysis (in depth data collection)	Qualitative methods	Interview; semi-structured interviews.
Others	Any method that does not fit into the above classifications. Includes life-cycle analysis and total cost analysis.	

Sections 2.4.1 to 2.4.4 describe the different categories that have been used to classify the reviewed papers.

2.4.1 Choice between few or finite alternatives

This class of problems involves making a decision or assisting with a decision process where the decision maker must select between a few or several (usually 3 to 8) alternatives, for instance between alternative projects, technology options or feedstock types. Usually the decision is based on more than one criteria, if based on a single criteria the decision is likely to be straightforward and there is no need for decision analysis techniques.

A common group of methods from the optimisation with finite options category is a family of outranking methods based on the principle of pairwise comparisons, probably the most well-known of these methods is the Analytical Hierarchy Process (AHP) method. The ELECTRE and PROMETHEE Methods also belong to this category. At the core of these methods is are two key techniques; pairwise comparison matrixes and normalisation. Pairwise comparison tables involve comparing each alternative against one another with regards to a particular criterion. The AHP uses a particular scale and gives a relative preference weighting for each alternative as the output, an advantage of the AHP method is that it allows for a check to be made of the consistency of decision maker responses. The PROMETHEE method is helpful when the nature of preference between different alternatives is complex. When one alternative is considered preferable but only up to a particular limit for instance. The ELECTRE method is very similar and also allows for indifference and preference thresholds, veto thresholds are also included in ELECTRE(III) that can allow the decision maker to resolve conflicting criteria, with the result that the response is forced to be inconsistent.

PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) is a multi-criteria decision aid methodology developed by Jean-Pierre Brans and Bertrand Mareschal since 1982. PROMETHEE is an outranking method based on the pairwise comparison of different options against the criteria defined by the decision maker. The user is able to assign weightings to each criteria and the preference ranking takes into account the degree to which one alternative is preferred over another. More complexity can be added by including thresholds for preference, this would allow alternatives that only marginally preferable to be taken as equal and set a threshold for what is defined as preferable (a 20% improvement for instance could be the preference threshold). The level of preference can also be given a function, this is helpful for instance if a 30% preference is considered just as desirable as a 90% preference for a particular criterion.

Geometric Analysis for Interactive Assistance (GAIA) is often then used to better visualise the outcomes of the decision process. PROMETHEE GAIA software has been developed to assist in the application of this method and is available for download Mareschal (2011).

ELimitation Et Choix Tradusant la REalité (ELECTRE - Elimination and Choice Expressing Reality) was introduced in the mid-1960's by SEMA consultancy employee Bernard Roy (Gass and Assad, 2005). ELECTRE relies upon the weighted sum technique for making business decisions. The ELECTRE process involves two parts, firstly deciding the relationships between different actions or options, secondly a weighting of preference for each action is determined using a veto thresholds and importance coefficients approach Figueira et al. (2005).

Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) is a multi-criteria method which uses an evaluation matrix similar to those of the AHP, ELECTRE and PROMETHEE methods but can handle either crisp, stochastic or fuzzy measurements of the performance of each alternative against a given assessment criteria. Software has also been developed to further facilitate the application of the NAIADE method.

2.4.2 Choice between many or infinite alternatives

Problems that do not allow for selection between a few clearly discrete or distinct alternatives are categorised into the ‘many or infinite alternatives’ category for this review. This describes any problem where the decision maker is faced by a continuum of choices or by a large number of difficult to compare options. This choice is made more complex when multiple criteria are introduced, in these problems a choice must be made from a wide (or infinite) selection of alternatives, each of which are difficult to evaluate quickly against one another. Most of the problems faced by the papers reviewed in this category are however solvable, a ‘best’ solution can be found with accuracy. Some sub-problems of the transport and logistics application area however are more mathematically difficult and depending on the exact nature of the problem could be classed as NP-hard problems that require heuristic optimisation methods to solve.

When only a single criteria is important in a problem with many alternatives the most common approach is to use a mathematical optimisation algorithm. This usually involves creating a single objective function (O.F.) and asking the algorithm to find the solution that maximises or minimises that function. Cost, profit or lead time for instance may be the only term appearing in an objective function. More complex metrics can also be used such as price sensitivity, net present value or some measurement of risk. Along with the objective function a set of constraints are also required. These constraints set limits on where the solution can be found. A well-constructed optimisation problem should be bounded so that the solution cannot become infinitely large or small.

For the vast majority of problems the constraints and objective function are linear; however non-linear constraints and objective functions can be treated in a similar fashion. Figure 2.2 shows the optimal solution for a problem with either linear and linear and non-linear constraints. The objective function for both diagrams is to maximise the quantity on the x axis and the y axis with equal preference weighting whilst being above the blue constraint, below the red and green constraints. In some situations more than one optimal solution may be available, for example if the objective function were to maximise the quantity on the y axis only, the problem shown on the right would have more than one optimal found along the line of the green constraint. In such a situation the optimal solution is better described as a frontier, specifically the pareto efficient frontier.

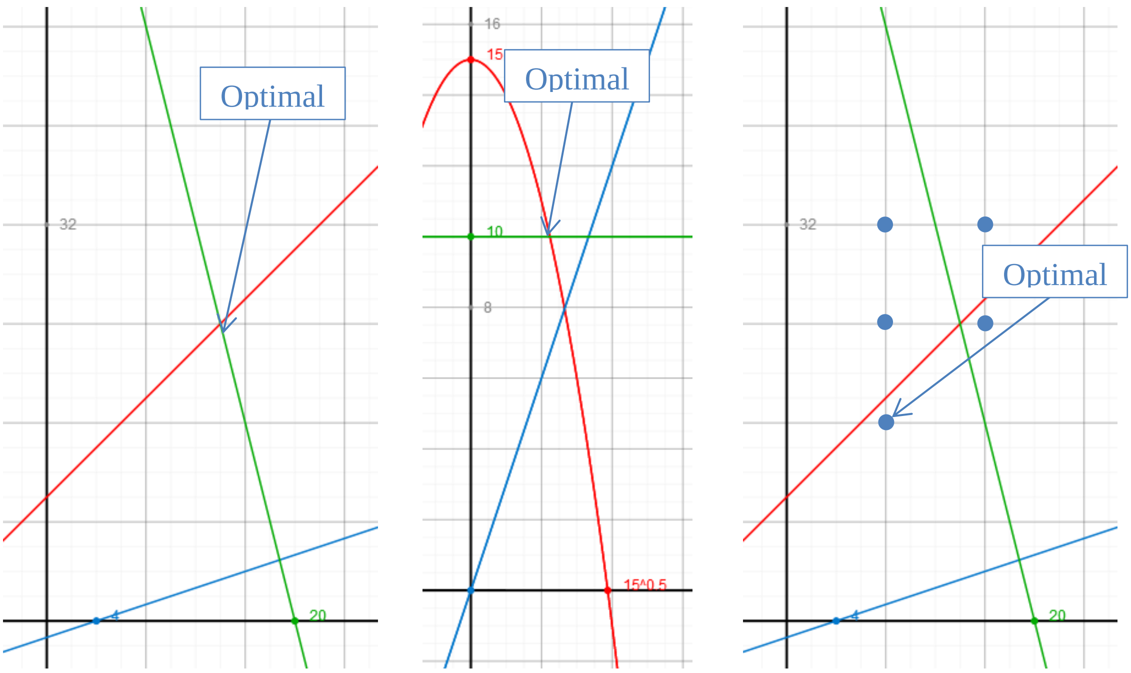

Figure 2.2 Left to Right: Optimal feasible solution for linear constraints; non-linear constraint and integer objective function with linear constraints.

Figure 2.2 shows each constraint as a continuous variable, the objective function is also considered as continuous. In some problems however this is not the case as some variables may only be available in integers or particular values. This makes the problem more mathematically complex. A quick way to find an optimal in this scenario is to remove the integer properties and solve as a linear programming problem, then simply select the closest integer values, however this can lead to sub-optimal solutions and in some cases to infeasible solutions being selected. Pure Integer Linear Programming (ILP) problems are fairly unusual but difficult to solve, heuristic or approximation methods are currently the most successful and timely method of solving such problems. More frequently encountered are mixed integer problems. In mixed integer linear programming (MILP) problems only some of the constraints are integers; this is common for logistics problems where particular warehouses or factories should be considered as either built or not built for the purposes of the analysis. In Figure 2.2 the possible solutions are represented by the blue points, solutions can only exist at these points. The optimal feasible solution is not the closest to the optimal solution for the continuous linear programming problem shown on the left. This approach is applied in several of the reviewed papers. (Parker et al., 2010, Dal-Mas et al., 2011, Kim et al., 2011)

2.4.3 Predicting the future

Simulation methods are a powerful tool for policy makers and project developers. As with all modelling approaches to decision making the aim is to create a mathematical model that represents the real world situation as closely as is required by the decision maker. Simulation modelling is conventionally applied in engineering for fast virtual prototyping of products and components but simulations of supply chains, operational models, networks, interactions and other management practices are also common. Closely related to simulation are scenario models or situational models. These sub-categories of prediction models aim to provide the decision maker with a range of possible, plausible results from a certain decision. This is frequently applied to modelling of environmental impacts of various incentive policies for government decision makers.

The advantage of predictive models is their relative low cost, the ability to forecast for many scenarios quickly and the ability to observe the impact of changing decisions at any time-period in the future. The disadvantage is the difficulty in creating accurate models over long time horizons, especially for systems as complex as econometric or climate models. Not only are the models difficult to make accurate, but it can be near impossible to measure how accurate they are.

2.4.4 Qualitative methods

This category of problems covers those papers which apply qualitative data collection methods to investigate and solve challenges around bioenergy. Qualitative methods allow issues and areas of interest to be investigated in a greater level of depth than can be achieved with surveys or most traditional quantitative methods. These studies take a different approach to the studies that use the methods discussed in section 2.4.1 and 2.4.3 above and are therefore able to capture different types of information on the problems being addressed.

The compromise between qualitative methods and quantitative methods is usually described as being due to difficulties in generalising from a single or a few qualitative case studies or data points up to a generalizable rule for all cases or data points. However the detail qualitative studies can reveal is essential to properly understand the types of systems that are being modelled using quantitative methods.

2.5 Observations on the literature

This section contains some observations on the reviewed literature. In particular the following sections aim to answer several questions regarding the existing body of literature.

1. Which problems have attracted the most attention?
2. Which methods are most frequently applied?

3. What are the national contexts of the reviewed papers?

Sections 2.5.1 to section 2.5.4 respectively answer these questions and section 2.5.5 gives a summary of the reviewed literature. Other observations on the literature are given in section 2.5.4

2.5.1 Which problems have attracted the most attention?

The most popular barrier category addressed in the literature is technology selection with 33 papers (24%) of all reviewed papers. Of these 24 used optimisation methods that selected between few alternatives to choose between either different types of biomass technology, renewable technology or energy generation technology. This is the most popular combination of problem and method.

The next most popular combination of method and research problem was selecting locations using optimisation via algorithm methods found in 16 out of the 21 studies on the location problem. The logistics and location problem are sometimes handled together and sometimes with capacity choice also incorporated into the optimisation model. Combining these categories shows that 44 contributions were made to these three areas with 32 of those using algorithm optimisation methods.

Although much attention has been paid to the logistics, capacity and location parts of the supply chain problem, no literature exists on the selection of suppliers at either the strategic or tactical level. Previous work has used algorithms to determine which sources should be used (Ayoub et al., 2009, Ghilardi et al., 2009, Gold and Seuring, 2011). But no authors address the barriers raised in Iakovou et al. (2010) and (Adams et al., 2011) regarding supply and demand contracts, perceptual challenges, the unsettled bioenergy market and uncertainty regarding legislation, equipment, seasonal variation and adaptability. There is a body of literature that applies previously developed methods to the bioenergy problem, but these often fail to account for the nuances that make the problems faced by bioenergy supply chain managers different to those faced by conventional supply chain managers.

The problem of policy setting and regulatory impacts on industry was studied by 15% (19) of the papers, 11 of those selecting between a finite number of alternatives. This trend in the literature towards selecting between technology options, between incentive schemes and looking at the impact of policy on technology deployment may be due to the focus of governments and policy makers. If research were allocated based on the problems being faced by governments attempting to identify the best de-carbonisation route available for their territory a top-down approach may be expected to be popular in the literature.

Papers on sustainability, or at least one pillar of the sustainability debate make up the bulk of the remaining reviewed literature. The treatment of sustainability issues is not coherent throughout the literature reflecting differences in understanding and attitudes to sustainability between different authors and national contexts. Clearly a key area for the success of bioenergy this area is not well defined from a practitioners view. Although legislative measures and standards are being introduced inconsistency between reports and policies makes decision making in this area more complex (CCC, 2011, DECC, 2012e).

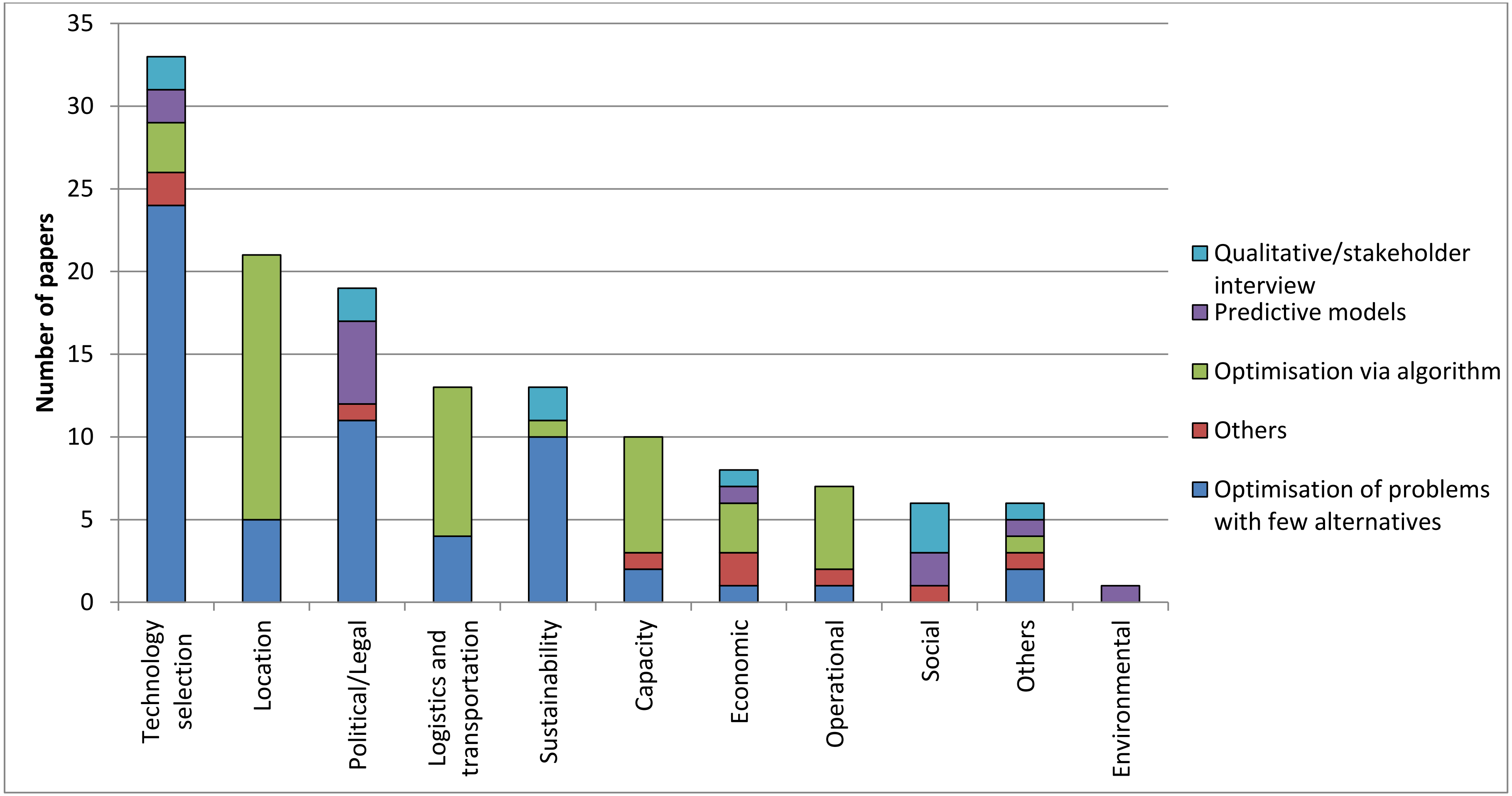

Figure 2.3: Findings showing problem area addressed and the method used

2.5.2 Which methods are most frequently used?

The most popular method applied to the bioenergy industry can be classified under the optimisation of problems with few alternatives which is used by 42 (44%) of the reviewed papers. The next most popular method is optimisation via algorithm with 31 (33%) of papers. This could be considered as an imbalance in the approaches being taken, especially as the field is so clearly dominated by quantitative studies. However these results could be due to the nature of the field. The use of secondary data, models and weighting techniques is suitable for some of the barriers identified in section 2.2 but the spread of research in Figure 2.4 indicates that some richer, qualitative information on problems and solutions may be missed by the current literature.

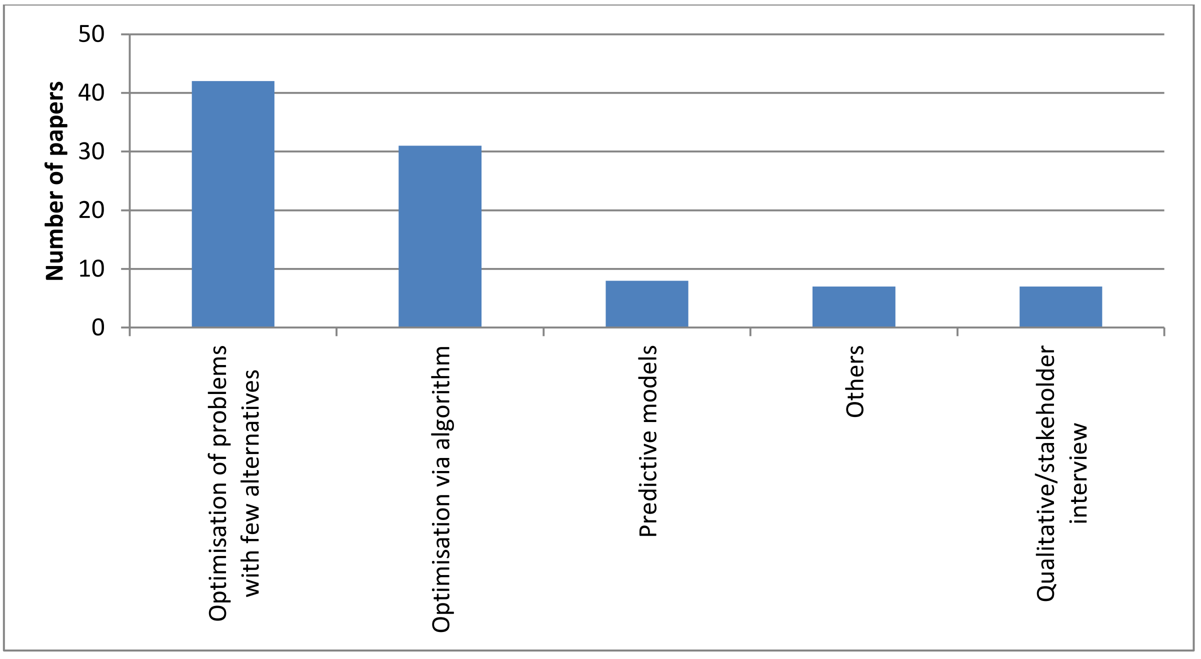

Figure 2.4: Number of papers in review and the methods applied

2.5.3 National contexts of studies

Figure 2.5 shows the papers that use some form of national context, either as a case study or as a context for the research findings. Studies in a European context dominate this chart and account for 79% of those reviewed papers that use a national context. Figure 2.6 shows that the UK is the most studied country within the reviewed literature with nearly twice as many papers reviewed than the next most popular countries, Greece, Spain and Italy. This result may also be due to the bias introduced by government interest filtering down through funding bodies into research. The balance will also be skewed by the total amount of research published in each country although researchers also frequently conduct research overseas.

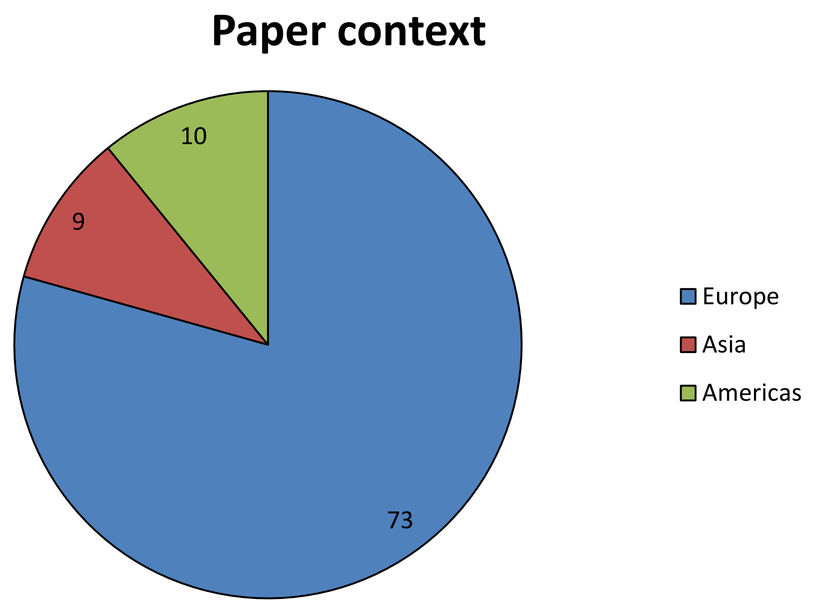

Figure 2.5: Distribution of paper contexts divided into continental region

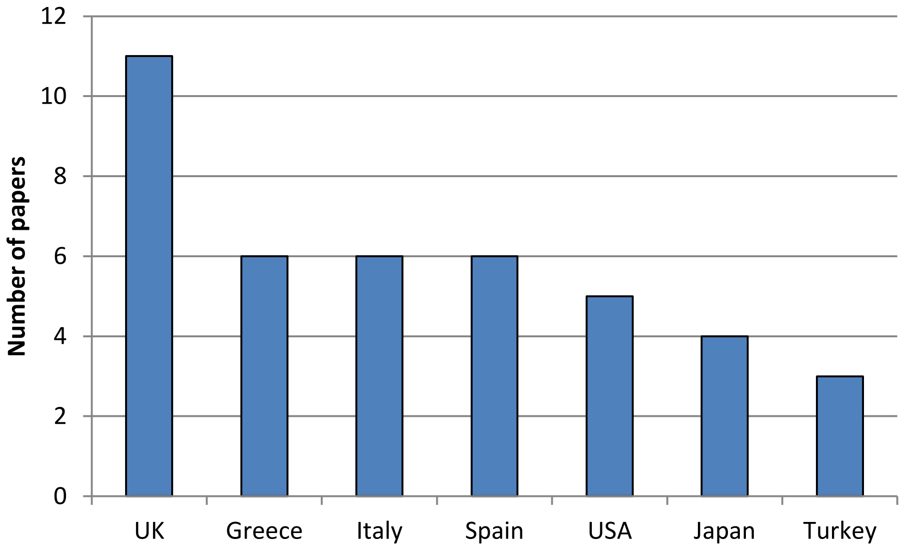

Figure 2.6: National context of reviewed papers

2.5.4 Other observations

Figure 2.7 shows that the body of literature reviewed mainly comes from the period after 2007. 83 (87%) of the 95 reviewed papers were published in or after 2007. 69 (73%) of the reviewed papers were published between 6 journals and over half were published in just 3 journals, biomass and bioenergy, energy policy and energy as shown in Figure 2.8. This indicates that the body of literature on bioenergy is rapidly growing in line with interest in bioenergy systems from industry and government. The field is focused and although many journals have published in the area, 29 different publishing journals were identified; a specialist academic domain is being created.

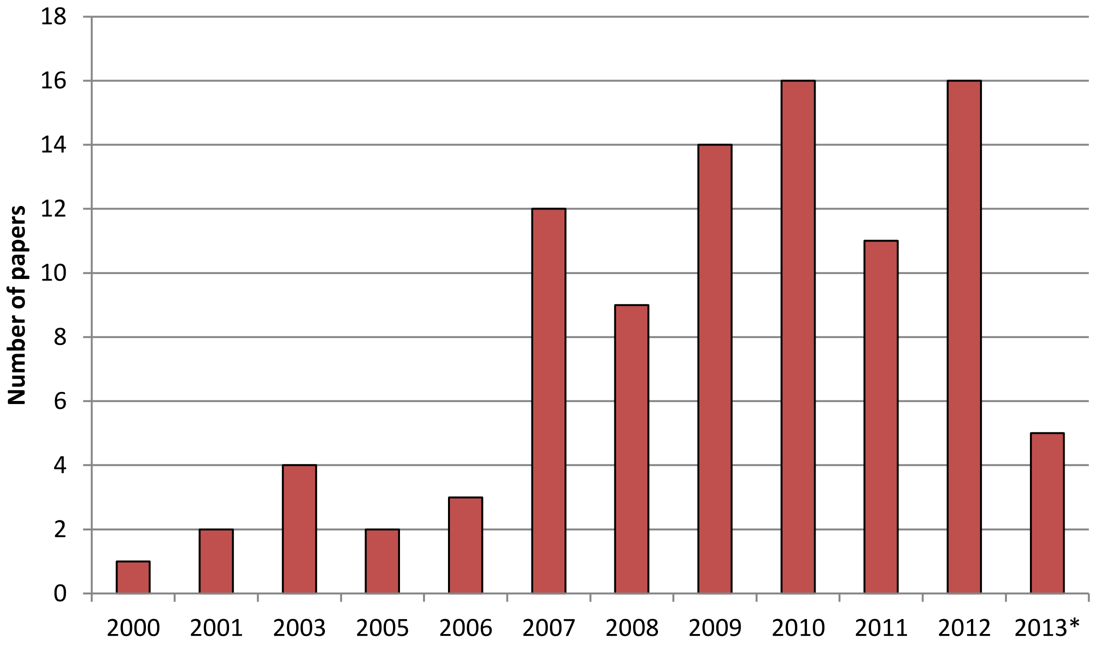

Figure 2.7: Date of publication for reviewed papers

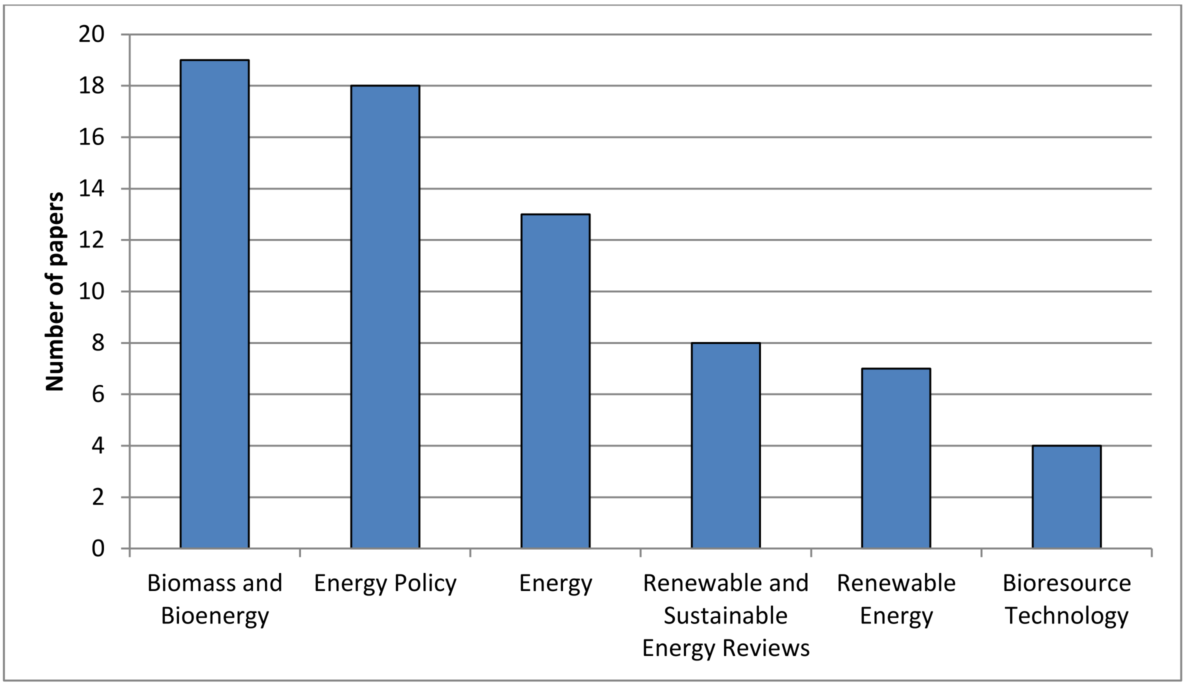

Figure 2.8: Top 5 publishing journals for reviewed papers

2.5.5 Summary of literature review

There is a rapidly expanding body of literature that aims to address problems encountered in bioenergy deployment. There is a smaller but significant and fairly consistent body of literature examining and identifying barriers to deployment. In general the problems or barriers identified can be matched to the areas of academic study for the bioenergy field.

The literature on barriers to bioenergy deployment identified in section 2.2 is very rarely mentioned in the literature that attempts to address that literature (indeed only Herran and Nakata (2008) explicitly mention any of the literature on barriers). This is partly due to timeliness, the literature identifying problems does not significantly pre-date the reviewed literature, but equally it could be said that the barriers are still being observed despite the research being published.

The reviewed literature consists partly of papers that take a top-down approach to whatever problem area the paper seeks to address. Those papers that aim to select or rank technologies based on some measure of sustainability, performance or satisfaction of some other criteria, as well as those papers that aim to make policy recommendations and those that estimate bioenergy resources all take a viewpoint representative of a central decision maker or government body. Broadly these papers aim to influence the type of technology deployed or policy implemented and take a fairly interventionist approach, hence the top-down approach. This is true across all scales of deployment.

Contrastingly there is a section of the reviewed literature that takes more of an operational viewpoint although these are most accurately described as being at the tactical level. Such tactical level studies tend to focus on logistics, capacity and location issues. These problems are closely interrelated, the capacity of a particular facility, demand or supply dictates how much biomass must be converted and moved. The properties of the biomass change the optimal logistics structure and there are several pre-treatment technologies that can influence the best logistics solution. The temporal nature of biomass is also studied as being important to the layout and logistics of a biomass supply chain and several papers examine the differences in optimal logistics solution or facility location over a certain time horizon (Čuček et al., 2012, Pérez-Fortes et al., 2012, Pokoo-Aikins et al., 2010).

A few of the papers addressing barriers to bioenergy mention stakeholder involvement, only Buchholz et al. (2007) examined bioenergy problems from a tactical or operational level whilst fully incorporating the opinions of different stakeholders. The other papers that look at tactical or operational level decisions either assume their criteria from other sources, or assume that sustainability is the key driver for decision making and perform an analysis based on that assumption. The work by Buchholz et al. (2007) is an attempt to investigate the difference between different decision support systems based on a case study in Africa and therefore addresses a slightly different type of issue compared to the related literature (as for instance Ayoub, Elmoshi et al. [2009]).

Referring to the value chain for biomass and organic wastes to bioenergy in chapter 1, the reviewed studies cover adding value through conversion to heat or power, densification of energy per kg, the transportation of material and the classification of material. Purification is a handling and separation activity and would not be expected to appear in the reviewed literature.

2.6 Literature gaps

The gaps in the literature on decision making for bioenergy schemes are summarised in the points below. The reviewed literature is growing rapidly and much research funding and researcher interest is being applied to these problems as they move up the political and social agenda. The gaps highlighted are intended as direction for future research.

- Multi-stakeholder approaches are not applied to the management of bioenergy supply chains
- No previous literature addresses the supplier evaluation and selection problem for bioenergy supply chains
- There is a lack of practitioner orientated literature in the reviewed literature. Top-down planning and decision making at government level dominates.
- The identified barrier for decision making in the context of uncertain feedstock, variability and uncertainty regarding equipment is not addressed by any of the reviewed literature
- Stakeholder opinion is recognised as key to bioenergy project success but is not frequently integrated into the decision making process by studies in the reviewed literature.
- None of the reviewed literature considers the upgrading of bioenergy value by blending or mixing materials to allow for re-classification.

2.7 Stakeholder Theory

Stakeholder engagement entered the thinking of managers and academics with Edward Freeman's book Strategic Management: A stakeholder approach (1984), a landmark book which introduced the idea of a firm or corporations purpose to be the creation of value for its stakeholders. Since then attempts have been made to formulate theories about stakeholder engagement, identification and relationships. Most notably Mitchel et al. (1997) which presented a method of stakeholder identification based on power, legitimacy and urgency although Freeman proposed a different method (Freeman, 1984) which was built on by Savage et al. (1991). Friedman and Miles (2002) also presented an alternative based on the nature of a firms relationship with its stakeholders. These ideas remain current and popular in both practice and literature with an active discussion of how theory should develop, in particular contributions from Friedman and Miles (2002) and Laplume (2008) have assisted with theory formulation in this complex areas.

The Mitchel et al. (1997) model of identification of salient stakeholders appears to remain the most easily applicable interpretation of stakeholder theory to practice, providing a framework for organisations to use when aiming to identify stakeholders for themselves. Stakeholder theory was adopted extensively by UK government from the mid-1990s onwards where it has been used as a blanket term to describe the public and any organisation or individual who holds a stake in the success of the focus organisation. This is close enough to Freemans often cited definition: "any group or individual who can affect or is affected by the achievement of the organizations objective" (Freeman, 1984) although in 2004 Freeman published the latest definition of stakeholder as "those groups who are vital to the survival and success of the corporation" (Freeman, 2004).

In 1995 Donaldson and Preston (1995) proposed a three-way division within stakeholder theory between normative stakeholder theory as discussed by Friedman and Miles (2002), instrumental stakeholder theory and descriptive stakeholder theory. Donaldson and Preston argue that instrumental stakeholder theory describes how organisations and managers should act to benefit themselves, whilst descriptive stakeholder theory describes how managers and organisations actually behave. However the original normative approach remains dominant in the literature and practice. Organisations acting to bring benefit to their stakeholders, not just shareholders. Friedman and Miles (2002) also introduced a slightly different perspective when proposing that organisations themselves are best considered as a group of stakeholders whom all desire to have their needs satisfied and interests fulfilled. Managers are therefore making decisions to the benefit of that stakeholder group; this leads to principles of corporate legitimacy and later Freeman introduces the doctrine of fair contracts containing rules on how contracts between organisations and stakeholders should be made. One of these rules was the principle of limited immortality which stated that the organisation should be managed as if there were no time-horizon. This principle echoes with themes around sustainability and sustainable management.

Stakeholder theory has also been adopted and applied across a massive range of applications from natural resource management (Reed et al., 2009), communications (Deephouse, 2000), marketing and consumer profiling (Bhattacharya and Sen, 2003) and form a base to much of the literature on corporate and social responsibility (Aguinis and Glavas, 2012) as it provides a rationale and justification for an organisation choosing to benefit a wider stakeholder group rather than a narrow shareholder group. After nearly three decades of gradual evolution and refinement stakeholder theory has bridged the gap into practitioners thinking, this has brought a new interest into how stakeholder can be engaged by organisations, when, and to what extent.

Engagement with stakeholders allows a decision maker to attempt to accommodate the opinions and preferences of others who may hold salience over either the success of the decision, or the decision itself. Stakeholder buy-in to projects or decisions can increase the likelihood of consensus over complex decisions. Stakeholder engagement is an important part of the planning consent process for construction projects in the UK for instance. According to De Lange et al. (2012) the literature over whether, and to what extent, stakeholder opinion should be included in decision making comes either from political science literature or development theory. Although De Lange et al. (2012) frame this discussion in the context of natural resource management for bio-energy resources rather than supplier selection or supply chain management there are parallels for any multi-stakeholder decision. Both literature sources confirm that stakeholder opinion is important "because without stakeholder participation, decision makers assume the risk of enforcing compliance on an unwilling public" (De Lange et al., 2012) citing (Maguire and Lind, 2004). However there are clearly potential drawbacks of wholesale stakeholder engagement. By giving too much power to potentially uninformed stakeholders the decision maker loses the ability to justly decide on the optimal alternative. The degree of involvement required by the public is investigated for the case of UK healthcare decision making in Litva et al. (2002) and also by Wiesman et al. (2003) the Australian healthcare system.

Another potential weakness in stakeholder theory worth noting is the perceived emphasis on negotiation over co-operation. This is extenuated by Freemans introduction of contracts which may imply that conflicts and disputes between stakeholder opinions can be resolved through compromise or negotiation. Given the wide and incommensurable nature of possible stakeholder opinions this could become an impossible task for managers of complex stakeholder groups.

2.8 Chapter summary

The ideas used in stakeholder management are closely related to those behind supply chain management. Both areas require managers to consider their environment or supply chain as a single entity with multiple requirements and groups to satisfy. Supply chain management can be viewed from a stakeholder management perspective; supply chain managers' role is to satisfy the needs of the stakeholders of the supply chain. The thinking of supply chain managers is also moving away from firm-centric views and towards a more systems based, all-encompassing approach, understanding the competitive advantage available through good supply chain management frees supply chain managers to act for the benefit of many firms and therefore many stakeholders. Modern SC managers aim to make decisions that are holistically beneficial for the supply chain and therefore decisions that best meet the needs of the supply chain stakeholders, rather than the focus firm stakeholders.

To make such decisions a new and expanding toolbox of methods are available for supply chain managers. Multi-objective and multi-criteria problems are frequently addressed when viewing the supply chain holistically. These methods have been seen to be well studied in a variety of contexts and the formalisation of the decision making process allows decision makers to be clear and transparent about the choices they make. Analytical methods also add a degree of robustness to the decision making approach, by utilising these methods managers can better explain the rationale behind their choices and better examine alternatives. Similarly other stakeholders can also view the decision process from their own viewpoint, perhaps allowing the supply chain to better meet the needs of its stakeholders.

Within the supply chain management field the supplier selection problem has attracted attention from multi-stakeholder approaches. It is recognised that by including the needs of those affected by the supplier selection problem a better final decision can be made. Although many models and methods exist and have been applied to the various selection problem types few offer a fully integrated decision support system type framework. As in de Boer (1998) the supplier selection process requires three main phases: Criteria selection, importance weighting and final selection. Combining these phases into one DSS has not attracted nearly as much academic attention as the individual phases alone.

Much of the supplier selection literature focuses on making a single choice between a finite numbers of suppliers as in the classic supplier selection problem. Few studies allow for a portfolio of suppliers to be selected based on multiple criteria, this contravenes other areas of the supply chain management literature that highlights the risks of using a single supplier for strategic supply choices in some instances.

There is a rapidly expanding body of literature on biomass and bioenergy as shown by the increasing attention from special issues, new journals and cross-disciplinary approached being taken by authors. The topic area remains immature however and there is a shortage of rigorous empirical work in areas of the industry identified as causing bottlenecks in development including the management and design of the supply chain. Previous works have addressed supply chain management for bioenergy projects only partially. Methods are available for solving particular problems for the design of supply chains, such as organising lowest cost logistics (Gold and Seuring, 2011, Ayoub et al., 2009), locating facilities (Bastin and Longden, 2009, Natarajan et al., 2012) and other operational issues. However none of the methods are sophisticated enough to incorporate all the possible temporal, quality, sensitivity, logistical and tactical decisions required to fully design a biomass supply chain. This shows the complexity of the challenge facing developers when they seek to convince financiers of the robustness of material supply for a project.

This thesis aims to contribute to the growing body of knowledge regarding the management of new bioenergy systems. By taking a lead from the requirements of the industry stakeholders rather than from policy makers this work aims to better satisfy the requirements for successful deployment of bioenergy. The approach of the thesis is based on an integration of our understanding of best practice for supply chain management and new insights into the needs of stakeholders in the industry. By creating a holistic and integrated decision support system for the strategic sourcing of biomass this research aims to partly address some of the barriers identified in section 2.2 whilst building on the existing literature by taking a developer perspective to the problem, addressing the strategic sourcing challenge and integrating the requirements of different stakeholders into that sourcing decision.

The benefits of such a DSS are that it provides a framework against which all stakeholders can view and influence the decisions being made by supply chain managers. The holistic success of the supply chain becomes the focus of the decision, not solely the financial benefit of the focus firm. By using such a framework it is hoped that secure, robust and reliable supply chains of biomass material for energy production can be designed, removing the doubt of investors, mitigating the negative environmental impacts and satisfying the social requirements of stakeholders in a transparent and consistent way. Such supply chains can bring much needed stability and certainty to a rapidly expanding market currently in flux, a market with the potential to realise both great societal benefits but also for great harm.

Chapter 3. Biomass Strategic Sourcing Framework - BioSS

3.1 Introduction

This chapter introduces the bioenergy strategic sourcing (BioSS) framework. This chapter gives an overview of the BioSS in section and describes how it fits with current project development practice in section 3.2. Then a description of the different operational modes is given in section 3.3.1 and sections 3.2.2 to 3.2.4 give an overview of the main components of the framework; the fuels library, supplier selection and order allocation modules. The BioSS is intended for knowledgeable users with access to a reasonable level of technical and computational resources.

3.2 BioSS overview

The aim of the BioSS is to provide biomass buyers and supply chain managers with a recommended supply portfolio that satisfies technical constraints and also reconciles tacit stakeholder requirements regarding the supply of biomass materials. BioSS is relevant to more than one stage of the project lifecycle and consists of 3 main modules, two of which are analytical in nature. The outputs of the framework show the decision maker how much material should be contracted for and which suppliers this material should be contracted from. This section describes the BioSS and its capabilities, dataflows and decision structure in section 3.2.1. The way that BioSS is integrated with current operating practices in bioenergy developers is shown in 3.2.1. Before this section 3.2.1 returns to the beginning of the research project and documents the requirements analysis and scoping phase of the research.

The BioSS should allow several methods to produce portfolio recommendations depending on the context of the application. The recommended portfolio will change if different requirements are made of the supply portfolio, for instance the user may want to find the lowest cost portfolio, the most reliable or the least environmentally damaging. This section firstly discusses how the BioSS can be integrated into the process used by developers and where it can contribute, secondly the requirements being placed on the BioSS in the different contexts are described and finally the framework structure is proposed with details on the methods that have been utilised to meet the requirements.

3.2.1 BioSS framework structure and characteristics

There is a distinct dataflow within the BioSS. Initially information on the type of biomass material and/or the suppliers of that material is required. Information on the technical operating parameters of the chosen technology, demand and capacity of each supplier are also required. This information is used as the input to an optimisation algorithm that gives a recommended portfolio showing how much material should be purchased from each supplier. Having produced a recommended portfolio the suitability of that portfolio is tested against the technical constraints using a Monte-Carlo simulation. This gives an indication of how frequently the fuel blend can be expected to deliver fuel outside of the technical constraints set by the technology.

Figure 3.1 gives overview of how information regarding suppliers, the characteristics of the fuel those suppliers can provide, constraints and any tacit requirements are fed into the optimisation model. The optimisation methods chosen for this DSS are discussed in section 3.2.4 as are the methods used to collect tacit requirements and explicit fuel property constraints. Figure 3.1 shows a dataflow for the BioSS at the contextual level, showing the BioSS as a black box with where information flows over the surface of the system. Figure 3.2 shows a more detailed flow of data through the BioSS, showing how each module feeds into the next to deliver a recommended portfolio.

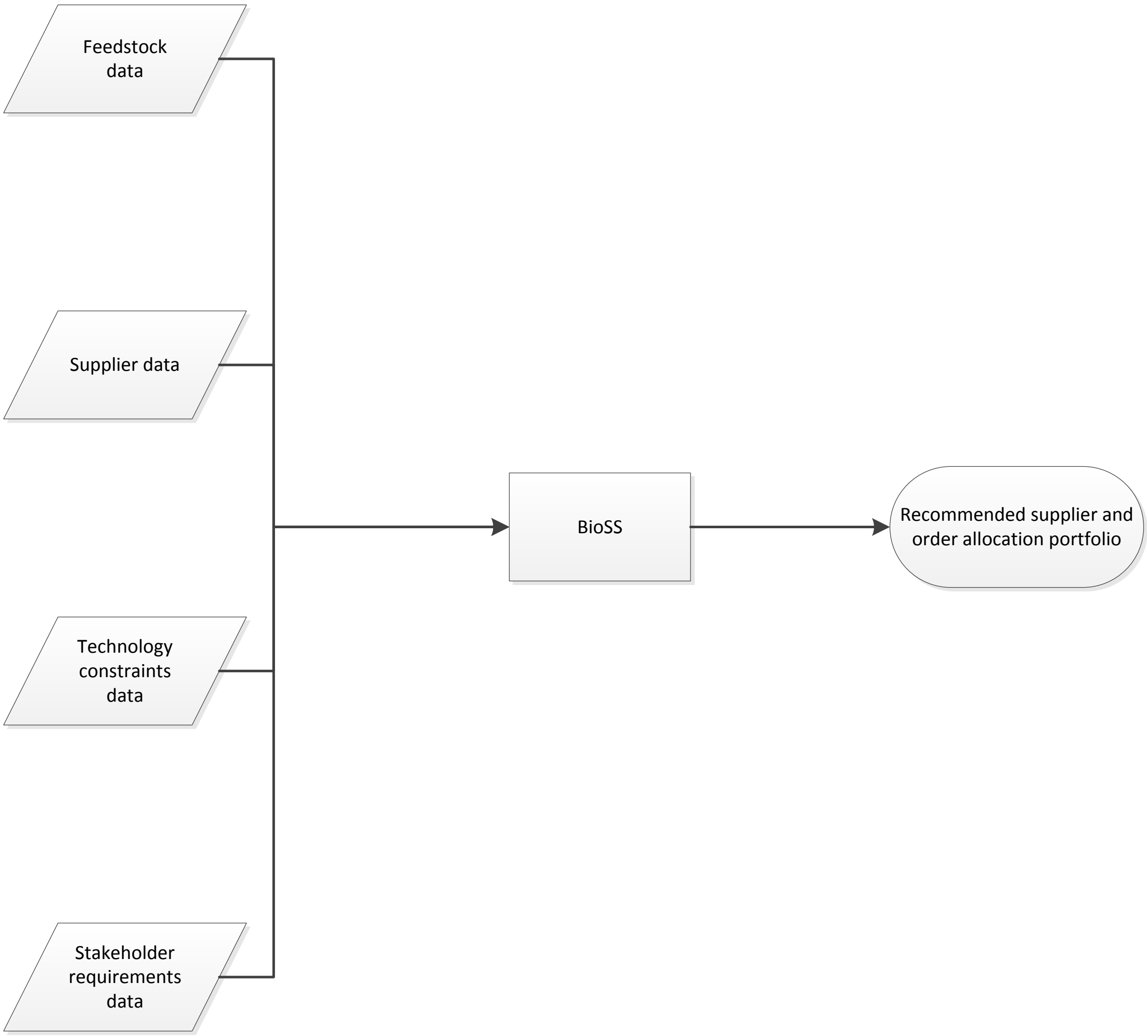

Figure 3.1: Top level dataflow diagram

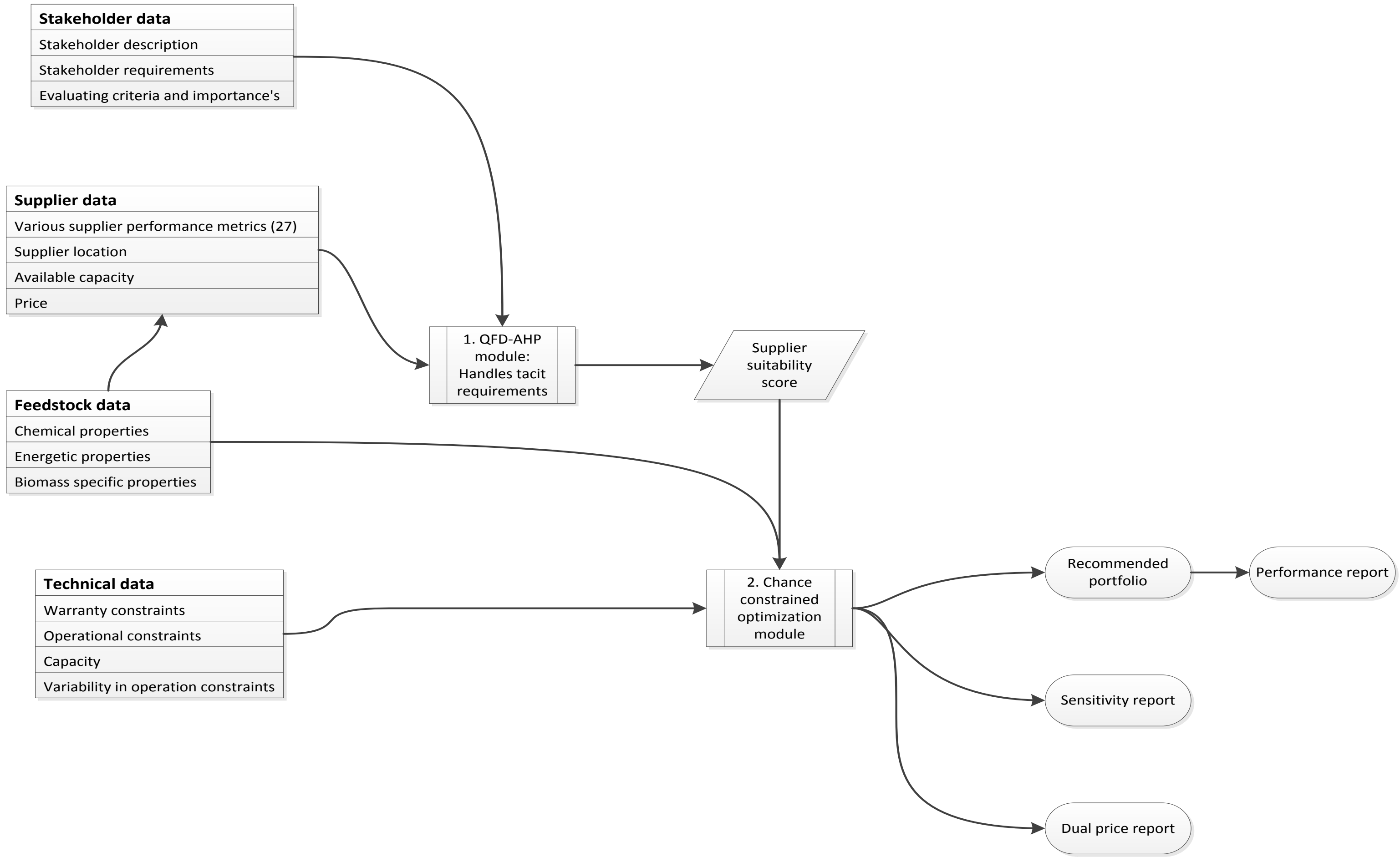

Figure 3.2: Module level dataflow

3.2.2 Fuels library

The fuels library is a permanent database available for the BioSS user to access when required. The library holds information on the expected composition of four important chemical factors that should be considered before a fuel supply contract is negotiated. The fuels library allows users to link records from the library directly into the optimisation module. Additionally the user can add, edit and remove data and records from the fuels library.

The fuels library contains records describing the average properties for 48 different material descriptions. The properties of moisture content, biomass energy content, lower heating value and ash content are reported for all 48 materials. The majority of the materials also have sulphur and chlorine properties reported and some waste derived records have additional properties reported

The fuels library is an important part of the BioSS as it allows for the rapid evaluation of potential fuel sources without the need for extensive fuel testing. Although the data in the fuels library is incomplete and some of the values are uncertain the library can facilitate a quicker and less costly appraisal of the available fuel suppliers. As more information on each known supplier is gathered the fuels library can be populated further, eventually turning the library into a valuable piece of intellectual property for the developer. The rapid access to this data, even only as a guide allows developers to experiment with different fuel provision scenarios for zero cost.

3.2.3 Supplier selection

The supplier selection module is a distinct part of the BioSS. Supplier selection differs from strategic sourcing in that strategic sourcing is a continuous process aimed at obtaining the best value product or service available considering the total cost of ownership and incorporating customer needs and the goals of the organisation. Supplier selection is merely the description of choosing one or more suppliers from the many available. The supplier selection process does not tell us how much material should be purchased from each supplier nor may the type of relationship the buyer expect to have with the supplier. Supplier selection can therefore be considered as part of the strategic sourcing process.

Approaches to supplier selection vary greatly across organisations and industries (de Boer et al., 2001). The selection process is not an exercise in finding the cheapest supplier, rather efficient supplier selection now takes into account multiple criteria, reviews by Dickson (1966) and later by Weber et al. (1991) find that the majority of research papers on supplier selection use multiple criteria methods (Ng, 2008). de Boer et al. (2001) split the supplier selection process into a framework decision stages and decision types. The decision types divide supplier selection problems into 'new buy', 'modified rebuy' 'routine straight rebuy' or 'strategic straight rebuy'. In BioSS.3 a 'new buy' type decision is being made, in BioSS.Op mode a 'strategic straight rebuy' decision is being made.

The BioSS framework therefore requires a supplier selection module that is able to operate on both rebuy and new buy problems. The method must be robust, providing solutions that are intuitive and consistent. The method should also be as transparent as possible and must also be able to handle multiple stakeholders with different opinions of what makes a good supplier. To this end the QFD-AHP process was selected. The QFD-AHP is an analytic method that translates the requirements of stakeholders into a preference weighting for each available supplier. The order allocation module can then use the preference weightings to determine how much material should be taken from each supplier.

3.2.4 Order allocation

In the BioSS the order allocation problem is treated independently of the supplier selection problem. However the order allocation problem requires input from the solution of the supplier selection problem for the BioSS.3 (fully specified model) to give a proper analysis. A wide body of literature has developed treating the supplier selection problem and order allocation problem using integrated methods, in practice this means using one method for the supplier selection stage and another method for the order allocation stage. For instance Ghorbani et al. (2012) combined SWOT and linear programming, Zouggari and Benyoucef (2012) used a fuzzy AHP method to score suppliers then a fuzzy TOPSIS simulation method to allocate orders between those suppliers. Ustun and Demı̇rtas (2008) combined the analytical network process (ANP) with multi-objective mixed integer linear programming (MOMILP) to address the same problem over different time periods for a manufacturing process.

The BioSS uses a different type of optimisation algorithm for the order allocation in the different stages. In BioSS.2 because the performance of the different suppliers is difficult or impossible to measure given the low level of supplier-buyer engagement and project knowledge a chance-constrained linear programming approach is used. In BioSS.3 and BioSS.Op mode the performance of each supplier is scored through the QFD-AHP and a chance constrained goal programming approach is used.

In BioSS.2 where MILP is applied the objective is to find a solution with the lowest cost that meets the requirements of the technology. The linear programming approach aims to find a solution that best satisfies a single objective function and is within any constraints set by the user. In the BioSS.2 case the constraints are the various fuel properties that must be adhered to for the chosen technology to operate properly. LP is helpful at this stage because it allows developers to quickly evaluate the estimated relative supply chain costs for different technology options for the fuel available to the project.

The GP approach used in BioSS.3 and BioSS.Op allows the user to select a portfolio that best satisfies the requirements of stakeholders whilst the chance constrained element of the algorithm ensures that the chemical properties of the blend portfolio remain viable. GP is an extension or generalisation of linear programming, in GP various goals are set for different attributes of the problem and the algorithm aims to find a solution that results in the minimum deviation from those goals. Each goal can be weighted if required. This goal based approach negates the usual problems of incommensurability and trade-off encountered for multi-criteria problems.

The QFD-AHP method has not previously been combined with GP in the supply chain management field. Karsak et al. (2003) used a similar approach for product design planning but without chance constraints and using the ANP rather than the AHP and Erdem and Göçen (2012) used AHP and goal programming (GP) for supplier selection and order allocation. Under most of the integrated supplier selection and order allocation research the properties of supplied goods are constant (traditional commodity based procurement problems) and chance constraints have not been previously used in this strategic sourcing context.

3.3 Integrating the BioSS with industry

Express Energy Ltd follows a structured process when developing projects. From interviews and informal conversations during the course of this research this appears to be a consistent approach across the bioenergy industry. Also referred to as 'stage-gate' the process is useful when developing a process improvement, business change or new product (Lester, 2007, Melton, 2007, Sutton, 2010). In this case the product is a biomass power project. In a stage-gate process the project is divided into several phases that map development towards the final project goal. This approach is helpful in development of construction and infrastructure projects as it limits the exposure of the developer by ensuring all elements of the project are developed together and no elements are over-developed or overspent in a situation where the project is not expected to develop as proposed.

Figure 3.3 shows the different phases that a project may pass through. Although this is a generic example the three main issues faced by project developers can be seen the run throughout the development process. These are arranging a suitable financial package, securing suitable planning permission for the project and designing a technically viable project.

For bioenergy projects these issues persist and it is the value adding function of Express Energy Ltd to produce a project that is viable under these themes. The strategic sourcing of biomass fuels helps to improve both the technical and financial viability of the project directly and indirectly influences the chances of success in the planning process. shows how the uncertainty associated with a project reduces as the developer makes decisions regarding the project design and spends more money on developing details of the project. The more uncertainty surrounding a project, especially its planning and technical design, the more difficult it is to reach a point where the project can be sold or money borrowed for development. Although uncertainty is never eliminated the developer aims to reduce that uncertainty to a level that potential investors can at least price any remaining risk. also shows where the BioSS framework proposed in this thesis can be applied. In the early stage the supplier selection problem is addressed as part of an iterative design process when the developer selects a suitable technology for the available resource. BioSS can also be applied when the technology has been selected and the developer is ready to begin the process of selecting a supply portfolio. Once the project is operational the operator can also use the BioSS to continually optimise the supply portfolio as more information on suppliers is gathered, new suppliers come into the market or existing supplies change or drop out of the market. BioSS therefore has three modes it can operate in; BioSS.2 (Stage 2), BioSS.3 (Stage 3) and BioSS.Op (operational stage).

Figure 3.3: Example of a stage-gated project development approach for a bioenergy power scheme

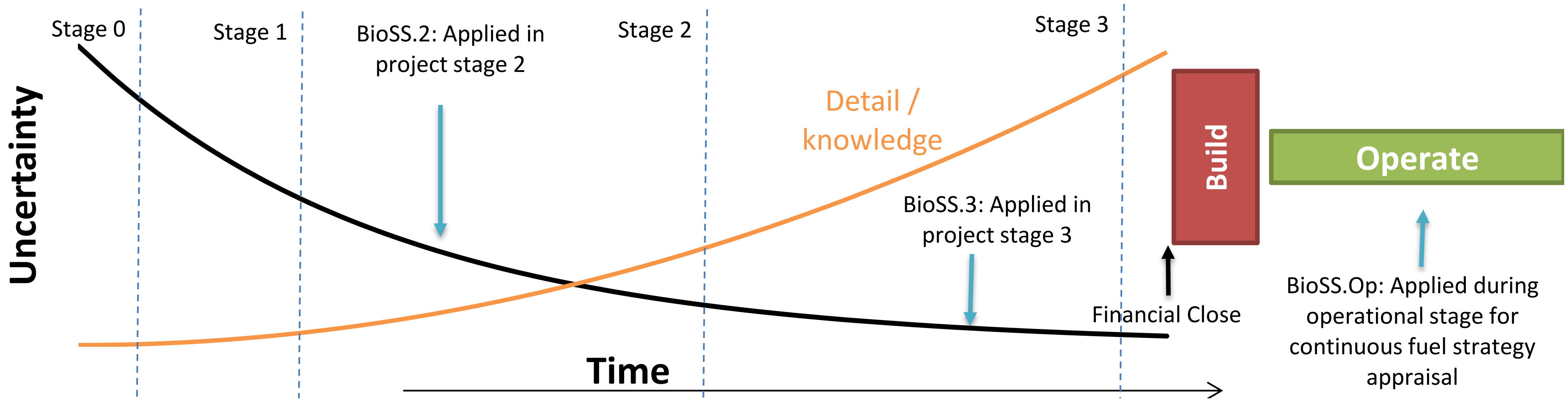

Figure 3.4: Application of BioSS modes through project lifecycle

3.3.1 Requirements analysis for BioSS

From the literature review presented in Chapter 2 it appears that there are several understudied areas regarding the biomass supply chain. It is also clear that the bioenergy supply chain has many stakeholders who hold a diverse range of opinions and make various requirements on the material type and source that is used for UK bioenergy schemes. This provides the motivation for creating a decision framework that helps biomass buyers when making this important and complex decision. Before the framework could be designed several interviews were held with Express Energy Ltd to identify the main capabilities of such a system and to understand more about the environment the decision framework must operate within. The outcomes of these interviews with various staff at Express Energy have been split by business function into fuel procurement, project finance, technical design and planning and permitting consent. The staff members described requirements that overlapped and the staff themselves do not fall neatly into these business functions.

The identified business functions at Express Energy are contracting and procuring fuel, obtaining project finance, technical design of the plant and obtaining planning consent. Each of these functions had different requests of the decision framework, each function is summarised below and Table 3.1 shows how the developed BioSS framework addresses these requirements.

<u>Procurement and contracting for fuel</u>

As described in the conventional strategic sourcing literature procurement requires a trade-off between several desirable factors, in this case cost and reliability of delivery.

<u>Obtaining finance</u>

For Express Energy to be able to construct a pant the project must pass through financial close, this requires financiers to commit to investment. According to Express Energy; risk as perceived for the financiers is split into contract length, the financial viability of the supplier and the reliability or experience of the supplier. An effective way to decrease the risk of supply failure may be to contract with a larger number of suppliers. This response reduces the impact of individual suppliers failing.

Technical plant design

The various pieces of equipment that actually make up the power station are expected to be delivered by a single contractor or technology provider. This technology provider will provide an operating specification for fuel that can be used in the power station. Some of the constraints set are due to performance of the exhaust filters whilst some are due to the risk of enhanced corrosion within the plant. Some of the chemical constraints are therefore slightly flexible whilst others are fixed. To obtain the incentives for biomass power generation the fuel blend should also be 90% biomass by energy content. The design process is iterative and at present each new technology option is compared to the available fuel to find a suitable match.

Obtaining planning consent

Obtaining planning permission for a project as complex as a bioenergy power station is a difficult and lengthy process. Developers attempt to gain stakeholder buy-in throughout the process, if successful opposition and delays to the project can be reduced or removed. From the experience of Express Energy observing other developers, and evidence from the literature (Upreti, 2004, Raven et al., 2009) the try and source of fuel is an important factor for the general public and other stakeholder groups who may object (NGO’s, forestry commission, industry.

Table 3.1: Business function at Express Energy Ltd matched against requirements made on the BioSS

Business function	Requirement	Rationale for requirement
Contracting for fuel procurement	Recommended a fuel portfolio based on • The cheapest option • The most reliable option	• The optimisation module can find the cheapest option that is within the technical constraints • If required the optimisation module can be set to select only the most reliable suppliers whilst also being within technical constraints
Obtaining project finance	Recommend a fuel portfolio that minimises perceived financial project risk through: • Selecting a combination of suppliers • Choosing reliable suppliers • Choosing creditworthy suppliers	• The user can set a minimum number of suppliers • The most reliable suppliers can be selected whilst remaining within technical constraints • The most creditworthy suppliers can be selected whilst remaining within technical constraints
Technical plant design	Recommend a fuel portfolio based on: • Always being within the technical limits • Being within the technical limits for some percentage of the time • Being within the technical limits all the time for some properties but only some of the time for other properties	• The portfolio can be set to ensure that delivered fuel is always within technical constraints • Each constraint can be given a percentage chance score. This determines how frequently a technical constraint can be exceeded on average.
Obtaining planning consent	Recommend a fuel portfolio based on: • Public acceptance of the fuel source • Planning authority acceptance of the fuel source	• The BioSS can find a portfolio that best meets the requirements of the wider stakeholder group • The BioSS can find a portfolio that best meets the requirements of one stakeholder only (if required)

3.3.2 Operational modes of the BioSS

This section explains the different features of the BioSS when applied in its different modes: Stage 2, Stage 3 and in the operational stage. For each stage the BioSS is able to handle slightly different quantities and quality of information suitable for the relevant stage of development.

3.3.3 BioSS in Stage 2

In this stage of project development a broad description of different alternatives for the project can be described. The developer may have located a suitable site for the project, have a good idea of the type of technology that will be used but not the technology provider and should be able to describe potential fuel sources in broad terms. The developer will most likely have some form of an estimate of fuel availability in the area or region. This estimate will be based on regional statistics, past experience and industry reports. Exact information will not be gathered from individual suppliers at this stage and the current flows of materials are often difficult to measure. Examples of regional and national resource assessment reports are EUBIA (2012), AEA (AEA, 2012, AEA, 2011), Dti (McKay et al., 2003), defra (2008), Northwoods (2008), Adas and Nnfcc (2008), the environment agency (Garstang et al.), Yan (Yan et al., 2011) and E4Tech (2008). In addition developers may commission private consultancy reports using a methodology more suited to the individual situation being faced. Methodologies have also been proposed in the academic literature for resource assessment, these approaches often use a geospatial information system to make estimates of biomass resources and potential of a particular area such as Kinoshita et al. (2009) and Viana et al. (2010) who looked forrest sourced wood fuel for at Yusuhara in Japan and Portugal respectively. Also Batzias et al. (2005) and Ma et al. (2005) who assessed animal manure resources for the purposes of siting conversion facilities and Graham et al. (2000) who used GIS to make an estimate of the price of purpose grown bioenergy crops.

In some cases there may be several or many alternative options for the site location, feedstock to be used and technology to be used at this stage of the project development. The BioSS in this mode can help to accelerate projects towards the next stages of development. The user can run a variety of scenario technologies (constraints) against a set of generic feedstocks taken from the fuels library. The output portfolio from the BioSS can be taken as a very approximate estimate of the different mixture of feedstock that may be required and the approximate annual cost of supply. This can then be used as an input to other tools used at this stage of development, particularly the business development case where operational costs must be estimated.

3.3.4 BioSS in Stage 3

At this stage the developer will have chosen most of the technologies they will use and will have a good idea of the exact chemical limits of the chosen equipment. Although design may change several times during this stage the level of knowledge detail known about the technology should remain similar. The developer will also know much more information about the potential suppliers in the area and will begin to request fuel specification data. Negotiations will be underway regarding contract terms and conditions and the suppliers will be under close scrutiny from the developer.

The BioSS handles this part of the development process by allowing the user to enter custom data into the fuels library, including this type of data gives greater confidence to the supply portfolio being recommended. Custom and archived fuels data can be combined in the optimisation module as required.

A new set of information also becomes important for the BioSS at this stage. The tacit requirements of stakeholders can be compared against the expected or known performance of particular suppliers. To do this properly all the fuels being input to the optimisation module must have a known and well understood supplier. The assessment of supplier performance is done by the developer but the importance weightings of each evaluating criteria against which the supplier is scored is set by stakeholders through the QFD-AHP process. The BioSS is designed to be optimised to find the combination of suppliers that best satisfies the needs of stakeholders but it can be run as a transaction cost only model where the cheapest compliant portfolio will be recommended.

The output shows the recommended portfolio of suppliers that should be selected and how much material should be contracted with each supplier. The output also shows a set of histograms resulting from a Monte-Carlo simulation that shows the extent to which the final fuel blend can be expected to be outside of the constraint limits. Also included in the output is a ‘duel cost report’ analysis that shows the expected cost of taking more or less from each supplier with regards to the objective function of the optimisation module.

When the tacit requirements, supplier performance, fuel data and technology constraints are all known with confidence the BioSS can be described as fully defined. In BioSS.3 the framework is data intensive and requires a large amount of care from the user and extensive data collection. This is justifiable in this case however as a well-designed supply chain can be important to project failure or success (Adams et al., 2011). The data required for the model is also not all additional to the process that developers would use without using BioSS.3. The structured approach to assessment and the feedstock composition data would be collected at some stage during the incumbent process.

3.3.5 BioSS in operational stage

In this stage the ownership of the project may have changed during the process of financial close. The BioSS.Op is aimed at the power station operator. In this situation a large part of the fuel supply is likely to be under contract following from the work in stage 3 and the output of BioSS.3. Any remaining fuel will be purchased from a spot market or on an opportunity basis. From comments made by UK bioenergy developers the percentage of the fuel supply under long term contracts is likely to be between 60-80% depending partly on the finance arrangement.

This presents a different challenge for the BioSS.3. In BioSS.3 the fuels library is used again to estimate properties of the potential new or spot market feedstock. The existing contracted fuel must be entered by the user and this can be locked in place. This allows the user to assess the best combination of known or expected spot market resources to complement the existing contracted portfolio. It can also allow the user to assess the implications of cancelling contracts or suppliers failing and to investigate the case where a further contract may be signed.

This phase brings a management decision for the operator regarding whether they should continue to consider tacit information in the sourcing decision during operation. According to the problem described by Express Energy the main motivator for industry to include stakeholder opinion in the strategic sourcing process is to ensure that finance and planning hurdles can be arranged. Theoretical contributions on procurement point towards good stakeholder satisfaction leading to successful projects and processes in general (Reuter et al., 2013, Friedman and Miles, 2002, Donaldson and Preston, 1995). However the main regulatory and legal motives for taking the approach described in BioSS.2 is removed following financial close. Without powerful stakeholders to hold developers to account it is possible that operators may move away from finding solutions that best meet stakeholder requirements and towards a lower cost solution, negating the improvement available through using an integrated decision framework as described for BioSS.2.

3.4 Research design

The BioSS will be validated using a combination of two life-like scenario cases and interview feedback from industry actors. Collecting and reporting all of the information required to properly validate the BioSS is a difficult task because of the lengthy development time of bioenergy projects and the commercially sensitive nature of agreements made between developers, operators and suppliers as well as the patchy information available during project development. Even if data could be collected from developers regarding their perceptions of individual suppliers this data may differ between developers and between projects. Therefore two notional case examples are created.

The two example scenarios have been created based on a number of case studies and case projects being developed and being operated. The cases are intended to be realistic and typical of expected future projects. For each scenario the BioSS is applied in each of its three stages, this demonstrates how the level of detail changes through the project cycle and how the BioSS meets the various requirements of the developer in its operation. The BioSS output for each scenario is compared against two traditional methods for strategic sourcing as are currently used, one being a transaction cost based approach and the other being a single stakeholder approach where that stakeholder is the developer. Express Energy has been used as that developer case. Therefore in total there will be 13 recommended portfolios to compare. 3 per scenario (for Bioss.2, BioSS.3 and BioSS.Op) plus 3 “cost only” based portfolios for each scenario, plus one portfolio that represents current practice for developers at stage 3.

3.4.1 Scenario 1

The project in scenario 1 is a proposed 45MW combustion facility located on a brownfield development site beyond the city limits. The combustion equipment selected comes with a warranty of 2 years and a detailed fuel specification. The warranty is only valid if the operator can show that the fuel used was within the required specification. The project is being developed by a private developer who plans to sell the project at financial close, the project is to be debt financed and the economic case for the project relies upon the ROC financial incentives for biomass electricity. The expected capital cost of the project is circa £300-400m

3.4.2 Scenario 2

The project for scenario 2 is a proposed 2MW gasification plant that will be operated as a combined heat and power (CHP) project in an urban centre. Linking to an existing district heating network and associated anchor heat users. The site is close to an existing material recovery facility (MRF) that is operated by the municipal council. The urban site means that emission restrictions are tight and planning constraints have limited the amount of traffic and the size of the plant. The gasification technology is sensitive to the properties of the feedstock being used and a tight specification has been provided by the technology supplier, no operating warranty is offered. The project is to be part debt financed with a major engineering company responsible for the project development and build also investing equity. Revenue will be generated from electricity sales and the associated ROC incentives and also heat sales and the associated renewable heat incentive (RHI) payments. The expected capital cost of the project is circa £15-25m

Data collection for the supplier selection module has been done using a combination of semi-structured interviews and literature review. The semi-structured interviews allowed participants freedom to express their opinions and requirements and the literature review was used to re-enforce the opinions given. LINGO was used to write the GP and LP algorithms and workshops and interviews were used to complete the QFD-AHP. Data collection for each module is discussed further in the relevant chapter.

3.5 Chapter summary

This chapter gives an overview of the BioSS, the three modes that it operates in (BioSS.2, BioSS.3 and BioSS.Op) and how these modes fit against the lifecycle of a bioenergy development project. The requirements placed on the BioSS are summarised according to Express Energy Ltd and the three modules of the BioSS (fuels library, supplier selection and order allocation) are briefly discussed. The method for validating the BioSS against current or alternative practice is also discussed with two case scenario projects introduced.

The BioSS is able to satisfy the requirements collected from Express Energy in one or more of the operating modes. A portfolio can be selected that is within the chemical limits for some or all of the time for some or all of the required properties. The BioSS can evaluate the impact of new suppliers coming into an existing portfolio from both a technical compliance perspective and from the perspective of all stakeholders of the supply chain. The recommended portfolio can account for and reconcile the various requirements made by the project stakeholders including creditworthiness, reliability and environmental and social performance. By using three modes the BioSS is flexible enough to integrate with the development process throughout the strategic sourcing process and remains helpful through the operating life of the plant. The operator and developer can use the BioSS to accelerate the development and deployment of bioenergy schemes whilst giving confidence to stakeholders and investors that the supply chain meets their requirements through a demonstrable and democratic sourcing process.

Chapter 4. Fuels Library

4.1 Introduction

This chapter describes the first element of the BioSS system, a fuels library. A fuels library is required to allow some estimation of the properties of potential fuel when the BioSS operates in Stage 2 or in the operational stage. In the early planning stages (Stage 2) information on potential suppliers or sources of fuel is sparse, different methodologies exist for predicting the quantity of fuel available, but identifying exactly what that fuel may be is a much more complex problem. The fuels library therefore contains estimates of fuel characteristics based on secondary data that can allow the developer to build a more informed picture of the available fuels for a given project.

In the operational phase the operator may be faced with spot-market trades where material is offered on a single purchase basis. In this case it is unlikely that the supplier will have undertaken detailed chemical tests on the material and the fuels library can be used to examine the possible impact on the existing portfolio mix of contacting for that material without going through extensive testing and associated costs.

In this chapter the form of the fuels library is described in section 4.2 with a description of how data from the library will be used for other modules of the BioSS, how data is stored and the structure of data. Section 4.3 describes the fuels library as it stands at the time of writing. The different material properties for which data is required are identified and different sources of secondary data on the characteristics of biomass are identified. In section 4.3.5 the completeness and accuracy of the data contained in the library is discussed. The chapter is summarised in section 4.4.

4.2 The BioSS fuels library

The fuels library part of the BioSS is a permanent database that is available for the user to assess the expected properties of a given description of biomass. Describing biomass properly is a difficult task, the potential buyer may have a wide variety of interests when deciding which material to purchase which are unknown to the supplier Differences in the description can be salient to these interests. For instance a common type of biomass description is ‘wood pellets’. However the exact size, what the source tree species was and how it has been handled or stored can affect properties such as the non-combustible content of the pellets (ash content), chlorine content and the energy content (important for the economics of a project) or moisture content (Koppejan, 2008).

The library provides the user with an estimate of certain fuel properties based on samples analysed in the past. Where possible the data is provided with ranges or uncertainties and a series of caveats showing where the data has come from and the testing method used for the samples.

Using a fuels library allows decision makers to decide at an early stage if they will further pursue a particular fuel source without spending a large amount of time or money. Usually in the first contact suppliers will provide a description of a material without a detailed analysis or specification. Later into the relationship the supplier may decide to analyse the material at their own cost in order to draw up a contract for supply. The supply contract will contain more detailed information on chemical and physical properties as well as delivery and payment terms. The fuels library can prevent suppliers and purchasers moving too far down this route and improve efficiency of development and supply.

The data contained in the fuels library could also be used to group fuels in different ways. If a developer were interested only in fuels with particular properties (perhaps if they had a particular technology in mind) fuel descriptions with only those properties could be identified through a simple search.

The fuels library is entirely based on secondary data and therefore can only report on material that has been tested in the past. The library presented brings together several sources to provide a more complete collection of relevant data. This inherently introduces inaccuracies and errors however it is hoped that the estimates made and descriptions used are helpful to get a supplier buyer relationship started, the library is not intended to replace the comprehensive testing required before supply contracts are signed. No new tests have been done as part of this thesis.

The fuels library can be used in two parts of the BioSS. Stage 2 and the operational stage. The integration with the other modules in the BioSS are described in the following sections.

4.2.1 Stage 2

In stage 2 little explicit information about potential suppliers has been obtained. Some companies that could provide a material supply may have been identified but no analytical data has been collected. The results of a resource assessment and competition mapping exercise may also be available and these would describe how much material can be expected to be available within a particular region and what type of material can be expected. There may also be some forecast of future material availability, single point sources such as sawmills or food and drink factories will also have been identified. Additionally developers may look overseas for biomass material, in this case it is again likely that at an early stage only qualitative information on each supply will be available.

The fuels library allows the procurement manager to quickly evaluate the biomass material available and to begin the process of matching the available material with the available or preferred technology at an earlier stage than in current practice. This facilitates a quicker and more efficient transition to stage 3 where a detailed fuels analysis is required and an iterative design process is used to select and design the conversion solution. By using the fuels library to begin this process at stage 2 the project can have a clearer definition of scope at an earlier stage, releasing other project development functions such as planning, transport, storage design and ash treatment strategies to be developed sooner.

4.2.2 Operational stage

In the operational stage of a project the BioSS can be used to evaluate how the procurement of spot market fuels will interact with the existing contracted portfolio of material. For existing contracts the procurement manager can be expected to have a good level of detailed results regarding quality and properties from the continuous testing required prior to entering the conversion process. However material may still be purchased on a spot market, short term contracts or from sources that were not suitable for the project finance procurement process in stage 3. For these new material sources the same problem is faced as in stage 2. Exact characteristics are difficult to predict and analysis is costly, especially for smaller suppliers.

In the operational stage the user will have entered information about existing supply contracts into their own personal copy of the library, the rest of the BioSS will then run as normal but will allow contracted quantities to be specified and locked. This reflects the requirements of developers who need to contract for 70-80% of the fuel pre-construction, leaving an element of fuel supply ‘floating’ on the spot market.

4.2.3 Fuels library architecture

The fuels library is intended to be fully editable by the user and fully flexible to allow users to edit any part of the library they see fit. For this reason the library has been collected into an excel table. This is a popular software package and should make it a simple task to move the collected library into other software packages, models or to manipulate and manage the data from within excel. The intended users of BioSS are expected to have some basic Excel and data manipulation skills.

Using a flexible and easy to edit fuels library also allows the user to enter their own data for fuels they encounter, analyse and contract with, this is important for the operational stage of the model. In stage 3 model the BioSS can either lookup data from the library or it can accept custom data entered by the user. The fuels library produced for this thesis is therefore only the beginning stages of what could become a valuable piece of intellectual property for a developer, merchant or aggregator of biomass. Additionally the user can change, remove or add to the properties of interest if they needed to; to suit the requirements of different technologies or to adapt to changing regulations for instance.

4.2.4 Standards for biomass

Standards are important for most industries, standards allow parties to agree to a level of quality that goods must meet or exceed for any exchange to occur. The standardisation of biomass materials introduces an unusual and unique challenge for standardisation organisations. Usually markets and standards grow together with suppliers, buyers and regulators involved in the process of standardisation (Hatto, 2010). In the case of biomass this is a difficult task given the rate of growth and range of suppliers, supplied materials and potential conversion technologies. For similar markets such as grain, cement, iron ore or coal (all of which are traded commodities) standards are created using levels, limits or thresholds of important properties that buyers use to judge the quality of the material. This approach is valid for biomass materials.

Several organisations have been working to create standards for biomass and bioenergy for technology and fuels. Standards play an important part in the development of exchange markets, allowing buyer and seller to better understand the nature of items being traded (Ferrantino, 2006, Steenhof et al., 2010, Loibnegger, n.d.). This topic is very salient for the bioenergy industry. Earlier designers of biomass boilers struggled to design efficient systems because there were no fuel standards to work towards, boilers were designed as more agricultural to accept variable fuels rather than for efficiency. To tackle this problem those economies that grew a bioenergy industry earlier than others began to develop fuel standards alongside equipment standards. These have later formed the basis of international standards, notably the European CEN/TS standards.

The Austrian Standards Institute ÖNORM developed its own standard for wood chips. This standard was split into classifications of moisture, chip size, density and ash. Many of the first boiler manufacturers gave fuel specifications based on this early wood chip standard. Simultaneously in Germany the Deutsches Institut fur Normung (German Standards Institute) developed the DIN 51731 standards. This has been continued and a DIN CERTCO standard was introduced in 2002 that integrated the ÖNORM and DIN standards for pellets. Further to this work the both Austrian and German institutes have continues to add to their own standards. The DIN-Geprufer Fachbetrieb-Pelletlogistik (pellet logistics) standard has been introduced requiring suppliers or merchants to provide information on the storage and transport of wood pellets. The ÖNORM M7137 standard has been introduced in Austria to look at the same area.

Sweden and Italy have also developed standards for pellets. The Swedish standard SS 187120 divides pellets into three classes depending on size and ash content. The Italian CTI-R 04/05 standard for solid biofuel uses 4 categories and includes a requirement for the reporting on the origin of biomass.

The introduction of these various standards may have helped certain exchanges by adding confidence for buyers. However the confusion over standards, boiler compatibility, testing methods, handling methods and differences in non-chemical or physical requirements makes buying wood pellets complex, confusing and unclear. There is also the potential that the sale of equipment made to certain national standards means that only pellets manufactured in the same country and standards environment as the boiler could be used under warranty. To prevent such a monopolised supply market and to stem further confusion the European Committee for Standardisation (CEN) stepped in.

The set of European standards for bioenergy are described as CEN/TC 335. This standard classifies fuels based on origin (under prCEN/TS 14961) and technical specifications (prCEN/TS 14961:2004). Some EU countries and international organisations also provide additional environmental labelling schemes for pellets which is also being adopted by European regulators. Table 4.1 summarises the most important elements of each of the national standards and also the BioGen code of best practice available in the UK.

Table 4.1: Biomass standards in operation within the EU.

Specification	Austria ÖNORM		Sweden SS 18 71 20			Germany DIN 51731 / DIN+			Italy CTI - R 04/05				UK - BioGen Code of good practice	
Classification	Pellets	Brickets	Group 1	Group 2	Group 3		**Length**	**Diameter**	A (No additives)	A (with additives)	B	C	Premium fuel pellets	Recovered fuel pellets
Diameter (mm)	4 – 20	20-120	<4	<5	<6	HP1	>30	>10	8	8	8	10		
Length (mm)	<100	< 400				HP2	15 - 30	6 - 10	6	6	6	10 - 25	<4 - 20	>10 - <20
						HP3	10 - 15	3 - 7						
						HP4	<10	1 - 4						
						HP5	<5	0.4 - 1						
Bulk Density (kg/m^3)			>600	>500	>500				620 – 720	620 – 720	620 – 720	>550	>600	>500
Fines in % <3mm			<0.8	<1.5	<1.5								<0.5%	<0.5%
Unit density	>1 kg/dm3	>1 kg/dm3				1 - 1.4 g/cm3								>0.528 kg/dm3
Moisture Content	<12%	<18%	<10%	<10%	<12%	<12%			<10 %	<10 %	<10%	<15%	<10%	<10%
Ash Content	<0.5%	<6%	<0.7%	<1.5%	>1.5%	<1.5%			<0.7%	<0.7%	<1.5%		<1%, <3% or 6%	<1%, <3% or 6%
Calorific value	>18 MJ/kg	>18 MJ/kg	>16.9 MJ/kg	>16.9 MJ/kg	>16.9 MJ/kg	17.5 - 19.5 MJ/kg			>16.9MJ/kg	>16.9MJ/kg	>16.2MJ/kg		>4.7 kWh/kg	>4.7 kWh/kg
Sulphur	< 0.04%	<0.08%	<0.08%	<0.08%	trace	<0.08 %			<0.05%	<0.05%	<0.05%		<300 ppm	<300 ppm
Nitrogen	<0.3%	<0.6%				<0.3 %			<0.3%	<0.3%	<0.3%			
Chlorine	<0.02%	<0.04%	<0.03%	<0.03%	Trace	<0.3 %			<0.3%	<0.3%			<800 ppm	<800 ppm
Arsenic						<0.8 mg/kg								
Cadmium						<0.5 mg/kg								
Chromium						<8 mg/kg								
Copper						<5 mg/kg								
Mercury						<0.05 mg/kg								
Lead						<10 mg/kg								
Zinc						<100 mg/kg								

Under the first part of the CEN/TS solid biofuels standards material is classified into the categories shown in Table 4.2 and then the material is compared against the levels and limits in Table 4.3 for the second part of the standard. The classification separates material using a 3 level hierarchy structure based on the materials origin. A material can be classified into any of the boxes in Table 4.2 although the intention is that most materials can be classified into the right most column. In 2005 CEN/TS14961:2005 was released which defines parameters to be reported and classes for each property. An accompanying set of standards has also been released detailing many other aspects of biomass testing including how samples should be taken, equipment to be used for sampling, methods for determining chemical composition and durability and so on, these are shown in Table B.1 in Appendix B. Also shown are the 2009 standards released by the British standards council for testing calorific value, ash content density and so forth. The levels shown are for biomass pellets, similar standards and levels exist for wood chips and hog fuel (mixed sized wood particles) although bulk density is also required to be reported (CEN, 2012). Also being developed are standards for biomass briquettes, logs, sawdust, shavings, bark, bales from grasses, energy crops, olive residues and fruit seeds.

Table 4.2: Biomass classifications within CEN/TS 14961

Forest and plantation wood	Whole trees	Deciduous wood
		Coniferous wood
		Short rotation coppice
		Bushes
		Blends and mixtures
	Stemwood	Deciduous wood
		Coniferous wood
		Blends and mixtures
	Logging residues	Fresh/Green (including leaves or needles)
		Dry
		Blends and mixtures
	Stumps	Deciduous wood
		Coniferous wood
		Short rotation coppice
		Bushes
		Blends and mixtures
	Bark (from forestry operations)	
	Landscape management (Woody biomass)	
Wood processing industry by-products and residues	Chemically untreated wood residues	Wood without bark
		Wood with bark
		Bark (from industry operations)
		Blends and mixtures
	Chemically treated wood residues	Wood without bark
		Wood with bark
		Bark (from industry operations)
		Blends and mixtures
	Fibrous waste from pulp and paper industry	Chemically untreated fibrous waste
		Chemically treated fibrous waste
	Chemically untreated wood	Wood without bark
		Bark
		Blends and mixtures
	Chemically treated wood	Wood without bark
		Bark
		Blends and mixtures
Blends and mixtures		

The technical requirements for biomass pellets are based on dimensions of the pellets, moisture content, ash, sulphur, nitrogen, durability and additives. Each tested material will be specified as falling into one of the bands within each category.

The CEN TS 335 has been working on other fuels as well as pellets. To continue the standardisation of biomass materials working groups have been created for different parts of the effort to create an international standard for solid biofuels. At the same time as Europe is creating these standards the USA has been developing its own pellet market from its own sizable agro-forestry industry and the working groups are tasked with creating an international standard (ISO). The ISO standards are unavailable to the author at the time of writing but could be incorporated to the fuels library at a later date. The diagram in Figure 4.1 shows the plan for bringing all these standards together to form a single standard for solid biomass.

Table 4.3: Technical aspects to be reported for biomass pellets under CEN/TC 335 (adapted from Hahn, 2004)

Diameter (D)	D06 ≤6mm ± 0,5 mm	D08 ≤8 mm ± 0.5 mm	D10 ≤10 mm ± 0.5 mm	D12 ≤12 mm ± 1 mm	D25 ≤25 mm ± 1 mm
Length (mm)	≤5x Diameter	≤4x Diameter	≤4x Diameter	≤4x Diameter	≤4x Diameter
Ash (w% of dry basis)	A0.7 ≤0.7 %	A1.5 ≤1.5 %	A3.0 ≤3.0 %	A6.0 ≤6.0 %	A6.0+ >6.0 %. (actual value to be stated)
Moisture (w% as received)	M10 ≤10 %	M15 ≤15 %	M20 ≤20 %		
Sulphur (w% of dry basis)	S0.05 ≤0.05 %	S0.08 ≤0.08 %	S0.10 ≤0.10 %	S0.20+ >0.20 % (actual value to be stated)	
Nitrogen	N0.3 ≤0.3 %	N0.5 ≤0.5 %	N1.0 ≤1.0 %	N3.0 ≤3.0 %	N3.0+ >3.0 % (actual value to be stated)

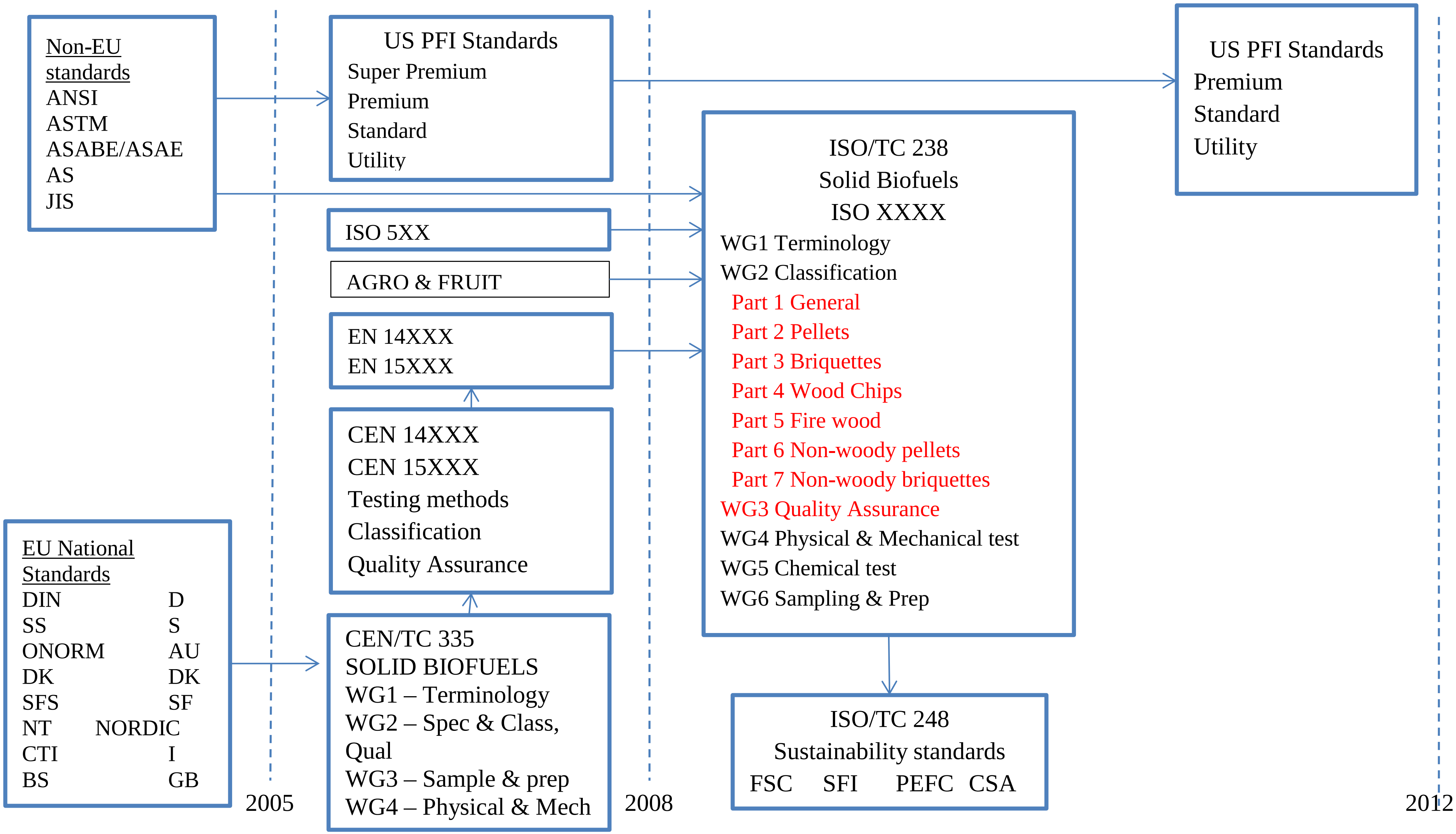

Figure 4.1: Development of standards for solid biofuels (adapted from Melin, 2011)

4.2.5 Other standards for biomass like materials

Alongside the work by the CEN/TC 335 working groups standards have either already been created or are in development for other types of biomass like materials. In some cases these overlap with the definitions under CEN/TC 335 (recycled wood products for instance) and in some cases these standards are complimentary as for the standardisation of waste derived fuels. Waste derived fuels come in several forms and their description is not yet formalised. Refuse derived fuel (RDF) is a popular nomenclature in the UK waste management industry whilst solid recovered fuel (SRF) is used in the cement industry and the European waste market. This material can come from any waste stream although solid municipal and mixed commercial and industrial waste streams are most common (as opposed to agricultural, hazardous or segregated waste streams). The material can be in pellet form or occasionally as 'fluff'; a low density unstructured mixture of shredded mixed materials.

Standards for solid waste derived fuels have been developed by the European Committee for Standardisation (CEN) who looked at materials covered by the waste incineration directive (WID), an EU directive about fuels being used for energy generation that have come from waste sources. According to the European Recovered Fuels Organisation (ERFO) the standard covers those materials covered by WID but not by CEN/TC 335. This standard is named CEN/TC 343 "Solid recovered fuels". The published documents for CEN/TC 343 are also detailed in appendix B. The standards for classes are shown in Table 4.4. After much negotiation and several meetings the CEN working group reduced the number of key reporting properties from 7 to just 3: Net calorific value, chlorine content and mercury content. The group decided to drop Tellurium (Tl) and Cadmium (Cd) from the standard as they felt that measuring these chemicals added no value to the standard as Mercury (Hg) was found to be the limiting factor. This assumption however was made on the cement kiln industry, by far the largest customer for waste derived fuels, and there is no comment made for the bioenergy or waste incineration industries. (van Tubergen et al., 2005)

Table 4.4: CEN/TS 15359 chemical properties for classification of solid recovered fuels (CEN, 2011)

Aston University

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Efforts to classify and categorise biomass samples are on-going and this work is covered in section 4.3.3. Behind the efforts to classify biomass in this type of way is a belief that a market can only function if the properties of the material being traded are known accurately. By knowing the properties and labelling material properly that material becomes a commodity for which two parties could negotiate a price. At the end of this chapter the existing literature on sample data is cross-referenced against the existing standards to examine which material descriptions fall into each category (where data is available). To this end section 4.3 reviews the existing literature on biomass characterisation and uses a variety of sources to identify the salient properties for procurement managers when purchasing material.

4.3 The fuels library

This section shows how the fuels library has been constructed. The various sources that data has been collected from and the method used to determine the properties used in the library are discussed.

4.3.1 Properties

The CEN/TC 335 standard contains a set of chemical properties that should be reported on before a batch of material can be said to have met the relevant standard. These chemical parameters are: Ash content, moisture content, chlorine content, nitrogen content, sulphur content. In addition the CEN/TC 343 standard requires net calorific value and mercury to be reported.

Interviewing the technical director at Express Energy it became clear that they have their own wider range of chemical requirements. These chemical requirements and the limits set depend on the technology that Express Energy select, usually this is provided in the terms of warranty. For the plant to be covered by warranty the claimant (operator) must be able to show that the fuel used was within the specified limits. Different technology providers have different limits and different ways of expressing those limits. According to Express Energy the properties remains the same between different combustion technology providers but the limits change. According to (Koppejan, 2008) the property limits change for different technology types, gasifier technologies have a different set of chemical needs to combustion for instance. Some of the properties are also dependant on the technology used for exhaust filtration and the regulatory environment of the project. Different areas may have different requirements regarding emissions to air leading to different technology selections and different properties or limits being set.

Following engagement with Express Energy sodium (Na), potassium (K) and Flourine (F) were added to the properties list. A number of heavy metals were also said to be important: Cadmium (Cd), Tellurium (Tl), Lead (Pb), Zinc (Zn), Tin (Sn), Copper (Cu) and Aluminium (Al). All of which are reported under the waste incineration directive (WID). These properties are expressed in mg/kg on a dry basis[2]. The most important properties identified by Express Energy for the stage 2 BioSS were net calorific value (MJ/kg) and biomass energy content (% of total energy input).

[2] Dry basis means that moisture has been removed from the fuel sample before the chemical composition was tested. This means that impurities soluble in water are also available.

The various other chemical requirements aside from bioenergy and energy content are discussed in section 4.3.2

4.3.2 Impacts of chemical constraints

This section describes the impact of the different chemical properties reported for biomass fuels on the performance of equipment, pollution levels and health impacts. Section 4.3.2.10 gives a final list of properties that are reported in the BioSS fuels library.

4.3.2.1 Net calorific value

Net calorific value is a measure of the energy released when a material is converted. Calorific value is inherent in the material, different materials have different calorific values. Calorific value is expressed either as gross (GCV or Higher Heating Value [HHV]) or as net (or Lower Heating Value [LHV]). In net calorific value the energy required to drive moisture out of the material is accounted for. This means that some materials with very high moisture contents may have a negative net calorific value as the energy stored in the dry matter is not sufficient to drive all the moisture out of the feedstock sample (Koppejan, 2008, Grammelis, 2011).

4.3.2.2 Biomass energy value

Biomass Energy Value is a more convoluted concept that appears to be unique to the UK regulatory environment. In order to claim renewable obligation (RO) certificates (ROCs) a generator (using combustion for instance) must be able to provide evidence that the material combusted was actually biomass and not derived from fossil fuel. The threshold requirement for a material to be classed as biomass under the RO legislation is currently 90% (DECC, 2012a, DECC, 2012d). This threshold is determined by energy content of the input fuel. This raises a problem for generators aiming to use residual or recovered materials; because the energy density of biomass is so low compared to fossil fuels it only takes a small weight of fossil fuel derived material in a large weight of biomass to drop the biomass energy content significantly. Coal for instance (LHV = 25-34MJ/kg) is much more energy dense than wood (17-18MJ/kg) (McIlveen-Wright et al., 2007). So a feedstock of just 5% coal and 95% biomass by weight is therefore enough to drop the biomass energy content to 89%. Making the plant ineligible for the lucrative RO incentive scheme. Considered in terms of volume this effect is exaggerated. This effect is of concern for polluted or mixed biomass streams where biomass may be attached to, impregnated with or coated by small amounts of plastic or paint.

4.3.2.3 Moisture Content

The moisture content of biomass fuels can vary widely. When first harvested wood can have a moisture content of over 60% by weight. This has several connotations for its conversion, storage transportation and processing. Wood biomass can be dried naturally outdoors in piles, split logs or stacks without large costs, to bring the moisture content below around 35% indoor storage is required and for moisture contents below around 15% energy must be input to evaporate the remaining moisture. Other materials may not respond in the same way however and there are many concerns to be addressed in the storage and handling of all biomass materials.

Most biomass is biologically active in some way. This means that the percentage of dry matter may be decomposed by fungus or bacteria if conditions are not properly controlled, resulting in a reduction of total energy content. Such activity can also generate high levels of heat within the fuel pile possibly leading to spontaneous combustion. According to van Koop (Koppejan, 2008) wood chips stacked at a pile height of over 8m can be vulnerable to self-ignition. This problem appears to have plagued the UK’s only large scale coal to biomass power conversion at Tilbury docks near London where a fire in the storage area has stopped generation at the time of writing.

The main economic impact of moisture content is that eventually the moisture must be driven off in the conversion process and does not release energy (moisture is lost as steam or condensate). If transport costs relate to weight this means that moving even 20% moisture content fuel around can increase transport costs per kWh of energy transported by 20%.

There are also technical impacts of high moisture content fuels, mainly in the design of the conversion facility. Handling large amounts of steam can cause problems for maintaining steady combustion temperatures and the performance of filters for the exhaust gas. Large amounts of steam can also change the way that pollution permits are issued and measured, for some installations pollution is measured by calculating up from the volume of gas that leaves the plant, if most of this gas is water vapour it can affect the accuracy of such calculations meaning more sophisticated measurement methods are required.

4.3.2.4 Ash Content

The ash content is measured as percentage weight of the fuel. Ash is a term used to describe parts of the fuel that are not combusted or converted. Ash is generally aggregate material such as grit, bricks, sand or cement. Ash can enter biomass materials in a number of ways, for trees sand and dirt gets caught in the bark and slowly incorporated into the tree, during harvesting biomass may be laid on the ground or moved in machinery previously used for aggregates. In fuels derived from waste ash can come from any number of sources. For fuels grown specifically for energy ash levels can be controlled through proper handling and processing, just using concrete bases for moving materials can reduce ash content (Koppejan, 2008). Ash is of relevance to boiler manufacturers for two main reasons. Firstly because any non-combustible material inside the combustion chamber can affect the flow of combustion gasses around the material and therefore reduce efficiently. Secondly, and more importantly because as the rest of the material combusts into gasses and vapour the ash remains, in the right conditions this ash can form onto heat transfer pipes and other delicate parts of the boiler as a glass like deposit referred to as clinker. The build-up of clinker not only damages the total system efficiency but also creates areas where pollutants can become concentrated and corrode the boiler material (Zevenhoven-Onderwater et al., 2001, Grammelis, 2011).

In combustion processes the input material is reduced in weight and volume and the remaining material is referred to as ash. Ash is split into two categories, bottom ash and fly ash. Bottom ash is collected from below the fire pit and fly ash from the filtration of exhaust gasses. Depending on the contents of the input material bottom ash can be used in various manufacturing processes; often as an ingredient for aggregate building products and hardpack for road construction, even as a fertiliser (Dahl et al., 2009). Fly ash is likely to contain many of the toxins and metals captured from the stack emissions and is more difficult to deal with and is usually sent to landfill. Research is in progress to incorporate fly ash into secondary products however (Ahmaruzzaman, 2010).

4.3.2.5 Chlorine content

Chlorine is a naturally occurring chemical in many biomass sources including wood and is found in variable amounts in municipal and commercial wastes. Chlorine is a reactive non-metal element that can form a large range of other chemicals when subjected to heat and in the presence of other reagents. Most troubling for technology manufactures is Hydrochloric Acid (HCl). This strong acid corrodes the metal coatings used within boilers, potentially leading to leaks and component failure. Chlorine in waste streams has long been a problem for waste incineration plants and various methods have been proposed to deal with high-chlorine waste streams (Grammelis, 2011).

4.3.2.6 Nitrogen and sulphur content

When combusted nitrogen within the fuel can react with oxygen to form Nitrous Oxide (NO_2 and NO), referred to generally as NOx emissions. Once in the atmosphere NOx reacts with moisture in the atmosphere and eventually forms nitric acid (HNO_3. Sulphur within the fuel undergoes a similar set of chemical reactions to eventually create atmospheric sulphuric acid (H_2SO_4 from SOx). Together sulphuric and nitric acid combine to cause “acid rain”. Acid rain has a lower PH than neutral due to the presence of these acids and can have devastating effects on ecosystems, forestry, fish and marble or bronze statues. Because of this acid rain effect the levels of NOx and SOx are strictly controlled by regulations in many countries including the UK where exhaust emissions are monitored and controlled by DEFRA. Plant designers usually deal with NOx and SOx emissions by changing the combustion temperature and finding some abatement solution for the exhaust gasses. However the formation of acids within the boiler, filters or equipment can increase maintenance problems (Koppejan, 2008, Grammelis, 2011).

Nitrogen content is not included in the fuels library. According to Express Energy the combustion temperature can be adjusted to manage the emission of NOx emissions. Additionally the nitrogen content of the fuel is not a good measurement for the emission of NOx gasses as different nitrogen based compounds will emit NOx at different rates. This also applies for the other thermochemical conversion processes. Nitrogen is however important in for anaerobic digestion facilities where the nitrogen content of the residue digestate is used to set its value as a fertiliser substitute.

4.3.2.7 Sodium and potassium content

Sodium is a common element and under the high temperatures of combustion can take many chemical reaction routes. Of concern to equipment manufactures is its ability to form sodium peroxide (commonly bleach) which can corrode components within the plant. Sodium can also form unusual and corrosive chemicals with other elements from the fuel under high temperatures, vanadium for instance combines with sodium to form vanadates which can dissolve several metal oxides including chromium oxide – often used to protect steel or iron components within energy from waste plants. Potassium is one row below sodium on the periodic table and therefore has similar properties and reaction pathways causing similar problems. Both sodium and potassium also lower the ash melting point of a fuel. This can increase problems associated with clinker formation and hot-spots forming inside the combustion chamber.

4.3.2.8 Fluorine content

Under combustion conditions fluorine within a fuel reacts to form hydrogen fluoride (HF). Hydrogen fluoride is a dangerous gas that reacts with water to form a strong acid (hydrofluoric acid). In its concentrated form hydrofluoric acid can be fatal in small amounts of contact exposure. As a gas HF can also be fatal. Furthermore it is highly corrosive reacting especially strongly with metal oxides. Its emission is strictly regulated.

4.3.2.9 The heavy metals

Heavy metals is a broad, poorly defined phrase used to describe elements with metallic properties. Some of these metals are required for organic life and found naturally in the ecosystem (Iron, Zinc and manganese for instance are described as vitamins for human consumption). However in large quantities they can be toxic and harmful (Alloway, 1995). Different heavy metals have different health and environmental impacts. Mercury, lead, chromium and cadmium are poisons in sufficient concentrations. Zinc and lead can cause corrosion of materials as well as health problems. The emission of heavy metals is tightly controlled for these reasons. One characteristic of heavy metal pollution is the bio-accumulation of poisonous materials through the food chain, this happens when pollutants are taken up in small quantities by organisms at the bottom of the food chain (algae or plants) and then move up the chain through herbivores into predators such as fish or birds which accumulate larger amounts of the toxin which could eventually enter the human food chain. This effect happens with metals because they do no decompose over time in the way organic toxins do.

Heavy metals are of greatest concern when dealing with the conversion of waste derived fuels, the European waste incineration directive (WID) controls for eleven elements and sets thresholds for emissions. Those elements are: Arsenic, cadmium, cobalt, chromium, copper, mercury, manganese, nickel, lead, tin and thallium. Biomass fuels tend to not contain high levels of such pollutants but larger combustion plants may still be subject to pollution controls similar to those of the WID.

The bio-accumulation effect has been used for the remediation of contaminated land in the UK. Certain plants and crops show a greater tendency for the uptake of polluting metals from the soil and store these metals within the plant (phytoremediation). This has been proposed as a potentially lucrative source of biomass for energy conversion. By collecting and converting (through combustion) plants gown on polluted land the filtration system of the bioenergy plant can capture polluting metals from the ground, slowly reducing the pollutant level in the soil and bringing contaminated land back into use (defra and ADAS, 2002).

4.3.2.10 Final list of properties

Table 4.5 shows the full list of properties that have been identified as important when considering fuel (and technology) selection. The list has been compiled from literature sources, national and international standards, regulations and through interviews with Express Energy Ltd.

Table 4.5: List of feedstock/fuel properties to be considered in BioSS and fuels library.

Property		Abbreviation \ symbol	Most common unit of measurement	Impact
Non-chemical properties	Biomass energy content	BEC	% of total energy content	Economic performance;
	Net calorific value	NCV	(MJ/kg)	Economic performance; material feed rate; plant design
	Moisture content	MC	% by weight	Plant design; storage design; storage durability; dry matter losses; self-ignition.
	Ash content	Ash	% by weight	Ash production/disposal; ash end use; plant design;
	Sulphur	S	% by weight	Pollution (SOx); corrosion; maintenance
	Chlorine	Cl	% by weight	Pollution levels; corrosion' plant design; maintenance;
	Fluorine	F	mg/kg	Pollution (HF)
	Sodium	Na	mg/kg	Corrosion; maintenance
	Potassium	K	mg/kg	Corrosion; maintenance
Heavy metals	Mercury	Hg	Pollution; Ash utilisation	Pollution levels, ash utilisation
	Cadmium	Cd	mg/kg	
	Tellurium	Tl	mg/kg	
	Lead	Pb	mg/kg	
	Zinc	Zn	mg/kg	
	Tin	Sn	mg/kg	
	Aluminium	Al	mg/kg	

Several properties have been omitted from Table 4.5, most notably the physical properties that are specified under the CEN standards for solid biofuels. Durability, size dimensions, friction, dust and the amount of fine material present are all omitted. This is because under the proposed operating procedure that Express Energy Ltd are proposing the incoming biomass material will be treated prior to entering the conversion facility. This pre-treatment process aims to homogenise the incoming material by shredding and mixing the material and possibly also compressing that homogenous material into pellets or briquettes. Therefore physical constraints of purchased material will change prior to entering the conversion facility.

4.3.3 Data sources

There are several significant efforts to characterise and classify biomass materials on-going in both Europe and the USA. In addition there are many academic papers with an engineering focus that have performed some form of fuel analysis in order to analyse and compare the performance, the process of standardisation has also required extensive testing of materials. The fuels library presented here compiles these sources into descriptions for material matching the classification given in Table 4.2 as well as several other categories for non-biomass (CEN/TC 343) materials that may also be available to UK bioenergy developers.

The library has been compiled to provide a general estimate of properties that a potential, untested fuel source may have. The approach taken when compiling the data for the fuels library is to include as many material descriptions as possible as well as generic descriptions that are commonly provided by material suppliers at an early stage. This is inline with the aim and purpose of the fuels library which is to help developers assess which sources and suppliers of biomass may be useful for the project in advance of extensive chemical testing.

The range of biomass sources is massive and the task of characterising the different sources is essentially endless. Many factors can affect the exact properties of a material sample meaning that even re-testing a sample from the same source can yield different results. To further complicate the data collection process for the fuels library there are different testing methods and different authors may test for only some properties depending on what they are interested in studying. Results may also vary depending on the type of equipment that has been used, although the introduction of testing standards under CEN/TC 343/355 have reduced this problem. The result is that any effort to collect and aggregate data needs to take one of two approaches. Either (1.) systematically categorise materials sample by sample and gradually build up a library of standardised test data. Or (2.) aggregate all data that appears to be from a similar or related source and give a broad range of properties that could be expected from samples taken from a new source. The first approach is that taken by the European funded project BioDat. The BioSS fuels library takes the second approach.

The BioDat database (BIODAT, 2012) has been created by the PHYDADES project (PHYDADES, 2012) funded by the Intelligent Energy Europe Programme and run by the energy research centre of the Netherlands (ECN, 2012). BioDat was preceded by the Phylis database (PHYLLIS, 2012a), BioDat differs from Phylis in that data entered to BioDat is required to have been processed using the CEN/TS testing standard. Phylis is a user built system that allowed records to be added from tests not using the standard methods. Work is on-going with a new release of a combined database in August 2012 (PHYLLIS, 2012b).

In the USA a similar programme is being undertaken by the US Department of Energy under the energy efficiency and renewable energy department. The biomass feedstock and properties database uses American Society for Testing and Materials guidelines and reports on a wide range of properties depending on the test being done. Few of the samples in the database have been subjected to the full range of tests and the data therefore has major gaps. The data contained however is useful for the purposes of the fuels library (USDoE, 2004).

Similar issues arise when research papers report on biomass properties. Because researchers are usually interested in the performance of a piece of equipment or process details on feedstocks and testing methods are sometimes brief or unclear. Using a literature review several papers have been identified that do provide information on at least some of the properties of interest shown in Table 4.5. Many of the papers identified in the search for papers that characterise biomass also appear in one of the above databases, data from these was omitted to avoid repetition. This left five sources to be integrated with the fuels library (Koppejan, 2008, McIlveen-Wright et al., 2007, Vassilev et al., 2012a, Vassilev et al., 2012b, Vamvuka and Kakaras, 2011) along with the standards for solid recovered fuels (van Tubergen et al., 2005) and solid biomass (Loibnegger, n.d.).

The fuels standards have been entered as fixed values assuming the worst case for each property. For the biomass sources where data exists a mean and standard deviation is given. The Gausian distribution is used for the fuels library as it is expected to be the most likely distribution that properties will follow, the Gaussian distribution is also easy to understand and familiar to most intended users of the database. In reality it may be that the weibull distribution provides a better fit for experimental results and the user has the option to use this distribution in BioSS if they feel the fit is more suitable. Negative values are not allowed in BioSS and any occurrence of negative values are set to zero for the optimisation algorithms. Similarly any distribution tail over 100% is capped to 100%.

All of the data collected and compiled for the fuels is secondary, no laboratory experiments have been done as part of this research. The secondary data has been arranged in a different way to previous attempts at classification according to the different aims of the BioSS fuels library.

Having reviewed the available data as described in section 4.3.3 it is evident that for most available data records all the properties in Table 4.5 are not reported on. However the NCV, MC and Ash content are usually reported, Chlorine content is also often reported. Biomass energy content is not reported in the databases as it is a UK specific constraint. Therefore assumptions have been made for each record in the library.

4.3.4 Screenshots

The fuels library is presented as two related tables. In Table 6 the mean values for the properties of different materials are shown. In Table 7 the corresponding standard deviation for that property and material combination is shown. The incompleteness of the data can be seen from the sample of material records shown. Some materials have been tested for a wider range of properties than others. Refuse derived fuels (RDF) are tested for all of the properties identified in Table 4.5 whilst poultry manure is tested for all properties apart from mercury (Hg). In general the materials described as waste or by-products are more likely to have received wider testing than more ‘conventional’ biomass sources such as straw or hardwood chips. However the conventional biomass sources have received more attention and more samples have been tested. Straw is the most tested material type in the BioSS fuels library with 100 samples taken.

In the samples below three records for solid recovered fuel (SRF) appear according to the ERFO standards (van Tubergen et al., 2005). Each representing material with a different reported combinations of LHV, Cl and Hg showing that some samples could have higher pollutant contents than others but a higher calorific value, the issue of better or worse quality SRF is therefore difficult to judge outright.

The SRF and solid biofuels standards only require certain properties to be reported on. For the properties that are missing but are commonly reported for other materials an estimate has been made according to information gathered by ERFO and from other sources.

Figure 4.2 shows the moisture content, ash content and lower heating value for a different range of samples from the fuels library. The chart shows the variation between different material samples for these key properties. Although heating value remains fairly constant over most of the samples moisture and ash contents can vary greatly. Comparing the three records shown in Figure 4.2 for 'bark' materials shows an enormous variation for instance.

Overall the BioSS contains 48 material records consisting of data from a total of 451 samples. Many more are available on the BioDAT and US DoE databases however the incompleteness of the records, the lack of consistent testing methods and the scarcity of tested records has led to the omission of these records from the BioSS fuels library.

Table 4.6: Mean values for material properties within the BioSS fuels library.

Description	Notes/Source	# of samples	Biomass Energy Content	Moisture Content	Lower heating value (LHV or NCV) Dry basis	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Mixed Hardwood Chips	BIODAT; Koppejan	18	100	15.19	18.36	0.95	0.07	293.6								
Park wastes, Council thinnings	BIODAT	6	97	35.27	18.7	25.2	0.16	860.3								
Urban pruning waste	BIODAT	9	93	32.81	19.75	8.49	0.06									
Wood Chips (Generic)	BIODAT; D.R. McIlveen-Wright, Y. Huang, S. Rezvani, Y. Wang (2007)	46	100	13.13	18.94	1.45	0.04									
Straw (Generic)	BIODAT; US DoE EERE Program - Biomass database; D.R. McIlveen-	100	100	11.66	18.81	5.5	0.11									

	Wright, Y. Huang, S. Rezvani, Y. Wang (2007); BioDat; Koppejan															
Bark (Generic)	BIODAT; Koppejan	13	100	36.84	19.54	3.46	0.06									
Torrefied, Palm Oil Kernal	BIODAT	6	100	0	19.57	3.83	0.06									
Wood, Demolition (Generic)	BIODAT	9	80	12.09	18.5	4.97	0.09	942.3	60.4							
Wood, Used (Class C)	BIODAT	5	85	21.86	19.09	1.3	0.03	208.9								
Wood, Used (Class B)	BIODAT	3	90	26.73	19.12	0.93	0.03	133.8		340	580					
RDF (Generic)	BIODAT	12	50	12.14	21.97	17.93	0.44	7386.4	88.2	2772.6	1593.7	0.2	1.9	232.1		5200.9
RDF (High Biomass Content)	BIODAT	1	85	10	17.48	38.07	0.73	2583.6	83	1400	4200		4.1	436		43000
Olive residues	BIODAT; Koppejan	6	100	12.21	21.29	10.03	0.13	3243.1		851.9	24817.3			16.4		1539
Animal Waste, Chicken Poultry	BIODAT	18	100	39.57	17.67	26.47	0.8	4168.3	13.5	3638.6	29431.4		0.3	341.2		695.5

SRF [LHV 1, Cl 3, Hg 1]	ERFO		50	15	25	17		1				0.02				
SRF [LHV 1, Cl 5, Hg 5]	ERFO		50	15	25	17		3				0.5				
SRF [LHV 2, Cl 1, Hg 2]	ERFO		50	15	20	17		0.2				0.03				

Table 4.7: Standard deviation of material properties within the BioSS fuels library. Materials corresponding to Table 6.

Description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Mixed Hardwood Chips	0	13.36	0.24	0.45	0.09	220								
Park wastes, Council thinnings	9.7	10.88	0.57	11.29	0.06	506.9								
Urban pruning waste	9.3	14.37	1.51	8.2	0.02									
Wood Chips (Generic)	0	12.03	0.76	0.99	0.06									
Straw (Generic)	0	11.01	2.46	7.07	0.14									
Bark (Generic)	0	28.02	2.43	2.95	0.03									
Torrefied, Palm Oil Kernal	0	0	1.68	0.95	0.05									
Wood, Demolition (Generic)	8	2.88	0.71	5.79	0.07	257.8	38.8							
Wood, Used (Class C)	8.5	4.1	0.08	0.34	0.01	196.9								
Wood, Used (Class B)	9	5.29	0.08	0.22	0.01	51.9		173.4	88.7					
RDF (Generic)	5	12.21	2.28	6.44	0.23	4411.4	0.4	257.9	324.8	0	1.5	154.5		3132.8
RDF (High Biomass Content)	8.5													
Olive residues	0	2.53	1.37	5.56	0.04	585.1		636.2	7678.2			2.2		705.7
Animal Waste, Chicken Poultry	0	27.27	0.89	7.51	0.5	2646.7	0	1403.9	8317.3		0	41.9		214.3
SRF [LHV 1, Cl 3, Hg 1]	10	2	0	2	0	0				0				
SRF [LHV 1, Cl 5, Hg 5]	10	2	0	2	0	0				0				
SRF [LHV 2, Cl 1, Hg 2]	10	2	0	2	0	0				0				

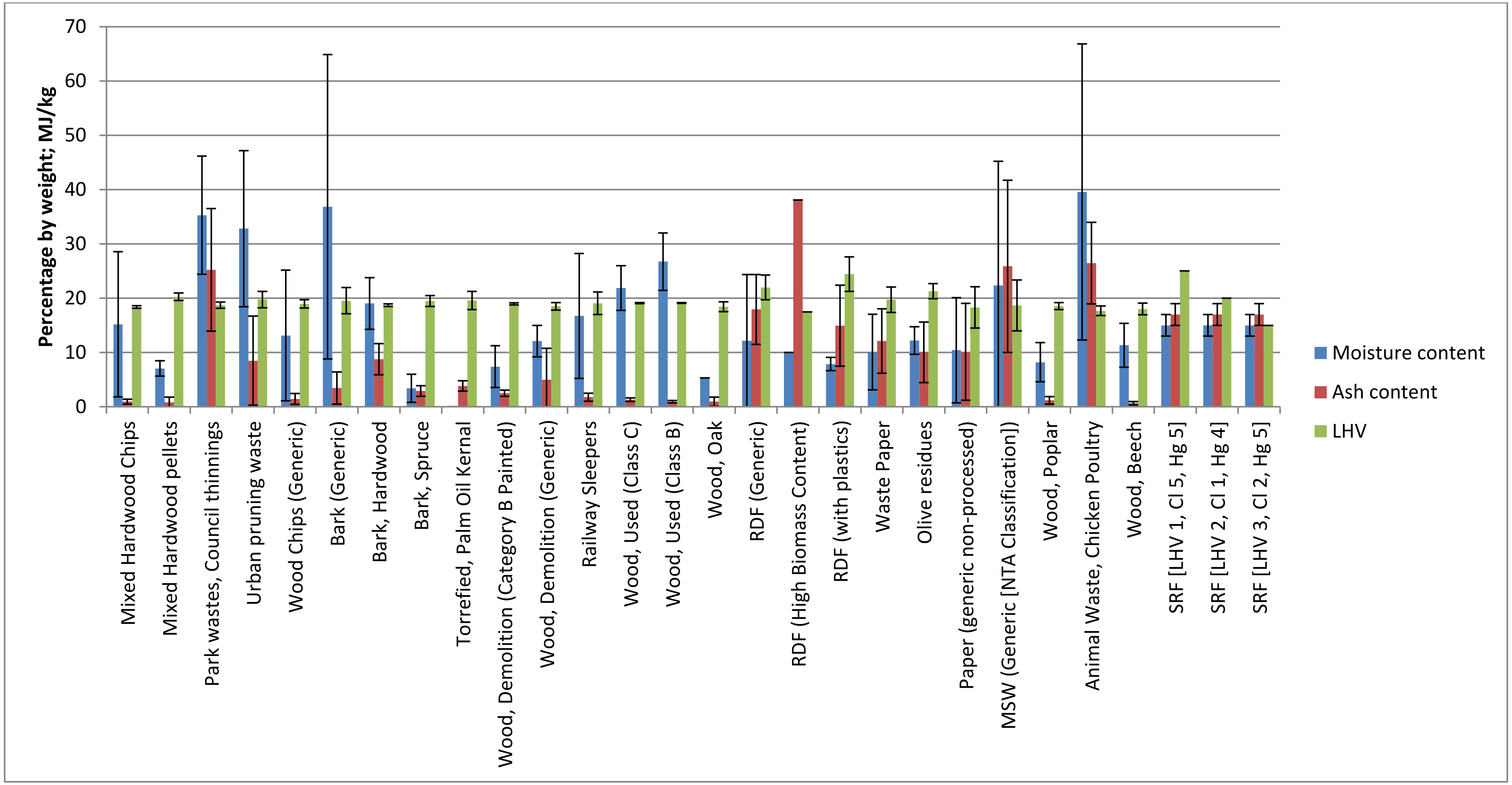


Figure 4.2: Moisture content, ash content and lower heating value for a range of samples from the BioSS fuels library

4.3.5 Completeness and accuracy

The fuels library is intended to be a guide for developers at a stage when project uncertainty is high and the development pathway is unclear. The library is not intended to replace comprehensive feedstock testing by either suppliers or buyers. Therefore commercial decisions should not be based on the contents of the library alone, the library should be used to improve the efficiency of the procurement business function for biomass developers and operators.

There are some major problems with extrapolating data from very small numbers of samples. For the purposes of the fuels library and the BioSS the distributions have been taken as Gaussian, however there is nowhere near enough raw data to draw such a distribution with any degree of confidence. The Gaussian distribution has been selected here however other distributions may be more suitable, there is not sufficient data to draw conclusions on the statistical accuracy or otherwise of the entries in the fuels library. However it does provide a platform to which extra records and data could be added. As the library is used it is intended that users will enter extra information they have collected whilst investigating suppliers. This simple knowledge management method will become helpful for developers as they consider new suppliers and new sources of material. By accruing such information between projects the library can also become a source of intellectual property and competitive advantage.

Of the 48 different material descriptions appearing in the BioSS fuels library only 3 have data available for the full list of 14 properties shown in Table 4.5. Those are Sewage sludge, Hemp (generic) and paper sludge (various process stages). Of the 14 properties only 5 are reported for all of the material records. They are biomass energy content (which has been estimated), moisture content, net calorific value, ash content and sulphur content. 36 materials have data for chlorine content.

When considering this type of information for decision making purposes it is important to remember that each material source will be slightly different and to understand where the variation and standard deviations have come from. Variation of test results for each material description in the library can come from

- Variation in the actual sample being tested; some parts of the sample may have different properties to other parts of the sample
- Variation in the properties of the material; the material may have certain properties some of the time under certain conditions, and different properties at other times under different conditions. E.g. under drought, monsoon, disease or with different soil types the chemical properties may change.
- Storage and handling; the way the material has been handled and stored prior to testing can make a difference to the properties recorded. All the samples in the BioSS fuels library are described as tested 'as received'. Prior pre-treatment, storage time and conditions are not described in the material description.
- Aggregation of test data; material properties may be different between areas. Pine grown in a Scandinavian climate may be different to that grown in North America, but both samples will be described as 'pine'.
- Systematic errors; errors in equipment, sampling method and number of samples taken may combine to give inaccurate data.

The combination of a sparsely populated library of data and a mixture of reasons for uncertain results means that any prospective buyer must complete their own testing and measurement prior to signing any supply contract.

4.4 Summary

This chapter summarises the fuels library that is used in the BioSS system. The library is intended as a starting point for biomass procurement managers when they begin to look to secure materials for projects. The fuels library contains approximate estimates of what the buyer may expect to find when investigating materials. 5 key properties are estimated for the materials described in the fuels library and this information is represented as a mean and standard deviation. 14 properties are identified as being important for buyers of biomass but only a small number of material descriptions have data for all of these properties.

The fuels library allows users to fully edit, add to and adjust records. 48 materials are reported in the final version of the fuels library along with data for a range of standards relevant to the bioenergy industry. These standards allow the buyer to quickly evaluate any material that has been tested according to a particular standard using a worst case approach. The fuels library integrates with the BioSS in stage 2 and the operational stage. In stage 2 it can allow developers to evaluate potential biomass sources and their compatibility with chosen technologies without the need for extensive testing, improving the efficiency of the supplier evaluation and shortlisting process. In the operational phase it can be used in a similar way but to evaluate how potential new sources could influence the performance of an existing contracted portfolio.

Chapter 5. Supplier Selection

5.1 Introduction

This chapter discusses the supplier selection part of the BioSS decision framework. The supplier selection problem fits as a sub-problem of the strategic sourcing problem faced by the bioenergy industry, managers must consider the aptitude of the supplying company as well as the quality of the material they are offering for supply. This chapter starts with a short review of previous literature on supplier selection and its importance to industry sectors that share some common ground with the bioenergy industry. A description of what supplier selection means in the context of the BioSS and how this part of the framework interacts with the rest of the decision framework. In section 5.2 the QFD-AHP method is proposed as suitable for treatment of the supplier selection problem in this context. In section 5.3 the method is applied to information captured from industry stakeholders and observations and a discussion of the findings are made in section 5.4. Section 5.5 concludes the chapter and all of the data used and the full QFD-AHP process is included in Appendix C.

This research area fits into the main BioSS system, the QFD-AHP method presented in this chapter provides a framework that allows decision makers and stakeholder groups to place importance weightings on different evaluating criteria, against which individual sources can be judged, giving a score to each source. Chapter 6 will discuss the order allocation part of the BioSS which will integrate the outputs from the method in this chapter into the strategic sourcing decision.

Supply chain management for biomass schemes is a multi-stakeholder, multi-criteria decision (Adams et al., 2011, Buchholz et al., 2009, Upham et al., 2007). The choice of supplier can also have wide-ranging environmental and social impacts. The incorrect choice of supplier can lead to an unsustainable system, due to, for instance, refusal of project finance, unreliable operation of the bioenergy plant, depletion or failure of fuel supply, and extensive environmental damage through deforestation and greenhouse gas emissions (van Dam and Junginger, 2011, Gold and Seuring, 2011).

According to Prajogo et al. (2012) and others, including Narasimhan et al. (2001) and Talluri and Sarkis (2002), supplier assessment and performance measurement is a key part of supply chain management. They also explain that as competition has moved from a firm level to a supply chain level, suppliers have become important to the performance of the buying firm. Huang and Keskar (2007) discuss the importance of formalizing this supplier assessment using performance metrics as well as aligning the supplier selection process with business strategy and product life-cycle stage, an idea mirrored in the design of the BioSS. Elsewhere in the literature the discussion between taking a resource based view and a relational view is influencing the way that suppliers are assessed, selected and managed. Perhaps due to the immaturity of the sector supplier selection for biomass for energy has not been fully discussed using these approaches. .

More established biomass based industries have been well studied in the literature as documented by D'Amours et al. (2008) for the forestry and pulpwood industry a case study by Carlsson and Rönnqvist (2005) which illustrates how operational management modelling assisted with the logistics design and customer integration at a large wood products company in Europe. However the case study by Koskinen (2009) finds that supply chain management practices are not fully integrated with the procurement process of a large paper manufacturer. The waste resource has attracted less attention regarding its strategic procurement as would be expected given that it has traditionally not been viewed as a product for procurement. Waste combustion is well studied from a technical and life-cycle perspective, most relevantly by Fruergaard and Astrup (2011) and Burnley et al. (2011) as are the collection and logistics of waste management (Longden et al., 2007, Beigl et al., 2008, Caputo et al., 2003, Cheng and

Hu, 2010, Haastrup, 1998, Iakovou et al., 2010, Karagiannidis et al., 2009, Skovgaard et al., 2005).

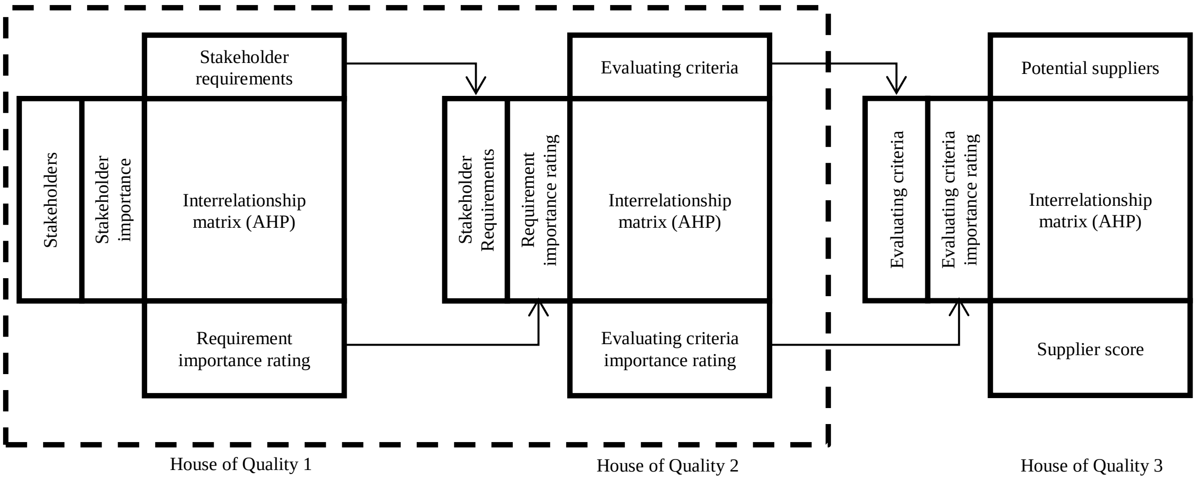
5.2 Methodology

This section describes the QFD-AHP method that has been selected for the supplier selection part of the BioSS. This method has been chosen as it is a robust and transparent approach that allows for the consideration of many stakeholder requirements, all of different nature. It also allows tacit and explicit factors to be considered in a single appraisal. The output of the method is a relative preference score and ranking for each potential supplier. This section outlines the QFD-AHP method and shows the steps that are required. The method requires collection of some primary data and the method to collect this is described in section 5.2.3. Section 5.3.1.1 reports on the stakeholders and their requirements then section 5.3.3 reports and describes the evaluating criteria identified by this research. Using these requirements and criteria weightings are then given to each relationship and the importance of each evaluating criterion is calculated for a general case applicable to Express Energy Ltd in section 5.3.4.

5.2.1 The QFD-AHP for supplier selection

To better align supplier selection (and sourcing strategy) with corporate/business strategy, the QFD-AHP method has been developed by Ho et al. (2011). The QFD (Quality Function Deployment) allows for various stakeholders to express their requirements and also to translate these criteria into multiple comparable evaluating criteria for supplier selection are then used to benchmark suppliers. The most important information that the QFD provides is the weights of evaluating criteria, which are derived from the importance ratings of stakeholder requirements together with the relationship strength between each stakeholder requirement and each evaluating criterion. Generally in QFD, both importance ratings of stakeholder requirements and relationship weightings are determined by the decision makers arbitrarily. This may result in a certain degree of inconsistency, and therefore degrade the quality of decisions made. To overcome this drawback, the AHP (Analytical Hierarchy Process) is used to evaluate them consistently. The AHP allows decision makers and stakeholders to set relative weightings for any set of alternatives through a pairwise comparison matrix. The QFD-AHP method ensures successful strategic sourcing because it allows the decision maker to choose suppliers that can satisfy the majority of the conflicting requirements raised by the key stakeholders. This is useful for the UK bioenergy problem where many stakeholders hold salience and may have conflicting requirements .

Figure 5.1 shows an overview of how the QFD-AHP method fits together. The AHP is used for the interrelationship matrices and the importance scores found for House of Quality (HoQ) 1 and 2 are passed to the next House of Quality. The result is that the broad requirements in HoQ 1 percolate down to the final supplier score. A single decision maker would find it difficult to judge supplier performance against each requirement directly, especially for



requirements made by other stakeholders. The QFD-AHP method overcomes this difficulty.

Figure 5.1: QFD-AHP method schema

The QFD-AHP method is described in the steps shown in this section. The method comprises of series of two houses of quality (HoQ), which is a tool of QFD. Both HoQ1 (refer to steps 1 to 5) and HoQ2 (refer to steps 6 to 9) has an interrelationship matrix. These matrices are completed using the AHP. This process allows different stakeholder groups to express and rank their requirements in HoQ1, and then for the importance of various evaluating criteria in terms of fulfilling the stakeholder requirements is assessed in HoQ2. The importance weightings of evaluating criteria could be used to benchmark and select between potential biomass suppliers.

Step 1: Identify the stakeholder groups.

Step 2: Determine the importance rating of each stakeholder group in terms of the influence over the project.

Step 3: Identify the stakeholder requirements.

Step 4: Determine the relationship weights between the stakeholder groups and stakeholder requirements using AHP (steps 4.1 to 4.7).

Step 4.1: AHP pairwise comparison

Construct a pairwise comparison matrix,

Equation 5.1

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix},$$

where n denotes the number of elements (stakeholder requirements in HOQ1), and a_{ij} refers to the comparison of element i to element j with respect to each criterion (stakeholder groups in HOQ1). The 9-point scale, shown in Table 1, can be used to decide on which element is more important and by how much.

Step 4.2: AHP synthesisation

Divide each entry (a_{ij}) in each column of matrix A by its column total. The matrix now becomes a normalized pairwise comparison matrix,

Equation 5.2

$$A' = \begin{bmatrix} \frac{a_{11}}{\sum_{i \in R} a_{i1}} & \frac{a_{12}}{\sum_{i \in R} a_{i2}} & \cdots & \frac{a_{1n}}{\sum_{i \in R} a_{in}} \\ \frac{a_{21}}{\sum_{i \in R} a_{i1}} & \frac{a_{22}}{\sum_{i \in R} a_{i2}} & \cdots & \frac{a_{2n}}{\sum_{i \in R} a_{in}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{a_{n1}}{\sum_{i \in R} a_{i1}} & \frac{a_{n2}}{\sum_{i \in R} a_{i2}} & \cdots & \frac{a_{nn}}{\sum_{i \in R} a_{in}} \end{bmatrix},$$

where R denotes the set of stakeholder requirements, that is, $R = \{1, 2, \ldots, n\}$.

Step 4.3: Compute the average of the entries in each row of matrix A' to yield column vector,

Equation 5.3

$$C = \begin{bmatrix} c_{1k}^{1} \\ \vdots \\ c_{nk}^{1} \end{bmatrix} = \begin{bmatrix} \dfrac{\left(\dfrac{a_{11}}{\sum_{i \in R} a_{i1}} + \dfrac{a_{12}}{\sum_{i \in R} a_{i2}} + \cdots + \dfrac{a_{1n}}{\sum_{i \in R} a_{in}} \right)}{n} \\ \vdots \\ \dfrac{\left(\dfrac{a_{n1}}{\sum_{i \in R} a_{i1}} + \dfrac{a_{n2}}{\sum_{i \in R} a_{i2}} + \cdots + \dfrac{a_{nn}}{\sum_{i \in R} a_{in}} \right)}{n} \end{bmatrix},$$

where c_{ik}^{1} denotes the relationship weightings between stakeholder requirement i and its corresponding stakeholder group k in HOQ1.

Step 4.4: AHP consistency verification

Multiply each entry in column i of matrix A by c_{ik}^{1}. Then, divide the summation of values in row i by c_{ik}^{1} to yield another column vector,

Equation 5.4

$$\overline{C} = \begin{bmatrix} \overline{c}_{1k}^{1} \\ \vdots \\ \overline{c}_{nk}^{1} \end{bmatrix} = \begin{bmatrix} \dfrac{c_{1k}^{1} a_{11} + c_{2k}^{1} a_{12} + \cdots c_{nk}^{1} a_{1n}}{c_{1k}^{1}} \\ \vdots \\ \dfrac{c_{1k}^{1} a_{n1} + c_{2k}^{1} a_{n2} + \cdots c_{nk}^{1} a_{nn}}{c_{nk}^{1}} \end{bmatrix},$$

where $\overline{C}$ refers to a weighted sum vector.

Step 4.5: Compute the averages of values in vector $\overline{C}$ to yield the maximum eigenvalue of matrix A,

Equation 5.5

$$\lambda_{\max} = \frac{\sum_{i \in R} \overline{c}_{ik}^{1}}{n}.$$

Step 4.6: Compute the consistency index,

Equation 5.6

$$CI = \frac{\lambda_{\max} - n}{n - 1}.$$

Step 4.7: Compute the consistency ratio,

Equation 5.7

$$CR = \frac{CI}{RI(n)},$$

where $RI(n)$ is a random index of which the value is dependent on the value of n, shown in Table 2. If CR is greater than 0.10, then go to step 4.1. Otherwise, go to step 5.

Step 5: Compute the importance rating of each stakeholder requirement,

Equation 5.8

$$w_i^1 = \sum_{k \in S} p_k c_{ik}^1,$$

where S denotes the set of company stakeholders, that is, $S = \{1, 2, \ldots, m\}$, and p_k denotes the importance of stakeholder group k.

Step 6: Copy the stakeholder requirements (step 3) and their corresponding importance ratings (step 5) into HOQ2.

Step 7: Identify the supplier evaluating criteria.

Step 8: Determine the relationship weightings between evaluating criteria i and its corresponding stakeholder requirements k, c_{ik}^2, using AHP (steps 4.1 to 4.7). Note that, in HOQ2, R denotes the set of evaluating criteria, that is, $R = \{1, 2, \ldots, n\}$, whereas S denotes the set of stakeholder requirements, that is, $S = \{1, 2, \ldots, m\}$.

Step 9: Compute the importance rating of each evaluating criterion

Equation 5.9

$$w_i^2 = \sum_{k \in S} \overline{w}_k^1 c_{ik}^2,$$

where $\overline{w}_k^1$ is computed in step 5.

5.2.2 Data required

All the stages of the QFD-AHP require data input. For HoQ 1 to be formed the salient stakeholders must be known along with their requirements regarding the bioenergy supply chain. For HoQ 2 the evaluating criteria must be known and the strength of relationship between each evaluating factor and requirement must also be known. Each stakeholder therefore must complete at least the relevant AHP matrix for HoQ 1 to indicate the relative weighting of each of their requirements.

The data that is required for this method is therefore summarised as: stakeholder groups, stakeholder importance, stakeholder requirements, evaluating criteria and available suppliers. The method also requires the following information to be collected to complete the interrelationship matrices: relationship between stakeholders and their requirements, relationship strength between evaluating criteria and requirements, performance of suppliers against evaluating criteria.

5.2.3 Data collection and participants

To obtain the relevant stakeholders, their requirements and the associated evaluating criteria a combination of literature review and semi-structured interviews have been used. The pairwise comparisons were completed by each stakeholder group where available (central and local government stakeholders were unavailable for this) and reviewed by staff from Express Energy Ltd and bioenergy specialists from the European Bioenergy Research Institute (EBRI).

Semi-structured interviews are described by Dunn (2005: 80) as a spectrum of interview structures and techniques. At one end are structured interviews that “follow a predetermined and standardised list of questions... At the other end of the continuum are unstructured forms of interviewing such as oral histories… In the middle of this continuum are semi-structured interviews.” Semi-structured interviews take an informal tone and allow the interviewer to ask open questions whilst providing the flexibility to investigate the issues raised in sufficient depth. The interviewer must be able to guide the interview partially to elicit the information required, therefore several open questions are asked around the main themes of the interview. The theme guide used for the semi-structured interviews conducted for this part of the research is shown in Table 5.1 along with some question prompts that were used during the interviews.

Table 5.1: Theme guide for interviews with stakeholders

Theme/topic	Question prompts
Stakeholders	Which stakeholder groups would you recognise as being important when selecting biomass suppliers?
Stakeholder requirements	What do you think are the main requirements and motivations when selecting a supply of biomass for energy?
Evaluating Criteria	When evaluating suppliers, what factors would you look for. If several can you rank them in importance? (EC)
Methods used	Do you use a specific method or approach already when selecting or prioritising Biomass suppliers?
Inadequacies	Are there any problems you know of with the existing methods used? Any inadequacies or inefficiencies?

Table 5.2 shows the stakeholder groups considered to be important to the bioenergy industry according to different academic literature sources. These sources discuss stakeholder groups on a general bioenergy project level rather than specifically regarding the supply of material and supply chain, these groups are also intended to cover all scales and technologies within the bioenergy sector. Most recently Adams et al. (2011) provides a presentation of barriers and drivers towards implementing bioenergy in the UK which identified stakeholders as suppliers, developers, end-users and government as the main stakeholder groups. As this work is concerned with selecting suppliers using an analytical ranking method suppliers are not considered as a stakeholder group. This allows the requirements that are made on suppliers to be clearly understood.

Stakeholders are also mentioned on many occasions in the grey literature on bioenergy. The UK Bioenergy Strategy document (DEFRA, 2007) and the 2009 renewable energy strategy document (DECC 2009) but stakeholder groups are never explicitly identified. Similarly European level documents identify that stakeholders are important but do not generally provide an explicit list. The 2005 Biomass Task Force report to the UK government document does however identify stakeholders that were interviewed in Appendix C of the report (DEFRA 2005) all of who fit into the above categories and a report by EcoFys (2010) presented as part of the EU bioenergy sustainability criteria addresses stakeholders who can be grouped as utilities/energy buyers.

The groups identified in the literature as Utilities and Developers/Operators are, for the purposes of the BioSS, very similar and have been grouped together although these are reported as distinct stakeholder groups in the literature. The highly deregulated UK energy market features companies who may be involved only in electricity buying and selling, only in generation, only in development of capital assets, or in the case of the bigger energy firms, involved in all these areas simultaneously. This blurring of roles is a result of the UK regulatory system and will not apply to all national contexts.

According to the description by Marshal and Rossman (1999) the individual participants chosen for interview were also so called 'elites' within the organisation. Elites individuals are those considered to be influential, prominent or well informed within the organization or community and are selected based on their expertise in the areas relevant to the research. This was especially true in the case of project developers and operators and for financial or investment actors. Interview data was only used for individuals with first-hand experience of the bioenergy industry in these cases. For the environmental groups the organisations were contacted and asked to identify a suitably qualified individual internally. For the cases of the general public and local government such elites do not usually exist, and if they did there would be questions about the exact project history of individuals being interviewed. Therefore local government participants were selected internally (as for the environmental groups) from local council management groups at the strategy level (as opposed to the planning level) and their opinions were combined with published spatial planning strategy, waste management and renewable energy strategy documents. The general public were not consulted directly in this research as the level of knowledge on the bioenergy sector required to access the questions being asked was expected to be beyond the average general public respondent. Instead the opinions of the public were collected through semi-structured interviews with local councillors in areas where bioenergy projects have been proposed. The councillors were asked to report on issues and concerns that had been raised by the public they represented as well as describing the projects proposed in their areas.

Table 5.2: Stakeholders identified within the bioenergy literature and participants

Bioenergy Stakeholder group	Literature sources	Number of participants
Financial groups and project partners/investors	(Elghali et al., 2007, Iakovou et al., 2010)	5
Environmental groups	(Elghali et al., 2007, Heidrich et al., 2009, Stidham and Simon-Brown, 2011, Upham et al., 2007, van Dam and Junginger, 2011)	3 plus documents
Developers/Operators and Utilities	(Elghali et al., 2007, Adams et al., 2011, Stidham and Simon-Brown, 2011, Turcksin et al., 2011, Upham et al., 2007, van Dam and Junginger, 2011)	5
National government and policy makers	(Adams et al., 2011, Elghali et al., 2007, Iakovou et al., 2010, Stidham and Simon-Brown, 2011, Upham et al., 2007, van Dam and Junginger, 2011)	Documents only
Local government	(Heidrich et al., 2009, Stidham and Simon-Brown, 2011, Turcksin et al., 2011, van Dam and Junginger, 2011, Upham et al., 2007)	4 plus documents
Community/public	(Elghali et al., 2007, Stidham and Simon-Brown, 2011)	4
Social Non-Governmental Organizations (NGOs)	(Stidham and Simon-Brown, 2011, Turcksin et al., 2011, van Dam and Junginger, 2011)	Documents only

5.3 Implementation

This section discusses the findings of this section of the research. Section 5.3.1.1 discusses the comments made by interviewees regarding the salient stakeholders for bioenergy supply chains. Section 5.3.2 then discusses the responses to requirements outlined by each stakeholder group and identifies supporting literature. Section 5.3.3 identifies factors that interviewees mentioned that they used to measure performance of suppliers. Section 5.3.4 then presents a case based on an Express Energy project that shows how the evaluating criteria are given weightings and which evaluating criteria are most and least important. Firstly section 5.3.1.1 looks at identifying the salient stakeholders and then their requirements.

5.3.1.1 Stakeholders

When asked to identify which stakeholder groups participants viewed as most salient to the successful design and operation of a supply chain there was a high level of agreement with most participants identifying their own and the other identified stakeholder groups as important. The exception was the social NGO group identified by several authors (van Dam and Junginger, 2011, Stidham and Simon-Brown, 2011, Turcksin et al., 2011) which was not identified by any other stakeholder group as being important in the decision making process. This could be due to participants operating in slightly different contexts to those identified in the existing literature. There are many social NGO's in the UK, although non with a clear focus on bioenergy and biomass. There are also rural employment organisations and social wellbeing organisations however none of those identified and contacted were able to offer any comment on the topic of sourcing and supplying biomass, their focus was on heat use, pricing and billing.

Table 5.3: Responses to question regarding other salient stakeholder groups. Ticks indicate where a group in the rows identified groups in the columns as being important.

Interviewed stakeholder group \ Stakeholder groups identified by participants	Financial groups and project partners/investors	Environmental groups	Developers/Operators	National government and policy makers	Local government	Community/public	Social NGOs
Financial groups and project partners/investors		✓	✓	✓	✓		
Environmental groups	✓		✓		✓	✓	
Developers/Operators	✓	✓		✓	✓	✓	
National government and policy makers							
Local government		✓	✓	✓		✓	
Community/public		✓	✓				
Social NGOs							

5.3.2 Stakeholder requirements

Requirements in the QFD-AHP method are a set of desirable characteristics that the selected supplier(s) should be able to satisfy as best as possible, in other words, the final solution should meet the requirements identified by the stakeholders. Through questioning and the loose structure of the interviews several requirements became clear from participant responses. Some requirements were also evident from the grey literature study of UK and EU policy documents. The requirements identified are listed in Table 5.4 along with an explanation of each and identifying stakeholder groups.

Table 5.4: Requirements identified from stakeholder interviews and government documents

Requirements	Identifying stakeholder groups
A good supplier should be able to offer an attractive business to business contract	Financial groups and project partners/investors; Developers/Operators;
A good supplier should be able to provide good contract conditions regarding the supply of fuel	Financial groups and project partners/investors; Developers/Operators;
A good supplier should be able to provide material reliably and within the quality specification required	Financial groups and project partners/investors; Developers/Operators;
The supply of materials should have a low environmental impact	Environmental groups; Developers/Operators; National government and policy makers; Local government; Community/public;
A good supplier should be financially credible	Financial groups and project partners/investors; Developers/Operators; National government and policy makers
The supply of materials should have a positive social impact	National government and policy makers; Local government;
National energy security should be improved	National government and policy makers

<u>A good supplier should be able to offer an attractive business to business contract</u>

This requirement describes the perceived quality of the contract being offered (or discussed) between the supplier and the buyer. Several interviewees stated that they had experience of suppliers who were unable or unfamiliar with supply contracts of the type required. This requirement covers only the contract and how favourable the terms offered by the supplier are to the buyer. Usually the focus is on “remittances” [C2] or “remedies” [C5] in the case of undersupply, supply failure or the supplier going out of business.

A good supplier should be able to provide good contract conditions regarding the supply of fuel

The supplier should be required to offer a good contract regarding the specification of the fuel being delivered. The specification could include a variety of chemical and physical properties as described in Chapter 4. This requirement indicates that suppliers and supplier portfolios will be judged partly on how favourable the contract conditions are to the buyer in this area. This requirement is comparable to the traditional supply chain management quality control systems and is different to the requirement above which more closely mirrors commercial risk management in traditional supply chain management.

A good supplier should be able to provide material reliably and within the quality specification required

This requirement concerns the same issue as that discussed above but does not focus on the contractual terms. Several interviewees pointed out that suppliers may "offer a brilliant contract because it's what we want to see" [C5] but obviously are "not in a position to honour that contract" [C3]. This requirement therefore concerns the perceived ability of a supplier to deliver material within the required specification and in a reliable fashion. In traditional supplier selection literature this requirement could be described as pre-contract auditing, a process designed to identify shortcomings in the suppliers business operations.

The supply of materials should have a low environmental impact

Biomass is part of the UK renewable energy strategy because it is considered to be a low or zero carbon source of energy, (DECC, 2011c). The requirement to be environmentally sustainable is recognised in several EU and NGO documents on biomass with a focus on the carbon footprint (EC, 2012, CCC, 2011, FoE, 2011). This requirement goes slightly beyond the carbon implications of selecting a biomass supplier and covers all environmental impacts resulting from the supplier activities such as biodiversity (UNEP-WCMC, 2012), water use and emissions to air (FoE, 2002).

A good supplier should be financially credible

A major theme of the interviews with developers and financiers was the financial credibility of the supplier. This is a result of the contract based exchange market that currently characterises the bioenergy industry. A contract is "essentially worthless if the supplier is not in a position to stand behind it" [C1], meaning if the supplying company is not large enough to match the financial remedies in the case of supply failure or undersupply then that supplier should be considered unfavourably.

The supply of materials should have a positive social impact

As with environmental impact several policy and strategy documents mention the employment benefits of using bioenergy, especially when sourced domestically from rural communities (Adas and Nnfcc, 2008, CCC, 2011, DECC, 2012j, DECC, 2011c, DECC, 2012a). Positive social impact can take different forms but employment is the main tangible impact of bioenergy.

National energy security should be improved

National energy security is a large topic which is highly relevant to the bioenergy industry, Winzer (2012) provides a detailed review of the meaning and definitions of energy security which includes many methods to quantify the energy security of a nation. For the purposes of this study energy security is evaluated not quantifiably but using the definition offered by Winzer (2012) as 'continuity of energy supply'. Bioenergy is seen by governments around the world as an opportunity to reduce dependency on imported fuels and to give better control to national governments regarding the setting of energy prices, key to a nation's economy (DECC, 2012i, DECC, 2012c).

5.3.3 Evaluating criteria

The relevant evaluating criteria have been obtained from mining the interview responses. In many instances the identified criterion have been found to overlap either with similar criterion identified in previous bioenergy literature or in existing literature on supplier selection where such issues are well studied.

Table 5.5 shows which stakeholders identified different criteria along with any corresponding literature sources from the operations management literature and the bioenergy literature. The last section of the table shows evaluating criteria that are unique to this research and have not been documented previously. Each criterion is described in brief in sections 5.3.3.1 to 5.3.3.3. The second House of Quality (HoQ2) is then constructed in section 1.1.1.1.

Table 5.5: Evaluating criteria and their identifying sources.

	Evaluating criteria	Financial groups and project investors	Environmental Groups	Developers/ operators	National government and policy makers	Local government	Community public	Literature source
Bioenergy literature review	CO_2 (equivalent) emissions per MWh	✓	✓	✓	✓	✓	✓	(Kaya and Kahraman, 2010, Jovanovic et al., 2010, Beck et al., 2008, Terrados et al., 2009, Madlener et al., 2007, Begić and Afgan, 2007, Afgan and Carvalho, 2003, Karagiannidis et al., 2009, Upham and Speakman, 2007, van Dam and Junginger, 2011, Zhou et al., 2007, BTG, 2008)
	Land use change		✓		✓			(BTG, 2008)
	Rural jobs created or safeguarded				✓			(Upham and Speakman, 2007, Elghali et al., 2007, Upham et al., 2007)
	Base cost of material (£/MWh)	✓		✓				(Longden et al., 2007, Karagiannidis et al., 2009, Buchholz et al., 2009, Kaya and Kahraman, 2010)
Operations management literature review (Ho et al	Dependency on imports	✓	✓	✓	✓			(Madlener et al., 2007, Buchholz et al., 2009, van Dam and Junginger, 2011)
	Visibility along supply chain	✓		✓				(Buchholz et al., 2009, van Dam and Junginger, 2011, Madlener et al., 2007)
	Distance from customer	✓						(Braglia and Petroni, 2000, Gencer and Gürpinar, 2007, Hou and Su, 2007, Liu et al., 2000, Ng, 2008, Perçin, 2006, Sarkar and Mohapatra, 2006, Sevkli et al., 2007, Yang and Chen, 2006)
	Ease of communication/ personal relationship			✓				(Chen et al., 2006, Perçin, 2006, Sarkis and Talluri, 2002)
	Track record	✓		✓				(Çebi and Bayraktar, 2003, Chan, 2003, Chen and Huang, 2007, Gencer and Gürpinar, 2007)
	Quality control process and mechanisms in place			✓				(Chan et al., 2007, Choy and Lee, 2002, Gencer and Gürpinar, 2007, Narasimhan et al., 2001, Sarkar and Mohapatra, 2006, Sevkli et al., 2007, Talluri and Narasimhan, 2004)

	Size of balance sheet	✓		✓				(Braglia and Petroni, 2000, Muralidharan et al., 2002, Barla, 2003, Çebi and Bayraktar, 2003, Chan, 2003, Choy and Lee, 2003, Ulukan et al., 2003, Wang et al., 2004, Choy et al., 2005, Liu and Hai, 2005, Wang et al., 2005, Bayazit, 2006, Bevilacqua et al., 2006, Chen et al., 2006, Perçin, 2006, Sarkar and Mohapatra, 2006, Yang and Chen, 2006, Chan et al., 2007, Chen and Huang, 2007, Gencer and Gürpinar, 2007, Huang and Keskar, 2007, Wu et al., 2007, Bottani and Rizzi, 2008)
	Financially robust and credible counterparty	✓		✓				
Criteria from interviews	Performance against EU sustainability assurance standards		✓	✓				
	Long term contract available	✓		✓				
	Take or Pay clause conditions	✓	✓	✓				
	Traceable (Chain of custody)	✓		✓				
	Public Finance Initiative (PFI) backing	✓						
	Fixed price (or known escalator)	✓		✓				
	Clear definition of material		✓				✓	
	Guarantee of fuel quality available			✓				
	Supplier stability within bioenergy market	✓		✓				

	FSC accreditation		✓	✓	✓			
	Alternative end use (Best use of biomass)		✓					
	Diversion of material from landfill		✓		✓			
	Environmental regulatory environment within which the supplier operates	✓	✓	✓				
	Biodiversity change				✓	✓		
	Small and medium enterprise (SME) Employment created				✓	✓		

5.3.3.1 Evaluating criteria from bioenergy literature

CO_2 (equivalent) emissions per MWh

The only criterion identified by members of all stakeholder groups as being important in the supplier selection process. Also popular in the academic literature the CO_2(e) (equivalent) emissions per MWh (a unit of energy) generated refers to the recognised methodology for measuring greenhouse gas (GHG) emissions released due to the activity of the supplier. For applications in supplier selection this refers to all upstream operations such as GHG emissions from transporting the material, pre-processing material and storage or decomposition of the biomass. Emissions per MWh is specified as a requirement (BTG, 2008) that suppliers should be able to provide, by referencing to the energy content comparability is ensured (rather than CO_2(e)/tonne).

Concerns were raised by developers and financiers that the mere existence of a threshold value for CO_2(e)/MWh introduced some uncertainty for buyers. The EU or UK government could tighten legislation at any point and exclude material that has been contracted for under the previous legislation, no provision for grandfathering policy decisions made in previous climates is made in the existing legislation. "There is some regulatory risk… regarding sustainability standards." [A2].

Land use change

As well as measuring the direct GHG emissions from producing and delivering the biomass fuel the EU also requires that for biomass to be described as 'sustainable' it should have a low indirect land use change impact. This means that no 'carbon sinks' should be destroyed in order to grow bioenergy crops.

The EU sustainability standards for solid biomass specify emission levels that are required for fuels to be described as biomass. The threshold for sustainable biomass is currently set as at least 35% less CO_2(e)/MWh than the average EU fossil energy mix. This threshold will rise to 50% in 2017 and 60% in 2018.

Rural jobs created of safeguarded

Employment created in rural economies features in various government documents on biomass and biomass strategy as well as in environmental NGO reports. Scottish Natural Heritage (SNH) recognised that “the bioenergy industry provides opportunities for enhanced rural employment…” (SNH, 2009). The bioenergy strategy (DECC, 2012i) contained evidence from a report by NNFCC estimating that 2020 employment from the UK feedstock supply could employ between 4,900 and 7,000 people in 2020 (McDermott, 2012).

The UN has also investigated bioenergy with regards to the employment but has looked at potential in developing countries. A food security report (FAO, 2012) for the UN reported that “the bioenergy sector can create a new market for producers and offer new forms of employment” however it also pointed out that the type of employment and any performance towards development goals depended on the structure of the operation. Concerns over labour conditions and health and safety issues have lead the UK to create the Bioenergy and food security criteria and indicators project (BEFSCI) which has good practice guidelines for the sector when engaging with international suppliers (BEFSCI, 2012). A separate UN department on climate change mitigation has also published reports mentioning rural job creation and job creation in general (UNEP, 2012).

Base cost of material (£/MWh)

Clearly price is a very important element when arranging an exchange of any type. Developers and finance groups had a fairly flexible approach to the costs of materials in general describing cost as “Important” but also describing an operating window of fuel value. “As long as the project remains viable overall we can take some material that looks expensive” [C5]. The measurement used by the power sector for price of material (feedstock) is cost per MWh, this shows how much the buyer is spending to purchase a unit of energy. The timber industry however deals in cost per tonne of material whilst the logistics industry may also deal in cost per unit volume of material.

The term base cost is used here as a way to catch all cost relevant factors that may be offered by a supplier. In a contract situation the supplier may offer a fixed price for a short term followed by a fixed future price, or a price escalator may be written into the contract. Interestingly interviewees appeared sceptical regarding such mechanisms highlighting drawbacks regarding "long term contract escalators are always a model of the future in some respect, it's difficult for a supplier to agree to limiting the price… for biomass" [A2] and about what the escalator could be based on; "should the contract link [the] price of biomass to interest rates or retail price index?" [A3]. Instead of escalators developers described processes for "renegotiating the price each year" [C2] and "locking price for a short period for certain finance providers, then renegotiating later" [C5]. This last comment by [C5] shows how developers treat different investment types as discrete within the project finance structure, some investors may demand that the price is fixed for the debt term, others may be more flexible and the developers are aware that the feedstock contract should mirror these requirements.

5.3.3.2 Evaluating criteria from operations management literature

Dependency on imports

Dependency on imports was highlighted by 4 of the 6 stakeholder groups interviewed. Generally buyers expressed a wish to contract with domestic material as supported by national government policy. Domestic suppliers were perceived as less risky with regards to project acceptance. The issue for buyers was not necessarily that the material came from overseas but rather that the buyer had no control over where the material would be sourced from. Suppliers who had a domestic base but in reality aggregated imported material were regarded with caution.

Visibility up supply chain

This criterion relates to the number of tiers of the supply chain that the buyer has knowledge of. In traditional supply chains this is an important issue with regards to quality and reliability. In bioenergy supply chains this is described in similar terms to the tractability of the material. The difference is that for chain of custody a buyer may accept that the material has come from a particular source by trusting the labelling or certification scheme. For materials where no such scheme is available the buyer will wish to understand as much of the upstream supply chain as possible. "Making projects work is easier if the material is locally sourced" [A2], "There are other hidden costs such as transport that we may wish to consider, we need to know where the stuff is coming from to make a judgement on how exposed we are." [C2]. One respondent also mentioned that they would "look for tier 2 contracts" to reassure themselves of the reliability of upstream operations

Distance from customer

In this context distance means physical distance. This was only mentioned by investors and finance groups who mentioned that there was a "country risk associated with bringing material in from overseas" [A3] as is described in the literature (Braglia and Petroni, 2000, Gencer and Gürpinar, 2007). Concern was expressed particularly over how wise it was to bring waste material over long distances and between regulatory boundaries "C&I [Commercial and Industrial] waste arisings in a locality could be OK, we would prefer it if anything from outside [the region] were contracted through a large waste management company" [A4]

Ease of communication/ personal relationship

This criterion has been widely reported in the operations research literature and relates to the personal interactions between staff of the different companies. This has been a difficult area for analytical methods to handle, hence the development of multi-criteria and fuzzy, grey or linguistic based decision support systems (Power, 2003). Only developers/operators mentioned this criterion but it was mentioned in several of the interviews. “You need to meet the people. How up for this are they?” [C2], “Those that know their eggs and understand what we require and why we require it are more suitable” [C1].

Track record

As could be expected the track record of a supplier featured in interview data from financiers and developers/operators. Those that mentioned this criterion did caveat their comments by explaining that they understood the bioenergy market was suitable for newcomers.

Quality control process and mechanisms in place

This criterion is important to those parties that will actually be engaging in the supplier-buyer relationship. Operators wanted to see evidence that the supplier had put in place adequate controls for testing its own products and minimising failure rates. None of the interviewees provided specific examples of this but several indicated they would visit individual suppliers to assess operations before any agreement was reached and as part of an ongoing audit process. This is in line with descriptions from Narasimhan et al. (2001) and the assessment of quality systems as in Sevkli et al. (2007).

Size of balance sheet

The financial position of the supplier was frequently mentioned by developers and finance groups but less often by operators who had already passed through financial close. This is due to the contract based relationships that proposed projects use to reduce risk and therefore the price of debt finance. This requirement is expressed by developers because it is passed to them by investors. “Eventually the bank will ask the question, can we recover our losses from that supplier in the case of failure?” [A4]. Balance sheet is only one method for describing the financial position of a company but it was mentioned explicitly as a measurement device separately from the general financial credibility of a supplier.

Financially robust and credible counterparty

This criterion is mentioned frequently in the operations management literature. Where balance sheet reflects the financial position of a company as described by Braglia and Petroni (2000), (Choy and Lee, 2002) and Muralidharan et al. (2002) being financially robust and credible (or creditworthy) describes a collection of financial management, capability, revenue streams. Neither previous authors nor interviewees have been able to explicitly state a methodology for assessing this type of financial performance.

5.3.3.3 Evaluating criteria from interviews

Sustainability assurance scheme

The EU sustainability assurance scheme is made of two main parts, greenhouse gas emissions to atmosphere and land use change. Land use change refers to the extent to which deciding to use a supplier would lead to the conversion of land from one purpose or state to that required to provide biomass for energy. This is intended as a mechanism to address issues around reducing natural forestry, existing farmland and other valuable natural resources. Land use change can also lead to direct and indirect CO_2 emissions which form the other major indicator of the EU sustainability assurance certificate. As a certificate biomass material is either accredited as qualifying for the sustainability assurance scheme or not. However due to comments in recent UK legislation regarding the tightening of the standard buyers look for supplies which can exceed the minimum requirements for certification.

Long term contracts available

The criteria 'Long term contracts available' relates to the length of contract that the supplier is willing to offer, this is important when developers aim to attract project finance from investors as many investors will be unwilling to lend money beyond the length of the fuel supply contract. This criterion arose in every interview with both finance groups and developers. Fixed price terms were also commonly mentioned by these groups. Different developers had slightly different attitudes to price although all felt it was an important criterion along with the 'base cost of material (£/MWh)' criterion. The discussions are well summarized by one participant who stated "As long as the price is acceptable, and we know what it is into the future, that's OK" indicating that fuel price is viewed as a constraint more than as a variable that should be minimised. This perhaps supports the idea that bioenergy is purchased with a relationship view in the mind of the purchaser rather than a more resource based view where we would expect to see transaction cost thinking more dominant.

Take or pay clauses

Take or pay clauses refer to the specific contract conditions being offered in the case that the buyer is unable to accept material from the supplier in the contract. The terms in these clauses tend to broadly reflect the flexibility of the supplier to supply other customers or to reduce supply. As with quality guarantees these terms can be directly compared between suppliers.

Traceable (Chain of custody)

The buyer may desire that the material being purchased is traceable and a chain of custody (CoC) can be demonstrated. This simply means evidence showing where the material has come from and who has handled it between the origin and destination. This is an important concept when calculating the carbon footprint of the material and also for the Forestry Stewardship Council (FSC) accreditation. FSC accreditation is awarded to forests which are “managed in an environmentally appropriate, socially beneficial and economically viable manner” (FSC, 2012), this is audited and managed by the forestry stewardship council.

<u>Public finance initiative (PFI) backing</u>

Public finance initiatives (PFI’s) were seen as some participants as a good route for projects to attract project finance. Using supplies and suppliers backed by government or municipal bodies of some kind were mentioned as being more reliable and secure, removing the usual corporate risk associated with contracting with private suppliers. This is loosely related to the ‘supplier stability within bioenergy market’ criterion which relates to the perceived likelihood that a supplier will remove themselves from the bioenergy supply market and turn towards other ventures. This appeared as a particular concern when contracting with farmers who can switch away from energy crops without significant investment should the economic conditions favour such a switch.

<u>Clear definition of material</u>

Often in the development of a bioenergy scheme the fuel material will be described as “biomass” in any proposal documents or planning drafts. This can cover a very wide variety of materials, not all of which will be agreeable to all stakeholders and not all of which are necessarily sustainable. The criteria ‘clear definition of’ refers to the ability of a supplier to properly describe the materials that will be received during the course of the delivery contract.

Diversion of material from landfill

Waste materials destined for landfills could make attractive fuels for bioenergy projects, diversion of materials from landfills is a target for local government and environmental groups, this criterion should be considered as similar to the alternative end use (best use of biomass) criterion. Regarding this the interviewed environmental groups stated that only material which cannot be used for any better application than energy recovery should be used. If there is a possibility to use the material more efficiently, at lower environmental cost then that option should be taken over energy recovery. This follows the principles of the waste hierarchy of first to prevent, reduce, re-use, recycle, recover, and finally dispose.

Environmental regulatory environment

The criterion 'environmental regulatory environment within which the supplier operates' is one of the more subjective of the qualitative criteria identified and refers to both the strength and stability of the national and local regulations governing the activities of the supplier. This is important for biomass sources to avoid exploitation of natural and virgin forest, exploitation of local people and over exploitation of natural resources such as water. Across the board of participants consistency in regulations was considered important and some purchasers would avoid suppliers from countries with poor or weakly regulated and poorly enforced environmental regulations.

Biodiversity change

Biodiversity change is linked to land use change. Some impacts of using crops differently, harvesting differently or not recycling material could have potential impacts on the level of biodiversity in the area where material is supplied from (positive or negative). There are formal methods for the measurement of biodiversity (Magurran, 2004) although in many practical applications the assessment would need to be made subjectively.

Small and medium enterprise (SME) employment created

SME employment created relates to the wider socio-economic impacts of contracting with a supplier. In some government documents this type of job creation is also referred to as safeguarding of employment. Small and medium enterprises for the EU are defined in the EU SME user guide (EC, 2003).

5.3.4 Case example of QFD-AHP process

This section shows an example based on the experiences of Express Energy and the opinions of interviewees and workshop participants. The example moves through the first two houses of quality and gives a resulting importance weighting to each evaluating criteria.

The weightings shown in the case study used below are taken from a particular mix of researchers and practitioners. It may be that by using different participants a different relationship weighting would be obtained. Participants have been chosen for their general expertise and interest in bioenergy projects however and they have been asked to consider a general bioenergy supplier rather than a specific case. Therefore although the relationship weightings cannot be strictly generalised to all bioenergy projects the intention is to find a set of results that will be typical rather than exceptional for future bioenergy projects. As the BioSS is deployed and more information is gathered by developers on these relationship weightings a more robust picture could be constructed, over time this may give developers sufficient confidence to use a weightings set as a constant reference. The constant changes in policy and opinion however mean that this may be unrealistic for most developers. The evaluating criteria and requirements however should not vary significantly between projects of the same type. It is possible that importance may drop to zero for certain relationships or importance scores in some instances.

1.1.1.1 Constructing HoQ1

Before House of Quality 1 can be completed an importance rating must be given to each stakeholder group. This has been done by Express Energy Ltd in this case as they are the ultimate decision maker when selecting a supplier.

The results for this process are shown in Table 5.6 and the normalised table with stakeholder importance ratings shown in Table 5.7. The stakeholder importance score is used to calculate the requirement importance shown in Table 5.8. The consistency ratio is calculated for each pairwise comparison and shown in the top left cell of each normalised data table. The workings are shown for the first comparison only.

Table 5.6: Original stakeholder importance matrix

	Financial groups and project partners/investors	Environmental groups	Developers/ Operators	National government and policy makers	Local government	Community/public
Financial groups and project partners/investors	1	5	3	6	4	7
Environmental groups	0.2	1	0.333	3	0.333	5
Developers/Operators	0.333	3	1	3	4	7
National government and policy makers	0.167	0.167	0.333	1	0.25	2
Local government	0.25	3	0.25	4	1	5
Community/public	0.143	0.2	0.142	0.5	0.2	1

Table 5.7: Normalized stakeholder importance matrix with importance score calculated

Stakeholder importance pairwise [CR=0.078]	Financial groups and project partners/investors	Environmental groups	Developers/ Operators	National government and policy makers	Local government	Community/public	Stakeholder importance score
Financial groups and project partners/investors	0.478	0.404	0.593	0.343	0.409	0.259	0.414
Environmental groups	0.096	0.081	0.066	0.171	0.034	0.185	0.105
Developers/Operators	0.159	0.243	0.198	0.171	0.409	0.259	0.240
National government and policy makers	0.080	0.013	0.066	0.057	0.026	0.074	0.053
Local government	0.119	0.243	0.049	0.229	0.102	0.185	0.155
Community/public	0.068	0.016	0.028	0.029	0.020	0.037	0.033

The consistency ratio is computed as follows

$$C = \begin{bmatrix} 6.823 \\ 6.098 \\ 7.098 \\ 6.158 \\ 6.539 \\ 6.187 \end{bmatrix}$$

$$\lambda_{\max} = \frac{6.824 + 6.098 + 7.098 + 6.158 + 6.539 + 6.187}{6} = 6.484$$

$$CI = \frac{6.484 - 6}{6 - 1} = 0.097$$

$$CR = \frac{0.0097}{1.24} = 0.078$$

As the consistency ratio (CR) is below 0.1 the response can be said to be consistent according to Saaty (1980). This is also the case for the relationship matrices calculated in section 1.1.1.1.

For each stakeholder a pairwise comparison is created that aims to discover which of the requirements made by that stakeholder are most important. During the interviews there was overlap and confusion between requirements and evaluating criteria. Therefore only some of the interviews provided helpful data to complete HoQ1. In other cases an average response has been taken and rounded to provide a consistent response, this was the case for financial groups and for developers. The ranking order given by each interviewee was the same in all but two cases and the responses therefore did not require extensive pre-analysis.

Table 5.19 to Table 5.26 show the normalised pairwise comparisons and importance scores given to each requirement by financial groups, developers and operators, national government and local government stakeholders. The other stakeholder groups expressed only one requirement and therefore have an importance score of 1.

HoQ1 is shown in Table 5.8 with the calculated requirement importance score and importance ranking. The environmental impact of the supplied material is the most important requirement closely followed by financial credibility. National energy security is the least important requirement, recognised as it is by only one stakeholder group with a low importance score.

Table 5.8: House of Quality 1. Requirements and stakeholders with calculation of requirement importance.

Requirements / Stakeholder Groups	Stakeholder importance	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved
Financial groups and project partners/investors	0.414	0.350	0.146	0.071		0.433		
Environmental groups	0.105				1.000			
Developers/Operators	0.240	0.223	0.476	0.157	0.045	0.100		
National government and policy makers	0.053				0.551	0.051	0.270	0.131
Local government	0.155				0.200		0.800	
Community/public	0.033				1.000			
Requirement importance		**0.198**	**0.175**	**0.067**	**0.209**	**0.206**	**0.138**	**0.007**
Rank		**3**	**4**	**6**	**1**	**2**	**5**	**7**

5.3.4.1 Constructing HoQ2

Table 5.9 shows where evaluating criteria are relevant to each requirement; these are the evaluating criteria which will have non-zero values in House of Quality 2.

Table 5.9: Requirements and corresponding evaluating criteria

Requirement	Relevant Evaluating Criteria
A good supplier should be able to offer an attractive business to business contract relations	Long term contracts; take or pay clauses; track record; personal relationship/ease of communication
A good supplier should be able to provide good contract conditions regarding the supply of fuel	Contract has PFI back up; fixed price; base cost of material (£/MWh); clear definition of fuel; guarantee of fuel quality available
A good supplier should be able to provide material reliably and within the quality specification required	Traceable (chain of custody); visibility; quality control mechanisms in place; guarantee of fuel quality available; supplier stability (in biomass market); dependency on imports
The supply of materials should have a low environmental impact	CO_2/MWh; land use change; FSC accreditation; diversion of material from landfill; environmental regulatory environment in which the supplier operates; performance against sustainability assurance certificate indicators; biodiversity change
A good supplier should be financially credible	Credit strength; size of balance sheet; financially robust or credible counterparty;
The supply of materials should have a positive social impact	Rural jobs created or safeguarded; SME employment created
National energy security should be improved	Long term contracts; visibility; distance from buyer; dependency on imports

Having identified the criteria perceived to be important by the various stakeholder groups three workshops were help to identify areas in the interrelationship matrix that are non-zeros. The workshops were held with experts from the operations research field, experts from the bioenergy field and staff from Express Energy ltd. The weighting in the interrelationship matrix for HoQ2 represents the strength of the relationship between evaluating criteria and requirements. The stronger the relationship the more a supplier performing well against a particular evaluating criteria satisfies the requirements of our stakeholder group.

Details of the matrix used to compute relationship weightings for HoQ 2 (the weightings of evaluating criteria against relationship in Table 5.9) are shown in Appendix C. The relationship matrix for financial credibility is shown in Table 5.10 along its normalised equivalent in Table 5.11.

Table 5.10: Initial pairwise comparison for financial credibility requirement

A good supplier should financial credibility	Credit strength	Size of balance sheet	Financially robust or credible counterparty
Credit strength	1	3	0.2
Size of balance sheet	0.334	1	0.143
Financially robust or credible counterparty	5	7	1

Table 5.11: Normalized pairwise comparison for financial credibility requirement

Normalized comparison for financial credibility	Credit strength	Size of balance sheet	Financially robust or credible counterparty	Weighting score
Credit strength	0.158	0.273	0.149	0.193
Size of balance sheet	0.053	0.091	0.106	0.083
Financially robust or credible counterparty	0.789	0.636	0.745	0.724

The importance score of each evaluating criteria can now be computed using Equation 5.8 as in HoQ1. The complete HoQ2 is shown in Table 5.12. The individual interrelationship AHP matrices are shown Table C.12 to Table C.25 in Appendix C. The 5 highest and lowest ranked evaluating criteria are shown in Table 5.13.

Table 5.12: House of Quality 2

Stakeholder requirements	Importance rating	1. Long Term Contracts	2. Take or pay Clauses	3. Track record	4. Personal relationship	5. Contract has PFI back up	6. Fixed price	7. Traceable (chain of custody)
1. A good supplier should be able to offer an attractive b2b contract	0.198	0.112	0.271	0.554	0.063			
2. A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.175					0.075	0.327	
3. A good supplier should be able to provide material reliably and within the quality specification required	0.067							0.252
4. The supply of materials should have a low environmental impact	0.209							
5. A good supplier should be financially credible	0.206							
6. The supply of materials should have a positive social impact	0.138							
7.National energy security should be improved	0.007	0.056						
Importance Rating		0.023	0.054	0.110	0.013	0.013	0.057	0.017
Rank		13	7	2	20	19	6	16

Stakeholder requirements	Importance rating	8. Base cost of material (£/MWh)	9. Clear definition of fuel	10. Visibility	11. Quality control mechanisms in place	12. Guarantee of fuel quality available	13. Supplier stability (in biomass market)	14. Distance from buyer
1. A good supplier should be able to offer an attractive b2b contract	0.198							
2. A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.175	0.392	0.056			0.150		
3. A good supplier should be able to provide material reliably and within the quality specification required	0.067			0.167	0.051	0.397	0.090	
4. The supply of materials should have a low environmental impact	0.209							
5. A good supplier should be financially credible	0.206							
6. The supply of materials should have a positive social impact	0.138							
7.National energy security should be improved	0.007			0.295				0.110
Importance Rating		**0.068**	**0.010**	**0.013**	**0.003**	**0.053**	**0.006**	**0.001**
Rank		**5**	**22**	**18**	**27**	**8**	**25**	**28**

Stakeholder requirements	Importance rating	15. CO2/MWh	16. Land Use change	17. FSC accreditation	18. Alternative end use (Best use of biomass)	19. Diversion of material from landfill	20. Environmental regulatory environment in which the supplier operates	21. Performance against sustainability assurance certificate indicators
1. A good supplier should be able to offer an attractive b2b contract	0.198							
2. A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.175							
3. A good supplier should be able to provide material reliably and within the quality specification required	0.067							
4. The supply of materials should have a low environmental impact	0.209	0.372	0.156	0.055	0.094	0.196	0.032	0.069
5. A good supplier should be financially credible	0.206							
6. The supply of materials should have a positive social impact	0.138							
7.National energy security should be improved	0.007							
Importance Rating		**0.078**	**0.033**	**0.012**	**0.020**	**0.041**	**0.007**	**0.014**
Rank		**4**	**12**	**21**	**14**	**10**	**23**	**17**

Stakeholder requirements	Importance rating	22. Credit strength	23. Size of balance sheet	14. Financially robust or credible counterparty	25. Rural jobs created or safeguarded	26. Dependency on imports	27. SME employment created	28. Biodiversity change
1. A good supplier should be able to offer an attractive b2b contract	0.198							
2. A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.175							
3. A good supplier should be able to provide material reliably and within the quality specification required	0.067					0.042		
4. The supply of materials should have a low environmental impact	0.209							0.025
5. A good supplier should be financially credible	0.206	0.193	0.083	0.724				
6. The supply of materials should have a positive social impact	0.138				0.667		0.333	
7.National energy security should be improved	0.007					0.539		
Importance Rating		**0.040**	**0.017**	**0.149**	**0.092**	**0.007**	**0.046**	**0.005**
Rank		**11**	**15**	**1**	**3**	**24**	**9**	**26**

Table 5.13: Highest and lowest 5 evaluating criteria

Top 5 evaluating criteria	Importance score	Lowest 5 evaluating criteria	Importance score
Financially robust or credible counterparty	0.149	Dependency on imports	0.007
Track record	0.110	Supplier stability (in biomass market)	0.006
Rural jobs created or safeguarded	0.092	Biodiversity change	0.005
CO_2/MWh	0.078	Quality control mechanisms in place	0.003
Base cost of material (£/MWh)	0.068	Distance from buyer	0.001

5.4 Observations and discussion

From Table 5.5, the stakeholder groups of “Finance groups” and “Developers/Operators” had similarly aligned interests, both requiring favourable contractual conditions, quality and financial credibility. This shows that operators and developers have aligned their interests with the finance sector as they seek to attract investment. This was mentioned by one participant from the finance stakeholder group “Anyone other than the major utilities has to project finance. Projects are too big for most companies to do on balance sheet” [A1]. Even if a project were to be entirely equity funded by some large utility it is likely that similar requirements would be made on suppliers. These contracts and the conditions within them appear critical to the successful operation and development of bioenergy schemes. They are at the centre of a finance deal between investors and developers, without suitable suppliers in place it is unlikely that affordable investment will be forthcoming. However, a conflict then can appear as suppliers are unwilling to fix themselves into contracts for long periods when as one participant from the finance stakeholder group stated: “Everybody thinks this is going to take off, so why would you want to lock in for 15 years if it turns out you’re locked in at the wrong price?” [A2].

The insistence of financial stability, credibility, track record and fixed prices is likely to lead to the exclusion of major parts of the biomass supply market. By requiring well established blue collar type businesses smaller, less affluent suppliers are disadvantaged. These smaller suppliers may be able to provide many of the other attributes required and would be attractive were the finance related requirements not being made, they may also hold a majority of the available regional and domestic biomass resource. When reflecting on this one developer mentioned that “there is really quite a small group of very large global suppliers that are properly suitable against these criteria, in reality we need to do business with smaller companies” [C3]. Whilst this is true of waste materials which may be largely controlled by the animal feed industries forestry is slightly different as one participant from the finance stakeholder group pointed out “US forestry ownership is dominated by pension funds and large scale investors so balance sheet strength is pretty good there.” [A4]

Energy security is shown as a fringe requirement in this process, only mentioned by central government reports. In reality this issue is seen as important by developers and operators, however this group is more likely to protect themselves from material supply failure using commercial contracts than changing the source location of materials, the definition of a secure supply is different due to the different perspectives of these stakeholders. There is a heavy reliance on the nature and favourability of contracts between buyers and suppliers in the bioenergy industry, this is evident from the results and from qualitative data from the interviews.

Five of the six stakeholder groups identified environmental impact as an important requirement. Environmental related evaluating criteria feature heavily in the supplier selection lists. The most commonly referenced criterion is the CO_2 emissions per MWh of energy being delivered. This criterion, along with land use change, forms the EU sustainability standard against which biomass suppliers can be measured and found to be compliant or otherwise. ‘Performance against EU sustainability standard’ is included as a separate criterion as it appeared as such in the interview data. The UK is one of the only countries in the world to have implemented biomass sustainability requirement legislation. However, this attempt to partly commoditize and set a base-standard for sustainability has eventually resulted in further uncertainty for the market due a recent UK report which suggested that the standards for sustainability regarding solid biomass should be “tightened” (CCC, 2011). Therefore, developers are seeking “Standards that go beyond the sustainability standard” [C2] for any material that may be contracted for.

Distance from buyer was found to be of very low importance. This reflects the global nature of sourcing biomass for the UK market. Many of the recent waves of proposed UK biomass power stations are located at deep water ports to keep options for importing materials open to those operators. The nature of the business and the scale of on-site storage also mean that distance from supplier to buyer is of less importance as delays can well be tolerated. This is mirrored in the fossil fuel industries where fuels are purchased from around the world on various exchange platforms. From interview data with material buyers of both biomass and fossil fuels, it appears that fossil fuel suppliers are not subject to any of the requirements regarding environmental sustainability, social impact and are also largely not required to have particularly secure financial backgrounds. This may reflect the uncertainty associated with operating in a non-commodity dominated market.

5.5 Conclusion

The QFD-AHP method is rigorous and robust, it is able to produce outputs that are intuitive for the user as a result of the built in checks for consistency. In the case presented the process is completed for the case of Express Energy examining a typical or general project. In practice developers may change weightings of stakeholder importance depending on the nature of a specific project. For the case presented in this chapter the entire QFD-AHP for supplier selection is not fully implemented, to do so would require extensive information on each potential supplier to the project. This information is either unavailable or is commercially sensitive for Express Energy Ltd or the supplier. Because the bioenergy industry is in a continuing to develop at the time of writing much of the supplier performance against evaluating criteria may not be available to the buyer and they therefore must make some subjective assessment of supplier performance. If this judgement is not done correctly the final decision made could turn out to be poor, undermining the advantage of using an analytical approach in the first place.

The approach of combining interview data with a literature review as back-up was suitable for identifying stakeholders, requirements and evaluating criteria. Requirements and evaluating criteria were found to be frequently confused with one another by both interviewees and in the literature. Several of the interviewees were more comfortable with the phrase ‘sub-requirement’ in place of evaluating criteria. The semi-structured interview approach was suitable and allowed interviewees the freedom to talk about the aspects they thought were most important and to fully explain and think about their responses. Most of the evaluating criteria identified were supported by evidence from the literature, those that are supported could be considered as more reliable for the decision process whilst those that are not may be unique to the bioenergy industry.

Chapter 6. Order Allocation

6.1 Introduction

This chapter discusses the order allocation module within the BioSS framework. The order allocation consists of a mathematical model that is used to produce a recommendation regarding which suppliers of biomass materials should be contracted with and how much material should be taken from each. This chapter is divided into an introduction section where the order allocation problem and the blending or mixing problem are introduced in section 6.1.1 and section 6.1.2 respectively along with relevant previous literature. Section 6.1.3 discusses these problems as encountered by the biomass buyer. In section 6.2 the method that has been used to address this problem is described including the model formulation in section 6.2.1 and how the performance of the recommended blend is measured using a Monte-Carlo analysis in section 6.2.2, section 6.2.3 shows screenshots of the model's different parts and describes the user interface flow. The module is applied to all three of the BioSS stages and each application is shown in section 6.3 along with a comparison against a less sophisticated approach. Section 6.4 has a discussion of the results and efficacy of the method used. Finally the chapter is concluded in section 6.5.

The aim of the optimisation module within BioSS is to allow the decision maker to efficiently model and process the complex information that must be accounted for in the strategic sourcing decision for biomass. The model allows for the rapid redesign and prototyping of supply chains against different technology options, allowing the decision maker to make more effective choices about which types of suppliers to pursue for contracts and how new suppliers may influence the performance of the final fuel blend.

6.1.1 The order allocation problem

Order allocation is a term used to describe any process of determining how orders should be awarded or distributed between the set of available suppliers (Aissaoui et al., 2007). In the original model of the problem all suppliers within the set supply identical goods of identical quality with an identical level of service and therefore suppliers only compete on price. The decision maker must allocate sufficient orders to meet the demand whilst minimising the total cost. Solving the order allocation problem is fairly straightforward in this formulation and is helpful when the cheapest supplier cannot fulfil the entire demand of the buyer. The real power of solving the order allocation problem becomes evident as more complex information on each supplier is and variation exists between suppliers and when more complex requirements are made. Aspects such as delivery time, communication, reliability, flexibility and returns policy amongst others are conventional service related considerations when selecting suppliers, indeed in reality price is never the sole consideration in a purchasing decision, especially for strategically important items (Talluri and Sarkis, 2002, Ho et al., 2010). In situations where the product or service being ordered is not exactly the same from each supplier quality indicators must also be considered. This results in a complex problem environment where the decision maker must be able to balance the various requirements of quality, service and price, whilst meeting the demand constraint. Usually the supplier performance against each requirement of the buyer is calculated and the buyer aims to find a supply portfolio that meets demand whilst best satisfying the selection criteria (Aissaoui et al., 2007, Sarkis and Talluri, 2002). This type of extension is shown in Figure 6.2. A more expensive final solution may be selected in return for a higher overall performance.

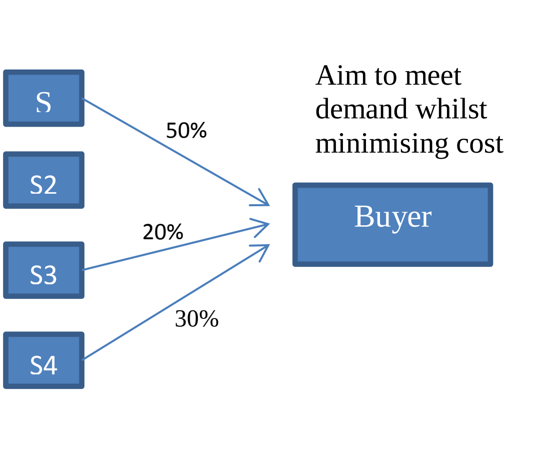


Figure 6.1: Simple order allocation model based on transaction costs only

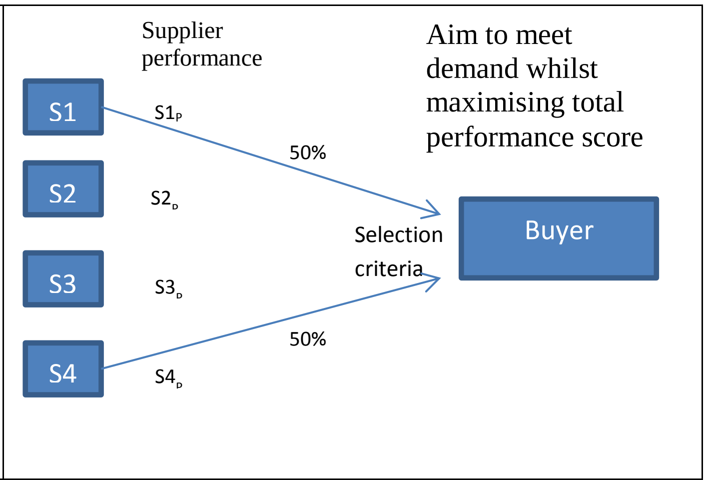


Figure 6.2: Order allocation considering supplier performance. Results in a higher price but better performing supplier portfolio

Other improvements to the model can include minimum order constraints, where only orders over a certain size can be made and discounts are available for orders over a particular threshold. Sensitivities to certain parameters can also be included, exposure to fuel price for instance could be limited or required to be minimised. Some problems also require that some temporal element is included in the model, certain suppliers may only be available at certain times of year for instance, or some orders must be allocated differently over different time periods (Tempelmeier, 2002). Uncertainty methods have also been applied to the order allocation problem where the demand and supply constraints may change in future periods.

According to the review by Aissaoui et al. (2007) the literature on supplier selection (or vendor selection) with order allocation can be split into three main categories: What products to order? How much to order and from who? And in which periods should orders be placed in? These decisions are made against a background structure of the supplier selection decision developed by de Boer et al. (2001) into a framework that moves from definition of the problem through to formulating criteria, measuring supplier performance against those criteria and finally making the final choice. The type of choice being made is also split into four categories in de Boer's framework, new tasks, modified rebuy, straight rebuy (routine) and straight rebuy (strategic). de Boer et al. (2001) also offered an approximate structure showing where different methods are applied to the above decision stages, this is adapted and reproduced in Figure 6.3. Order allocation appears in the final selection stage of this model and according to the reviews by Aissaoui et al. (2007), Ho et al. (2010) and de Boer et al. (2001) the approaches used are always quantitative. The qualitative criteria are incorporated into the order allocation models via the quantification stage where suppliers are rated in some way against the various criteria identified as important for the final allocation choice.

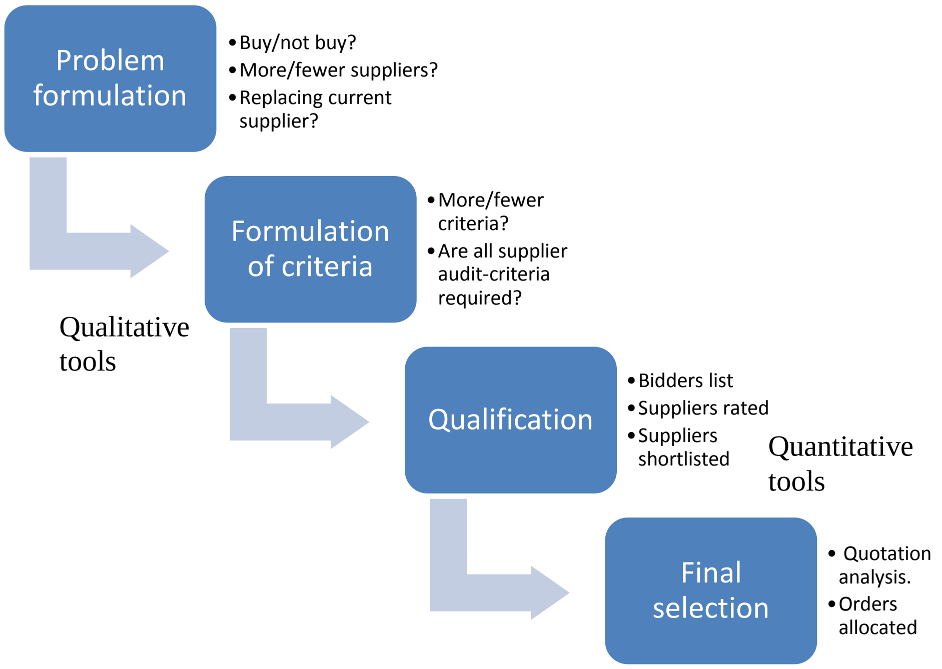


Figure 6.3: Positioning of decision methods against structure of supplier selection (adapted from de Boer et al., 2001)

There are several methods that can be used for both the weighting of criteria importance and the ranking of suppliers. The method(s) selected in these stages therefore affect the outcome of the final selection, regardless of the method used to actually allocate orders. However according to all the review papers mentioned previously it is the final selection phase that attracts most attention from researchers.

The specific methods used in the final selection phase are most generally classified as mathematical programming models, several sub-method classifications are also evident. The oldest and most applied method is the linear weighting method (Timmerman, 1986). This requires that each criterion is given a weighting reflecting its importance to the final decision and decision maker. The supplier that scores highest against the different criteria considering this weighting factor is the most desirable and is selected first. If that supplier cannot meet demand alone the next highest performing supplier is selected for any remaining until demand is satisfied.

Later other authors have adapted the approach to mitigate the impact of some shortcomings the method has under certain circumstances. Improvements to the process of rating and evaluating suppliers with incomplete data available and the correct weighting of criteria have been made. Much of the difficulty of such weightings is to do with the ability of the decision maker to assign an exact point value to the relative weighting and to performance. The analytic hierarchy process (AHP) was proposed by Narasimhan (1983) and later by Barbarosoglu and Yazgaç (1997) and others to address this shortcoming. The AHP allows the decision maker to measure consistency of their own responses and also removes the need for the decision maker to make point value judgements of performance and importance, a verbal scale is used instead. The analytical network process (ANP), an extension of AHP, was developed to accommodate interrelationships between criteria, was also applied to give weightings (Sarkis and Talluri, 2002). As fuzzy set theory was developed these techniques were also applied to the weighting problem. In a fuzzy approach the decision maker is able to use approximate values along with using linguistic responses. For instance in fuzzy methods the weighting can be specified as “approximately 0.4”. The application of fuzzy set theory has been improved by incorporating other methods including AHP (Ulukan et al., 2003, Bevilacqua et al., 2006).

6.1.2 The blending problem

The blend problem, or mixing problem is a well-studied problem within operations research and is a classic example of the application of linear programming methods. The aim is to blend (or mix) various component ingredients to create a product with certain specified characteristics. The problem occurs in many material trading, blending and simple mixing production problems. Commonly studied areas include mixing components for food (Bilgen and Ozkarahan, 2007), animal feed (Babić and Perić, 2011), smelting processes especially iron ore (Zhang et al., 2011, Kumral, 2003), metals (Sakallı et al., 2011) fertilizer, petrol (Singh et al., 2000) and oil. The terminology of mix and blend are often interchanged in the literature, however they should not be confused with the "product mix" problem which is concerned with the combination of products that a manufacturer should produce. The blend problem is concerned with how much of a raw material to purchase.

The classic example of a linear programming blend problem is given in Murty (2008) and Murty and Rao (2004) to blend barrels of different fuel types together to give a required octane rating. The decision maker must decide how many barrels of each constituent fuel type to purchase in order to make a final blend with the required characteristics. There may be limits, costs or constraints associated with the problem in various ways and these are represented by constraints for the linear programming model. For instance a finite amount of each constituent fuel may be available. The objective of the decision maker is also important; in the classic problem formulation the aim is to make a blend with the lowest overall price. With a few simple statements about the problem the linear programming model for any blend problem can be properly formed. In the fuels case, availability of each constituent fuel, octane number of each fuel, required octane number, cost of each constituent fuel and perhaps the total amount of product fuel required. If the demand is essentially infinite the problem can be represented as constituent parts where the decision variables are not "barrels of fuel *i*" but instead "percentage of fuel *i* in blend". The decision variables in this type of problem are synonymous with the allocation of orders for a particular constituent fuel.

Further complications have been included to create more accurate models of the business environment. For the fuel blending problem different values of profit realised for fuels of differing octane levels can be included, this is actually a blend problem combined with a product mix problem, simultaneously solved using linear programming. Discounts may be available for constituent fuel orders over a certain size or multiple discount levels may be offered, a minimum order size may also apply.

As models become more sophisticated their definition as “blend problems” becomes lost, rather the linear programme is designed to solve a specific problem that has specific characteristics of importance (Bantzig, 1998). The main areas of extension, innovation and complexity that have been combined with the blend problem are: the mix problem (as above), differing time horizons (Glismann and Gruhn, 2001), integrating logistics and warehousing functions, soft constraints, and uncertainty. Uncertainty can be either in the quality of the constituent fuels, uncertain requirements for the final blend or both. Uncertainty is usually dealt with using stochastic or probabilistic methods (Sakallı et al., 2011) although fuzzy applications have also been developed (Rong and Lahdelma, 2008). Soft constraints are helpful where constraints are expressed as targets rather than constraints, for instance in situations where a blending process should run alongside shift patterns it may be desirable to cap the daily production to coincide with shift lengths, but there if flexibility that if a greater profit can be generated by running for slightly longer (or shorter) that can be accepted. For this type of target the sub-type of linear programming (LP) called goal programming (GP) was developed. Soft constraints can also be represented as chance constraints where the probability that a constraint will be broken is controlled by the LP. As methods become more popular integration of problems and sophistication of methods is increasing, Li and Chen (2011) for instance proposed a method integrating stochastic methods, fuzzy methods, intervals and linear programming to help reduce costs in a transportation problem for waste management. As this trend continues researchers are able to improve more complex real world blend problems using more sophisticated models.

6.1.3 The biomass buyers problem

The biomass buyer is faced with the challenge of securing a blend of material which will meet the technical requirements defined by the conversion technology, meet the total demand and best satisfy the stakeholder group who hold power over project success. This is an application case of the problems discussed in sections 6.1.1 and 6.1.2. To further complicate the decision a large amount of uncertainty is associated with the chemical characteristics of the fuels being purchased. As discussed in chapter 4 fuel characteristics can change within deliveries, over time and due to external factors such as weather. Part of the aim of BioSS is to open up new sources of biomass as being available for conversion, expanding the utilisation of bioenergy resources. The optimisation module must therefore be able to handle variable characteristics.

Following discussion with operators and developers the technical constraints are usually determined by the technology supplier and are used to define the terms of equipment warranty. The constraints placed on material entering the conversion process are determined by a combination of constraints within the process, including exhaust gas filters and scrubbers, transfer and drying equipment and any thermal or biochemical conversion.

In line with other work on strategic sourcing suppliers of biomass are assessed not just on cost performance but also on the characteristics of the material they supply (quality) and the tacit characteristics according to the extent to which that supply of material satisfies stakeholder requirements including supplier reliability. As identified in the review by Scott et al. (2012) and chapter 2 no previous research exists that takes this approach to the problem faced by biomass buyers. Previous research focusing on deciding which technologies to use and which sources should be used from a logistics or total transport cost perspective.

6.2 Method

This section discusses the method used in BioSS. Firstly linear programming is discussed and then chance constrained programming is discussed before the model formulation is given in section 6.2.1. The model used is described as a stochastic chance-constrained optimisation program and is best categorised broadly as a stochastic optimisation method.

Linear programming is a sub-set or special case of mathematical modelling method. The method gives the best available outcome for a particular mathematical model of the real world. The method only applies if the relationships within the model are linear, if non-linear relationships exist, non-linear programming is more suitable. Linear programming is a powerful tool for decision makers as it allows for rapid assessment of optimal solutions and gives an opportunity for sensitivity analysis and scenario analysis to be carried out on the model of interest. Mathematically linear programs are those that consist of three main attributes:

- There is an objective function. E.g. Maximise: $_{i=1}^{n} \rho_i \cdot x_i$
- There are some set of constraints of the form: Subject to:

  $x_1 \geq 10;$

  $x_2 \leq 30;$
- All decision variables are positive and real numbers. $x_i \geq 0, \ \forall i$

Two key areas of all linear programming problems are the “feasible region” and optimal surface or “pareto surface”. The feasible region describes all possible combinations of decision variables that lead to a solution that does not violate any of the constraints. The pareto surface describes those particular points where a change in any of the decision variables will not give a solution that results in better performance against the objective function, i.e. points on the pareto surface are optimal and described as pareto efficient points (Hosseini et al., 2012, Dantzig, 1998, Bertsimas and Tsitsiklis, 1997). In most linear programing problems only one optimal point will exist but in some cases large numbers of pareto efficient points may exist where the objective function gives the same value, the pareto surface is not necessarily continuous, complex problems may have a landscape of optimal points appearing in different area of the solution space or solution volume (Hosseini et al., 2012).

Linear programming was introduced in Chapter 2 under a discussion about optimisation problems with many alternatives. Simple problems are fairly straightforward to visualise, especially if when only a small number of decision variables and constraints are required. Figure 6.4 shows a simple linear programming problem in graphical form. The green boundary marks the edge of the to the feasible region whilst the blue lines show the constraints: $2x_1 + 3x_2 = 12,\ x_1 + x_2 = 5,\ x_1 = 4.$ The red lines represent the objective function. The problem show is a maximisation problem and the objective function is to maximise $2x_1 + x_2$. The two black points shows where the objective function is greatest. This is the optimal point for this problem and exists at $x_1 = 4, x_2 = 1$. Giving an objective function of 9.Graphically this type of problem can be thought of by imagining the red line (objective function) moving towards higher values until it meets a constraint. To solve a linear programming problem the feasible region must be bounded to prevent the objective function disappearing to infinity.

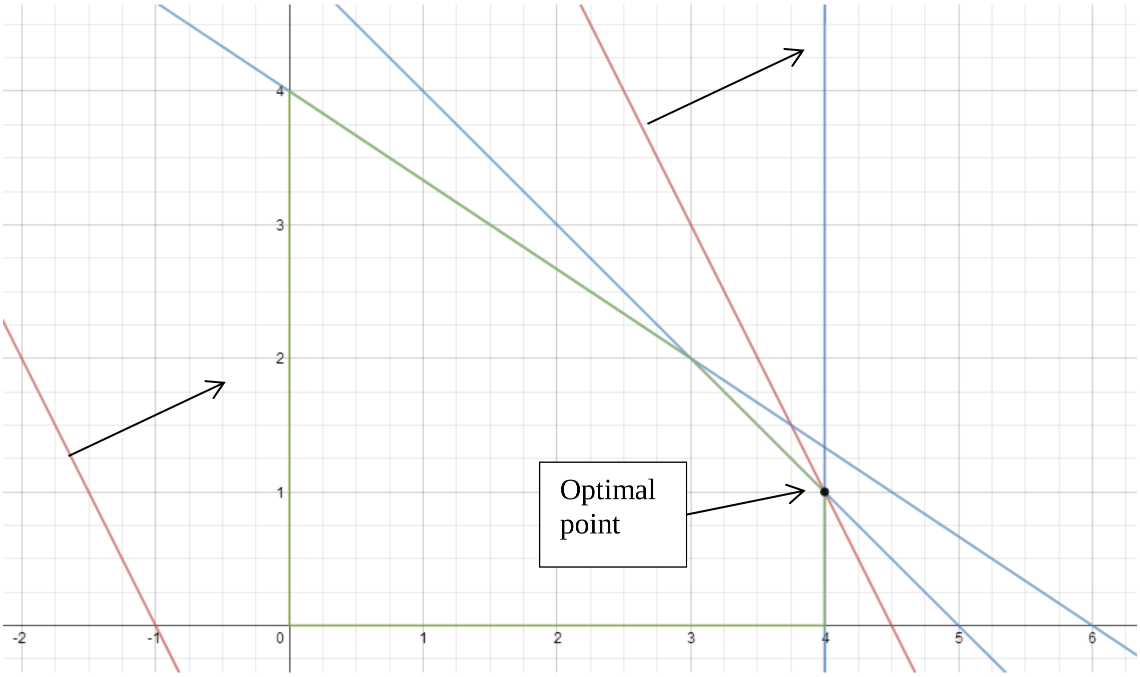


Figure 6.4: Graphical representation of linear programming problem showing 3 constraints (blue) and the objective function (red)

As problems become more complex more than one decision variable and many constraints come into effect. Interactions between constraints and between decision variables can change the shape of the feasible space in unexpected ways. The resulting feasible region (or volume for 2 or more decision variables) can have a complex form. When aiming to locate the optimal combination of decision variables a trade-off usually exists between computational and time efficiency against accuracy. Most optimisation algorithms use some form of improvement technique . For maximisation problems this is described as hill climbing. This type of approach involves picking an arbitrary or given starting combination of decision variables and change each one until a more attractive solution is found, then beginning the process again until no further improvement can be made. In minimisation problems the approach is the same but reversed, the algorithm looking to climb down the hill towards lower values of the objective function (Bantzig, 1998, Hillier and Lieberman, 2002).

In situations with smooth, graduated pareto surfaces this is a suitable and efficient technique, however in some instances this may result in the recommended solution not being the true (or global) optimum. Figure 6.5 shows a solution space with several local peaks in the objective function where a hill climbing algorithm may stop searching, not locating the global optimum solution elsewhere in the solution space (Bertsimas and Tsitsiklis, 1997). There are several techniques to mitigate against this, introducing random variations to the path (random walk or Monte-Carlo methods), introducing many starting locations (multi-start methods) and even searching the entire solution space point by point (global search) although this increases computing time dramatically. Other methods improve efficiency by using a two stage approach, for instance randomly sampling to find the most suitable start points then launching a hill-climbing style algorithm from some set of most favourable sample points (Hillier and Lieberman, 2002). For most linear problems these types of techniques are not required however, problems with very large solution spaces and complex surfaces may benefit and this has been the focus of research. More complex are the group of problems referred to as NP hard, meaning they cannot be solved within polynomial time, in other words as the problem gets more complex the computation time to find the global optimum becomes exponentially larger. To deal with these problems a class of optimisation methods referred to as heuristic optimisation methods has been developed. Methods including simulated annealing, tabu search, ant colony optimisation and genetic algorithms can all obtain a feasible solution that is fairly close to the global optimum within a fraction of the time and computing power.

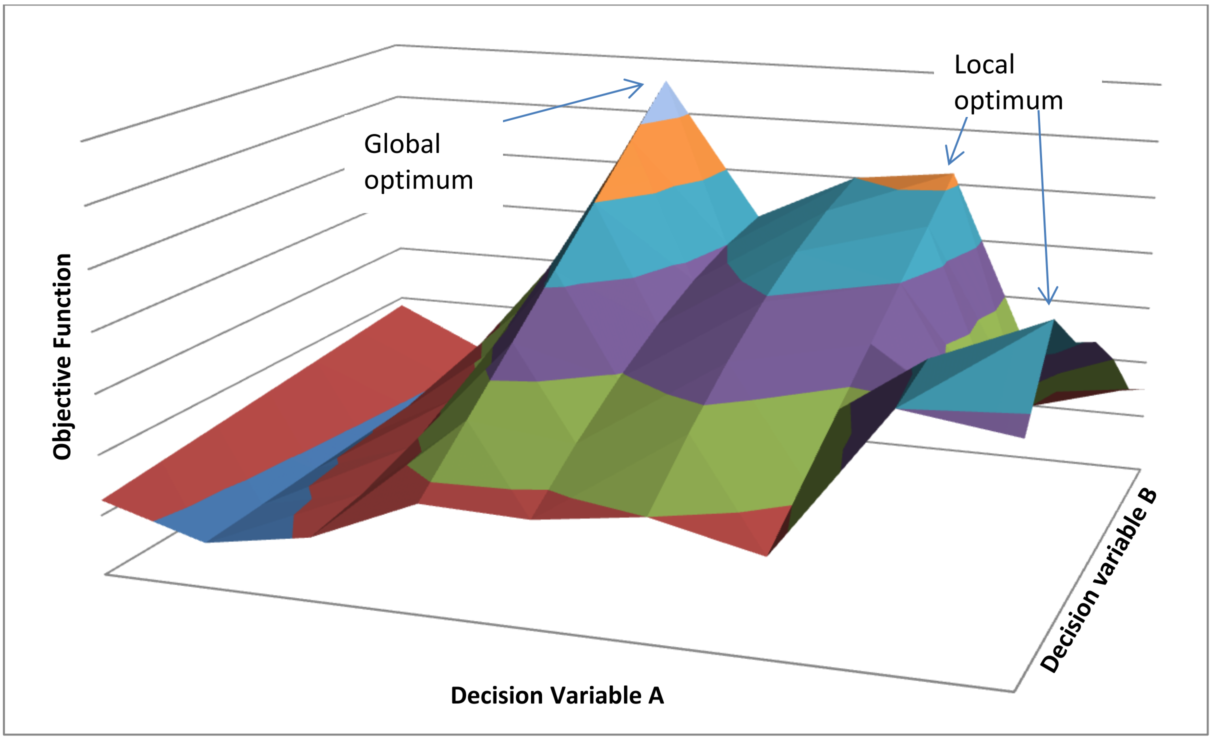


Figure 6.5: A pareto surface showing several local optima points and one global optimum point.

For complex pareto surfaces such as that shown in Figure 6.5 the shape of the surface is determined by a combination of the decision variables, constraints and the objective function. In the problem faced by biomass buyers many decision variables exist; one per supply of material rather than two as shown in Figure 6.5 and the entire solution space cannot therefore be drawn.

Chance constrained programming is a well-established tool for planning under uncertainty; the method involves replacing constraints that have associated uncertainty or uncertain elements with some probability distribution function that models the uncertainty or variation. The resulting probabilistic constraint equalities are then converted to a series of deterministic equivalent linear (or non-linear) problems where each probabilistic variable is generated from the given information on the distribution (Rossi et al., 2006, Birge and Louveaux, 1997). Many deterministic problems are then generated and solved to give a good representation of the situation being modelled. The advantage of this method is that an answer can be reached without extensive computation as would be required for a heuristic or probabilistic method and non-crisp constraints are also allowed (Kall and Stein, 1994). This is important for the biomass buyer's problem because the technology constraints may not always be strictly enforced as discussed in the implementation section in 6.3. The chance-constrained model has some disadvantages associates with accuracy and confidence in results. The method relies on a number of deterministic equivalent models being created to cover a wide enough range of probable inputs that the result is robust. When inputs have large variations the sample size should be increased to allow for the deterministic equivalent models to cover enough of the distribution to give an accurate model. The sample size also relates to the accuracy of compliance with the chance-constraints. To demonstrate this if a very small sample size of, say 10, were chosen, only ten deterministic equivalent models would be created and each stochastic variable in the model would be given 10 different values. These would then be solved to find the optimal solution that allows the chance-constraints to be met. If one of the constraints had a chance-constraint value of 0.9, one of the 10 models would be allowed to exceed this constraint. However if the chance constraint was 0.95 the solution would be sub-optimal as the model must force 10 out of the 10 models to comply with all constraints to ensure the chance constraint of 0.95 (5%) is not exceeded. The sample size is therefore a key variable when running chance-constrained models and should be as large as possible. The larger the sample size however, the longer computation time will be (Birge and Louveaux, 1997). The result of this is that the optimal solution provided by chance-constrained programmes cannot always be guaranteed as the absolute global optimal, there is always a chance that by increasing the sample size a more optimal solution can be found that is still feasible. When the model is run and completed the LINGO command window does display 'global optimal' when it has fully completed the optimisation algorithm, if the algorithm is not completed the window displays 'feasible'. All of the results reported in this thesis are from 'globally optimal' model runs. Although these are global as far as LINGO is concerned, a higher sample size may always result in a higher objective function.

In the bioenergy buyers problem there are some situations where the constraints are fixed and must be strictly adhered to, in the case of other constraints there may exist some room for manoeuvre and the final blended portfolio may be allowed to have properties that could sometimes exceed the constraining limit. For instance the formation of acids from chlorine and sulphur content will be tightly controlled with regards to stack emissions, however the plant equipment may be able to handle slightly more of these chemicals some of the time, incurring an increased maintenance cost whilst remaining within emissions limits. Alternatively the moisture content of material is required to be within certain constraints, too dry and incomplete combustion may occur, too wet and the steam will affect combustion efficiency and contribute to corrosion of the innards of the plant, the limits set by the manufacturer are strictly enforced during the period of warranty, typically two years for large boilers. Following consultation with Express Energy and other developers and technology providers it may be helpful to allow the blend characteristics to 'wander' over the limits occasionally but ensure that usually they are met for the majority of operating time. Setting a cost incurred to each exceedence over the limit is however very difficult without extensive operational data, therefore this will not be included in the model shown in section 6.2.1.

6.2.1 Model formulation

The method used to in the BioSS to allocate orders between potential suppliers uses a linear programming approach with chance-constraints, also known as chance constrained programming. The objective of the biomass buyer is to find a portfolio that best satisfies stakeholder requirements, a satisfaction score is assigned to each supplier. Therefore the objective function is as in (1). Notation is shown in Table 6.1 and the general form of the model is shown below.

Table 6.1: Notation

Indices
i: Supply of biomass material $i = 1, 2, 3, \dots n$
j: Material characteristic $j = 1, 2, 3, \dots m$
Parameters
ω_i: Weighted relative score of supplier against stakeholder requirements
V_i: Unit cost of supply i.
D: Demand
C_i: Capacity of supply i available
$P_{i,j}$: Concentration of characteristic j in material i.
$\underline{L}_j$: The lower constraint for the blend regarding characteristic j.
$\overline{L}_j$: The upper constraint for the blend regarding characteristic j.
$\underline{p}_j$: The user set limit on how frequently the lower limit for characteristic j can be exceeded
$\overline{p}_j$: The user set limit on how frequently the upper limit for characteristic j can be exceeded
Decision variables
x_i: Quantity of orders to be allocated to supplier i.

Objective function:

$$\boldsymbol{max}: \sum_{i=1}^{n} \boldsymbol{\omega_i \cdot x_i} \tag{10}$$

Subject to:

$$\sum_{i=1}^{n} \boldsymbol{x_i \geq D} \tag{11}$$

$$\boldsymbol{x_i \leq C_i} \quad \forall \boldsymbol{i} \tag{12}$$

$$Prob\left(\frac{\sum_{i=1}^{n} x_i \cdot P_{i,j}}{D} \geq \underline{L}_j\right) \leq \underline{\boldsymbol{p}}_{\boldsymbol{j}} \quad \forall \boldsymbol{j} \tag{13}$$

$$Prob\left(\frac{\sum_{i=1}^{n} x_i \cdot P_{i,j}}{D} \leq \overline{L}_j\right) \leq \overline{\boldsymbol{p}}_{\boldsymbol{j}} \quad \forall \boldsymbol{j} \tag{14}$$

$x_i \geq 0 \;\; \forall i$ **(15)**

This objective function assumes that there is a linear relationship between satisfaction and the amount of material taken from a particular supplier. This is a conventional assumption in mixing problems but it may be the case that satisfaction is a more complex construct than is acknowledged by this assumption. An alternative objective function would be to find the lowest cost portfolio available using (16). This is used to provide an alternative potfolio blend in some of the applications shown in section 6.3.

$$Min \sum_{i=1}^{n} V_i \cdot x_i \qquad \textbf{(16)}$$

The constraint shown in (2) requires that the quantity of material provided is at least equal to meet demand. Constraint (3) requires that the orders allocated from each supply source do not exceed the capacity available. The constraint shown in (4) requires that the probability that the blend has characteristics that are less than the lower constraints for characteristic *j* is not greater than the corresponding chance constraint. (i.e. the user can allow for the constraint to be breached some of the time). Similarly the constraint in (5) requires the probability of the blend characteristics for characteristic *j* exceeding the upper limits is less than the corresponding chance constraint as set by the decision maker. This is shown graphically in Figure 6.6 which shows the probability density function of some characteristic *j* of the fuel blend (modelled as a Gaussian distribution) and shows the region outside of the constraint. Constraints (13) and (14) set the limit on the size of the red region shown in Figure 6.6.

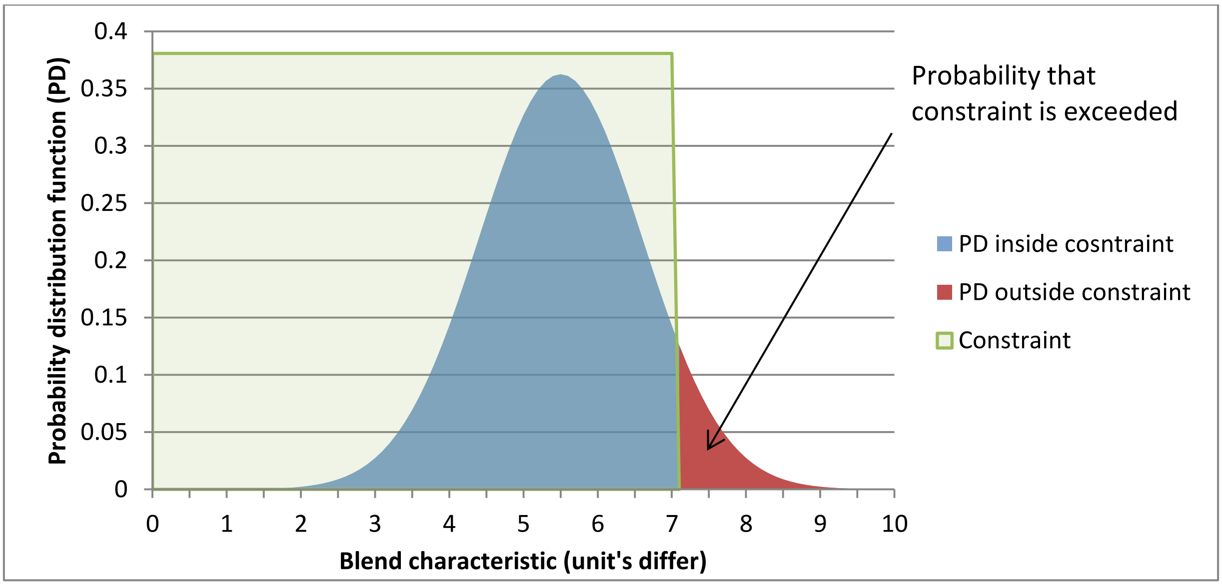


Figure 6.6: A probability distribution curve showing distribution of a blend characteristic and the region the breaches the constraint.

$P_{i,j}$ represents the characteristic j of supply i is the stochastic element of the program. In chance constrained programs $P_{i,j}$ is changed according to the associated distribution function to create the different deterministic linear programs that are to be solved. An important element that affects the quality of results obtained from chance constrained programming is the number of deterministic equivalent models that are generated, referred to the sample number. The more deterministic equivalent models that can be processed the more accurate the result obtained will be, the chance constrained elements of the model are reported as either satisfied or unsatisfied for each deterministic equivalent model created. As with most computational methods, especially when dealing with stochastic problems, there is a compromise between computation speed and accuracy. For the experiments a sample rate of 350 was used and the solver required around 2 – 5 minutes to complete on a 2.6GHz machine with 4GB RAM and was found to be generally stable although occasional crashes did occur during optimisation, especially for larger sample sizes. This is due to the longer computation time and a time-out limitation in the LINGO software rather than any fundamental instability in the construction of the model. Even when the sample size is lower to speed up solving time the solver gives solutions that are close to being able to meet the constraints but may exceed constraints slightly more than specified but not greatly. On the other hand if the sample size is too low a clearly non-optimal solution may be produced. This heuristic element of chance constrained programming is a drawback of the approach and is especially evident when dealing with many stochastic variables.

6.2.2 Monte-Carlo analysis

To measure the performance of the recommended portfolio against the constraints a Monte-Carlo simulation is used. This involves generating random inputs based on the variation of $P_{i,j}$ to simulate many instances of the constituent feedstocks being blended together. The results of the Monte-Carlo analysis allow the decision maker to test how frequently the recommended portfolio can be expected to exceed the constraints. The Monte-Carlo simulation runs 10,000 iterations for each characteristic of the blend of interest. The general guidance for Monte-Carlo analysis is to use as many iterations as feasible, striking a balance between computation time and accuracy to ensure a proper distribution of results is obtained (Hauskrecht and Singliar, 2003). For the 14 characteristics of interest in this model (as discussed in chapter 4) this required around 20 minutes to complete and report to an excel spreadsheet.

6.2.3 Model structure and screenshots

The optimisation model was written in the LINGO 13.0 software package and published to run within excel from a macro. The lingo script sits within the excel spreadsheet to allow future editing. The user is able to request that BioSS optimises either for the lowest cost or for the highest supplier score.

The first part of the model that the user should interact with is the fuel input screen. The user selects the required fuel description from a drop-down box and the data from the corresponding entry from the fuels library (chapter 4) is inserted as the model inputs. If the user wishes to enter custom data they should edit the fuels library. This input screen is shown in Figure 6.7.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Source Characteristics	Biomass Energy Content	Moisture Content	Lower heating	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al	Supplier score	Capacity	Is this supplier locked into a contract?		How much is the	Unit cost	Standard Deviation Table	Biomass Energy	Moisture Con	Lower heating	Ash c
	kJ/kg	Wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	N/A	tonnes/year			tonnes/year	£/tonne		kJ/kg	Wt %	MJ/kg	wt%
Hardwood Bark and shavings (Supplier B)	96.0	25.0	19.0	12.9	0.1	1.2	-	312.0	127.6	-	-	-	-	-	0.0952	4,000	☑ Contract locked	1	4,000	£14.00		1.3	2.1	3.5	
Poplar woodchip - passively dried (User)	100.0	21.2	19.5	0.6	0.0	341.3	-	28.5	2,550.0	-	-	-	-	10.0	0.1189	3,039	☑ Contract locked	1	3,039	£25.00		-	2.3	0.6	
Hardwood pellets (Supplier A)	100.0	3.5	20.1	1.2	0.5	220.0	15.0	180.0	510.0	-	0.5	0.8	1.0	50.0	0.1089	8,750	☐ Contract locked		-	£25.00		-	1.1	0.5	
Olive residues (User)	98.0	7.0	20.1	3.0	0.1	663.9	-	121.5	4,512.9	-	-	-	-	193.5	0.0992	15,000	☐ Contract locked		-	£40.00		0.0	1.4	1.5	
	98.0	15.0	18.2	9.0	0.1	0.0	-	-	-	-	-	-	-	-	0.0688	30,000	☐ Contract locked		-	£7.00		-	1.4	3.5	
	40.0	7.9	24.4	14.9	0.4	6,187.8	-	-	-	0.7	2.0	500.0	-	-	0.0931	22,000	☐ Contract locked		-	-£10.00		4.0	1.2	3.2	
	85.0	10.0	17.5	1.0	0.7	624.7	83.0	1,400.0	4,200.0	-	4.1	436.0	-	2,150.0	0.1095	11,500	☐ Contract locked		-	-£20.00		8.5	1.0	1.8	
Softwood (Generic)	100.0	34.3	17.9	3.1	0.2	-	-	-	-	-	-	-	-	-	0.0558	10,000	☐ Contract locked		-	£22.30		-	3.5	0.9	
Willow (Generic)	100.0	17.7	18.4	1.8	0.1	-	-	-	-	-	-	-	-	-	0.1429	2,500	☐ Contract locked		-	£38.00		-	14.5	0.5	
Pellets DIN 51731 Standard (User tested)	100.0	10.8	15.4	0.3	233.9	98.1	-	40.0	340.0	-	0.2	19.0	0.9	99.0	0.1078	5,000	☐ Contract locked		-	£45.00		-	-	-	

Wood chips (User)
Olive residues (User)
Demolition wood (supplier A)
Hardwood pellets (Supplier A)
Hardwood Bark and shavings (Supplier B)
Italian wood pellets (Imported; Supplier C)
SRF (Supplier D)
RDF (Supplier E)

	A	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1	Source Characteristics	Capacity	Is this supplier		How much is the	Unit cost	Standard Deviation Table	Biomass Energy	Moisture Con	Lower heating v	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
2		tonnes/year	locked into a contract?		tonnes/year	£/tonne		kJ/kg	Wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
3	Hardwood Bark and shavings (Supplier B)	4,000	☑ Contract locked	1	4,000	£14.00		1.3	2.1	3.5	2.2	0.0	0.3	-	5.5	7.3	-	-	-	-	-
4	Poplar woodchip - passively dried (User)	3,039	☑ Contract locked	1	3,039	£25.00		-	2.3	0.6	0.7	0.0	11.0	-	-	297.5	-	-	-	-	1.0
5	Hardwood pellets (Supplier A)	8,750	☐ Contract locked		-	£25.00		-	1.1	0.5	0.3	0.0	8.4	4.0	28.6	35.4	-	0.1	0.0	-	2.0
6	Olive residues (User)	15,000	☐ Contract locked		-	£40.00		0.0	1.4	1.5	0.9	0.0	225.1	-	11.5	974.3	-	-	-	-	60.4
7	Recycled Wood grade A (User)	30,000	☐ Contract locked		-	£7.00		-	1.4	3.5	2.3	0.0	0.0	-	-	-	-	-	-	-	-
8	RDF (with plastics)	22,000	☐ Contract locked		-	-£10.00		4.0	1.2	3.2	7.5	0.3	2,722.6	-	-	-	-	-	-	-	-
9	RDF (High Biomass Content)	11,500	☐ Contract locked		-	-£20.00		8.5	1.0	1.8	6.5	-	95.9	4.7	261.0	785.0	-	1.9	129.7	-	654.0
10	Softwood (Generic)	10,000	☐ Contract locked		-	£22.30		-	3.5	0.9	1.1	0.3	-	-	-	-	-	-	-	-	-
11	Willow (Generic)	2,500	☐ Contract locked		-	£38.00		-	14.5	0.5	1.2	0.0	-	-	-	-	-	-	-	-	-
12	Pellets DIN 51731 Standard (User tested)	5,000	☐ Contract locked		-	£45.00		-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 6.7: Fuels data input sheet

Figure 6.7 shows the LINGO solver running to find the cheapest available portfolio and the excel interface where the recommended portfolio is output to.

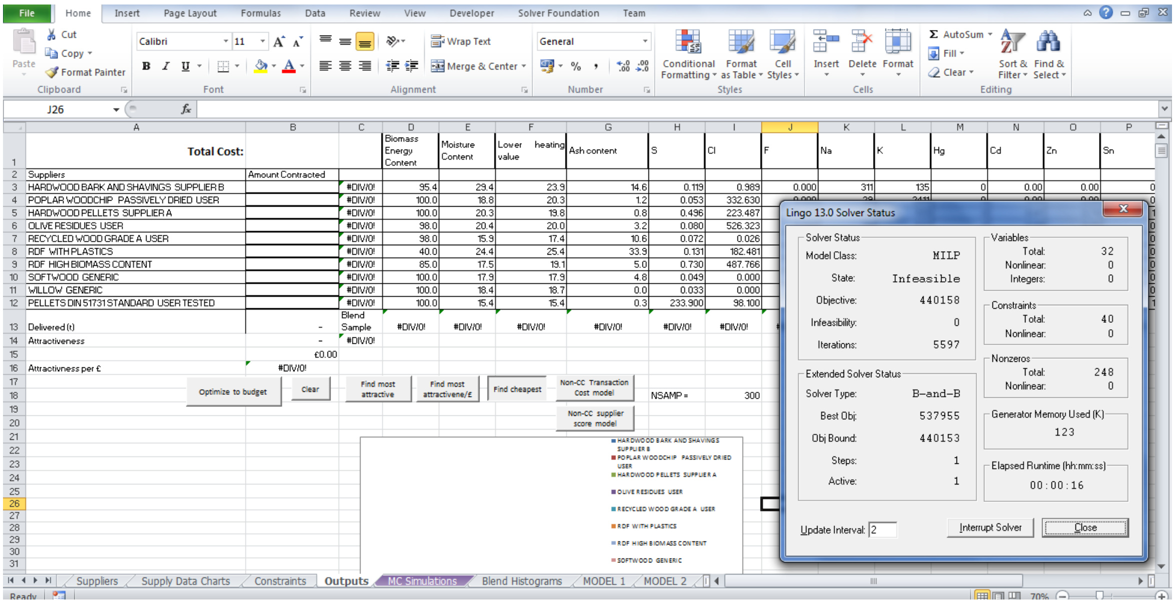


Figure 6.8: Screenshot of BioSS interface showing LINGO solver operating

The Monte-Carlo analysis runs within excel and gives a set of output results including mean and standard deviation of the expected blend results. The Monte-Carlo analysis is summarised in histograms for each chemical constraint and a cumulative distribution is also shown to indicate how the blend distribution deviates from a normal distribution, this output screen is shown in Figure 6.8.

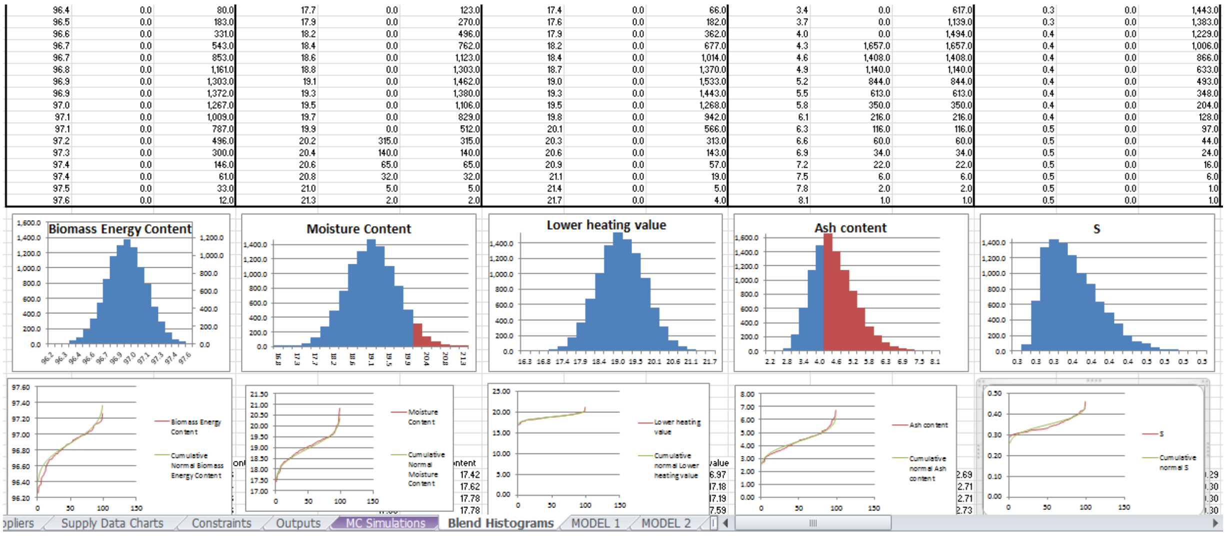


Figure 6.9: Monte-Carlo output screen

6.3 Implementation

This section shows the application of the various modes of the optimisation module of the BioSS. BioSS.2, BioSS.3 and BioSS.Op are run for a single example application. The different modes run with different amounts of data showing how BioSS can handle the changing levels of detail being added during the development process. This section is split into modes of the BioSS that broadly correspond to stages of development as discussed in chapter 3.

6.3.1 BioSS.2

In BioSS.2 the project is at a very early stage and most of the suppliers have not been approached, however a high-level resource assessment has been carried out and quantities of available material of various types have been shortlisted and are expected to be available in approximate quantities.

The technology constraints have been estimated based on the expected technology choice at this early stage of development but no technology provider has been selected. The chance constraints are set to reasonably tightly between 0.9 and 0.95 to allow the developer to gain a good view of the potential cheapest portfolio and the constraints that are of most interest, it is expected that this stage will partly inform the technology selection for the project. These constraints will be tightened and changed as the project moves towards BioSS.3. The available materials have been estimated in a resource assessment report that is not included as part of the scope of BioSS. The materials identified as being available are shown in Table 6.2 along with the expected price and capacity of each source. Full data on the characteristics of each available feedstock are shown in Appendix D under Table D.1 and Table D.2. Table 6.3 shows the constraint values that are expected for the conversion technology type. These constrains are generic at the BioSS.2 stage and are based on previous experience.

At this stage the developer only has approximate estimates of regional biomass availability and does not have sufficient information to take a judgement on the suitability or otherwise of any of the potential biomass sources. Therefore only the objective function for minimising supply portfolio cost can be used. The results are shown in Table 6.2 as tonnes ordered from each supplier and the representing percentage of the final blend. For comparison a non-chance constrained method has also been used to recommend an alternative solution. This alternative only uses the mean values for each characteristic. Because individual suppliers have not been identified at this stage the supplier performance weightings cannot be considered, therefore the objective function shown in (10) cannot be used. Instead the portfolio can be optimised for the lowest cost using the objective function shown in (16).

Table 6.3 shows the results of the Monte-Carlo analysis showing the mean values of the blend for each characteristic of interest and how frequently the blend exceeded the relevant constraint limits.

Table 6.2: Feedstock identified as being available estimated price and capacity

Source Description	Capacity	Unit cost	Recommended lowest cost blend	Recommended lowest cost blend without chance constraints
	Tonnes/ year	Cost/tonne	Tonnes/ year	Tonnes/ year
Refuse derived fuel	50,000	£3.00	26.6 (0.1%)	0.0 (0.0%)
Recycled wood	25,000	£15.00	1209.5 (4.8%)	1727.2 (6.9%)
Demolition wood	10,000	£7.50	2804.1 (11.2%)	0.0 (0.0%)
Solid recovered fuel	15,000	-£4.00	2822.4 (11.3%)	9861.8 (39.4%)
Virgin softwood	20,000	£25.00	17163.9 (68.7%)	13411.0 (53.6%)
Virgin hardwood	22,000	£35.00	973.4 (3.9%)	0.0 (0.0%)
Portfolio cost			£491,131	£321,735

Table 6.3: Monte-Carlo results

	Biomass energy content	Moisture content	Lower heating value	Ash content
Units	(%)	wt%	MJ/kg	wt%
Lower limit (Chance constraint)	90 (1)	7 (1)	15 (0.9)	
Upper limit (chance constraint)	100	20 (0.9)	23 (0.9)	4.0 (0.95)
Chance constrained lowest cost recommended blend: Mean (% constraint exceeded by)	94.80 (0.74%)	17.70 (0%)	17.71 (0%)	2.86 (3.32%)
Non-chance constrained lowest cost recommended blend (% constraint exceeded by)	90.11 (52.4%)	16.19 (0.0%)	16.20 (12.7%)	4.00 (49.8%)

The portfolio recommended when using the chance-constrained program is within the chance constrained limits. The portfolio exceeds the limits for ash content 3.3% of the time, lower than the permitted 5% (0.95). The constraint for biomass energy content is exceeded 0.7% of the time however and this is not within the chance constraints. The histograms for both characteristics are shown in Figure 6.11. This is likely to be the binding constraint for the solution space. The solution could have been improved by taking more material from the lower cost sources such as the refuse derived fuel, solid recovered fuel or the demolition wood. However these sources have higher ash contents than the higher cost sources (17.9%, 7% and 5.0% respectively) and could have pushed the average blend characteristics beyond the 4% limit more frequently than is allowed for. They also have lower biomass energy contents (50% and 80% respectively) that may have prevented the model from selecting these sources.

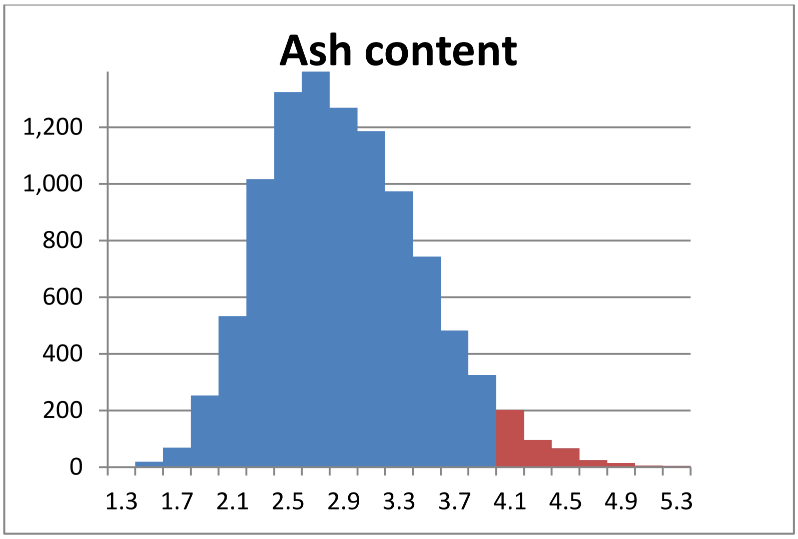


Figure 6.10: Histogram for ash content in chance-constrained model output in BioSS.2

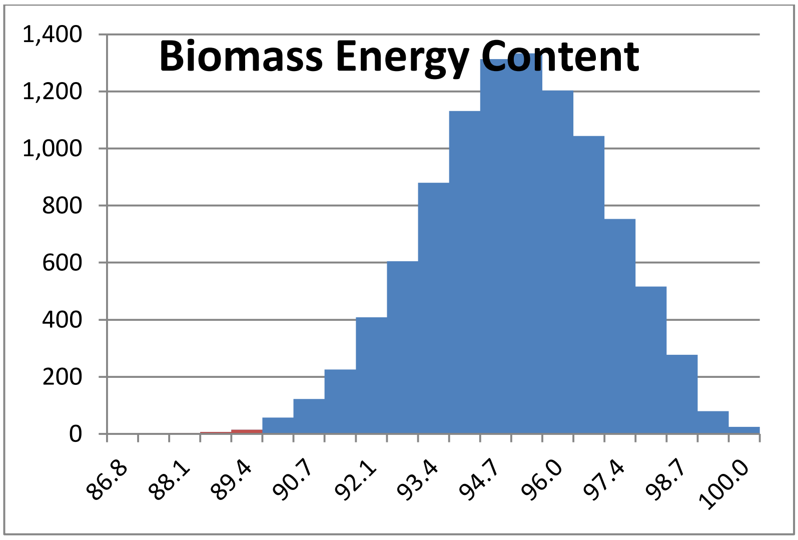


Figure 6.11: Histogram of biomass energy content for chance-constrained model output in BioSS.2

In the non-chance-constrained model refuse derived fuel and demolition wood is not selected at all because the solid recovered fuel (SRF) appears to be more attractive. In the non-chance-constrained model the binding constraints are the ash content and the biomass energy content. Recycled wood has a higher ash content than demolition wood and is selected for 7% of the blend, solid derived fuel (SRF) makes up a large proportion of the blend and is the cheapest source with an ash content above the limit (7%) and a biomass energy content below the required limit (75%). Therefore if these limits are to be further exceeded the model would choose to allocate more orders to the SRF supplier than the RDF supplier as it has better characteristics and is cheaper and there is available capacity.

6.3.2 BioSS.3

At the BioSS.3 stage more information is available to the buyer about the available biomass sources. Information has been gathered about the companies that can supply material and about the fuels they are providing. This includes more information on the complete chemical characteristics of the fuel and also information on the performance of each supplier with regards to their ability to satisfy the stakeholder requirements as identified in Chapter 5. This adds granular detail to the resource assessment exercise that informs the BioSS.2 stage and firm figures have now been obtained for unit cost and capacity for each supply of material. Other potential fuels have been identified through approaching specific suppliers. The composition of available material has been confirmed using lab tests, usually paid for by the supplier.

Table 6.4 shows the set of potential fuel sources, the associated supplier score from the QFD-AHP method and the basic unit price. As with the other BioSS modes the input data for fuels is shown in Appendix D in Table D.3 and Table D.4.

Table 6.5 shows the performance of blends recommended using different optimisation models and objective functions according to the Monte-Carlo analysis. The maximum score blend is using the chance constrained programming approach and maximising for stakeholder satisfaction, as per equation (10). The lowest cost blend also uses the chance constrained model but uses the objective function as shown in equation (16). The two ‘non-CC’ blends are created using a model that does not use the chance-constrained approach and blends only based on the average characteristics of the fuel, one non-CC blend is generated for each objective function.

Table 6.4: Feedstocks identified as being available estimated price and capacity

Source Description	Supplier score	Capacity	Unit cost	Recommended highest score blend		Recommended lowest cost blend		Non-chance constrained highest score blend		Non-chance constrained lowest cost blend	
	(ω_i)	tonnes/ year	Cost/tonne	Orders allocated (tonnes/yr)	% outside of constraint	Orders allocated (tonnes/yr)	% outside of constraint	Orders allocated (tonnes/yr)	% outside of constraint	Orders allocated (tonnes/yr)	% outside of constraint
Hardwood pellets [User tested]	0.0952	9,350	£40.00	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
RDF [User tested]	0.1189	4,200	-£3.00	3471.1	13.9%	1,019.9	4.1%	0.0	0.0%	4,200.0	16.8%
Wood chips [user tested]	0.1089	6,500	£25.00	6,500.0	26.0%	6,500.0	26.0%	6,500.0	26.0%	6,500.0	26.0%
Hardwood pellets [user tested]	0.0992	50,000	£45.00	7,578.0	30.3%	0.0	0.0%	0.0	0.0%	3,351.0	13.4%
Pellets din 51731 standard [User tested]	0.0688	13,200	£40.00	0.0	0.0%	10,178.8	40.7%	9,430.0	37.7%	0.0	0.0%
Demolition wood [User tested]	0.0931	10,000	£14.00	0.0	0.0%	987.1	3.9%	1,025.9	4.1%	0.0	0.0%
Recycled wood grade A [User tested]	0.1095	7,000	£20.00	3,621.9	14.5%	0.0	0.0%	0.0	0.0%	2,922.8	11.7%
Hardwood bark and shavings [User tested]	0.0558	4,000	£6.00	0.0	0.0%	3,831.0	15.3%	4,000.0	16.0%	0.0	0.0%
Willow generic [User tested]	0.1429	7,500	£38.00	3,829.0	15.3%	318.5	1.3%	0.0	0.0%	7,500.0	30.0%
SRF [User tested]	0.1078	25,000	-£5.00	0.0	0.0%	2,164.7	8.7%	4,044.1	16.2%	526.2	2.1%
Total	1.00	136,750		25,000	100%	25,000	100%	25,000	100%	25,000	100%
Portfolio score				2,816		2,114		2,998		2,111	
Portfolio cost (£/yr)				£711,038		£604,676		£641,520		£557,844	

Table 6.5: Performance of the 4 different portfolios being examined.

Constraint	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Lower Limit (Chance constraint)	90 (1.0)	7 (1.0)	15.00 (0.9)											
Upper Limit (Chance constraint)		20 (1.0)	23(1.0)	4 (1.0)	500 (0.9)	750 (1.0)	2000 (0.95)	5000 (0.95)	3000 (0.95)	2.5 (1.0)	5 (1.0)	500 (1.0)	600 (1.0)	1000 (1.0)
Maximum score blend mean; (% of time constraint exceeded)	91.01 (0.03%)	18.45	18.46	3.27 (0.44%)	3.61	572.11 (0.06%)	407.47	883.32	817.68	0.20	0.52	34.03	92.02	115.80
Lowest cost blend mean, (% of time constraint exceeded	92.99	16.40	16.41 (0.03%)	3.37 (0.66%)	106.74	608.37 (0.71%)	209.10	835.99	779.79	0.33	0.33	27.34	65.59	102.93
Non-CC maximum score blend; (% of time constraint exceeded)	90.00 (49.59%)	17.82	17.83	4.02 (50.49%)	4.36	707.54 (26.51%)	503.89	1,154.21	935.72	0.32	0.51	42.71	120.36	131.19
Non-CC lowest cost blend; (% of time constraint exceeded)	93.88	16.44	16.43 (2.45%)	4.00 (50.27%)	88.49	752.84 (51.23%)	24.27	940.88	833.97	0.53	0.24	12.08	44.90	60.96

6.3.3 BioSS.Op

BioSS.3 is a critical phase of project development, the project moves through project finance and planning permission phases. Contractors are appointed and the ownership structure of the plant is established. Once completed and operating the problem facing the buyers of biomass is to continue to ensure the feedstock supply is operating optimally. From discussions with interviewees and Express Energy Ltd it is likely that around 75%-85% of a feedstock contract will be locked into medium or long-term contracts at the point of financial close. The remaining 15%-25% of the fuel supply can be sourced from whatever spot-market mechanism is available, essentially this is a floating element of the fuel supply. As well as being interested in how new potential sources of fuel could affect the supply portfolio the buyer may also be interested in re-contracting for the fixed element of the fuel supply when the initial agreements expire. This environment has been mentioned by Express Energy and the other developers that have been interviewed during this research. Operators of coal power stations involved with co-firing biomass and coal have also described a similar operational mode.

To handle these situations BioSS has an operational phase mode which allows the user to specify which supplies are locked into contracts and to decide on the best way to allocate the remaining floating element between the available suppliers. In this mode the optimisation model is forced to allocate the specified number of orders to the specified suppliers.

To demonstrate this mode the BioSS.Op is run for a scenario where the operator has locked into long-term contracts with some of the suppliers recommended in BioSS.3. Some of the supplier contracts have expired and some proportion of fuel supply has been left on the floating market. Three suppliers remain within contract, the wood chips supplier, the hardwood chips supplier and the refuse derived fuel (RDF) supplier. A new landscape of suppliers is now available for the operator to allocate orders between and these are shown in Table 6.6. Also shown in Table 6.6 is the quantity under contract, the available capacity from new suppliers, associated unit cost and the portfolio as recommended by BioSS.Op. The new supplies have also been assigned a preference score, again this could be assigned using a variety of methods but the QFD-AHP method presented in chapter 5 would give a consistent and robust weighting, although perhaps at the expense of time.

In BioSS.Op the plant has been operating for several years and any warranty on the plant has expired. The operator also has a better understanding of maintenance costs associated with certain chemicals being present within the fuel blend. As a result the chance constraints have been changed to allow for more exceedance in some characteristics. These are shown in brackets in Table 6.10 along with the mean values for the blend and the Monte-Carlo analysis results. The non-chance constrained models are again shown for comparison.

Table 6.6: Available and contracted supplies for BioSS.Op.

Source Description	Supplier score	Capacity	Quantity contracted for	Unit cost	Recommended Portfolio (highest score)	Recommended portfolio (lowest cost)	Non Chance-constrained model highest score	Non Chance constrained model lowest cost
		tonnes/ year	Tonnes/yr	Cost/tonne	Tonnes/yr (% of blend	Tonnes/yr (% of blend)	Tonnes/yr (% of blend)	Tonnes/yr (% of blend)
Recycled wood (Class C)	0.0960	1,500	-	£5.00	1,500.0 (6.0%)	1,500.0 (6.0%)	1,500.0 (6.0%)	1,500.0 (6.0%)
RDF [User tested]	0.1219	3,471	2,500	-£3.00	2,500.0 (45.5%)	2,500.0 (10.0%)	2,500.0 (10.0%)	2,500.0 (10.0%)
Wood chips [user tested]	0.0889	6,500	6,500	£25.00	6,500.0 (26.0%)	6,500.0 (26.0%)	6,500.0 (26.0%)	6,500.0 (26.0%)
Hardwood pellets [user tested]	0.1016	7,578	7,578	£45.00	7,578.0 (30.3%)	7,578.0 (30.3%)	7,578.0 (30.3%)	7,578.0 (30.3%)
Olive residues (User tested)	0.0708	3,000	-	£13.50	2,697.2 (10.8%)	3,000.0 (12.0%)	3,000.0 (12.0%)	1,613.2 (6.5%)
Straw (Generic)	0.0885	1,450	-	£21.00	1,450.0 (5.8%)	1,169.9 (4.7%)	293.4 (1.2%)	1,450.0 (5.8%)
Wood from local aggregator	0.1121	1,250	-	-£7.00	1,250.0 (5.0%)	1,250.0 (5.0%)	1,250.0 (5.0%)	1,250.0 (5.0%)
Imported Torrefied, Palm Oil Kernal	0.0573	15,000	-	£24.00	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)
RDF (High Biomass Content; user tested)	0.1493	1,500	-	£0.00	1,500.0 (6.0%)	1,500.0 (6.0%)	1,500.0 (6.0%)	1,500.0 (6.0%)
SRF (User tested)	0.1136	1,500	-	-£8.50	24.8 (0.1%)	2.1 (0.01%)	878.6 (3.5%)	1,108.8 (4.44%)
Portfolio Cost:					£561,412	£559,811	£537,564	£537,564
Portfolio score:					2,483	2,477	2,529	2,529

Table 6.7: Results of Monte-Carlo analysis for BioSS.Op

Constraint	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Lower Limit (Chance constraint)	90 (1.0)	7 (1.0)	15.00 (0.9)											
Upper Limit (Chance constraint)	100 (1.0)	20 (0.9)	23 (0.95)	4 (0.7)	500 (0.9)	250 (0.9)	2,000 (0.75)	5,000 (0.75)	3,000 (0.75)	2.5 (1.0)	5 (1.0)	500 (1.0)	600 (1.0)	1000 (0.7%)
Highest score blend Mean (% constraint exceeded)	92.23	18.64	18.64	3.05 (2.26%)	2.76	654.47 (5.85%)	307.86	835.22	1,433.06	0.19	0.70	54.42	71.71	323.60 (1.84%)
Lowest cost blend: Mean (% constraint exceeded)	92.24	18.69 (0.01%)	18.69	2.96	2.76 (0.70%)	658.28 (6.63%)	307.80	824.68	1,519.22 (0.07%)	0.18	0.70	54.48	70.94	325.92 (2.18%)
Non-CC highest score blend: (% constraint exceeded)	91.47 (0.37%)	18.40	18.41	3.19 (4.30%)	2.80	765.01 (58.12%)	314.11	1,012.53	1,423.60	0.30	0.73	55.35	80.98	321.96 (1.78%)
Non-CC lowest cost blend: (% constraint exceeded)	91.59 (0.26%)	18.53	18.54	2.95 (0.30%)	2.79	764.56 (57.87%)	313.70	969.11	1,636.55 (0.98%)	0.27	0.72	55.25	78.32	329.68 (2.48%)

6.4 Results and discussion

The chance constrained programming approach has provided a recommended blend of materials that complies with the constraints in most cases. In each of the non-constrained portfolios the constraints have been breached, often by significant margins. This is expected as the non-chance constrained approach does not take into account the stochastic distribution of feedstock characteristics.

In BioSS.2 the model recommends a portfolio that slides slightly outside of the required threshold for biomass energy content, according to the Monte-Carlo analysis 0.74% of deliveries will fall below the 90% threshold as shown in the histogram in Figure 6.11 and Table 6.3. The ash content also exceeds the associated constraint in BioSS.2 but in that case the exceedence is within the 5% (0.95) limit specified by the user. The non-chance constrained approach finds a solution that exceeds the chance constraint in three of the four characteristics being reported on, the non-chance constrained portfolio is around £170,000 cheaper than the chance constrained portfolio, but over half of the blended tonnage would not be compliant for the conversion plant.

In BioSS.3 the fully specified model is applied with the user now able to consider relative supplier score. The chance constrained portfolio that aims to maximise supplier score is £106,400 (17.5%) more expensive than the portfolio recommended using the lowest cost objective function and scores 33% more favourably regarding the portfolio performance against stakeholder requirements. From stakeholder theory the better an organisation is able to meet its needs the more successful it is likely to be The best portfolio in the eyes of the stakeholder group may not be the best portfolio in the eyes of the developer or operator of the scheme but the extra money would be well spent if it avoids project failure due to disgruntled stakeholders and poor publicity due to unsuitable suppliers being selected. Provided the economics of the project are viable using the recommended portfolio there is much risked and little gained by saving money on the supply in exchange for jeopardising the success of the project.

The chance-constrained model was able to find a solution that complied with the specified chance-constraints in every mode for every constraint to within 1% of the chance constraint limit. The chance-constraints were breached in BioSS.2 for biomass energy content for the by 0.74%; in BioSS.3 the biomass energy content was exceeded by 0.03%, the ash content exceeded by 0.44% and the chlorine content exceeded by 0.06% for the lowest cost portfolio. In the BioSS.3 highest score portfolio biomass energy content was exceeded by 0.66% and chlorine by 0.71%.for the best score portfolio. In BioSS.Op all the constraints were met. As could be expected the non-chance-constrained models always recommended portfolios where one or more constraints was exceeded according to the Monte-Carlo analysis, usually by over 20%.

There are some constraints where the chance constrained solutions exceed the acceptable probability threshold. Most significantly the chlorine content of the lowest cost blend is found to be 1.7% over the constraint limit. This is due to a limitation in the chance constrained method used. The chance constrained method works by generating many equivalent models that are deterministic in nature, replacing those variables set as stochastic with a deterministic equivalent based on the specified distribution. The number of deterministic equivalent models that are to be solved is set by the sample number (NSAMP), in this case 300. 300 deterministic equivalent models are therefore created and solved. Where the model is faced by very wide distributions this sample rate may not be high enough to capture sufficient width of scenarios to properly model the distribution, effectively the optimisation algorithm in unaware of the longer tails of fuel characteristics which may turn out to be significant to the final blend if a large proportion of supply is taken from those highly variable cases. A similar issue arises when there are massive differences between the chemical content of materials, for instance where most of the supplies have low chlorine contents and one has a chlorine content an order of magnitude or more greater than the others, in this case the sample size may not be big enough to find all instances of combinations of material that exceed the threshold. Both of these problems are encountered regarding the chlorine content of available feedstocks for BioSS.3 as shown in Figure 6.10.

Limited sample size is an inherent problem with the method that cannot be easily overcome without adding significant processing time or power. Alternatively a limit could be set on the proportional size of standard deviation that can be processed by the model to prevent errors. This has not been done however as the aim of the optimisation module is to handle the widely variable nature of biomass materials, rather than exclude materials because they are variable or uncertain, the model should aim to always consider them for inclusion to the portfolio. This allows the power scheme to access more of the biomass market.

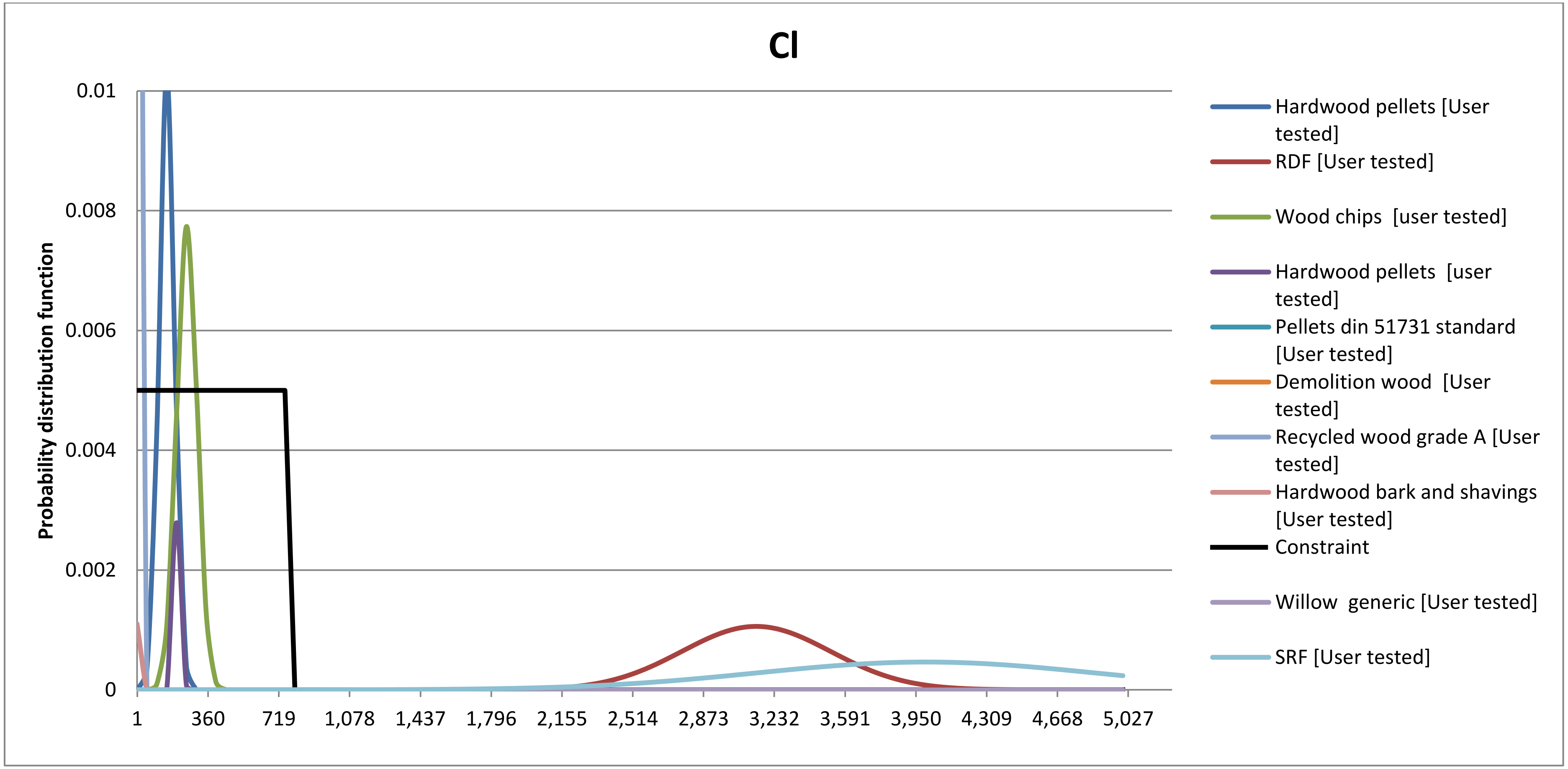


Figure 6.12: Chlorine content of fuels in BioSS.3

As in BioSs.2 the solutions recommended by the non-chance constrained solutions for the BioSS.3 stage significantly exceed the acceptable thresholds on several of the chemical constraints, although they do outperform their chance-constrained equivalents.

The BioSS.3 stage is crucial to the long-term success of the project. If poor suppliers are selected at this stage they will most likely be signing into long-term contracts for a good proportion of the plant lifetime. In addition the influence of other stakeholder groups is largest at this stage when the project is made public during the planning permission process and investors are required to move towards financial close. It is at this stage that most of the larger scale UK biomass combustion projects have stalled (RESTATS and DECC, 2013b).

The BioSS.3 allows the option to either optimise the portfolio for the best performing solution or for the lowest cost solution. Many other approaches to multi-criteria or multi-objective optimisation replace the objective function with a metric that calculates some form of utility or value; say for instance, satisfaction per pound spent. This has been deliberately avoided in BioSS. This type of approach implies that the developer can directly or indirectly ‘trade’ some element of project revenue or financial success for stakeholder satisfaction. In the bioenergy that may mean trading profit for environmental impact, sustainability, energy security or reliability. From the results of chapter 5 this is not how stakehodlers view bioenergy projects, success and project profit are non-commensurable. To include this type of metric would also go against the ethos of policy motivations for bioenergy and best practice regarding stakeholder engagement for project management (Reed, 2008, Mathur et al., 2008). Rather the

BioSS aims to maximise stakeholder satisfaction within the technical constraints of the conversion technology. The lowest cost option is presented for comparison.

As with all decision support systems the BioSS can provide only ‘support’ for the decision maker. It is likely that in reality the developer will be unable to negotiate the exact portfolio that is recommended in BioSS as suppliers change and negotiations progress. The BioSS gives the decision maker a starting point and can be used to give a rapid appraisal of portfolio performance as the exact quantity contracted for, price and contract clauses change during contract negotiations.

In BioSS.Op the chance constrained model is able to find solutions that are always within the chance constrained limits, the model works as expected forcing the solution to include the contracted fuel supplies. The differences between the solutions are less pronounced as only the floating percentage of the blend are being optimised for and the two solutions have similar costs and performance scores. Figure 6.11 shows how similar the solutions are for the situation presented. In other situations, or where a larger fraction of the fuel is to be re-signed the contrast may be greater.

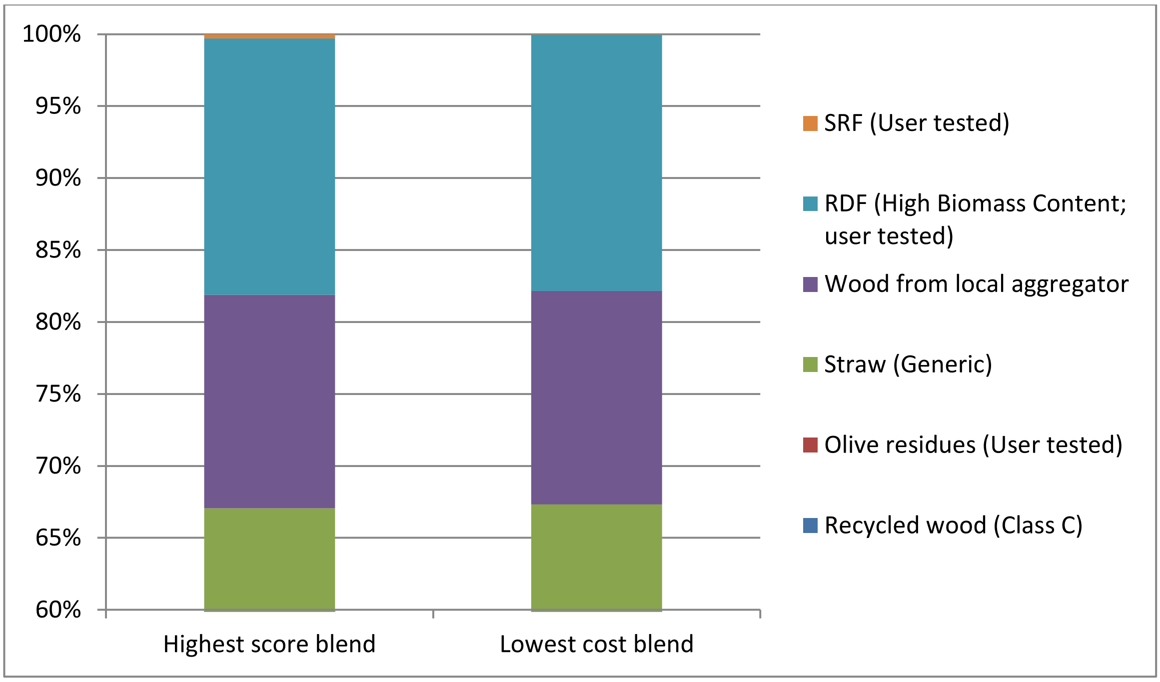


Figure 6.13: BioSS.Op split of floating element of fuel portfolio

By providing 3 modes of operation the BioSS is able to contribute throughout the development lifecycle. At the early development stage the fuels library is used to make estimates regarding 4 key biomass characteristics and to assess the available feedstock against technological constraints using BioSS.2. At financial close BioSS.3 is used to find a portfolio that gives the best outcome for the stakeholder group given detailed information about each potential supplier. At the operational stage BioSS.Op allows the decision maker to evaluate new sources of material as they become available to the project and to loosen the technological operating constraints if required.

6.5 Conclusions

The BioSS has been shown to find solutions for the problem of strategic sourcing of biomass materials as feedstock for conversion plants in the three phases of development represented by BioSS.2, BioSS.3 and BioSS.Op. The chance constrained approach always outperformed the non-chance constrained approach as would be expected. Clearly using only the mean or average value for biomass materials is not feasible when aiming to optimise supplier portfolios due to the inherent variation of biomass characteristics. Equally using the maximum or even quartile figures to inform supplier selection has its disadvantages. The aim of the biomass buyer is to make the best use of the mixture of fuels available. This is best done by considering portfolios or blends of available materials. By including only those materials that comply with the constraints on an individual basis much of the value within the biomass supply chain, both from a stakeholder perspective and financial value, would be excluded. BioSS offers a form of rapid prototyping for supply chain design, allowing the decision maker to quickly evaluate the impact of new suppliers on the overall performance of the project supply portfolio.

The presented model could be easily adjusted and applied to other bioenergy or bio-economy value adding functions such as the blending of compost materials, blending of material prior to wood pellet manufacture or the blending of digestate residues from AD processes with other materials to optimise the final fertilizer characteristics.

As well as recommending order allocations the BioSS optimisation model can also be used to quickly evaluate existing suppliers and proposed portfolios using the Monte-Carlo approach. This is a simple and easily understood method that is not currently used by the industry. Along with standardised lab testing that is being introduced and increased auditing of biomass suppliers the information required by BioSS is likely to be available for biomass buyers when making these decisions. If data is not available on material characteristics however the fuels library discussed in chapter 4 can be used to complete gaps, although this will not be accurate it could prevent unnecessary expenditure on testing clearly unsuitable materials and allow buyers to evaluate a wider selection of feedstocks. This could improve development efficiency and success rates. Although designed for expert users the system is run from a widely available software package and is fully customizable and unlocked, with the optimisation model written and embedded the user is free to make improvements to the data input and presentation if required.

Chapter 7. Implementation

7.1 Introduction

This chapter demonstrates the application of the BioSS framework. Two scenarios are described based on situations encountered by UK bioenergy development companies. The BioSS is applied to three different stages of the project development using BioSS.2, BioSS.3 and BioSS.Op. Scenario 1 is based on a large scale combustion facility of the type being developed by Express Energy Ltd, scenario 2 is based on a smaller scale gasification projects in an urban environment where chemical constraints are different. Stakeholder requirements are also different between the two scenarios. Scenario 1 is discussed in 7.2.1 and scenario 2 in 7.2.2. Each scenario is run through the BioSS.2 and BioSS.3 stage. For scenario 1 the importance of different stakeholders changes between the BioSS.3 and BioSS.Op stages and the framework is therefore used again to optimise the floating element of the fuel supply for scenario 1.

Both scenarios assume the same fuel is available from the same suppliers to allow for a comparison to be made. The recommended portfolios are shown in section 7.2 and the results are presented and discussed in section 7.3. The chapter is concluded with a discussion of the application of the BioSS model in section 7.4.

Whilst chapters 4, 5 and 6 have focused on one single research problem as described in chapter 1 this chapter describes the application of the entire BioSS framework and shows how differing stakeholder influence, project type and scale change the portfolio recommended by BioSS. As BioSS is an expert system a good level of user knowledge is required and assumed, BioSS is intended as an industry tool to support managers in decision making, not an evaluation tool for suppliers, the public or other stakeholder groups. Ultimately it is the project developer that makes the strategic purchasing choice.

7.2 Test Scenarios

As described in chapter 3 the BioSS framework has three operating modes, BioSS.2 where little information is known about the nature of the available supply, BioSS.3 where the model is fully specified and the decision maker must make choices regarding the contracting of supply portfolios and BioSS.Op where the plant has been operating and may have some legacy contracts that need to be complimented by new suppliers. In the fully specified model for BioSS.3 the framework consists of two main stages, the allocation of supplier preference weightings according to stakeholder satisfaction, and the allocation of orders to realise the optimal total stakeholder satisfaction. The optimisation module uses a chance constrained programming approach that incorporates the weighting scores. The weighting scores are obtained using an integrated QFD-AHP method consulting with the relevant stakeholder groups.

The implementation of the BioSS in its three modes is shown below.

7.2.1 Scenario 1

The project in scenario 1 is a proposed 120MW combustion facility consisting of two 60MW plants located on a brownfield development site beyond the nearest city limits requiring a total of 350,000 tonnes of material per year. The combustion equipment selected comes with a warranty of 2 years and a detailed fuel specification. The warranty is only valid if the operator can show through testing records that the fuel used was within the required specification. The project is being developed by a private developer who plans to sell the majority stake in the project at financial close, retaining a minority ownership of revenue during project operation. The project is to be debt financed and the economic case for the project relies upon the ROC financial incentives for biomass electricity. The expected capital cost of the project is circa £250-300m.

The important stakeholder groups are national level non-governmental organisations (NGO's), national policy makers and planning departments and the investment consortium. Local populations are not considered to have significant influence over the scheme. Using the popular interest-influence grid for stakeholder mapping proposed by Eden and Ackermann (1998) the different stakeholder groups have been plotted in Figure 7.1.

Different authors have improved the stakeholder mapping process by adding new dimensions such as legitimacy (Mitchell et al., 1997) , support (Turner, 2007) and cooperation or threat (Savage et al., 1991). The method used in Figure 7.1 is the influence-interest grid usually credited to Eden and Ackermann (1998) but updated in Bryson (2004). This grid has stakeholders plotted using the power or influence they have over a project on one axis and the interest they have on the other axis. Eden and Ackermann (1998) then labelled each quadrant as either subjects, players, crowd or context setters, although these labels are frequently changed by authors depending on the application the grid is being used for. Usually this type of stakeholder mapping is used to identify which groups should receive most attention from managers. The stakeholder map shown in Figure 7.1 shows the stakeholder situation in the BioSS.3 stage of project development, at stage BioSS.Op the situation may change and insufficient information is available in BioSS.2. The aim of the project developer in this scenario is to successfully build and sell the power project. Therefore the stakeholder group of financial investors are the most important key-player stakeholder group. Also in the key-player category are environmental groups. As discussed in chapter 5 environmental groups can influence the success of projects by objecting to planning permission and influencing or motivating other stakeholder groups to object. Local government and the local community are the subjects in this type of development project and must be satisfied, they have high interest but low influence (or power) over project success. National government have power over the project success as they are the key decision maker for project go-ahead but have no active interest, this makes them a context setter under Bryson's framework.

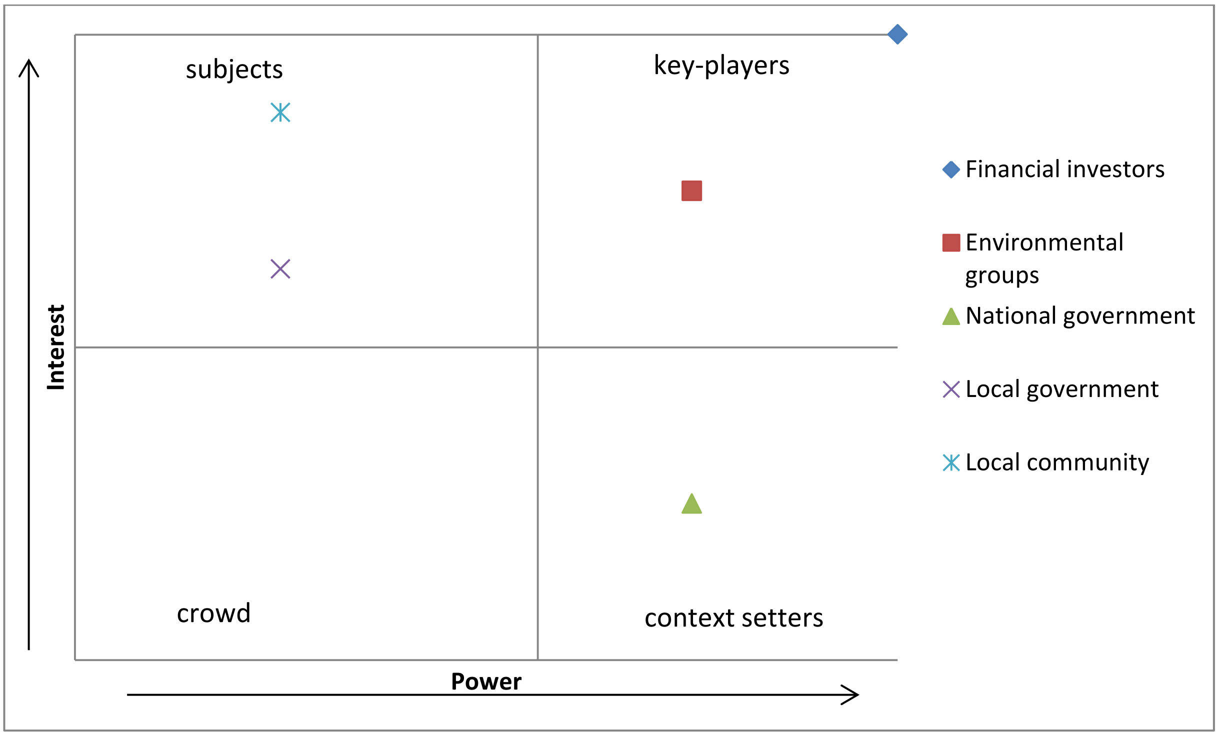


Figure 7.1: Stakeholder power and interest for scenario 1 in BioSS.3 stage

The combustion plant requires around 350,000 tonnes of biomass material per year. The plant is based around a large steam turbine generator which is fed steam by several large boiler units. The intention is that the plant will, when operating, displace some of the UK baseload coal generation and trade power on the wholesale market, benefiting from renewable obligation certificates (ROCs). To be granted ROCs the project must use a fuel blend that is more than 90% biomass by energy content (defra, 2008). The conversion plant technology will be provided by a third party who will also be involved with the plant construction under an engineering procurement and construction (EPC) contract but not the on-going ownership of the plant. The technology provider has provided specifications of the fuel that can be used under warranty in the boilers. The project must comply with all relevant legislation in the UK, namely the waste incineration directive (if waste streams are to be used as a fuel) (Directive, 2000, Grosso et al., 2010), the large combustion plant directive (EC, 2001b, McIlveen-Wright et al., 2013) and the various national and local planning policy statements including PPS22 (ODPM, 2004).

At the time of writing examples of existing projects similar to this scenario include the various projects under development by ECO2 (ECO2, 2013), the two plants being developed by Express Energy (Express-Energy, 2013), a project on the docks of the river Tees being developed by MGT power (MGT, 2013), two plants being developed by Helius energy (HeliusEnergy, 2013a, HeliusEnergy, 2013b) and the less public projects by Aker solutions (Aker, 2010) and Real ventures (Real-Ventures, 2013). Some typical plan layout schemes are shown in Table 7.1 along with an environmental group protest against a Forth Energy project.

Table 7.1: Images of large scale combustion projects in the UK

Figure 7.2: Helius Energy's Southampton project	**Figure 7.3: MGT Power River Tees Project**
Figure 7.4: Forth Energy's Rosyth biomass power station architects drawing (ADS, 2013)	**Figure 7.5: Protests against large scale biomass projects in Scotland (BBC, 2011)**

Aston University

Illustration removed for copyright restrictions

7.2.1.1 BioSS.2

At BioSS.2 stage the developer has received a high level evaluation of biomass resources that would be available to the project. No individual suppliers have been identified and numbers are approximate. BioSS.2 allows the developer to examine how the estimated fuels can be blended together to give a suitable blend for the preferred technology provider. The user selects from the pre-specified generic fuel descriptions that match those reported in the resource assessment study and assigns the relevant cost and capacity figures, alternatively if more detailed information is available they can enter their own custom information. At this stage the developers are working towards or have produced a scoping document, this is the projects first real engagement with stakeholders at any level and the first formal document produced about the project. Express Energy Ltd produced such a document for a project near Wolverhampton UK which contained the figure in Figure 7.6 and the following quote regarding the type of fuels that will be used by the project.

"GP.54 will generate energy from a range of fuels delivered by road including: recovered wood, Solid Recovered Fuel (SRF) manufactured from non-hazardous commercial wastes and biomass. The project includes facilities for manufacturing SRF on site from residual commercial waste feedstock. SRF may also be delivered to the site from third party suppliers. The maximum input of fuel and feedstock will be 250,000 tonnes per year." (Express-Energy and SKM-Enviros, 2011)

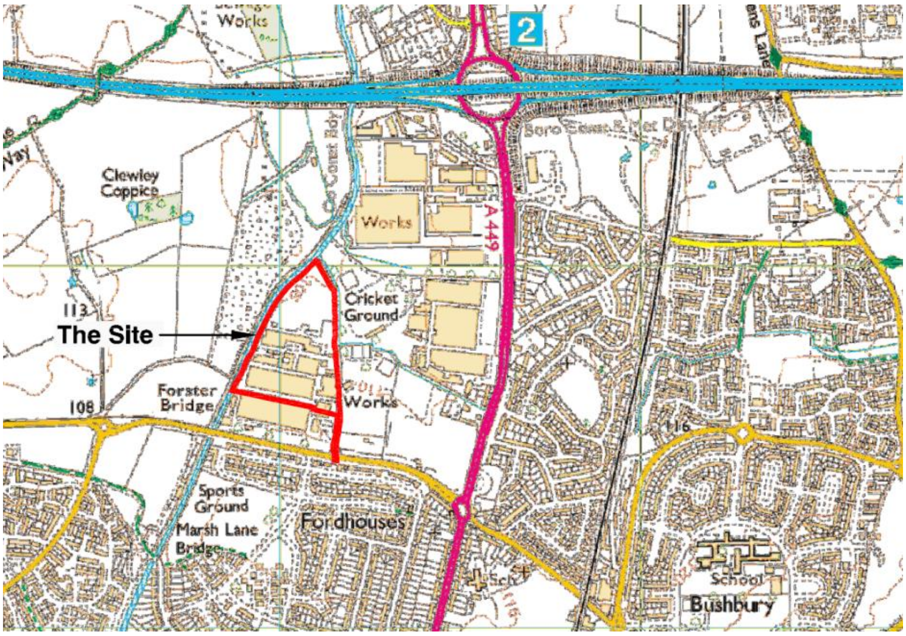


Figure 7.6: Typical site map in scoping document at BioSS.2 stage

BioSS.2 recommends the lowest cost blend given the technical constraints specified by the user. Technical constraints used are shown in Table 7.3 along with the results from the Monte-Carlo analysis that shows how frequently the recommended supplier portfolio can be expected to exceed constraints. The input data is shown in Appendix E under Table E.1 and Table E.2.

Table 7.2: available fuel sources for BioSS.2 in scenario 1.

Source Description	Capacity	Estimated unit cost	Recommended lowest cost blend
	Tonnes/ year	Cost/tonne	Tonnes/ year (% of blend)
Imported wood pellets	350,000	£55.00	132,990.1 (38.0%)
Imported wood chip	150,000	£65.00	150,000.0 (42.9%)
Waste wood available in region	50,000	£8.00	50,000.0 (14.3%)
SRF available within region	15,000	-£15.00	15,000.0 (4.3%)
SRF within 100 miles	150,000	£5.00	2,009.9 (0.6%)
RDF within region	50,000	-£10.00	0.0 (0.0%)
RDF available within 100 miles	150,000	£20.00	0.0 (0.0%)
Estimated total cost	£17,249,504		

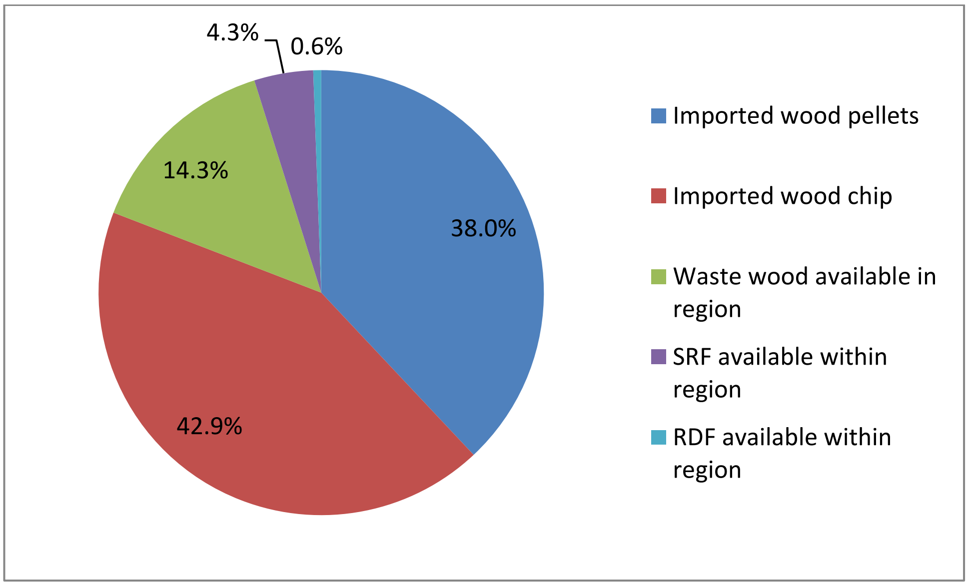


Figure 7.7: Scenario 1 BioSSS.2 blend

Table 7.3: BioSS.2 stage constraints and Monte-Carlo results (scenario 1)

	Biomass energy content	Moisture content	Lower heating value	Ash content
Units	(%)	wt%	MJ/kg	wt%
Lower limit (Chance constraint)	90.0 (1.0)	10.0 (1.0)	17.0 (1.0)	
Upper limit (chance constraint)		22.0 (1.0)	23.0 (0.9)	3.0 (1.0)
Chance constrained lowest cost recommended blend: Mean (% constraint exceeded by)	98.64 (0.0%)	18.82 (0.0%)	18.81 (0.0%)	2.28 (0.4%)

The recommended blend is dominated by imported material with some regional waste wood and a small amount of waste based fuels. The recommended portfolio takes all of the available overseas wood chip and all of the available regional waste wood and SRF. Only a small amount of the more expensive SRF delivered from further afield is taken and none of the RDF material is taken. The RDF ash content is higher than for SRF, according to the Monte-Carlo results ash content is exceeded by 0.4% and this is likely to be the reason for no RDF being selected3. The overall cost of the supply is £17,249,504. The performance of the supply blend against stakeholder requirements is not calculated as insufficient information is available on each supply to make a well judged assessment.

7.2.1.2 BioSS.3

As the project develops much more work has been completed on the project following the scoping document stage. The preferred technology supplier has been appointed and the planning permission process has formally begun. The developer is working towards a position of financial close where part or complete ownership of the project will change. At this stage the stakeholders mapped in

[3] RDF has a mean Ash content of 10% by weight whilst SRF has 7% by weight.

Figure 7.1 become influential in the developers thinking as they work towards signing contracts with different feedstock suppliers. The developer is simultaneously working on other project development areas such as construction scheduling, contractor procurement, insurance and the arrangement of financial close. The negotiation of feedstock supply can be a lengthy and complex process with clauses and caveats required to cover eventualities such as supply failure or suppliers going bankrupt or being bought out.

In the UK there is no legal requirement under planning law for companies to announce the source of material for projects beyond the tonnage being delivered and the number of lorry movements required to deliver material. At the time of writing Express Energy have the Tilbury Green Power project developed to financial close stage suitable for BioSS.3, in this case they have made a press release describing one of the main material supplier for the project as shown below.

"UK-based energy provider Tilbury Green Power (TGP) has agreed a new partnership with biomass fuel provider Hadfield Wood Recyclers.

Under the contract Hadfield will supply more than 50,000 tonnes of wood a year to TGP's new power facility in Tilbury Docks, Essex. TGP is approved to use up to 650,000 tonnes of fuel per year at the facility including SRF and biomass fuel from virgin and recovered wood."(Bioenergy-news, 2012)

Before the project can be closed the developer must have contracts for at least a proportion of biomass supply matching the level of debt gearing in the project. Signing such contracts requires the developer and supplier to work together and for the developer (the buyer) to have good access to information on the supplier.

Under BioSS.3 the developer then completes the QFD-AHP process with regards to the known stakeholder group importance shown in Figure 7.1.

The first house of quality within the QFD-AHP method (HoQ1) for scenario 1 requires that each stakeholder is given a relative importance score. This is done by the developer using the normal AHP approach, the pairwise comparison table produced is shown in Table 7.4, the normalised table for this AHP is shown in F. Table 7.4 is completed using scores agreed with Express Energy for this type of project. The importance score for each supplier is calculated and becomes the importance score used in HoQ1.

Table 7.4: Pairwise comparison for stakeholder importance in BioSS.3 scenario 1

	Financial investors	Environmental groups	National government	Local government	Local community	Developers and operators	Calculated importance score
Financial investors	1.00	3.00	6.00	7.00	4.00	8.00	0.430
Environmental groups	0.33	1.00	4.00	6.00	5.00	7.00	0.281
National government	0.17	0.25	1.00	2.00	0.50	3.00	0.078
Local government	0.14	0.14	0.50	1.00	0.25	2.00	0.048
Local community	0.25	0.20	2.00	4.00	1.00	5.00	0.132
Developers and operators	0.13	0.14	0.33	0.50	0.20	1.00	0.033
Total	2.02	4.74	13.83	20.50	10.95	26.00	1.000

The consistency ratio for this pairwise comparison is 0.052, below the 0.1 threshold for consistency.

HoQ1 is completed using the weightings and requirements identified in Chapter 5. The resulting ranking is shown in Table 7.5. The complete HoQ1 is shown in Table F.2 in Appendix F.

Table 7.6 shows the eventual results of HoQ2. Given the different influences of the stakeholder groups the most important evaluating factor for this scenario is that the supplier should be financially credible, followed by having a good track record and then by the creation or safeguarding of rural jobs and then CO_2 savings realised due to the contract being agreed.

Table 7.5: HoQ1 results for scenario 1 BioSS.3

Requirement	Requirement importance score	Rank
The supply of materials should have a low environmental impact	0.3695	1
A good supplier should be financially credible	0.1961	2
A good supplier should be able to offer an attractive b2b contract	0.1676	3
The supply of materials should have a positive social impact	0.1181	4
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.0997	5
A good supplier should be able to provide material reliably and within the quality specification required	0.0428	6
National energy security should be improved	0.0062	7

Table 7.6: HoQ2 results for scenario 1 BioSS.3

Evaluating Factor	E.F importance score	Rank
Financially robust or credible counterparty	0.142	1
CO2/MWh	0.137	2
Track record	0.093	3
Rural jobs created or safeguarded	0.079	4
Diversion of material from landfill	0.073	5
Land Use change	0.058	6
Take or pay Clauses	0.045	7
Base cost of material (£/MWh)	0.039	8
SME employment created	0.039	9
Credit strength	0.038	10
Alternative end use (Best use of biomass)	0.035	11
Fixed price	0.033	12
Guarantee of fuel quality available	0.032	13
Performance against sustainability assurance certificate indicators	0.026	14
FSC accreditation	0.02	15

Long Term Contracts	0.019	16
Size of balance sheet	0.016	17
Environmental regulatory environment in which the supplier operates	0.012	18
Traceable (chain of custody)	0.011	19
personal relationship	0.011	20
Biodiversity change	0.009	21
Visibility	0.009	22
Contract has PFI back up	0.007	23
Clear definition of fuel	0.006	24
Dependency on imports	0.005	25
Supplier stability (in biomass market)	0.004	26
Quality control mechanisms in place	0.002	27
Distance from buyer	0.001	28

A shortlist of 10 suppliers have been identified as suitable for consideration as suppliers to the project. Each of these suppliers is then compared against each evaluating criteria from Table 7.6. Because a fairly large shortlist was created and because of the likelihood of suppliers being added or removed from the shortlist during the negotiation period up to financial close the AHP method is unsuitable for assigning scores in this case. Express Energy decided that a suitable system for them would be a simple 1 to 10 scale for each evaluating factor. This allows for those evaluating factors that are Boolean to be handled by assigning either 1 or 10 and allows the decision maker to rapidly assign scores. Ultimately 280 weightings must be assigned to complete the final scoring chart, therefore ease of completion and rapid assessment is important. If using the AHP to assign scores it is unlikely that responses would be consistent in all cases and also unlikely that the process would be repeated were the shortlist to change. The 1 to 10 assessment scale is easily repeated for new suppliers, requiring only 28 new judgements. The score given to each supplier for each evaluating factor is then normalised against the scores given to the other suppliers to give a weighted score up to 1 of relative performance against that evaluating criteria. These normalised scores are then multiplied by the evaluating factor importance from HoQ2 to give an overall score for each supplier. The complete score charts are shown in Appendix F in Table F.4 and Table F.5. The results from HoQ3 are shown in Table 7.7.

The fuel characteristics for each supplier are shown in Appendix E under Table E.3 and Table E.4. The results of the optimisation model are shown in Table 7.8 with the Monte-Carlo analysis results shown in Table 7.9.

Table 7.7: HoQ3 results for scenario 1

Biomass supply	Score	Rank
Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	0.1109	1
Established regional SRF producer [LHV 2, Cl 3, Hg 2]	0.1097	2
Established regional RDF with high biomass content producer	0.1092	3
National wood chip supplier	0.105	4
Imported hardwood pellets (Canada)	0.1039	5
National demolition wood aggregator	0.1035	6
Imported wood pellets (compliant with Italian A standard)	0.0942	7
Imported olive residue (Greece)	0.094	8
Start-up waste management company - SRF	0.0936	9
Local small demolition wood aggregator	0.076	10

Table 7.8: Recommended portfolio for scenario 1 at BioSS.3 stage

Source Characteristics	Supplier score	Capacity	Recommended portfolio (% of blend)
Units		Tonnes/yr	Tonnes/yr
Imported wood pellets (compliant with Italian A standard)	0.0942	140,000	80,911.8 (23.1%)
Imported hardwood pellets (Canada)	0.1039	100,000	100,000.0 (28.6%)
Imported olive residue (Greece)	0.0940	150,000	0.0 (0.0%)
National wood chip supplier	0.1050	100,000	100,000.0 (28.6%)
Local small demolition wood aggregator	0.0760	130,000	0.0 (0.0%)
National demolition wood aggregator	0.1035	100,000	19,107.6 (5.5%)
Start-up waste management company - SRF	0.0936	200,000	0.0 (0.0%)
Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	0.1109	300,000	11,400 (3.3%)
Established regional SRF producer [LHV 2, Cl 3, Hg 2]	0.1097	80,000	1,657.6 (0.5%)
Established regional RDF with high biomass content producer	0.1092	250,000	36,922.3 (10.5%)
Total cost	£9,664,302		
Portfolio score	3,596.9		

Table 7.9: Results of Mnote-Carlo analysis on recommended portfolio for BioSS.3 scenario 1

Blend characteristic	Lower constraint (chance constraint)	Upper Constraint (chance constraint)	Blend mean	Expected percentage of blend exceeding constraints
Biomass Energy content	90 (1.0)		95.17	0.0%
Moisture content	7 (1.0)	20 (0.95)	17.75	0.0%
Lower heating value	15 (0.95)	23 (0.95)	17.79	0.0%
Ash content		4 (0.95)	3.46	6.38%
Sulphur (S)		500 (1.0)	116.73	0.0%
Chlorine (Cl)		1,500 (1.0)	1,069.57	0.0%
Fluorine (F)		1,500 (1.0)	4.35	0.0%
Sodium (Na)		3,000 (1.0)	51.46	0.0%

Potassium (K)		3,000 (1.0)	145.79	0.0%
Mercury (Hg)		2 (1.0)	0.55	0.0%
Cadmium (Cd)		5 (1.0)	0.21	0.0%
Zinc (Zn)		750 (1.0)	0.22	0.0%
Tin (Sn)		500 (0.9)	0.29	0.0%
Aluminium (Al)		1,000 (0.9)	14.29	0.0%

The Monte-Carlo analysis shows that the ash content can be expected to exceed the limit of 4% by weight, 6.38% of the time. The chance constraint for this limit is 0.95, therefore the blend is compliant with constraints for all but 1.38% of the time, if this is acceptable for for the buyer they may progress, if not the model could be run again with a higher sample number, or the portfolio could be modified manually. The histogram for ash content from the Monte-Carlo analysis is shown in Figure 7.8. Figure 7.9 shows the distributions of ash content for the recommended suppliers, the imported pellets do not have distribution data and is therefore not shown as a distribution. All other characteristics are within the specified constraints. Ash content is therefore the binding constraint, preventing a higher objective function being obtained, the ash content constraint is therefore the binding constraint in this case. In normal linear programming problems binding constraints allow the dual price to be calculated. This is the amount by which the objective function could be improved if the constraint were relaxed by a single unit (Hillier et al., 1990). This shows the developer that a better portfolio could be selected if a technology that could accept higher ash content feedstock could be selected. This type of calculation is not possible in chance-constrained programming as the constraint is already breached some of the time.

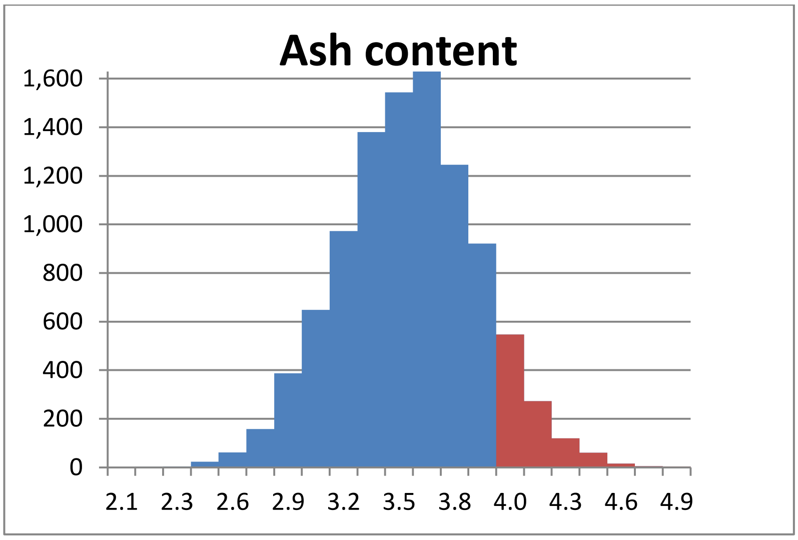


Figure 7.8: Histogram of ash content for BioSS.3 scenario 1

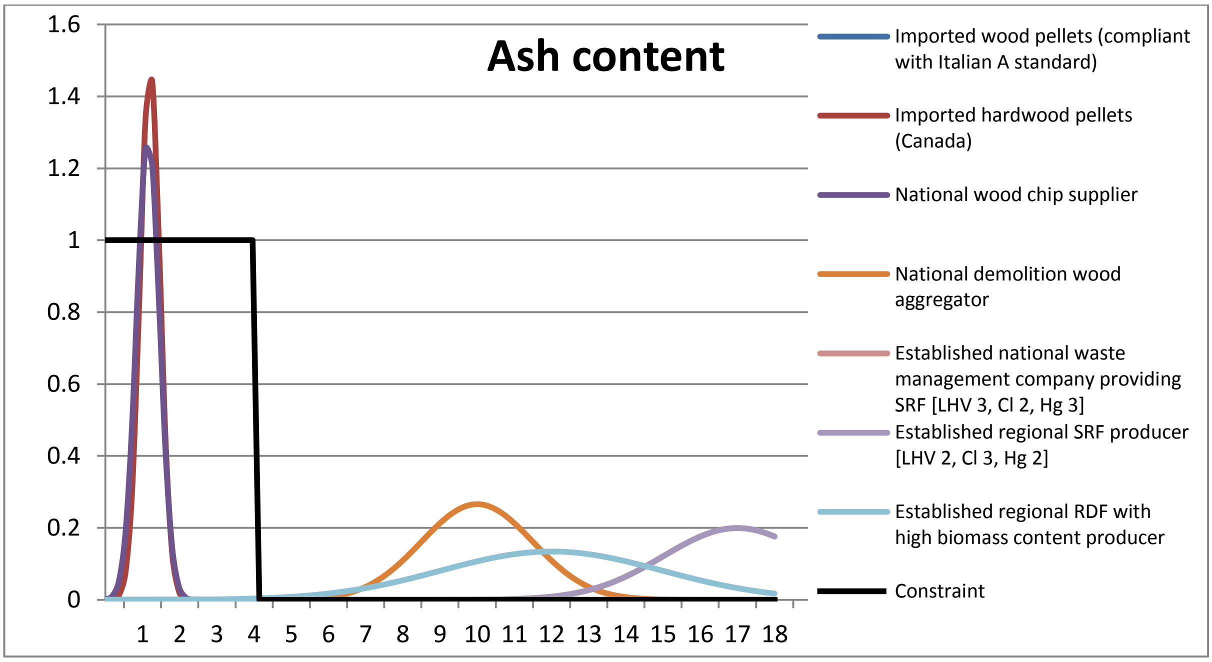


Figure 7.9: Ash content of recommended suppliers

7.2.1.3 BioSS.Op

As described in chapter 6 the financial close and negotiation period is not expected to be smooth nor to exactly follow the recommendations made by BioSS.3. The recommended portfolio is intended as a tool to aid decision making and is useful for rapid appraisal of fuel portfolio and technology options. In the operational phase of the project the operator must secure material for the percentage of total fuel supply that is not locked into contract. Having navigated through financial close the stakeholder map for the operating plant is different to that of the proposed project. Some stakeholders have lost or gained power and some have lost or gained interest. The operational phase stakeholder salience scores are plotted in Figure 7.10. This change in stakeholder importance changes the preference weighting score given to each supplier.

To demonstrate the BioSS.Op in this scenario the same fuel providers are assumed to be available, two suppliers remain in contract and provide 39% of the total material supply. The constraints remain the same for the plant as in BioSS.2 but the supplier preference scores have changed as shown in Table 7.10. The resulting supplier weightings calculated from HoQ3, using the same scoring as given in BioSS.3 are shown in Table 7.11. For completeness the HoQ1 and HoQ2 data for BioSS.Op is shown in Appendix F under Table F.6 and Table F.7 respectively.

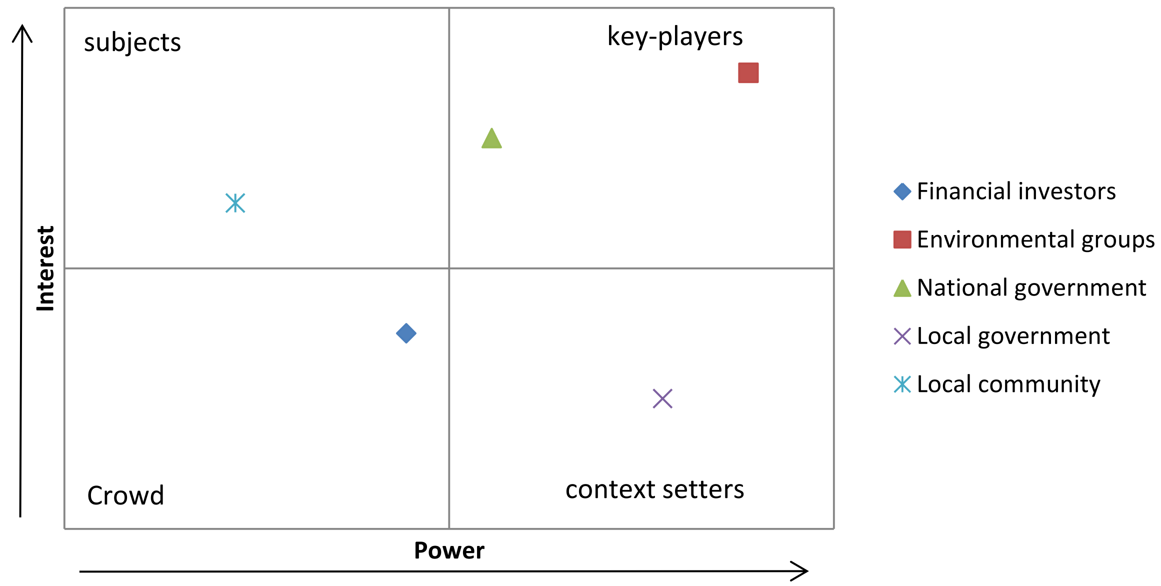


Figure 7.10: Stakeholder interest and power for operational project in scenario 1

Table 7.10: Pairwise comparison for stakeholder importance in BioSS.Op scenario 1

	Financial investors	Environmental groups	Developers and operators	National government	Local government	Local community	Calculated importance score
Financial investors	1.00	0.11	0.14	0.13	0.25	0.50	0.028
Environmental groups	9.00	1.00	5.00	3.00	6.00	7.00	0.448
Developers and operators	7.00	0.20	1.00	0.50	4.00	5.00	0.172
National government	8.00	0.33	2.00	1.00	4.00	5.00	0.225
Local government	4.00	0.17	0.25	0.25	1.00	3.00	0.083
Local community	2.00	0.14	0.20	0.20	0.33	1.00	0.045
Total	31.00	1.95	8.59	5.08	15.58	21.50	1.00

The consistency ratio for this pairwise comparison is 0.063, below the 0.1 threshold for consistency.

Table 7.11: Recommended portfolio for BioSS.Op scenario 1

Source Characteristics	Supplier score	Capacity or contract	Recommended portfolio (% of blend)
Units		Tonnes/yr	Tonnes/yr
Imported wood pellets (compliant with Italian A standard)	0.0966	140,000	4,455.2 (0.0%)
Imported hardwood pellets (Canada)	0.1077	100,000	100,000.0 (28.6%)
Imported olive residue (Greece)	0.0999	94,747.5 (Locked)	94,747.5 (27.1%)
National wood chip supplier	0.1081	100,000	100,000.0 (28.6%)
Local small demolition wood aggregator	0.0730	130,000	0.0 (0.0%)
National demolition wood aggregator	0.1041	100,000	0.0 (0.0%)
Start-up waste management company - SRF	0.0902	200,000	2,355.5 (0.7%)
Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	0.1074	300,000	5,025.3 (1.4%)
Established regional SRF producer [LHV 2, Cl 3, Hg 2]	0.1058	80,000	0.0 (0.0%)
Established regional RDF with high biomass content producer	0.1074	43,417.4 (Locked)	43,417.4 (12.4%)
Total cost	£6,607,059		
Portfolio score	3,653		

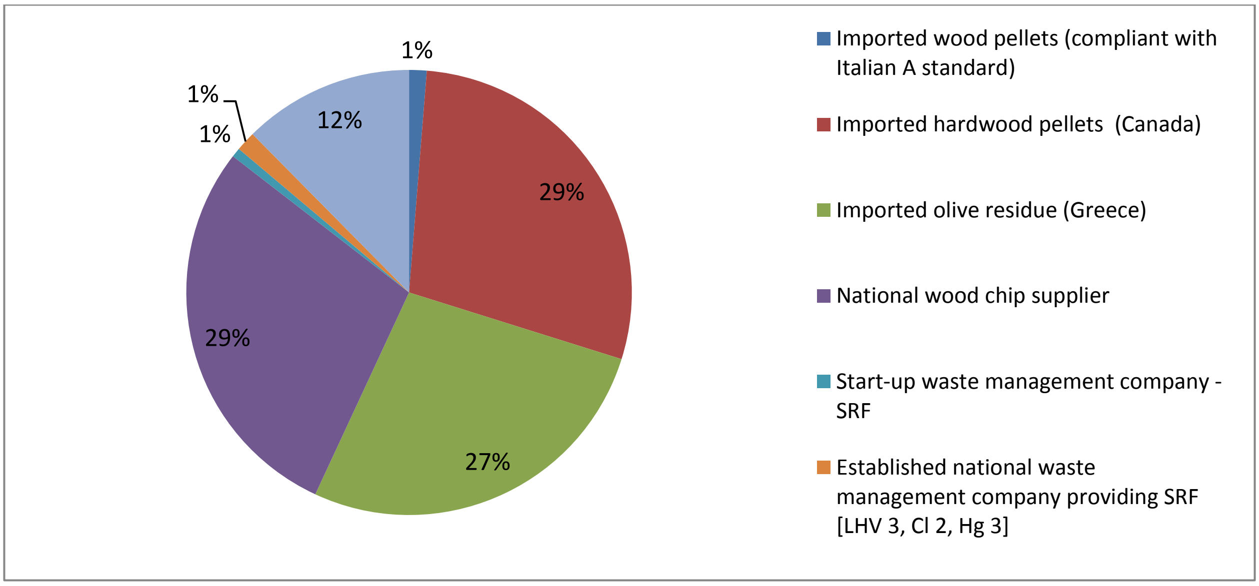


Figure 7.11: Recommended blend for BioSS.Op scenario 1

For the blend recommended in BioSS.3 the ash content is again the binding constraint with 5.20% of the blend material expected to be outside of the 4% as content constraint. Again this indicates an inaccuracy in the chance constrained program although the blend only exceeds the 5% (0.95) allowance by 0.2%. All other constraints are not exceeded.

7.2.2 Scenario 2

The project for scenario 2 is a proposed 3MW gasification plant that will be operated as a combined heat and power (CHP) project in an urban centre, linking to an existing district heating network and associated heat users. The gasification technology is sensitive to levels of pollutants in the feedstock but can handle a wider range of calorific values and ash contents compared to the combustion technology being used in scenario 1 but a lower limit of pollutants is allowed in the fuel. No operating warranty is offered by the technology supplier. The project is to be majority financed with equity investment from a large engineering company who will also take responsibility for the construction and operation of the plant. Revenue will be generated from electricity sales and the associated ROC incentives and also heat sales and the associated renewable heat incentive (RHI) payments. The expected capital cost of the project is circa £15-25m. The plant requires a homogenous pelletized fuel. Therefore there is a shredding and pelletizing pre-treatment process upstream of the gasification process that binds the biomass material together and aims to mix the material as much as possible. BioSS is to be used to determine the strategic supply of material into this pelletizer.

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Figure 7.12: A dual shaft shredder (Vecoplanllc, 2013)

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Figure 7.13: A die head from a pellet mill (Vecoplanllc, 2013)

The importance of the various stakeholder groups in this project is different to that in scenario 1. Here the requirements of the local population and local government is very important as they will be required to engage as heat customers from the completed project and will also be required to not object to planning application and operations. National government does not have any real influence over projects at this scale as it falls below the 50MW threshold for infrastructure power projects which must be referred to central government planning (DECC, 2011b). Environmental groups again hold influence over this type of project, especially as it is in an urban environment. The power-interest grid for this scenario is shown in Figure 7.14.

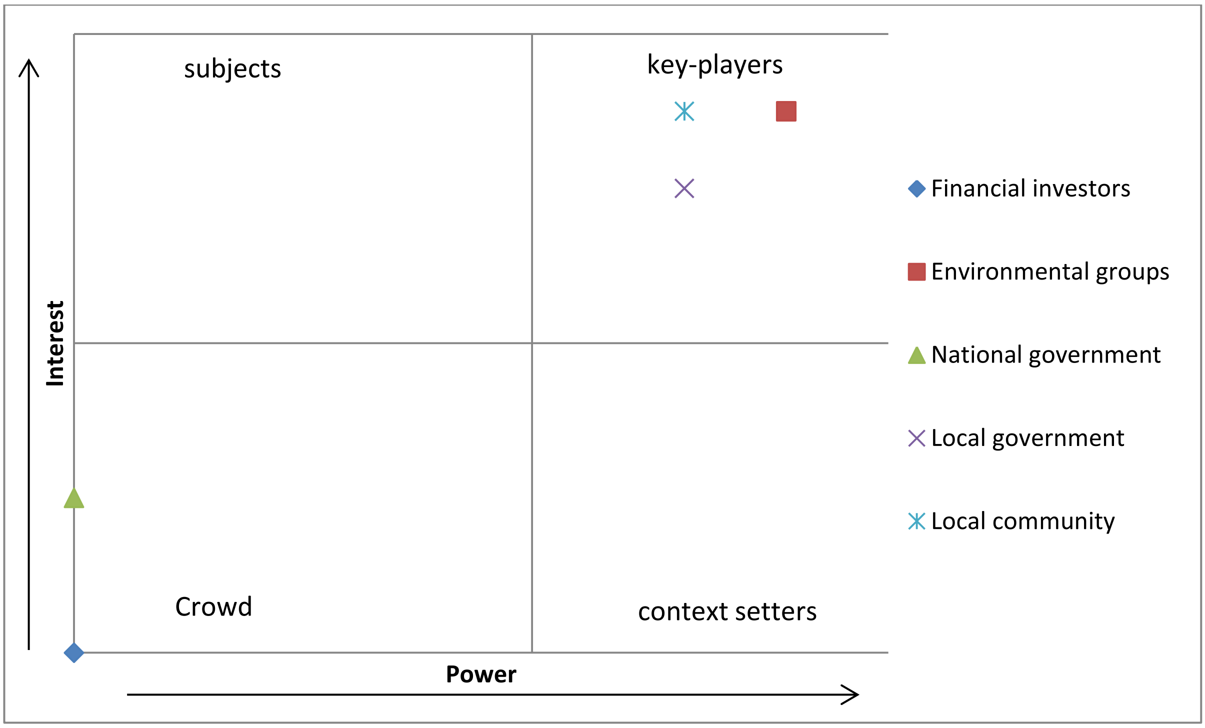

Figure 7.14: Stakeholder interest and power for scenario 2

This scenario demonstrates how the BioSS decision framework can be applied to different technology types that have different constraint values including total demand. To remain consistent with scenario 1 to allow some level of comparison to be made between the two scenario's the available fuel data is the same as in scenario 1. The total demand is 3,500 tonnes per year and the approximate electrical capacity is 3MW with an additional 6MW of heat also produced heating local buildings and processes. The capacity of the suppliers is reduced by 100 fold to reflect the reduced demand of the project in scenario 2.

At the time of writing this type of scheme is only at the proposal stage in the UK, no commercially operating waste to energy gasifiers are currently operational (RESTATS and DECC, 2013a). There are several applications and proposals in place for this type of technology at this type of scale including projects in Hull (EnergyWorks, 2013), Liverpool (Biossence, 2010) and Middlesbrough (Airproducts, 2010). Gasification technology is often co-located with other waste to energy and recycling technologies to treat residual organic wastes (Banks, 2010, Chinook-Energy, 2010, World, 2012). Some images from such project proposals and scoping documents are shown in Figure 7.15, Figure 7.16 and Figure 7.17 below.

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Figure 7.15: The Airpoducts proposal for the Tees Valley (Airproducts, 2010)	**Figure 7.16: The Rodecs® gasification system (Chinook-Energy, 2010)**
Figure 7.17: The Hull Energy Works project (EnergyWorks, 2013)	

7.2.2.1 BioSS.2

The same type of resource assessment exercise has been completed as for the BioSS.2 stage in scenario 1. The supply characteristics are the same as in scenario 1 and are shown in Table E.1 and Table E.2 in Appendix E. The recommended blend is shown in Figure 7.18 and Table 7.12 along with capacities and estimated costs. The constraints for the conversion technology being investigated in scenario 2 are shown in Table 7.13 along with the Monte-Carlo analysis results.

Table 7.12: Material supply, capacity, cost and recommended portfolio for scenario 2 at BioSS.2 stage

Source Description	Capacity	Estimated unit cost	Recommended lowest cost blend
	Tonnes/ year	Cost/tonne	Tonnes/ year (% of blend)
Imported wood pellets	3,500	£55.00	2389.2 (68.3%)
Imported wood chip	1,500	£65.00	0.0 (0.0%)
Waste wood available in region	500	£8.00	500.0 (14.3%)
SRF available within region	150	-£15.00	150.0 (4.3%)
SRF within 100 miles	1,500	£5.00	349.0 (10.0%)
RDF within region	500	-£10.00	111.8 (3.2%)
RDF available within 100 miles	1,500	£20.00	0.0 (0.0%)
Estimated total cost	£133,782		

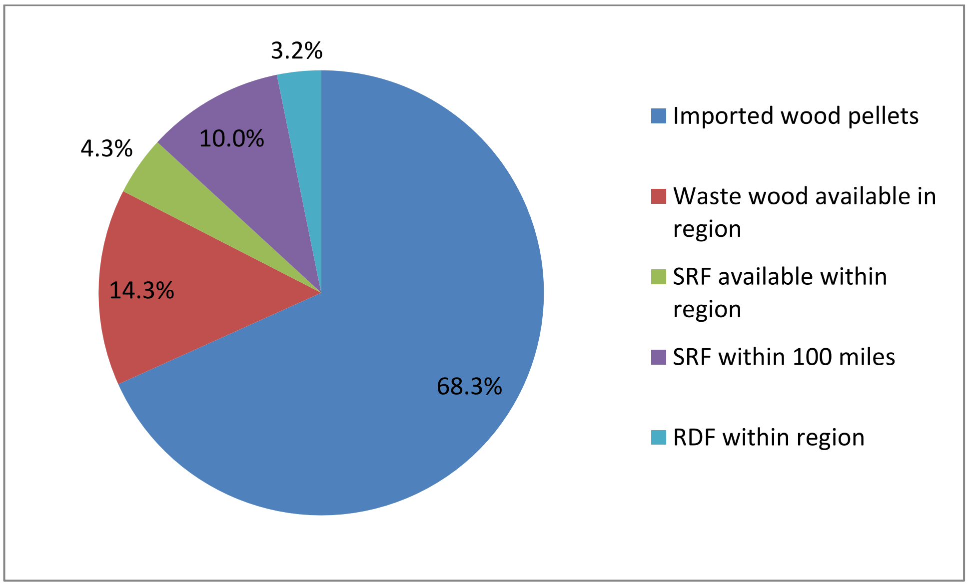

Figure 7.18: Recommended portfolio for BioSS.2 scenario 2

The recommended portfolio is dominated by wood pellets. From the Monte-Carlo analysis results shown in Table 7.13 it appears that moisture content is the restricting constraint, the blend exceeding this constraint 20% of the time, exactly the exceedence allowed by the chance constraint. Biomass Energy content however does breach the chance constraint (of 1.0), but only by around 0.5%.

Lower heating value exceeds the constraint within the chance constraint limits (0.4% out of 20%[0.8]). The histograms for biomass energy content and moisture content are shown in Figure 7.19 and Figure 7.20 respectively. The developer can now begin to search the market for individual suppliers that can approximately match the portfolio recommended by BioSS.2.

Table 7.13: Constraints and Monte-Carlo results for BioSS.2 scenario 2

Blend characteristic	Lower constraint (chance constraint)	Upper constraint (chance constraint)	Blend mean	Expected percentage of blend exceeding constraints
Biomass energy content	90 (1.0)		94.48	0.0%
Moisture content	10.0 (0.8)	20.0 (0.8)	18.74	20.01%
Lower heating value	17.0 (0.8)	23.0 (0.8)	18.83	0.41%
Ash content		10.0 (1.0)	3.84	0.0%

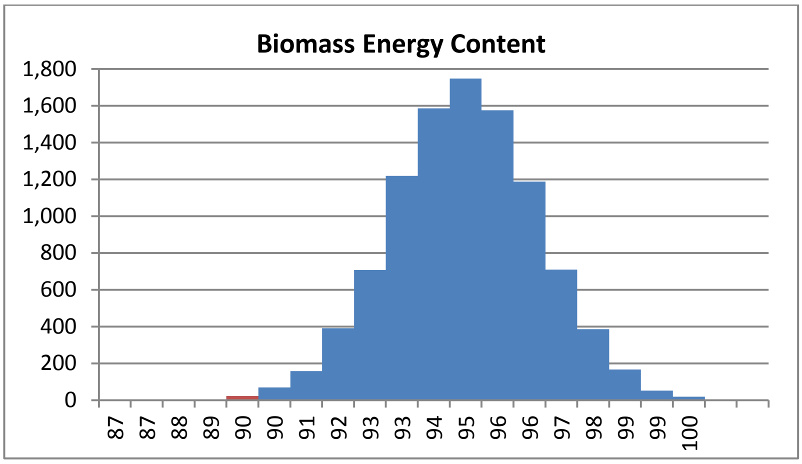

Figure 7.19: Biomass energy content histogram from BioSS.2 scenario 2

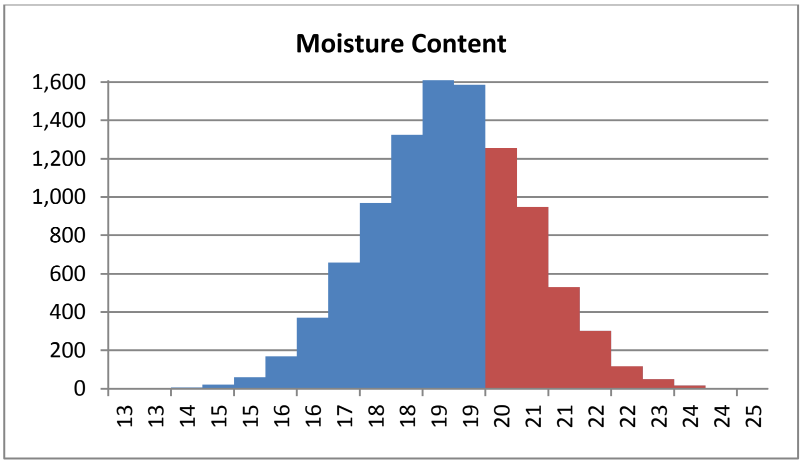

Figure 7.20: Moisture content histogram from BioSS.2 Scenario 2

7.2.2.2 BioSS.3

As in scenario 1 the developer has identified 10 different suppliers with whom the project could contract for material. The total amount of material available is greater than estimated at the BioSS.2 stage and there is sufficient material within the local region to meet the demand, the international pellet market is also available although the cost is high for small order quantities. To allow for a comparison with scenario 1 the same data has been used for chemical characteristics and price but the stakeholder importance has changed. This will allow the impact of changing stakeholder salience to be observed in the resulting portfolios. For completeness the data used and the supplier descriptions are given in Appendix F under Table F.9.

As in scenario 1 each stakeholder group has been given an importance score according to advice from Express Energy and the stakeholder map shown in Figure 7.10. Table 7.14 shows the stakeholder importance AHP table for scenario 2.

The re-allocation of stakeholder importance means that the evaluating factor weighting has also changed. The results of HoQ1 for scenario 2 in BioSS.2 stage are shown in Table 7.15 and the results of HoQ2 in Table 7.16.

Table 7.14: AHP to calculate stakeholder importance for BioSS.3 scenario 2

	Financial investors	Environmental groups	National government	Local government	Local community	Developers and operators	Importance score
Financial investors	1.00	0.11	0.33	0.17	0.13	0.20	0.027
Environmental groups	9.00	1.00	8.00	3.00	2.00	4.00	0.377
National government	3.00	0.13	1.00	0.13	0.13	0.33	0.043
Local government	6.00	0.33	8.00	1.00	1.00	4.00	0.216
Local community	8.00	0.50	8.00	1.00	1.00	5.00	0.250
Developers and operators	5.00	0.25	3.00	0.25	0.20	1.00	0.088

This pairwise comparison has a consistency ratio of 0.063, below the required 0.1 threshold.

Table 7.15: HoQ1 results for BioSS.3 scenario 2

Requirement	Requirement importance score	Rank
The supply of materials should have a low environmental impact	0.636	1
The supply of materials should have a positive social impact	0.258	2
National energy security should be improved	0.028	3
A good supplier should be financially credible	0.028	4
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.028	5
A good supplier should be able to offer an attractive b2b contract	0.021	6
A good supplier should be able to provide material reliably and within the quality specification required	0.01	7

Table 7.16: Results from HoQ2 for BioSS.3 scenario 2

Evaluating Factor	E.F importance score	Rank
CO2/MWh	0.237	1
Rural jobs created or safeguarded	0.172	2
Diversion of material from landfill	0.125	3
Land Use change	0.099	4
SME employment created	0.086	5
Alternative end use (Best use of biomass)	0.059	6
Performance against sustainability assurance certificate indicators	0.044	7
FSC accreditation	0.035	8
Environmental regulatory environment in which the supplier operates	0.021	9
Financially robust or credible counterparty	0.02	10
Biodiversity change	0.016	11
Dependency on imports	0.016	12
Track record	0.011	13
Base cost of material (£/MWh)	0.011	14
Visibility	0.01	15
Fixed price	0.009	16
Guarantee of fuel quality available	0.008	17
Take or pay Clauses	0.006	18
Credit strength	0.005	19
Long Term Contracts	0.004	20
Distance from buyer	0.003	21
Traceable (chain of custody)	0.002	22
Size of balance sheet	0.002	23
Contract has PFI back up	0.002	24
Clear definition of fuel	0.002	25
personal relationship	0.001	26
Supplier stability (in biomass market)	0.001	27
Quality control mechanisms in place	0.001	28

In contrast to scenario 1 at the BioSS.3 stage evaluating factors relating to environmental and social performance are now considered most important for the success of the final fuel portfolio. The CO_2 equivalent per unit of energy in the fuel is the highest ranked evaluating factor whilst rural job creation is the second most important and diversion of waste materials from landfill is the third. The least important evaluating factors are those softer aspects of the supplying companies' reputation and auditable aspects such as quality mechanisms, balance sheet size and stability within the biomass market. The new suppliers weighting according to the new evaluating factor importance scores is shown in Table 7.17 along with the recommended portfolio, supplier capacities and the unit cost for each supplier.

Table 7.17: Results for BioSS.3 scenario 2

Source Characteristics	Supplier score	Capacity	Recommended portfolio (% of blend)
Units		Tonnes/yr	Tonnes/yr
Imported wood pellets (compliant with Italian A standard)	0.0763	1,400	0.0 (0.0%)
Imported hardwood pellets (Canada)	0.1069	1,000	919.9 (26.3%)
Imported olive residue (Greece)	0.0941	1,500	0.0 (0.0%)
National wood chip supplier	0.1263	1,000	1,000.0 (28.6%)
Local small demolition wood aggregator	0.0973	1,300	0.0 (0.0%)
National demolition wood aggregator	0.0937	1,000	140.8 (4.0%)
Start-up waste management company - SRF	0.0882	2,000	0.0 (0.0%)
Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	0.1000	3,000	0.0 (0.0%)
Established regional SRF producer [LHV 2, Cl 3, Hg 2]	0.1027	800	0.0 (0.0%)
Established regional RDF with high biomass content producer	0.1222	2,500	1,439.3 (41.1%)
Total cost	£37,016		
Portfolio score	413.7		

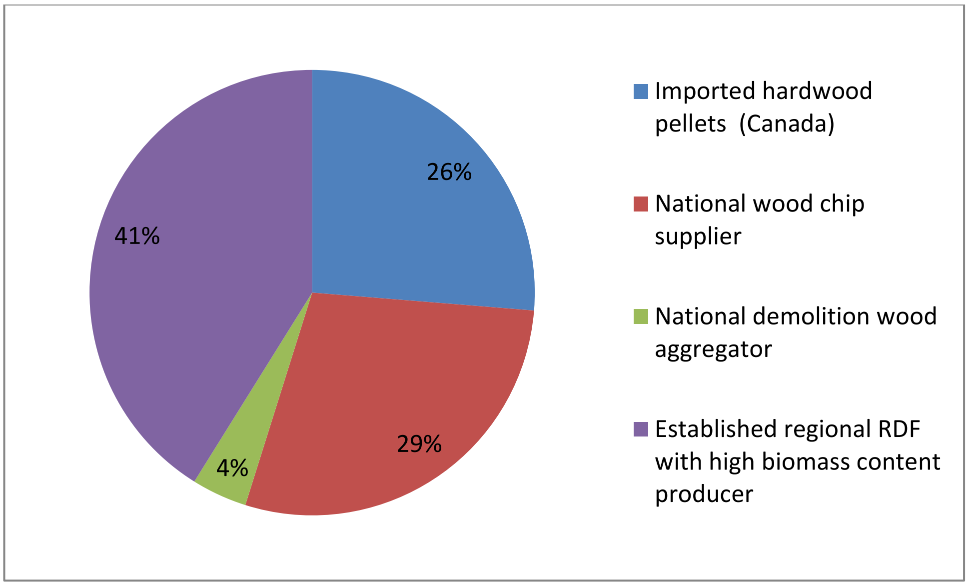

Figure 7.21: Recommended portfolio BioSS.3 scenario 2

The results of the Monte-Carlo analysis run on the recommended blend are shown in Table 7.18 along with the constraints and chance constraints (shown in parenthesis). The recommended blend exceeds the constraint for lower heating value, ash content and chlorine contents. All of these variables are within the chance constraints. The histogram for the chlorine content of the blend is shown in Figure 7.22, this constraint is exceeded 8.9% of the tine, within the 10% (0.9) permitted chance constraint limit and may be the binding constraint.

Table 7.18: Results of Monte - Carlo analysis for BioSS.3 scenario 2

Blend characteristic	Lower constraint (chance constraint)	Upper Constraint (chance constraint)	Blend mean	Expected percentage of blend exceeding constraints
Biomass Energy content	90 (1.0)		94.48	0.0%
Moisture content	8 (0.8)	20 (0.8)	16.37	0.0%
Lower heating value	14 (0.8)	23 (0.8)	16.35	0.76%
Ash content		10 (1.0)	6.01	0.06%
Sulphur (S)		50 (1.0)	0.33	0.0%
Chlorine (Cl)		150 (0.9)	129.98	8.94%
Fluorine (F)		150 (1.0)	3.95	0.0%
Sodium (Na)		200 (1.0)	47.18	0.0%

Potassium (K)		200 (1.0)	133.99	0.0%
Mercury (Hg)		0.2 (1.0)	0.02	0.0%
Cadmium (Cd)		0.75 (1.0)	0.46	0.0%
Zinc (Zn)		50 (1.0)	0.2	0.0%
Tin (Sn)		50 (1.0)	0.26	0.0%
Aluminium (Al)		35 (0.9)	13.13	0.0%

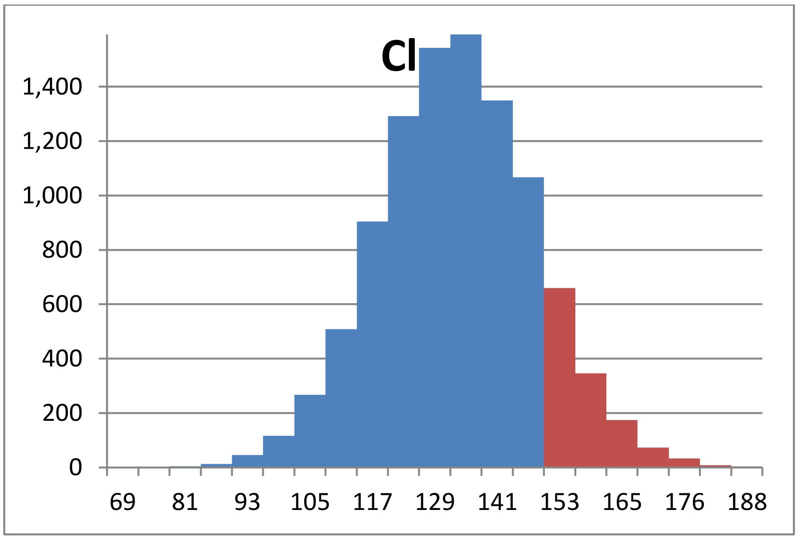

Figure 7.22: Chlorine histogram

7.2.2.3 BioSS.Op

The stakeholder weighting in the BioSS.Op stage for scenario 2 does not change from the BioSS.3, the project remains in the ownership of the turn-key engineering firm and the local community, local government and environmental groups still hold the same interest and influence over the project success and therefore the solution remains optimal providing the properties of the supplier and the material being supplied do not change.

7.3 Summary of results and discussion

The BioSS framework has been applied to two lifelike scenarios that reflect activities underway in the bioenergy industry of the UK. At the early project stage the BioSS is used to make an estimate of the cheapest portfolio of materials that the developer could achieve given the limited data available. As the project develops more data is collected and the entire, fully specified model can be applied. At the BioSS.3 stage the framework was seen to prefer suppliers that had a high supplier preference score and avoid those with a lower score. The technical constraints of the technologies were met within 2% in all of the models run. This percentage could be decreased by increasing the sample number above 300 but this would be at the expense of computation time. A summary of results for the two scenarios and the different BioSS modes is shown in Table 7.19.

Table 7.19: Results

BioSS mode	BioSS.2			BioSS.3			BioSS.Op		
Result	Score per tonne	Total cost	Cost per tonne	Score per tonne	Total cost	Cost per tonne	Score per tonne	Total cost	Cost per tonne
Scenario 1	N/A	£14,249,504	£40.7	0.10276	£9,664,302	£27.61	0.10438	£6,607,059	£18.9
Scenario 2	N/A	£133,782	£38.22	0.11821	£37,016	£10.58	0.11821	£37,016	£10.58

Because the input data for material characteristics and relative supply vs. demand remained the same between the two scenarios the difference in results is caused only by changing the weightings of different suppliers. Stakeholder weighting changed between BioSS.3 and BioSS.Op of scenario 1 and between scenario 1 and scenario 2. Technology constraints changed between scenario 1 and scenario 2.

The gasifier technology described for scenario 2 permits the constraints to be less rigidly enforced for moisture content and heating value and also for a wider range of ash contents but required a much tighter control of pollutant levels within the fuel blend. The constraints for the two technologies (as at BioSS.3 stage) are shown in Table 7.20 along with the chance constraints.

Table 7.20: Comparison of constraints

Constraint	Scenario 1		Scenario 2	
	Lower limit	Upper limit	Lower limit	Upper limit
Biomass Energy Content	90 (1.0)		90 (1.0)	
Moisture Content	7 (1.0)	20 (0.95)	8 (0.8)	20 (0.8)
Lower heating value	15 (0.95)	23 (0.95)	14 (0.8)	23 (0.8)
Ash content		4 (0.95)		10 (1.0)
S		500 (1.0)		50 (1.0)
Cl		1500 (1.0)		150 (0.9)
F		1500 (1.0)		150 (1.0)
Na		3000 (1.0)		200 (1.0)
K		3000 (1.0)		200 (1.0)
Hg		2 (1.0)		0.2 (1.0)
Cd		5 (1.0)		0.75 (1.0)
Zn		750 (1.0)		50 (1.0)
Sn		500 (0.9)		50 (1.0)
Al		1000 (0.9)		35 (0.9)

The different technology constraints between the two technology options means that different chemical constraints become binding (or active) and non-binding (or redundant) in the different scenarios. The same happens if a different shortlist of available suppliers is available. In scenario 1 ash content is observed to be the binding constraint limiting the objective function, in scenario 2 the chlorine content of the blend is likely to be the binding constraint.

The different technology constraints allow for a better performing fuel blend to be selected in scenario 2. The portfolio score for scenario 2 has a 14% improvement over the portfolio recommended for scenario 1 in BioSS.3. In scenario 1 there is only a small improvement between BioSS.3 stage and BioSS.Op stage, this is because only a fraction of the fuel blend is being re-negotiated and the ash content remains the binding constraint, excluding some higher performance suppliers.

As would be expected when accounting for a variety of stakeholder requirements in the decision making process there is not a clear relationship between the cost of recommended portfolio and the portfolio performance. In the cases presented in this chapter the BioSS.3 model has recommended a portfolio for scenario 2 that has a better stakeholder satisfaction score and is also less than half the price per tonne of the portfolio recommended in scenario 1. This again shows the benefit of using a flexible conversion technology that can accept wider ranges of feedstock. This is also reflected at the BioSS.2 stage where scenario 2 is able to use a cheaper solution than for scenario 1.

The 1-10 scoring system for scoring suppliers against evaluating criteria was clear and straightforward in that it does not require metrics or complex scales and automatically normalises the decision makers responses. However this convenience could be at the expense of reliability and consistency. The BioSS could easily be adapted to incorporate other weighting methods for this purpose but the potential number of suppliers and the possible addition and removal of suppliers should be considered.

When running the fully specified model in BioSS.3 computation time for the optimisation phase was around 15 minutes using a sample size of 300 (meaning 300 deterministic linear programming models are created and solved). The Monte-Carlo analysis part of BioSS then required around 30 minutes to complete for 10,000 iterations on each fuel characteristic. These times can be reduced by running a smaller sample size or less iterations, this would compromise on accuracy but would give the user a quicker answer if required. Outside of computation time there is a large time and effort commitment required to judge each supplier against the evaluating criteria. From comments by Express Energy some of these evaluating criteria can be assessed at a desktop level, through company searches or electronic correspondence but many of them should only be assessed through site visits or the negotiation of contracts. These activities occur regardless of the deployment of BioSS and therefore only a small additional time requirement is added in data entry. Given the importance of the decisions being made by biomass buyers such a time commitment is well justified. The BioSS also gives the buyer a structure against which to assess suppliers, allowing a more objective and thorough assessment to be made.

Utilising BioSS at this stage allows the developer to design a portfolio that suits the stakeholder group much more accurately than is possible using the current approach of ad-hoc contract negotiations. In the current approach suppliers compete for contracts with one another based on price and some loose perception of quality and reliability. In reality the market is so young and the material so variable that any single judgement of reliability or quality is difficult for buyers to make. The approach used in BioSS negates this problem by splitting the evaluation into discrete evaluating factors for the buyer to use when assessing suppliers. The whole framework is made more efficient if a standard set of relationship strengths can be re-used for many projects, this means that the various AHP interrelationship matrices in HoQ1 and HoQ2 do not need to be repeated in order to generate a recommended portfolio, saving time.

Using the BioSS gives the biomass buyer the ability to efficiently assess new suppliers against existing supply portfolios (in BioSS.Op), technology constraints and stakeholder requirements. The framework can also assist in evaluating different technology options against the available or contracted biomass supply. No such analytical method currently exists in academia or industry.

7.4 Conclusion

This chapter has demonstrated the application of the BioSS framework to two lifelike scenarios being faced by UK bioenergy buyers. At the early project stage a trimmed down version of the complete BioSS framework is applied to give a suggestion for how the project developer could proceed and how the selected technology could fit within the available biomass resource. Later in project development, towards the build stage the fully specified BioSS is demonstrated. The framework is shown to select a portfolio that complies with the technical constraints whilst also being the best performing blend of material according to the stakeholder group of the project.

BioSS is shown to be a flexible and relevant decision support tool for biomass buyers in various stages of the project. As stakeholder importance changes through the project life the BioSS is able to handle these changes through a single AHP that re-allocates stakeholder importance. In the case that suppliers become unavailable or available for any reason the performance can calculated and incorporated into BioSS using a simple 1-10 scale. This avoids the need to re-assess all the available suppliers each time one supplier changes their offering or becomes available.

The reported findings from the demonstration of BioSS in the two scenarios indicate the impact that taking the approach outlined in BioSS can have on the bioenergy industry. By allowing suppliers to blend materials together and to purchase from supplies that would otherwise not be considered if procuring from only supplies that exactly comply with the technology specification a more preferable portfolio of suppliers can be selected, the total cost of the supply portfolio can also be significantly reduced. This approach allows more of the available biomass resource to be converted into renewable energy, this allows further deployment of bioenergy in general, contributing towards the various renewable targets set out by EU and UK governments. The performance of those bioenergy schemes that are deployed can be improved by using the BioSS, this approach allows decision makers to balance the various complex requirements of bioenergy project stakeholders, reducing the risk of project failure through better engagement with stakeholder groups and a more transparent method of supplier selection and order allocation than current practice.

Chapter 8. Conclusion and future work

8.1 Introduction

This chapter concludes the thesis by reviewing the research outputs against the research objectives and discussing the extent to which each research problem has been addressed. The three problem areas addressed in this research; fuels library, supplier selection, order allocation and also the implementation of BioSS are discussed in section 6.2. The research outputs and method used for each problem area are summarised along with any results. Section 6.3 has a recap of the research aims and the contribution of this research to the academic literature gaps as identified in chapter 2 and the contribution to the UK bioenergy industry. The limitations of the method and the limitations of the research outcomes are discussed in section 6.4 with suggestions for developing the research and the BioSS framework further in section 6.5.

8.2 Problems addressed

The stated research aim in chapter 1 is to develop a strategic sourcing decision framework to assist UK developers in selecting which biomass sources should be used as feedstock for bioenergy projects. The research aims to improve development effectiveness and efficiency of UK bioenergy schemes by addressing the challenge of strategic sourcing of biomass material. In doing so the research aims to accelerate the deployment of UK bioenergy schemes towards meeting the 2020 target for renewable energy production and the wider target for reducing greenhouse gas emissions to prevent climate change.

The problem faced by managers when procuring biomass materials for energy was split into three distinct research areas. Firstly the problem of understanding the characteristics of a biomass material was addressed through the creation of a fuels library. This library of data was compiled from a wide number of sources and is intended to give developers an overview of what chemical and energetic properties to expect from different biomass sources based only on their description.

The second distinct problem was with regards to properly evaluating potential suppliers of material. No formal structure for biomass supplier evaluation previously exists in literature or practice and requirements differ between projects and stakeholders. Managers are required to choose suppliers who will be accepted by the project stakeholder group to allow for successful project development. However managers have no explicit understanding of factors considered important by the stakeholder group.

The third distinct problem faced by buyers of biomass is how to allocate orders for material between different suppliers. A final fuel blend must be created that satisfies the technological constraints of the conversion equipment chosen whilst also satisfying the stakeholder group as far as possible and the total material demand of the project.

To pull all of these research problems together a decision support framework for strategic sourcing of biomass was developed. This is the BioSS framework. Sections 6.2.1 to 6.2.3 discuss the three research areas and section 6.2.4 discusses the implementation of the BioSS framework.

8.2.1 Fuels library

As part of the research a fuels library has been produced. The aim of creating a fuels library as part of BioSS and also as a standalone resource is twofold. Firstly it can allow buyers to estimate the qualities of material from just a description without the need for extensive testing. This reduces the overall cost to the buyer associated with investigating sources of biomass that are not suitable and allows the buyer to focus their efforts on a suitable portfolio.

The fuels library is compiled from various online databases for solid biomass resources, international standards for solid biofuels and academic literature sources. Reporting of characteristics reported and test methods used are inconsistent between some sources and sometimes between records within data sources. This reflects the complexity in analysis and reporting of biomass sources. For instance some studies test for polluting metals by examining the concentration found within the ash that remains when the sample is fully combusted. However without reporting the original ash content of the material it is difficult to estimate with any confidence the original concentration of metals in the feedstock. In other cases because authors are interested in only one conversion pathway or the impact of only one characteristic on technology performance; only a few of the important characteristics are reported. This situation is changing with international standards for testing being introduced, especially in Europe under the CEN technical committee work. The most comprehensive and easily accessed database is the BioDat database managed by ECN laboratories in The Netherlands (BIODAT, 2012).

The fuels library contains around 100 different biomass feedstock descriptions, some of which are user input from data provided by suppliers and Express Energy. Also included are quality standards for solid recovered fuel (SRF), refuse derived fuel (RDF), biomass pellets and biomass chips. The library focuses on the chemical and energetic properties of the biomass rather than physical or handling properties. This is because BioSS is designed for use on projects where fuel blending is part of the proposal and some re-shaping, shredding, mixing and re-binding of materials is likely to happen anyway.

The fuels library reports on 14 characteristics of biomass that have been identified by Express Energy and are frequently discussed in the literature. Each of these characteristics is required to be controlled by biomass conversion equipment manufacturers or by pollution limits and therefore by the manufacturers of flue gas filtration equipment. There are of course more chemical characteristics within both legislative control and that are relevant to conversion performance, however these are so rarely reported and relatively uncommon in biomass sources that the fuels library excludes them. All of the records in the fuels library have information on the bioenergy content (as a percentage of total energy content), moisture content (percentage of weight), ash content (percentage of weight) and lower heating value (megajoules per kilogram, Mj/kg). These were identified by several interviewees and Express Energy as the most important characteristics to project success.

The fuels library can simply be modified and extended by the user without any advanced technical knowledge. The fuels library has been passed to Express Energy to allow them to continue populating the library with new test data as new supplies are encountered by the company. This allows the fuels library to grow into a source of intellectual property owned by Express Energy.

8.2.2 Supplier selection

The evaluation of suppliers has not previously been studied for the bioenergy industry as shown in chapter 2 and (Scott et al., 2012). To assist biomass buyers when evaluating and ultimately selecting suppliers a set of semi-structured interviews has been conducted with members of industry stakeholder groups and combined with information from policy documents, position statements and previous academic literature. A review of which stakeholders are considered important to the success of a bioenergy project and its supply chain revealed consistency between respondents and identified 6 key stakeholder groups. These stakeholder groups were then interviewed where possible and their requirements were identified. In the case of central government no respondent was available for interview but the requirements of this stakeholder have been made clear in several policy documents. Other stakeholder groups also had relevant position statement documents, policy documents and press releases that were used to support information collected by interview.

7 stakeholder requirements were identified from the 21 interviews and a total of 27 evaluating criteria were also identified. 4 of these factors were found within the bioenergy literature,8 from the operations management literature and the remaining 14 were new factors identified by the research. The collected data was used to complete the first two stages of the integrated QFD-AHP method for supplier selection (Ho et al., 2011). The interrelationship matrices were completed by running three workshops attended by experts where areas that were non-zero in each matrix were identified and each relationship was given a ranking and weighting.

The result of this section of the research was an importance weighting for each of the 27 identified evaluating criteria. This weighting reflects the requirements of the project stakeholder group can be used to evaluate potential suppliers in a way that is most acceptable to the stakeholder group. This is a powerful tool for developers who have previously been blind to the requirements and evaluating factors being applied by other stakeholders. By using the completed the interrelationship matrices the decision maker can quickly observe how differing stakeholder importance scores affect the priority weighting of different evaluating criteria. This is also valuable for suppliers, merchants and producers looking to better target their business offering.

8.2.3 Order allocation

The order allocation research problem produced a series of chance-constrained optimisation models that produce a recommended portfolio to the user. The recommended portfolio (or any user specified portfolio) can then be tested against the required set of constraints using a Monte-Carlo analysis. The user has a choice to either optimise for the lowest cost portfolio possible or for the highest performing portfolio possible with regards to the stakeholder requirements. The program is written in LINGO and embedded into Microsoft Excel with OLE (object linking and embedding) operations used to pass input data and results between the two platforms.

The optimisation program is able to recommend portfolios that meet the technical constraints of the conversion technology that material is being sourced for and also finding the best viable solution according to the objective function of the user. The program can handle either crisp or chance constrained constraints and is able to handle the stochastic nature of the input data on fuel characteristics. In the fuels library these characteristics are typically modelled as normally distributed but other distributions could be added to BioSS without extensive re-programming.

8.2.4 BioSS framework

Linking the three research outputs from section 6.2.1, 6.2.2 and 6.2.3 together forms a decision framework that can be used by developers to design better supply chains and make better supplier selections in the eyes of the project stakeholder group. The framework can be used to increase the success rate and resilience of bioenergy projects by allowing developers and buyers to make better choices regarding the selection of suppliers and allocation of orders. The buyer has better visibility of which factors are important to the project stakeholder group when selecting suppliers and also has a method to determine the best, technically viable portfolio of suppliers in the eyes of the stakeholder group.

The entire BioSS framework has been demonstrated in two scenarios encountered by the UK bioenergy industry. The framework produces different recommended portfolios for different stakeholder importance groups and for different technological constraints. Importantly the BioSS framework can also be applied at each major stage of a bioenergy project development lifecycle: the early phase when little information is available, the financial close stage when the model can be fully specified and contracts for supply are usually signed and also in the operational phase of the project.

8.3 Contribution of the research

This section describes the contribution of this research to the existing body of academic literature and understanding and to the bioenergy industry within the UK.

8.3.1 Academic contribution

The literature review in chapter 2 finds that there are several literature gaps regarding the treatment of bioenergy systems. These are summarised below:

- Multi-stakeholder methods are not applied to the problem of managing bioenergy supply chains

- Supplier evaluation and selection problems for bioenergy schemes are not addressed in the literature.
- The existing literature focuses on top-down planning and policy for bioenergy and largely ignores the approach of individual project development companies who will deliver the required bioenergy capacity
- Barriers have been identified regarding the tactical and operational levels of projects that are not addressed in the literature, especially for dealing with uncertainty of feedstock, variability and contracts for supply.
- Stakeholder opinion is not incorporated into optimisation approaches in a robust way
- No previous literature addresses the potential for blending biomass materials to meet fuel specifications.

This research provides a novel framework for supplier selection within the context of the project development lifecycle. The application of such a framework to the field of bioenergy is unique and contributes towards addressing the shortcomings in the literature identified above. The research compliments the existing literature by contributing against known barriers to bioenergy that are currently understudied. The literature review in chapter 2 finds a body of literature dominated by analytical approaches to organising logistics and locations for bioenergy projects. None of the reviewed papers identify how buyers can evaluate suppliers of biomass as addressed in chapter 5 of this research. No previous literature provides a structure or method for the blending of different biomass resources together as is addressed in chapter 4 and 6. Unlike the majority of the literature BioSS takes a pragmatic, industry led bottom-up approach by linking closely to existing development practice and placing responsibility for searching for and characterising individual suppliers with the project developer rather than any governing body.

The integration of various decision methods into decision frameworks is not a novel idea, however no previous authors have integrated the QFD-AHP method with a chance constrained optimisation program. Other authors have however used similar approaches to integrate supplier weightings into goal programming or linear programming models although never the QFD-AHP method.

The BioSS also represents a contribution to the decision support systems literature. The functionality of BioSS matches the data available at different stages of the development process and also incorporates a group decision making approach. Group decision support systems are usually applied in environments where many individuals or actors must come to some agreement over a decision. In BioSS however the voice of the group is given an active say in the design of the supply chain. If the buyer is able to follow the advice of BioSS to the letter they are effectively removed as decision maker and replaced by the stakeholder group. This complies with the ideas on stakeholder theory and engagement from Friedman and Miles (2002) and Laplume et al. (2008) about organisations performing best when they are managed as a collection of stakeholders. BioSS could therefore be considered an application of stakeholder theory as well as an application of the individual operations management methods (chance constrained optimisation and the QFD-AHP).

8.3.2 Industrial contribution

This research has been co-funded by an industry partner. The problems identified as key research areas for this work have come straight from experiences of the sponsoring company and their industry counterparts. This research has therefore been steered by industry but delivered using the most suitable techniques from the academic literature.

The key problem addressed by BioSS for biomass buyers is the order allocation problem – how much material should be contracted for, and from whom? In addressing this problem the research has produced other contributions that can assist the bioenergy industry. These are summarised as:

- A simple database of potential biomass sources with estimated mean and standard deviation data for at least 4 characteristics of the fuel and upto 14 characteristics
- A list of stakeholder groups considered important for bioenergy projects
- A list of the requirements those stakeholder groups hold when considering bioenergy supply chains as successful or otherwise.
- A list of measurable factors that correspond to the requirements laid out by stakeholder groups which can be used to assess individual suppliers
- A preference weighting score for each evaluating criteria
- A robust method for re-allocating importance scores to evaluating criteria should the business environment change
- A method for the rapid assessment of a portfolio of suppliers against the technical constraints of a technology using the Monte-Carlo analysis part of BioSS.
- A method for the rapid assessment of a technology and the associated constraints against the available biomass materials using the Monte-Carlo analysis part of BioSS.

The BioSS framework itself contributes to the bioenergy industry in several areas. The BioSS can be used by companies such as express to follow and be seen to follow good practice in the design of biomass supply chains. The framework allows stakeholders to become more involved in the decision making process and the supplier selection decision.

During the course of the research it has become clear that the operator or developer is actually interested in the final fuel mix rather than the function of contracting and supply itself. If Express Energy could agree with a single supplier for all of their fuel who met the financial performance requirements made by project investors this would be idea. Developers and operators would be better placed outsourcing the risk of supplier failure up the supply chain and focusing on the actual operation of the plant. As the market matures and grows this may be the dominant model. Under this model of outsourcing risk to a few key suppliers it is those suppliers who benefit from the application of BioSS. They may have different stakeholder groups and those stakeholder groups would have different importance ratings but the framework would still fully apply. It is this tier of the supply chain where the value that can be added by blending and successful strategic sourcing can be added.

A further impact of the application of BioSS into industry is that it opens up a wider range of biomass resources for conversion to bioenergy, especially waste resources. As discussed in chapter 1 it is these resources that have the highest potential for value addition when converted into bioenergy and also usually provide the greatest social and environmental benefits. Bringing this material into the supply chain reduces the overall cost of energy from biomass, increases the percentage of bioenergy deployment in the UK energy mix and reduces greenhouse gas emissions faster than if wastes and residues were not utilised fully. BioSS provides a robust, effective and efficient approach to enabling the utilisation of such waste derived materials in the bioenergy value chain.

8.4 Limitations of the research

This research has integrated several methods and approaches in both the application of the BioSS framework to the biomass buyer problem and also the collection of data for the research. This section discusses the most important known shortcomings of the firstly research method used and secondly the methods used within the BioSS framework.

8.4.1 Limitations of research method

The two main areas of data collection for the research are in the creation of the fuels library for chapter 4 and the identification of supplier evaluating factors, stakeholders and stakeholder requirements in chapter 5.

The information in the fuels library is a deliberately disparate and heterogeneous mixture of quality and source. The aim of the fuels library was to have at least one data point for as many different descriptions of biomass that may be encountered by biomass buyers as possible. This inevitably means compromising on quality and integrity of the captured data, where possible records have been amalgamated and average values calculated along with standard deviations. In other cases the reported information must be taken at face value and there is no way of validating or cross referencing the reported results. This is the very problem that the fuels library aims to overcome. The weakness of this section of the research is therefore that the data contained in the fuels library is inherently unreliable. In the practical application of BioSS this is not an issue as the developer will need to double check material characteristics prior to signing contracts anyway. The fuels library however is of little real use to other applications such as on-going research or model building.

The data collection for stakeholder requirements was through interview data supported by a literature review. This part of data gathering for the QFD-AHP method was reasonably simple to interpret and clear requirements were given by most stakeholder groups. The collection of evaluating factors was more complex as factors needed to be merged when slightly different terms or metrics of measurement were used. Overall this was done without needing to exclude any evaluating factors. The sample size for the interviews was hindered by access to knowledge within the bioenergy industry. Many potential participants who had agreed to interviews were unable to give insight into the supply side of the biomass industry; this was particularly evident when interviewing representatives of the local community and local government stakeholder groups.

As with all qualitative research there are dangers when generalising from a small sample of in-depth data. However as there is no previous work in this area the interview data collected is the only data against which buyers can assess stakeholder satisfaction. There is also danger of false information being given during the interview for various reasons, this is not considered to be very likely in the context of the research as participants are being asked for their opinion in a positive context, they are unlikely to give a response that they feel the researcher or other stakeholders want to hear. A larger sample size could have increased reliability of the factors and requirements identified although consistent responses between interviewees within stakeholder groups show that little variation is expected.

8.4.2 Limitations of methods in BioSS

There are some limitations associated with using the chance-constrained programming approach. A more accurate result is obtained by using higher sample numbers, meaning that the optimisation program is required to generate a higher number of deterministic equivalent models that must, when solved comply with the user specified chance constraints. The sample size used for all the experiments presented in this research is 300; each experiment was also run three times to ensure the solution was repeatable. From initial tests reducing the sample size to below 50 can result in changes to the recommended portfolio being made, reducing the sample size below 75 was found to result in small but significant exceedence over the allowed chance constraints. A sample size of much more than 300 made computation time over 10 minutes, especially for fully specified problems and problems high variation within the supplier material characteristics.

When faced by many supplies with wide variation in characteristics the model often struggled to find a solution and sometimes gave inconsistent results, finding a solution on one experiment run but not on another experiment run under identical conditions. This is due to the relative sample size against the variation in characteristic. Ideally this could be overcome by normalising all variation into the range 0 to 1 before the optimisation is run, however this approach compromises accuracy in reporting of much larger and smaller numbers as rounding errors in the lingo model are later scaled up for reporting. Such an approach could also make the model difficult for the user to fully understand and edit.

There are inherent limitations with the data being provided to BioSS for optimisation. There are likely to be systematic and random errors in the testing method, the scoring of suppliers, the reporting of supplier performance and the accuracy of self-reporting by suppliers. These are all problems within the industry regardless of BioSS and there is little that the user or BioSS can do to manage such inaccuracy.

It is possible that as external conditions for the bioenergy industry change the stakeholder groups, requirements and evaluating factors may need to change. This is also natural for any model of real world situations and the BioSS framework can remain the same whilst the data contained within can be refreshed and updated.

8.5 Future direction

The BioSS framework has been passed to Express Energy along with user guidance and tuition. On-going support through the first full application of each BioSS stage will also be given. In addition various results of the research are being applied to a new decision support system being developed under the Interreg inter-regional funding scheme of the European Union. The BioenNW project aims to further the deployment of advanced conversion technologies for bioenergy across North Western Europe and one outcome of the project is a decision support tool for developers. The methods used in BioSS will be adjusted to this tool and will become part of an on-going European network offering development support to new actors in the bioenergy industry.

There are several ways that the BioSS could be improved following this research. Due to activities and delays at Express Energy it was not possible to deploy BioSS at each stage of development using an action research approach. This type of approach could still be done in the future and would reveal how successfully the decision maker engaged with the framework and any problems that were encountered. Given the length of time required developing a bioenergy facility this would need to be an on-going research project with regular engagement.

The BioSS could be applied to other problems faced within the bio-economy. Proposed applications are to assist with the blending of composts to meet different quality grades, the mixing of digestate from anaerobic digestors that is currently landfilled if no fertilizer application can be found, the strategic sourcing of waste to produce RDF and SRF pellets, the blending of biodiesel or similar products.

There is potential for further research on the bio-economy generally including the mapping of different value adding processes against the suitable feedstocks and products. The BioSS addresses the upgrading of solid biomass through blending. Other value adding activities for biomass are aggregation, densification and transportation. These areas are partly studied in the existing literature on biomass and could be incorporated into a future version of BioSS that can assist supply chain managers to construct the most successful supply chain, rather than only select the most suitable suppliers. This type of decision support system tool would fit neatly with the expected future bio-economy where non-commodity materials are frequently traded outside of contracts to extract the highest value from this unconventional resource using conventional market designs.

8.6 Conclusion

A decision framework has been developed to assist bioenergy project developers in designing sustainable, robust and effective supply chains. The framework incorporates the opinions of the important project stakeholders to the supplier selection and order allocation decision and allows the project developer to select a portfolio blend with the highest possible performance considering both soft and crisp technological constraints and the uncertain and variable nature of biomass materials. The developed framework, BioSS, has been demonstrated against two scenarios with different stakeholder groups and different technological constraints. In both scenarios the framework was able to recommend a portfolio of suppliers at the three major project life-cycle stages.

Appendix A.

Table A.1: Proposed ROC banding rates currently under consultation – biomass related rates only. (Adapted from DECC, 2011a)

Technology	Current support (ROC/MW)	Proposed support (ROC/MW)
Advanced gasification	2	2013-15: 2 2015/16: 1.9 2016/17: 1.8
Advanced pyrolysis	2	2013-15: 2 2015/16: 1.9 2016/17: 1.8
Anaerobic digestion	2	2013-15: 2 2015/16: 1.9 2016/17: 1.8
Conversion of coal power stations to biomass	0	1
Co-firing of coal and biomass	0.5	0.5
Co-firing of biomass using enhanced technologies	0	1
Co-firing of biomass with combined heat and power (CHP)	1	1
Co-firing of energy crops	1	1
Co-firing of energy crops with CHP	1.5	1.5
Dedicated biomass power	1.5	1.5 upto 31st March 2016 1.4 beyond
Dedicated energy crops	2	2013-15: 2 2015/16: 1.9 2016/17: 1.8
Dedicated biomass with CHP	2	2013-15: 2
Dedicated energy crops with CHP	2	2013-15: 2
Energy from waste	1	0.5

Table A.2: Non-domestic RHI rates (adapted from DECC, 2012f)

Tariff name	Eligible technology	Eligible sizes	Tariff level (p/kWh)
Small biomass	Solid biomass including solid biomass contained in municipal solid waste (incl. CHP)	Less than 200 kWth	8.3 (tier 1)
			2.1 (tier 2)
Medium biomass		200 kWth and above; less than 1,000 kWth	5.1 (tier 1)
			2.1 (tier 2)
Large biomass		1,000 kWth and above	1.0
Small heat pumps	Ground-source heat pumps; water source heat pumps; deep geothermal 100kWth and above	Less than 100 kWth	4.7
Heat pumps		100 kWth and above	3.4
All solar thermal collectors	Solar thermal collectors	Less than 200kWth	8.9
Biomethane and biogas combustion	Biomethane injection and biogas combustion, except from landfill gas	Biomethane all scales, biogas combustion except for landfill gas	7.1

Appendix B.

Table B.1: CEN/TS standards (Source Centre, 2012)

CEN/TS 14588:2004	Solid biofuels - Terminology, definitions and descriptions
CEN/TS 14778-1:2005	Solid biofuels - Sampling - Part 1: Methods for sampling
CEN/TS 14778-2:2005	Solid biofuels - Sampling - Part 2: Methods for sampling particulate material transported in lorries
CEN/TS 14779:2005	Solid biofuels - Sampling - Methods for preparing sampling plans and sampling certificates
CEN/TS 14780:2005	Solid biofuels - Methods for sample preparation
CEN/TS 15104:2005	Solid biofuels - Determination of total content of carbon, hydrogen and nitrogen - Instrumental methods
CEN/TS 15105:2005	Solid biofuels - Methods for determination of the water soluble content of chloride, sodium and potassium
CEN/TS 15149-1:2006	Solid biofuels - Methods for the determination of particle size distribution - Part 1: Oscillating screen method using sieve apertures of 3.15 mm and above
CEN/TS 15149-2:2006	Solid biofuels - Methods for the determination of particle size distribution - Part 2: Vibrating screen method using sieve apertures of 3.15 mm and below
CEN/TS 15149-3:2006	Solid biofuels - Methods for the determination of particle size distribution - Part 3: Rotary screen method
CEN/TS 15150:2005	Solid biofuels - Methods for the determination of particle density
CEN/TS 15210-2:2005	Solid biofuels - Determination of mechanical durability of pellets and briquettes. Part 2: Briquettes
CEN/TS 15234:2006	Solid biofuels - Fuel quality assurance
CEN/TS 15289:2006	Solid biofuels - Determination of total content of sulphur and chlorine
CEN/TS 15290:2006	Solid biofuels - Determination of major elements
CEN/TS 15296:2006	Solid biofuels - Calculation of analyses to different bases
CEN/TS 15297:2006	Solid biofuels - Determination of minor elements
CEN/TS 15370-1:2006	Solid biofuels - Method for the determination of ash melting behaviour - Part 1: Characteristic temperatures method
BS EN 14774-1:2009	Solid biofuels - Determination of moisture content - Oven dry method. Total moisture: Reference method
BS EN 14774-2:2009	Solid biofuels - Determination of moisture content - Oven dry method. Total moisture: Simplified method
BS EN 14774-3:2009	Solid biofuels - Determination of moisture content - Oven dry method. Moisture in general analysis sample
BS EN 14775:2009	Solid biofuels - Determination of ash content
BS EN 14918:2009	Solid biofuels - Determination of calorific value
BS EN 14961-1:2010	Solid biofuels - Fuel specifications and classes - Part 1: General requirements
BS EN 15103:2009	Solid biofuels - Determination of bulk density
BS EN 15148:2009	Solid biofuels - Determination of the content of volatile matter
BS EN 15210-1:2009	Solid biofuels - Determination of mechanical durability of pellets and briquettes. Pellets

Table B.2: CEN/TC 343 published documents Source: http://www.cen.eu/CEN/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/Standards.aspx?param=407430&title=CEN/TC+343

Standard reference	Title
CEN/TR 14980:2004	Solid recovered fuels - Report on relative difference between biodegradable and biogenic fractions of SRF
CEN/TR 15404:2010	Solid recovered fuels - Methods for the determination of ash melting behaviour by using characteristic temperatures
CEN/TR 15441:2006	Solid recovered fuels - Guidelines on occupational health aspects
CEN/TR 15508:2006	Key properties on solid recovered fuels to be used for establishing a classification system
CEN/TR 15591:2007	Solid recovered fuels - Determination of the biomass content based on the 14C method
CEN/TR 15716:2008	Solid recovered fuels - Determination of combustion behaviour
CEN/TS 15401:2010	Solid recovered fuels - Determination of bulk density
CEN/TS 15405:2010	Solid recovered fuels - Determination of density of pellets and briquettes
CEN/TS 15406:2010	Solid recovered fuels - Determination of bridging properties of bulk material
CEN/TS 15412:2010	Solid recovered fuels - Methods for the determination of metallic aluminium
CEN/TS 15414-1:2010	Solid recovered fuels - Determination of moisture content using the oven dry method - Part 1: Determination of total moisture by a reference method
CEN/TS 15414-2:2010	Solid recovered fuels - Determination of moisture content using the oven dry method - Part 2: Determination of total moisture content by a simplified method
CEN/TS 15639:2010	Solid recovered fuels - Determination of mechanical durability of pellets
EN 15357:2011	Solid recovered fuels - Terminology, definitions and descriptions
EN 15358:2011	Solid recovered fuels - Quality management systems - Particular requirements for their application to the production of solid recovered fuels
EN 15359:2011	Solid recovered fuels - Specifications and classes
EN 15400:2011	Solid recovered fuels - Determination of calorific value
EN 15402:2011	Solid recovered fuels - Determination of the content of volatile matter
EN 15403:2011	Solid recovered fuels - Determination of ash content
EN 15407:2011	Solid recovered fuels - Methods for the determination of carbon (C), hydrogen (H) and nitrogen (N) content
EN 15408:2011	Solid recovered fuels - Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content
EN 15410:2011	Solid recovered fuels - Methods for the determination of the content of major elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti)

EN 15411:2011	Solid recovered fuels - Methods for the determination of the content of trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Tl, V and Zn)
EN 15413:2011	Solid recovered fuels - Methods for the preparation of the test sample from the laboratory sample
EN 15414-3:2011	Solid recovered fuels - Determination of moisture content using the oven dry method - Part 3: Moisture in general analysis sample
EN 15415-1:2011	Solid recovered fuels - Determination of particle size distribution - Part 1: Screen method for small dimension particles
EN 15415-2:2012	Solid recovered fuels - Determination of particle size distribution - Part 2: Maximum projected length method (manual) for large dimension particles
EN 15415-3:2012	Solid recovered fuels - Determination of particle size distribution - Part 3: Method by image analysis for large dimension particles
EN 15440:2011	Solid recovered fuels - Methods for the determination of biomass content
EN 15440:2011/AC:2011	Solid recovered fuels - Methods for the determination of biomass content
EN 15442:2011	Solid recovered fuels - Methods for sampling
EN 15443:2011	Solid recovered fuels - Methods for the preparation of the laboratory sample
EN 15590:2011	Solid recovered fuels - Determination of the current rate of aerobic microbial activity using the real dynamic respiration index

	Typical Markets	Typical Sources of Raw Material for Recycling.	Typical Materials	Typical Non – Wood Content Prior to Processing	Notes
Grade A. "Clean" Recycled Wood	A feedstock for the manufacture of professional and consumer products such as animal bedding and horticultural mulches. May also be used as fuel for renewable energy generation in non WID* installations, and for the manufacture of pellets and briquettes.	Distribution. Retailing. Packaging. Secondary manufacture e.g. joinery. Pallet Reclamation.	Solid softwood and hardwood. Packaging waste, scrap pallets, packing cases, and cable drums. Process off-cuts from manufacture of untreated products.	Nails and metal fixings. Minor amounts of paint, and surface coatings.	Some visible particles of coatings and light plastics will remain. Excludes grades below. Is a waste for W.M.Regs* requirements. Does not require a WID installation**
Grade B. Industrial Feedstock Grade	A feedstock for Industrial wood processing operations such as the manufacture of panel products, including chipboard and medium density fibreboard (mdf)	As Grade A, plus construction and demolition operations and Transfer Stations.	May contain up to 60% Grade A material as above, plus building and demolition materials and domestic furniture made from solid wood.	Nails and metal fixings. Some paints, plastics, glass, grit, coatings, binders and glues. Limits on treated or coated materials as defined by WID.	The Grade A content is not only costly and difficult to separate, it is essential to maintain the quality of feedstock for chipboard manufacture, and for PRN revenues. Some feedstock specifications contain a 5 – 10% limit on former panel products such as chipboard, MDF, and plywood. Excludes Grade D. Is a waste for W.M.Regs* requirements. Does require a WID installation, unless granted an exemption**
Grade C. Fuel Grade.	Biomass fuel for use in the generation of electricity and/or heat in WID** compliant	All above plus Municipal Collections,	All of the above plus fencing products, flat pack furniture made from board	Nails and metal fixings. Paints coatings and	Suitable only For WID installations**. Material coated and treated with

	installations	Recycling Centres Transfer Stations And Civic Amenity Recycling sites	products and DIY materials High content of panel products such as chipboard, MDF, plywood, OSB and fibreboard.	glues, paper, plastics and rubber, glass, grit. Coated and treated timber (non CCA or creosote).	preservatives as defined by WID may be included. Excludes Grade D Is a waste for W.M.Regs* requirements.
Grade D Hazardous Waste	Requires disposal at special facilities	All of the above plus fencing, trackwork and transmission pole contractors.	Fencing Transmission Poles Railway sleepers Cooling towers	Copper / Chrome / Arsenic preservation Treatments Creosote	Is a waste for W.M.Regs* requirements. Does require a special WID installation.

Appendix C.

Presented below are the various tables used in the QFD-AHP method. Table 5.17 and Table 5.18 show the pairwise comparisons for placing an importance rating on stakeholder importance. Table 5.19 to Table 5.26 show the pairwise comparisons used for each stakeholder to evaluate the importance of each requirement. Table 5.27 shows HoQ1. Table 5.28 to Table 5.41 show the original and normalised pairwise comparisons for each evaluating criteria against each relevant requirement. Table 5.42 shows HoQ2.

Table C.1: AHP pairwise comparison for stakeholder groups.

Stakeholder pairwise comparison	Financial groups and project partners/investors	Environmental groups	Developers/ Operators	National government and policy makers	Local government	Community/public
Financial groups and project partners/investors	1	5	3	6	4	7
Environmental groups	0.2	1	0.333	3	0.333	5
Developers/Operators	0.333	3	1	3	4	7
National government and policy makers	0.167	0.167	0.333	1	0.250	2
Local government	0.250	3	0.250	4	1	5
Community/public	0.143	0.2	0.143	0.5	0.2	1

Table C.2: Normalised pairwise comparison for stakeholder groups

Normalised stakeholder pairwise comparison	Financial groups and project partners/investors	Environmental groups	Developers/ Operators	National government and policy makers	Local government	Community/public	Importance score
Financial groups and project partners/investors	0.478	0.404	0.593	0.343	0.409	0.259	0.414
Environmental groups	0.096	0.081	0.066	0.171	0.034	0.185	0.105
Developers/Operators	0.159	0.243	0.198	0.171	0.409	0.259	0.240
National government and policy makers	0.080	0.013	0.066	0.057	0.026	0.074	0.053
Local government	0.119	0.243	0.049	0.229	0.102	0.185	0.155
Community/public	0.068	0.016	0.028	0.029	0.020	0.037	0.033

Table C.3: Pairwise comparison for financial groups

Financial groups and project partners/investors	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	A good supplier should be financially credible
A good supplier should be able to offer an attractive b2b contract	1	4	5	0.5
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.25	1	3	0.333
A good supplier should be able to provide material reliably and within the quality specification required	0.2	0.25	1	0.25
A good supplier should be financially credible	2	3	4	1

Table C.4: Normalised pairwise comparison for financial groups

Normalised table for financial groups	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	A good supplier should be financially credible	Importance score
A good supplier should be able to offer an attractive b2b contract	0.290	0.485	0.385	0.240	0.350
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.072	0.121	0.231	0.160	0.146
A good supplier should be able to provide material reliably and within the quality specification required	0.058	0.030	0.077	0.120	0.071
A good supplier should be financially credible	0.580	0.364	0.308	0.480	0.433

Table C.5: Pairwise comparison for developers

Developers/Operators	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible
A good supplier should be able to offer an attractive b2b contract	1	0.25	2	7	2
A good supplier should be able to provide good contract conditions regarding the supply of fuel	4	1	3	6	5
A good supplier should be able to provide material reliably and within the quality specification required	0.5	0.333	1	4	2
The supply of materials should have a low environmental impact	0.143	0.167	0.25	1	0.333
A good supplier should be financially credible	0.5	0.2	0.5	3	1

Table C.6: Normalised pairwise comparison for developers

Normalised table for developers/operators	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible	Score
A good supplier should be able to offer an attractive b2b contract	0.163	0.128	0.296	0.333	0.194	0.223
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.651	0.513	0.444	0.286	0.484	0.476
A good supplier should be able to provide material reliably and within the quality specification required	0.081	0.171	0.148	0.190	0.194	0.157
The supply of materials should have a low environmental impact	0.023	0.085	0.037	0.048	0.032	0.045
A good supplier should be financially credible	0.081	0.103	0.074	0.143	0.097	0.100

Table C.7: Pairwise comparison for national government

National government and policy makers	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved
The supply of materials should have a low environmental impact	1	7	3	5
A good supplier should be financially credible	0.143	1	0.167	0.25
The supply of materials should have a positive social impact	0.333	6	1	3
National energy security should be improved	0.2	4	0.333	1

Table C.8: Normalised pairwise comparison for national government

Normalised table for national government and policy makers	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved	Score
The supply of materials should have a low environmental impact	0.597	0.389	0.667	0.541	0.551
A good supplier should be financially credible	0.085	0.056	0.037	0.027	0.051
The supply of materials should have a positive social impact	0.199	0.333	0.222	0.324	0.270
National energy security should be improved	0.119	0.222	0.074	0.108	0.131

Table C.9: Pairwise comparison for Local government

Local government	The supply of materials should have a low environmental impact	The supply of materials should have a positive social impact
The supply of materials should have a low environmental impact	1	0.25
The supply of materials should have a positive social impact	4	1

Table C.10: Normalised pairwise comparison for local government

Normalised table for local government	The supply of materials should have a low environmental impact	The supply of materials should have a positive social impact	Score
The supply of materials should have a low environmental impact	0.2	0.2	0.2
The supply of materials should have a positive social impact	0.8	0.8	0.8

Table C.11: House of Quality 1

Requirements / Stakeholder Groups	Stakeholder importance	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved
Financial groups and project partners/investors	0.414	0.350	0.146	0.071		0.433		
Environmental groups	0.105				1.000			
Developers/Operators	0.240	0.223	0.476	0.157	0.045	0.100		
National government and policy makers	0.053				0.551	0.051	0.270	0.131
Local government	0.155				0.200		0.800	
Community/public	0.033				1.000			
Requirement importance	1.000	0.198	0.175	0.067	0.209	0.206	0.138	0.007

Table C.12: Pairwise comparison for business to business contracts

A good supplier should be able to offer an attractive b2b contract	Long term contracts	Take or pay clauses	Track record	Personal relationship
Long term contracts	1	0.333	0.143	3
Take or pay clauses	3	1	0.333	6
Track record	7	3	1	5
personal relationship	0.333	0.167	0.2	1

Table C.13: Normalised pairwise comparison for business to business contracts

Normalised table for providing a good b2b contract	Long term contracts	Take or pay clauses	Track record	personal relationship	Score
Long term contracts	0.088	0.074	0.085	0.200	0.112
Take or pay clauses	0.265	0.222	0.199	0.400	0.271
Track record	0.618	0.667	0.597	0.333	0.554
Personal relationship	0.029	0.037	0.119	0.067	0.063

Table C.14: Pairwise comparison for supply contract

A good supplier should be able to provide good contract conditions regarding the supply of fuel	Contract has PFI back up	Fixed price	Base cost of material (£/MWh)	Clear definition of fuel	Guarantee of fuel quality available
Contract has PFI back up	1	0.167	0.167	2	0.5
Fixed price	6	1	1	4	2
Base cost of material (£/MWh)	6	1	1	7	3
Clear definition of fuel	0.5	0.25	0.143	1	0.333
Guarantee of fuel quality available	2	0.5	0.333	3	1

Table C.15: Normalised pairwise comparison for supply contract

Normalised table for providing fuel supply contract conditions	Contract has PFI back up	Fixed price	Base cost of material (£/MWh)	Clear definition of fuel	Guarantee of fuel quality available	Score
Contract has PFI back up	0.065	0.057	0.063	0.118	0.073	0.075
Fixed price	0.387	0.343	0.378	0.235	0.293	0.327
Base cost of material (£/MWh)	0.387	0.343	0.378	0.412	0.439	0.392
Clear definition of fuel	0.032	0.086	0.054	0.059	0.049	0.056
Guarantee of fuel quality available	0.129	0.171	0.126	0.176	0.146	0.150

Table C.16: Pairwise comparison for specification reliability

A good supplier should be able to provide material reliably and within the quality specification required	Traceable (chain of custody)	Visibility	Quality control mechanisms in place	Guarantee of fuel quality available	Supplier stability (in biomass market)	Dependency on imports
Traceable (chain of custody)	1	2	5	0.5	3	6
Visibility	0.5	1	4	0.333	2	5
Quality control mechanisms in place	0.2	0.25	1	0.2	0.5	1
Guarantee of fuel quality available	2	3	5	1	6	7
Supplier stability (in biomass market)	0.333	0.5	2	0.167	1	3
Dependency on imports	0.167	0.2	1	0.143	0.333	1

Table C.17: Normalised pairwise comparison for specification reliability

Normalised table for specification reliability	Traceable (chain of custody)	Visibility	Quality control mechanisms in place	Guarantee of fuel quality available	Supplier stability (in biomass market)	Dependency on imports	Score
Traceable (chain of custody)	0.238	0.288	0.278	0.213	0.234	0.261	0.252
Visibility	0.119	0.144	0.222	0.142	0.156	0.217	0.167
Quality control mechanisms in place	0.048	0.036	0.056	0.085	0.039	0.043	0.051
Guarantee of fuel quality available	0.476	0.432	0.278	0.427	0.468	0.304	0.397
Supplier stability (in biomass market)	0.079	0.072	0.111	0.071	0.078	0.130	0.090
Dependency on imports	0.040	0.029	0.056	0.061	0.026	0.043	0.042

Table C.18: Pairwise comparison for financial credibility

A good supplier should be financially credible	Credit strength	Size of balance sheet	Financially robust or credible counterparty
Credit strength	1	3	0.2
Size of balance sheet	0.333	1	0.143
Financially robust or credible counterparty	5	7	1

Table C.19: Normalised pairwise comparison for financial credibility

Normalised table for financial credibility	Credit strength	Size of balance sheet	Financially robust or credible counterparty	Score
Credit strength	0.158	0.273	0.149	0.193
Size of balance sheet	0.053	0.091	0.106	0.083
Financially robust or credible counterparty	0.789	0.636	0.745	0.724

Table C.20: Pairwise comparison for environmental impact

The supply of materials should have a low environmental impact	CO2/MWh	Land Use change	FSC accreditation	Alternative end use (Best use of biomass)	Diversion of material from landfill	Environmental regulatory environment in which the supplier operates	Performance against sustainability assurance certificate indicators	Biodiversity change
CO2/MWh	1	4	7	5	3	8	6	8
Land Use change	0.25	1	4	2	0.5	6	4	6
FSC accreditation	0.143	0.25	1	1	0.25	2	0.5	3
Alternative end use (Best use of biomass)	0.2	0.5	3	1	0.333	3	2	4
Diversion of material from landfill	0.333	2	4	3	1	6	4	6
Environmental regulatory environment in which the supplier operates	0.125	0.167	0.5	0.333	0.167	1	0.25	2
Performance against sustainability assurance certificate indicators	0.167	0.25	2	0.5	0.25	4	1	3
Biodiversity change	0.125	0.167	0.333	0.25	0.167	0.5	0.333	1

Table C.21: Normalised pairwise comparison for environmental impact

Normalised table for environmental impact of fuels	CO2/MWh	Land Use change	FSC accreditation	Alternative end use (Best use of biomass)	Diversion of material from landfill	Environmental regulatory environment in which the supplier operates	Performance against sustainability assurance certificate indicators	Biodiversity change	Score
CO2/MWh	0.427	0.480	0.321	0.382	0.529	0.262	0.332	0.242	0.372
Land Use change	0.107	0.120	0.183	0.153	0.088	0.197	0.221	0.182	0.156
FSC accreditation	0.061	0.030	0.046	0.076	0.044	0.066	0.028	0.091	0.055
Alternative end use (Best use of biomass)	0.085	0.060	0.137	0.076	0.059	0.098	0.111	0.121	0.094
Diversion of material from landfill	0.142	0.240	0.183	0.229	0.176	0.197	0.221	0.182	0.196
Environmental regulatory environment in which the supplier operates	0.053	0.020	0.023	0.025	0.029	0.033	0.014	0.061	0.032
Performance against sustainability assurance certificate indicators	0.071	0.030	0.092	0.038	0.044	0.131	0.055	0.091	0.069
Biodiversity change	0.053	0.020	0.015	0.019	0.029	0.016	0.018	0.030	0.025

Table C.22: Pairwise comparison for supply of materials

The supply of materials should have a positive social impact	Rural jobs created or safeguarded	SME employment created

Rural jobs created or safeguarded	1	2
SME employment created	0.5	1

Table C.23: Normalised pairwise for suppl yof materials

Normalised tables	Rural jobs created or safeguarded	SME employment created	Score
Rural jobs created or safeguarded	0.667	0.667	0.667
SME employment created	0.333	0.333	0.333

Table C.24: Pairwise comparison for national energy security

National energy security should be improved	Long Term Contracts	Visibility	Distance from buyer	Dependency on imports
Long Term Contracts	1	0.2	0.333	0.143
Visibility	5	1	5	0.333
Distance from buyer	3	0.2	1	0.2
Dependency on imports	7	3	5	1

Table C.25: Normalised pairwise comparison for national energy security

Normalised table for national energy security	Long Term Contracts	Visibility	Distance from buyer	Dependency on imports	Score
Long Term Contracts	0.063	0.045	0.029	0.085	0.056
Visibility	0.313	0.227	0.441	0.199	0.295
Distance from buyer	0.188	0.045	0.088	0.119	0.110
Dependency on imports	0.438	0.682	0.441	0.597	0.539

Table C.26: House of quality 2. Requirements and evaluating criteria with evaluating criteria importance rating and rank

Stakeholder requirements	Requirement importance	Long Term Contracts	Take or pay Clauses	Track record	personal relationship	Contract has PFI back up	Fixed price	Traceable (chain of custody)	Base cost of material (£/MWh)
A good supplier should be able to offer an attractive b2b contract	0.198	0.112	0.271	0.554	0.063				
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.175					0.075	0.327		0.392
A good supplier should be able to provide material reliably and within the quality specification required	0.067							0.252	
The supply of materials should have a low environmental impact	0.209								
A good supplier should be financially credible	0.206								
The supply of materials should have a positive social impact	0.138								
National energy security should be improved	0.007	0.056							
Importance Rating		**0.023**	**0.054**	**0.110**	**0.013**	**0.013**	**0.057**	**0.017**	**0.068**
Rank		**13**	**7**	**2**	**20**	**19**	**6**	**16**	**5**

Clear definition of fuel	Visibility	Quality control mechanisms in place	Guarantee of fuel quality available	Supplier stability (in biomass market)	Distance from buyer	CO_2/MWh	Land Use change	FSC accreditation	Alternative end use (Best use of biomass)
0.056			0.150						
	0.167	0.051	0.397	0.090					
						0.372	0.156	0.055	0.094
	0.295				0.110				
0.010	**0.013**	**0.003**	**0.053**	**0.006**	**0.001**	**0.078**	**0.033**	**0.012**	**0.020**
22	**18**	**27**	**8**	**25**	**28**	**4**	**12**	**21**	**14**

Diversion of material from landfill	Environmental regulatory environment in which the supplier operates	Performance against sustainability assurance certificate indicators	Credit strength	Size of balance sheet	Financially robust or credible counterparty	Rural jobs created or safeguarded	Dependency on imports	SME employment created	Biodiversity change
							0.042		
0.196	0.032	0.069							0.025
			0.193	0.083	0.724				
						0.667		0.333	
							0.539		
0.041	**0.007**	**0.014**	**0.040**	**0.017**	**0.149**	**0.092**	**0.007**	**0.046**	**0.005**
10	**23**	**17**	**11**	**15**	**1**	**3**	**24**	**9**	**26**

Appendix D.

Table D.1: BIoSS.2 Mean values for characteristics

Feedstock description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	Estimated availability	Estimated unit cost
Units	kJ/kg	wt %	MJ/kg	wt%	tonnes/yr	£/tonne
Refuse derived fuel	50.0	12.1	22.0	17.9	50,000	£3.00
Recycled wood	98.0	15.0	18.2	9.0	25,000	£15.00
Demolition wood	80.0	12.1	18.5	5.0	10,000	£7.50
Solid derived fuel	75.0	6.2	13.0	7.0	15,000	-£4.00
Virgin softwood	100.0	12.9	18.3	1.2	20,000	£25.00
Virgin hardwood	100.0	34.3	17.9	3.1	22,000	£35.00

Table D.2: BioSS.2 standard deviation for feedstock characteristics

Feedstock characteristics	Biomass Energy Content	Moisture Content	Lower heating value	Ash content
Units	kJ/kg	wt %	MJ/kg	wt%
Refuse derived fuel	5.0	12.2	2.3	6.4
Recycled wood	-	1.4	3.5	2.3
Demolition wood	8.0	2.9	0.7	5.8
Solid derived fuel	15.8	1.3	2.6	1.4
Virgin softwood	-	3.1	0.3	0.3
Virgin hardwood	-	3.6	0.9	1.1

Table D.3: BioSS.3 mean values for characteristics

Feedstock description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al	Supplier score	Capacity	Basic unit cost
Units	kJ/kg	wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg		t/yr	£/t
Hardwood pellets [User tested]	100.0	9.5	20.1	1.2	0.0	151.2	12.1	160.4	467.5	-	0.5	1.1	-	10.0	0.0952	9,350	£40.00
RDF [User tested]	45.0	15.0	14.5	10.7	25.1	3,140.0	2,980.0	6,050.0	4,650.0	1.5	2.5	250.0	680.0	720.0	0.1189	4,200	-£3.00
Wood chips [user tested]	100.0	12.9	18.3	1.2	0.1	252.9	-	-	-	-	-	-	-	-	0.1089	6,500	£25.00
Hardwood pellets [user tested]	100.0	9.5	20.1	1.2	0.5	220.0	15.0	180.0	510.0	-	0.5	0.8	1.0	50.0	0.0992	50,000	£45.00
Pellets din 51731 standard [User tested]	100.0	10.8	15.4	0.3	233.9	98.1	-	40.0	340.0	-	0.2	19.0	0.9	99.0	0.0688	13,200	£40.00
Demolition wood [User tested]	65.0	20.0	17.8	10.0	0.1	0.1	-	-	-	-	-	-	-	-	0.0931	10,000	£14.00
Recycled wood grade A [User tested]	98.0	15.0	18.2	9.0	0.1	0.0	-	-	-	-	-	-	-	-	0.1095	7,000	£20.00
Hardwood bark and shavings [User tested]	96.0	25.0	19.0	12.9	0.1	1.2	-	312.0	127.6	-	-	-	-	-	0.0558	4,000	£6.00
Willow generic [User tested]	100.0	17.7	18.4	1.8	0.1	-	-	-	-	-	-	-	-	-	0.1429	7,500	£38.00
SRF [User tested]	75.0	6.2	13.0	7.0	1.4	4,000.0	150.0	5,400.0	4,250.0	3.3	1.0	30.4	276.0	146.0	0.1078	25,000	-£5.00

Table D.4: BioSS.3 Standard deviation values

Feedstock characteristics	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Units	kJ/kg	wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Hardwood pellets [User tested]	-	1.1	2.1	0.3	0.0	38.8	1.4	29.4	126.2	-	0.1	0.2	-	2.5
RDF [User tested]	2.3	0.8	2.0	1.0	3.3	376.8	670.5	90.8	767.3	0.1	0.4	16.3	71.4	144.0
Wood chips [user tested]	-	3.1	0.3	0.3	0.0	51.5	-	-	-	-	-	-	-	-
Hardwood pellets [user tested]	-	1.1	0.5	0.3	0.0	8.4	4.0	28.6	35.4	-	0.1	0.0	-	2.0
Pellets din 51731 standard [User tested]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Demolition wood [User tested]	5.0	4.4	4.1	1.5	0.0	-	-	-	-	-	-	-	-	-
Recycled wood grade A [User tested]	-	1.4	3.5	2.3	0.0	0.0	-	-	-	-	-	-	-	-
Hardwood bark and shavings [User tested]	1.3	2.1	3.5	2.2	0.0	0.3	-	5.5	7.3	-	-	-	-	-
Willow generic [User tested]	-	14.5	0.5	1.2	0.0	-	-	-	-	-	-	-	-	-
SRF [User tested]	15.8	1.3	2.6	1.4	0.2	860.0	4.5	972.0	850.0	0.5	0.1	2.9	55.2	11.7

Table D.5: BioSS.Op mean values for characteristics

Feedstock description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al	Supplier score	Capacity (contracted for)	Basic unit cost
Units	kJ/kg	wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg		t/yr	£/t
Wood, Used (Class C)	85.0	21.9	19.1	1.3	0.0	208.9	-	-	-	-	-	-	-	-	0.0960	1,500	£5.00
RDF (Supplier E)	45.0	15.0	14.5	10.7	25.1	3,140.0	2,980.0	6,050.0	4,650.0	1.5	2.5	250.0	680.0	720.0	0.1219	(2,500)	-£3.00
Wood chips (user)	100.0	12.9	18.3	1.2	0.1	252.9	-	-	-	-	-	-	-	-	0.0889	(6,500)	£25.00
Hardwood pellets (Supplier A)	100.0	9.5	20.1	1.2	0.5	220.0	15.0	180.0	510.0	-	0.5	0.8	1.0	50.0	0.1016	(7,578)	£45.00
Olive residues (User)	98.0	7.0	20.1	3.0	0.1	663.9	-	121.5	4,512.9	-	-	-	-	193.5	0.0708	3,000	£13.50
Straw (Generic)	100.0	11.7	18.8	5.5	0.1	-	-	-	-	-	-	-	-	-	0.0885	1,450	£21.00
Wood from aggregator	100.0	21.3	19.0	2.1	0.1	666.0	-	396.0	1,348.0	0.1	0.6	53.6	5.4	1,223.0	0.1121	1,250	-£7.00
Torrefied, Palm Oil Kernal	100.0	-	19.6	3.8	0.1	-	-	-	-	-	-	-	-	-	0.0573	15,000	£24.00
RDF (High Biomass Content)	85.0	10.0	17.5	1.0	0.7	624.7	83.0	1,400.0	4,200.0	-	4.1	436.0	-	2,150.0	0.1493	1,500	£0.00
SRF (Supplier D)	75.0	6.2	13.0	7.0	1.4	4,000.0	150.0	5,400.0	4,250.0	3.3	1.0	30.4	276.0	146.0	0.1136	1,500	-£8.50

Table D.6: BioSS.Op Standard deviation values

Feedstock characteristics	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Units	kJ/kg	wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Wood, Used (Class C)	8.5	4.1	0.1	0.3	0.0	196.9	-	-	-	-	-	-	-	-
RDF (Supplier E)	2.3	0.8	2.0	1.0	3.3	376.8	670.5	90.8	767.3	0.1	0.4	16.3	71.4	144.0
Wood chips (user)	-	3.1	0.3	0.3	0.0	51.5	-	-	-	-	-	-	-	-
Hardwood pellets (Supplier A)	-	1.1	0.5	0.3	0.0	8.4	4.0	28.6	35.4	-	0.1	0.0	-	2.0
Olive residues (User)	0.0	1.4	1.5	0.9	0.0	225.1	-	11.5	974.3	-	-	-	-	60.4
Straw (Generic)	-	11.0	2.5	7.1	0.1	-	-	-	-	-	-	-	-	-
Wood from aggregator	-	22.5	0.6	2.5	0.0	943.7	-	319.0	1,045.9	0.1	0.8	26.9	6.5	1,751.4
Torrefied, Palm Oil Kernal	-	-	1.7	1.0	0.1	-	-	-	-	-	-	-	-	-
RDF (High Biomass Content)	8.5	1.0	1.8	6.5	-	95.9	4.7	261.0	785.0	-	1.9	129.7	-	654.0
SRF (Supplier D)	15.8	1.3	2.6	1.4	0.2	860.0	4.5	972.0	850.0	0.5	0.1	2.9	55.2	11.7

Appendix E.

Table E.1: Average characteristics for input to BioSS.2 scenario 1 and 2.

Material description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content
	kJ/kg	Wt %	MJ/kg	wt%
Imported wood pellets	100.0	15.0	20.1	3.5
Imported wood chip	100.0	12.9	18.3	1.2
Waste wood available in region	99.0	30.3	18.9	0.8
SRF available within region	75.0	6.2	13.0	7.0
SRF within 100 miles	75.0	6.2	13.0	7.0
RDF within region	45.0	15.0	14.5	10.7
RDF available within 100 miles	45.0	15.0	14.5	10.7

Table E.2: Standard deviation of material characteristics for BioSS.2 scenario 1 and 2.

Material description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content
Units	kJ/kg	wt %	MJ/kg	wt%
Imported wood pellets	-	1.1	2.1	0.3
Imported wood chip	-	3.1	0.3	0.3
Waste wood available in region	-	2.9	0.0	0.2
SRF available within region	15.8	1.3	2.6	1.4
SRF within 100 miles	15.8	1.3	2.6	1.4
RDF within region	14.0	0.9	15.0	3.0
RDF available within 100 miles	14.0	0.9	15.0	3.0

Table E.3: Average characteristics data used in BioSS.3 and BioSS.Op for both scenario 1 and 2

Feedstock description	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al	Supplier score	Capacity	Basic unit cost
Units	kJ/kg	wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg		t/yr	£/t
Imported wood pellets (compliant with Italian A standard)	100.0	10.0	16.9	1.5	500.0	3,000.0	-	-	-	-	-	-	-	-	0.0958	14,000	£41.50
Imported hardwood pellets (Canada)	100.0	9.5	20.1	1.2	0.5	220.0	15.0	180.0	510.0	-	0.5	0.8	1.0	50.0	0.1053	10,000	£45.00
Imported olive residue (Greece)	98.0	7.0	20.1	3.0	0.1	663.9	-	121.5	4,512.9	-	-	-	-	193.5	0.0954	15,000	£25.00
National wood chip supplier	100.0	12.9	18.3	1.2	0.1	252.9	-	-	-	-	-	-	-	-	0.1062	10,000	£25.00
Local small demolition wood aggregator	85.0	13.3	20.1	9.5	15.0	2,000.0	2,750.0	3,525.0	1,102.0	0.0	1.8	253.0	350.0	120.0	0.0769	13,000	£12.00
National demolition wood aggregator	65.0	20.0	17.8	10.0	0.1	0.1	-	-	-	-	-	-	-	-	0.1049	10,000	£7.00
Start-up waste management company - SRF	75.0	6.2	13.0	7.0	1.4	1,500.0	150.0	5,400.0	4,250.0	3.3	1.0	30.4	276.0	146.0	0.0949	20,000	-£15.00
Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	50.0	15.0	15.0	17.0	-	6,000.0	-	-	-	12.0	-	-	-	-	0.1124	30,000	-£10.00
Established regional SRF producer [LHV 2, Cl 3, Hg 2]	50.0	15.0	20.0	17.0	-	10,000.0	-	-	-	6.0	-	-	-	-	0.1110	8,000	-£7.50
Established regional RDF with high biomass content producer	90.0	17.0	12.5	12.0	0.4	0.4	-	-	-	0.0	0.8	-	-	-	0.1107	25,000	-£25.00

Table E.4: Standard deviation data used in BioSS.3 and BioSS.Op for both scenario 1 and 2

Feedstock characteristics	Biomass Energy Content	Moisture Content	Lower heating value	Ash content	S	Cl	F	Na	K	Hg	Cd	Zn	Sn	Al
Units	kJ/kg	wt %	MJ/kg	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Imported wood pellets (compliant with Italian A standard)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Imported hardwood pellets (Canada)	-	1.1	0.5	0.3	0.0	8.4	4.0	28.6	35.4	-	0.1	0.0	-	2.0
Imported olive residue (Greece)	0.0	1.4	1.5	0.9	0.0	225.1	-	11.5	974.3	-	-	-	-	60.4
National wood chip supplier	-	3.1	0.3	0.3	0.0	51.5	-	-	-	-	-	-	-	-
Local small demolition wood aggregator	4.5	4.4	0.8	3.5	2.0	457.0	135.0	84.0	24.0	0.0	-	12.5	15.0	3.5
National demolition wood aggregator	5.0	4.4	4.1	1.5	0.0	-	-	-	-	-	-	-	-	-
Start-up waste management company - SRF	15.8	1.3	2.6	1.4	0.2	430.0	4.5	972.0	850.0	0.5	0.1	2.9	55.2	11.7
Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	10.0	2.0	-	2.0	-	-	-	-	-	-	-	-	-	-
Established regional SRF producer [LHV 2, Cl 3, Hg 2]	10.0	2.0	-	2.0	-	-	-	-	-	-	-	-	-	-
Established regional RDF with high biomass content producer	3.0	2.9	2.3	3.0	0.1	0.0	-	-	-	0.0	0.0	-	-	-

Appendix F.

Table F.1: AHP for weightings to input to HoQ1 scenario 1 BioSS.3

	Financial investors	Environmental groups	National government	Local government	Local community	Developers and operators	Weighting (average)	Rank	[C]	**λmax =**	6.32
Financial investors	0.50	0.63	0.43	0.34	0.37	0.31	0.430	1	6.66	Consistency index =	0.0643
Environmental groups	0.17	0.21	0.29	0.29	0.46	0.27	0.281	2	6.80	Consistency ratio =	0.0519
National government	0.08	0.05	0.07	0.10	0.05	0.12	0.078	4	6.17		
Local government	0.07	0.03	0.04	0.05	0.02	0.08	0.048	5	6.02		
Local community	0.12	0.04	0.14	0.20	0.09	0.19	0.132	3	6.12		
Developers and operators	0.06	0.03	0.02	0.02	0.02	0.04	0.033	6	6.16		
Total	1	1	1	1	1	1	1				

BioSS.3 Scenario 1

Table F.2: HoQ1 for BioSS.3 scenario 1

Stakeholder group	Stakeholder importance	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved
Financial groups and project partners/investors	0.430	0.350	0.146	0.071		0.433		
Environmental groups	0.281				1.000			
Developers/Operators	0.078	0.261	0.553	0.185	0.054	0.118		
National government and policy makers	0.048				0.551	0.051	0.270	0.131
Local government	0.132				0.200		0.800	
Community/public	0.033				1.000			
Requirement importance		**0.171**	**0.106**	**0.045**	**0.370**	**0.197**	**0.118**	**0.006**

Table F.3: HoQ2 for BioSS.3 scenario 1

Stakeholder requirements	Requirement importance	Long Term Contracts	Take or pay Clauses	Track record	personal relationship	Contract has PFI back up	Fixed price	Traceable (chain of custody)
A good supplier should be able to offer an attractive b2b contract	0.171	0.112	0.271	0.554	0.063			
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.106					0.075	0.327	
A good supplier should be able to provide material reliably and within the quality specification required	0.045							0.252
The supply of materials should have a low environmental impact	0.370							
A good supplier should be financially credible	0.197							
The supply of materials should have a positive social impact	0.118							
National energy security should be improved	0.006	0.056						
Evaluating factor importance score		**0.019**	**0.046**	**0.094**	**0.011**	**0.008**	**0.035**	**0.011**

Base cost of material (£/MWh)	Clear definition of fuel	Visibility	Quality control mechanisms in place	Guarantee of fuel quality available	Supplier stability (in biomass market)	Distance from buyer	CO2/MWh	Land Use change	FSC accreditation
0.392	0.056			0.150					
		0.167	0.051	0.397	0.090				
							0.372	0.156	0.055
		0.295				0.110			
0.041	**0.006**	**0.009**	**0.002**	**0.034**	**0.004**	**0.001**	**0.138**	**0.058**	**0.020**

Alternative end use (Best use of biomass)	Diversion of material from landfill	Environmental regulatory environment in which the supplier operates	Performance against sustainability assurance certificate indicators	Credit strength	Size of balance sheet	Financially robust or credible counterparty	Rural jobs created or safeguarded	Dependency on imports	SME employment created	Biodiversity change
								0.042		
0.094	0.196	0.032	0.069							0.025
				0.193	0.083	0.724				
							0.667		0.333	
								0.539		
0.035	**0.073**	**0.012**	**0.026**	**0.038**	**0.016**	**0.143**	**0.079**	**0.005**	**0.039**	**0.009**

Table F.4: Raw data for supplier evaluation used for both scenarios and all BioSS modes

Evaluating factors	Italian wood pellets (Imported; Supplier C)	Imported wood pellets (compliant with Italian A standard)	Imported hardwood pellets (Canada)	Imported olive residue (Greece)	National wood chip supplier	Local small demolition wood aggregator	National demolition wood aggregator	Start-up waste manageme nt company - SRF	Established national waste manageme nt company providing SRF [LHV 3, Cl 2, Hg 3]	Established regional SRF producer [LHV 2, Cl 3, Hg 2]	**Total**
Long Term Contracts	9	8	6	3	1	4	7	6	7	10	**61**
Take or pay Clauses	1	6	10	10	6	6	6	9	9	1	**64**
Track record	4	8	9	9	4	9	3	10	8	6	**70**
personal relationship	7	6	3	7	4	6	7	9	3	10	**62**
Contract has PFI back up	1	1	1	1	1	1	1	1	1	1	**10**
Fixed price	6	10	10	1	3	4	6	7	3	8	**58**
Traceable (chain of custody)	10	6	10	9	1	3	4	5	3	1	**52**
Base cost of material (£/MWh)	6	6	6	6	6	6	6	6	6	6	**60**
Clear definition of fuel	10	8	3	4	4	2	5	6	8	8	**58**
Visibility	2	2	10	6	7	7	4	4	6	7	**55**
Quality control mechanisms in place	10	6	1	3	6	9	2	3	2	8	**50**
Guarantee of fuel quality available	10	1	1	5	2	4	5	3	4	8	**43**
Supplier stability (in biomass market)	10	5	4	9	3	8	1	4	4	6	**54**
Distance from buyer	1	6	1	10	10	5	9	3	10	8	**63**
CO_2/MWh	9	8	7	9	9	9	8	10	9	10	**88**
Land Use change	9	9	10	10	10	10	10	10	10	10	**98**
FSC accreditation	10	10	1	10	1	1	1	1	1	1	**37**

Alternative end use (Best use of biomass)	8	6	6	5	6	6	9	10	9	10	**75**
Diversion of material from landfill	1	1	2	1	4	4	8	9	9	10	**49**
Environmental regulatory environment in which the supplier operates	9	9	9	9	9	9	8	8	8	8	**86**
Performance against sustainability assurance certificate indicators	8	8	9	7	10	10	10	10	10	10	**92**
Credit strength	8	6	3	3	2	9	7	9	9	5	**61**
Size of balance sheet	8	6	4	3	2	7	8	5	6	5	**54**
Financially robust or credible counterparty	8	6	4	3	2	8	7	7	8	5	**58**
Rural jobs created or safeguarded	1	10	8	10	5	3	1	1	1	3	**43**
Dependency on imports	1	1	1	10	10	10	10	10	10	10	**73**
SME employment created	1	1	2	9	5	5	2	3	6	9	**43**
Biodiversity change	1	1	1	1	1	1	1	1	1	1	**10**

Table F.5: HoQ3 for BioSS.3 scenario 1

Evaluating factors	Evaluating factor importance	Imported wood pellets (compliant with Italian A standard)	Imported hardwood pellets (Canada)	Imported olive residue (Greece)	National wood chip supplier	Local small demolition wood aggregator	National demolition wood aggregator	Start-up waste management company - SRF	Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	Established regional SRF producer [LHV 2, Cl 3, Hg 2]	Established regional RDF with high biomass content producer
Long Term Contracts	0.019	0.148	0.131	0.098	0.049	0.016	0.066	0.115	0.098	0.115	0.164
Take or pay Clauses	0.046	0.016	0.094	0.156	0.156	0.094	0.094	0.094	0.141	0.141	0.016
Track record	0.094	0.057	0.114	0.129	0.129	0.057	0.129	0.043	0.143	0.114	0.086
personal relationship	0.011	0.113	0.097	0.048	0.113	0.065	0.097	0.113	0.145	0.048	0.161
Contract has PFI back up	0.008	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Fixed price	0.035	0.103	0.172	0.172	0.017	0.052	0.069	0.103	0.121	0.052	0.138
Traceable (chain of custody)	0.011	0.192	0.115	0.192	0.173	0.019	0.058	0.077	0.096	0.058	0.019
Base cost of material (£/MWh)	0.041	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Clear definition of fuel	0.006	0.172	0.138	0.052	0.069	0.069	0.034	0.086	0.103	0.138	0.138
Visibility	0.009	0.036	0.036	0.182	0.109	0.127	0.127	0.073	0.073	0.109	0.127
Quality control mechanisms in place	0.002	0.200	0.120	0.020	0.060	0.120	0.180	0.040	0.060	0.040	0.160
Guarantee of fuel quality available	0.034	0.233	0.023	0.023	0.116	0.047	0.093	0.116	0.070	0.093	0.186
Supplier stability (in biomass market)	0.004	0.185	0.093	0.074	0.167	0.056	0.148	0.019	0.074	0.074	0.111
Distance from buyer	0.001	0.016	0.095	0.016	0.159	0.159	0.079	0.143	0.048	0.159	0.127
CO2/MWh	0.138	0.102	0.091	0.080	0.102	0.102	0.102	0.091	0.114	0.102	0.114
Land Use change	0.058	0.092	0.092	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
FSC accreditation	0.020	0.270	0.270	0.027	0.270	0.027	0.027	0.027	0.027	0.027	0.027
Alternative end use (Best use of biomass)	0.035	0.107	0.080	0.080	0.067	0.080	0.080	0.120	0.133	0.120	0.133
Diversion of material from landfill	0.073	0.020	0.020	0.041	0.020	0.082	0.082	0.163	0.184	0.184	0.204
Environmental regulatory environment in which the supplier operates	0.012	0.105	0.105	0.105	0.105	0.105	0.105	0.093	0.093	0.093	0.093

Performance against sustainability assurance certificate indicators	0.026	0.087	0.087	0.098	0.076	0.109	0.109	0.109	0.109	0.109	0.109
Credit strength	0.038	0.131	0.098	0.049	0.049	0.033	0.148	0.115	0.148	0.148	0.082
Size of balance sheet	0.016	0.148	0.111	0.074	0.056	0.037	0.130	0.148	0.093	0.111	0.093
Financially robust or credible counterparty	0.143	0.138	0.103	0.069	0.052	0.034	0.138	0.121	0.121	0.138	0.086
Rural jobs created or safeguarded	0.079	0.023	0.233	0.186	0.233	0.116	0.070	0.023	0.023	0.023	0.070
Dependency on imports	0.005	0.014	0.014	0.014	0.137	0.137	0.137	0.137	0.137	0.137	0.137
SME employment created	0.039	0.023	0.023	0.047	0.209	0.116	0.116	0.047	0.070	0.140	0.209
Biodiversity change	0.009	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Supplier Score		**0.096**	**0.105**	**0.095**	**0.106**	**0.077**	**0.105**	**0.095**	**0.112**	**0.111**	**0.111**

BioSS.Op Scenario 1

Table F.6: HoQ1 for BioSS.Op scenario 1

Stakeholder group	Stakeholder importance	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved
Financial groups and project partners/investors	0.028	0.350	0.146	0.071		0.433		
Environmental groups	0.448				1.000			
Developers/Operators	0.172	0.261	0.553	0.185	0.054	0.118		
National government and policy makers	0.225				0.551	0.051	0.270	0.131
Local government	0.083				0.200		0.800	
Community/public	0.045				1.000			
Requirement importance	1.000	0.055	0.099	0.034	0.642	0.044	0.127	0.029

Table F.7: HoQ2 for BioSS.Op scenario 1

Stakeholder requirements	Requirement importance	Long Term Contracts	Take or pay Clauses	Track record	personal relationship	Contract has PFI back up	Fixed price	Traceable (chain of custody)
A good supplier should be able to offer an attractive b2b contract	0.198	0.112	0.271	0.554	0.063			
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.175					0.075	0.327	
A good supplier should be able to provide material reliably and within the quality specification required	0.067							0.252
The supply of materials should have a low environmental impact	0.209							
A good supplier should be financially credible	0.206							
The supply of materials should have a positive social impact	0.138							
National energy security should be improved	0.007	0.056						
Evaluating factor importance score		**0.0078**	**0.0149**	**0.0304**	**0.0035**	**0.0075**	**0.0325**	**0.0085**

Stakeholder requirements	Base cost of material (£/MWh)	Clear definition of fuel	Visibility	Quality control mechanisms in place	Guarantee of fuel quality available	Supplier stability (in biomass market)	Distance from buyer	CO2/MWh	Land Use change	FSC accreditation
A good supplier should be able to offer an attractive b2b contract										
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.392	0.056			0.150					
A good supplier should be able to provide material reliably and within the quality specification required			0.167	0.051	0.397	0.090				
The supply of materials should have a low environmental impact								0.372	0.156	0.055
A good supplier should be financially credible										
The supply of materials should have a positive social impact										
National energy security should be improved			0.295				0.110			
Evaluating factor importance score	**0.0389**	**0.0056**	**0.0143**	**0.0017**	**0.0283**	**0.0031**	**0.0032**	**0.2387**	**0.1003**	**0.0354**

Alternative end use (Best use of biomass)	Diversion of material from landfill	Environmental regulatory environment in which the supplier operates	Performance against sustainability assurance certificate indicators	Credit strength	Size of balance sheet	Financially robust or credible counterparty	Rural jobs created or safeguarded	Dependency on imports	SME employment created	Biodiversity change
								0.042		
0.094	0.196	0.032	0.069							0.025
				0.193	0.083	0.724				
							0.667		0.333	
								0.539		
0.0600	**0.1260**	**0.0207**	**0.0443**	**0.0085**	**0.0037**	**0.0318**	**0.0845**	**0.0173**	**0.0423**	**0.0162**

Table F.8: House of Quality 3

Evaluating factors	Evaluating factor importance	Imported wood pellets (compliant with Italian A standard)	Imported hardwood pellets (Canada)	Imported olive residue (Greece)	National wood chip supplier	Local small demolition wood aggregator	National demolition wood aggregator	Start-up waste management company - SRF	Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	Established regional SRF producer [LHV 2, Cl 3, Hg 2]	Established regional RDF with high biomass content producer
Long Term Contracts	0.008	0.148	0.131	0.098	0.049	0.016	0.066	0.115	0.098	0.115	0.164
Take or pay Clauses	0.015	0.016	0.094	0.156	0.156	0.094	0.094	0.094	0.141	0.141	0.016
Track record	0.030	0.057	0.114	0.129	0.129	0.057	0.129	0.043	0.143	0.114	0.086
personal relationship	0.003	0.113	0.097	0.048	0.113	0.065	0.097	0.113	0.145	0.048	0.161
Contract has PFI back up	0.007	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Fixed price	0.033	0.103	0.172	0.172	0.017	0.052	0.069	0.103	0.121	0.052	0.138
Traceable (chain of custody)	0.009	0.192	0.115	0.192	0.173	0.019	0.058	0.077	0.096	0.058	0.019
Base cost of material (£/MWh)	0.039	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Clear definition of fuel	0.006	0.172	0.138	0.052	0.069	0.069	0.034	0.086	0.103	0.138	0.138
Visibility	0.014	0.036	0.036	0.182	0.109	0.127	0.127	0.073	0.073	0.109	0.127
Quality control mechanisms in place	0.002	0.200	0.120	0.020	0.060	0.120	0.180	0.040	0.060	0.040	0.160
Guarantee of fuel quality available	0.028	0.233	0.023	0.023	0.116	0.047	0.093	0.116	0.070	0.093	0.186
Supplier stability (in biomass market)	0.003	0.185	0.093	0.074	0.167	0.056	0.148	0.019	0.074	0.074	0.111
Distance from buyer	0.003	0.016	0.095	0.016	0.159	0.159	0.079	0.143	0.048	0.159	0.127
CO_2/MWh	0.239	0.102	0.091	0.080	0.102	0.102	0.102	0.091	0.114	0.102	0.114
Land Use change	0.100	0.092	0.092	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
FSC accreditation	0.035	0.270	0.270	0.027	0.270	0.027	0.027	0.027	0.027	0.027	0.027
Alternative end use (Best use of biomass)	0.060	0.107	0.080	0.080	0.067	0.080	0.080	0.120	0.133	0.120	0.133
Diversion of material from landfill	0.126	0.020	0.020	0.041	0.020	0.082	0.082	0.163	0.184	0.184	0.204

Environmental regulatory environment in which the supplier operates	0.021	0.105	0.105	0.105	0.105	0.105	0.105	0.093	0.093	0.093	0.093
Performance against sustainability assurance certificate indicators	0.044	0.087	0.087	0.098	0.076	0.109	0.109	0.109	0.109	0.109	0.109
Credit strength	0.008	0.131	0.098	0.049	0.049	0.033	0.148	0.115	0.148	0.148	0.082
Size of balance sheet	0.004	0.148	0.111	0.074	0.056	0.037	0.130	0.148	0.093	0.111	0.093
Financially robust or credible counterparty	0.032	0.138	0.103	0.069	0.052	0.034	0.138	0.121	0.121	0.138	0.086
Rural jobs created or safeguarded	0.085	0.023	0.233	0.186	0.233	0.116	0.070	0.023	0.023	0.023	0.070
Dependency on imports	0.017	0.014	0.014	0.014	0.137	0.137	0.137	0.137	0.137	0.137	0.137
SME employment created	0.042	0.023	0.023	0.047	0.209	0.116	0.116	0.047	0.070	0.140	0.209
Biodiversity change	0.016	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Supplier Score		**0.0912**	**0.1011**	**0.0920**	**0.1111**	**0.0923**	**0.0978**	**0.0988**	**0.1117**	**0.1098**	**0.1242**

BioSS.3 scenario 2

Table F.9: AHP for stakeholder importance weightings to use as input to scenario 2

	Financial investors	Environmental groups	National government	Local government	Local community	Developers and operators	Weighting (average)	Rank	[C]	**λmax =**	6.32
Financial investors	0.03	0.05	0.01	0.03	0.03	0.01	0.027	6.00	6.19	Consistency index =	0.0787
Environmental groups	0.28	0.43	0.28	0.54	0.45	0.28	0.377	1.00	6.53	Consistency ratio =	0.0634
National government	0.09	0.05	0.04	0.02	0.03	0.02	0.043	5.00	6.05		
Local government	0.19	0.14	0.28	0.18	0.22	0.28	0.216	3.00	6.72		
Local community	0.25	0.22	0.28	0.18	0.22	0.34	0.250	2.00	6.63		
Developers and operators	0.16	0.11	0.11	0.05	0.04	0.07	0.088	4.00	6.24		
Total	1	1	1	1	1	1	1				

Table F.10: HoQ1 for scenario 2

Stakeholder group	Stakeholder importance	A good supplier should be able to offer an attractive b2b contract	A good supplier should be able to provide good contract conditions regarding the supply of fuel	A good supplier should be able to provide material reliably and within the quality specification required	The supply of materials should have a low environmental impact	A good supplier should be financially credible	The supply of materials should have a positive social impact	National energy security should be improved
Financial groups and project partners/investors	0.027	0.350	0.146	0.071		0.433		
Environmental groups	0.377				1.000			
Developers/Operators	0.043	0.261	0.553	0.185	0.054	0.118		
National government and policy makers	0.216				0.551	0.051	0.270	0.131
Local government	0.250				0.200		0.800	
Community/public	0.088				1.000			
Requirement importance		**0.021**	**0.028**	**0.010**	**0.636**	**0.028**	**0.258**	**0.028**

Table F.11: HoQ2 for scenario 2

Stakeholder requirements	Requirement importance	Long Term Contracts	Take or pay Clauses	Track record	personal relationship	Contract has PFI back up	Fixed price	Traceable (chain of custody)
A good supplier should be able to offer an attractive b2b contract	0.0207	0.112	0.271	0.554	0.063			
A good supplier should be able to provide good contract conditions regarding the supply of fuel	0.0276					0.075	0.327	
A good supplier should be able to provide material reliably and within the quality specification required	0.0098							0.252
The supply of materials should have a low environmental impact	0.6359							
A good supplier should be financially credible	0.0278							
The supply of materials should have a positive social impact	0.2578							
National energy security should be improved	0.0282	0.056						
Evaluating factor importance score		**0.004**	**0.006**	**0.011**	**0.001**	**0.002**	**0.009**	**0.002**

Base cost of material (£/MWh)	Clear definition of fuel	Visibility	Quality control mechanisms in place	Guarantee of fuel quality available	Supplier stability (in biomass market)	Distance from buyer	CO2/MWh	Land Use change	FSC accreditation
0.392	0.056			0.150					
		0.167	0.051	0.397	0.090				
							0.372	0.156	0.055
		0.295				0.110			
0.011	**0.002**	**0.010**	**0.001**	**0.008**	**0.001**	**0.003**	**0.237**	**0.099**	**0.035**

Alternative end use (Best use of biomass)	Diversion of material from landfill	Environmental regulatory environment in which the supplier operates	Performance against sustainability assurance certificate indicators	Credit strength	Size of balance sheet	Financially robust or credible counterparty	Rural jobs created or safeguarded	Dependency on imports	SME employment created	Biodiversity change
								0.042		
0.094	0.196	0.032	0.069							0.025
				0.193	0.083	0.724				
							0.667		0.333	
								0.539		
0.059	**0.125**	**0.021**	**0.044**	**0.005**	**0.002**	**0.020**	**0.172**	**0.016**	**0.086**	**0.016**

Table F.12: HoQ3 for scenario 2

Evaluating factors	Evaluating factor importance	Imported wood pellets (compliant with Italian A standard)	Imported hardwood pellets (Canada)	Imported olive residue (Greece)	National wood chip supplier	Local small demolition wood aggregator	National demolition wood aggregator	Start-up waste management company - SRF	Established national waste management company providing SRF [LHV 3, Cl 2, Hg 3]	Established regional SRF producer [LHV 2, Cl 3, Hg 2]	Established regional RDF with high biomass content producer
Long Term Contracts	0.004	0.148	0.131	0.098	0.049	0.016	0.066	0.115	0.098	0.115	0.164
Take or pay Clauses	0.006	0.016	0.094	0.156	0.156	0.094	0.094	0.094	0.141	0.141	0.016
Track record	0.011	0.057	0.114	0.129	0.129	0.057	0.129	0.043	0.143	0.114	0.086
personal relationship	0.001	0.113	0.097	0.048	0.113	0.065	0.097	0.113	0.145	0.048	0.161
Contract has PFI back up	0.002	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Fixed price	0.009	0.103	0.172	0.172	0.017	0.052	0.069	0.103	0.121	0.052	0.138
Traceable (chain of custody)	0.002	0.192	0.115	0.192	0.173	0.019	0.058	0.077	0.096	0.058	0.019
Base cost of material (£/MWh)	0.011	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Clear definition of fuel	0.002	0.172	0.138	0.052	0.069	0.069	0.034	0.086	0.103	0.138	0.138
Visibility	0.010	0.036	0.036	0.182	0.109	0.127	0.127	0.073	0.073	0.109	0.127
Quality control mechanisms in place	0.001	0.200	0.120	0.020	0.060	0.120	0.180	0.040	0.060	0.040	0.160
Guarantee of fuel quality available	0.008	0.233	0.023	0.023	0.116	0.047	0.093	0.116	0.070	0.093	0.186
Supplier stability (in biomass market)	0.001	0.185	0.093	0.074	0.167	0.056	0.148	0.019	0.074	0.074	0.111
Distance from buyer	0.003	0.016	0.095	0.016	0.159	0.159	0.079	0.143	0.048	0.159	0.127
CO2/MWh	0.237	0.102	0.091	0.080	0.102	0.102	0.102	0.091	0.114	0.102	0.114
Land Use change	0.099	0.092	0.092	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
FSC accreditation	0.035	0.270	0.270	0.027	0.270	0.027	0.027	0.027	0.027	0.027	0.027

Alternative end use (Best use of biomass)	0.059	0.107	0.080	0.080	0.067	0.080	0.080	0.120	0.133	0.120	0.133
Diversion of material from landfill	0.125	0.020	0.020	0.041	0.020	0.082	0.082	0.163	0.184	0.184	0.204
Environmental regulatory environment in which the supplier operates	0.021	0.105	0.105	0.105	0.105	0.105	0.105	0.093	0.093	0.093	0.093
Performance against sustainability assurance certificate indicators	0.044	0.087	0.087	0.098	0.076	0.109	0.109	0.109	0.109	0.109	0.109
Credit strength	0.005	0.131	0.098	0.049	0.049	0.033	0.148	0.115	0.148	0.148	0.082
Size of balance sheet	0.002	0.148	0.111	0.074	0.056	0.037	0.130	0.148	0.093	0.111	0.093
Financially robust or credible counterparty	0.020	0.138	0.103	0.069	0.052	0.034	0.138	0.121	0.121	0.138	0.086
Rural jobs created or safeguarded	0.172	0.023	0.233	0.186	0.233	0.116	0.070	0.023	0.023	0.023	0.070
Dependency on imports	0.016	0.014	0.014	0.014	0.137	0.137	0.137	0.137	0.137	0.137	0.137
SME employment created	0.086	0.023	0.023	0.047	0.209	0.116	0.116	0.047	0.070	0.140	0.209
Biodiversity change	0.016	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Supplier Score		**0.0763**	**0.1069**	**0.0941**	**0.1263**	**0.0973**	**0.0937**	**0.0882**	**0.1000**	**0.1027**	**0.1222**

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