Using mobile distributed pyrolysis facilities to deliver a forest residue resource for bio-fuel production

by

Duncan Brown
BSc (Hons), University of Birmingham, 2009

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Supervisory Committee

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Dr. Andrew Rowe (Department of Mechanical Engineering)
Co-Supervisor

Dr. Peter Wild (Department of Mechanical Engineering)
Co-Supervisor

Abstract

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Co-Supervisor

Dr. Peter Wild (Department of Mechanical Engineering)

Co-Supervisor

Distributed mobile conversion facilities using either fast pyrolysis or torrefaction processes can be used to convert forest residues to more energy dense substances (bio-oil, bio-slurry or torrefied wood) that can be transported as feedstock for bio-fuel facilities. All feedstock are suited for gasification, which produces syngas that can be used to synthesise petrol or diesel via Fischer-Tropsch reactions, or produce hydrogen via water gas shift reactions. Alternatively, the bio-oil product of fast pyrolysis may be upgraded to produce petrol and diesel, or can undergo steam reformation to produce hydrogen.

Implementing a network of mobile facilities reduces the energy content of forest residues delivered to a bio-fuel facility as mobile facilities use a fraction of the biomass energy content to meet thermal or electrical demands. The total energy delivered by bio-oil, bio-slurry and torrefied wood is 45%, 65% and 87% of the initial forest residue energy content, respectively. However, implementing mobile facilities is economically feasible when large transport distances are required. For an annual harvest of 1.717 million m^3 (equivalent to 2000 ODTPD), transport costs are reduced to less than 40% of the total levelised delivered feedstock cost when mobile facilities are implemented; transport costs account for up to 80% of feedstock costs for conventional woodchip delivery. Torrefaction provides the lowest cost pathway of delivering a forest residue resource when using mobile facilities. Cost savings occur against woodchip delivery for annual forest residue harvests above 2.25 million m^3 or when transport distances greater than 250 km are required.

Important parameters that influence levelised delivered costs of feedstock are transport distances (forest residue spatial density), haul cost factors, thermal and electrical demands of mobile facilities, and initial moisture content of forest residues. Relocating mobile facilities can be optimised for lowest cost delivery as transport distances of raw biomass are reduced.

The overall cost of bio-fuel production is determined by the feedstock delivery pathway and also the bio-fuel production process employed. Results show that the minimum cost of petrol and diesel production is 0.86 $ litre^{-1} when a bio-oil feedstock is upgraded. This corresponds to a 2750 TPD upgrading facility requiring an annual harvest of 4.30 million m^3. The minimum cost of hydrogen production is 2.92 $ kg^{-1}, via the gasification of a woodchip feedstock and subsequent water gas shift reactions. This corresponds to a 1100 ODTPD facility and requires an annual harvest of 947,000 m^3.

The levelised cost of bio-fuel strongly depends on the size of annual harvest required for bio-fuel facilities. There are optimal harvest volumes (bio-fuel facility sizes) for each bio-fuel production route, which yield minimum bio-fuel production costs. These occur as the benefits of economies of scale for larger bio-fuel facilities compete against increasing transport costs for larger harvests. Optimal harvest volumes are larger for bio-fuel production routes that use feedstock sourced from mobile facilities, as mobile facilities reduce total transport requirements.

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Nomenclature

Acronyms

BCL	Battelle Columbus Laboratory
CRF	Capital recovery factor
FT	Fischer-Tropsch
GT	Green tonne
NPV	Net present value
ODT	Oven-dry tonne
ODTPD	Oven-dry tonne per day
ODW	Oven-dry wood
ROI	Renewable Oil International
SMR	Steam Methane Reformation
WGS	Water gas shift

Symbols

Note: all lower case symbols represent values or data input into the model and all upper case symbols represent values or data calculated by the model

c_i	Unit cost of i ($\$\cdot[\text{unit}]^{-1}$)
c_{mob}	Cost of mobile facility ($)
$c_{ref,k}$	Reference cost of bio-fuel facility k ($)
$c_{ref,tank}$	Reference cost of stainless steel tank ($)
$c_{tran,fix,j}$	Unit fixed cost of transportation for commodity j ($\$\cdot\text{tonne}^{-1}$)
$c_{tran,var,j}$	Unit variable cost of transportation for commodity j ($\$\cdot\text{km}^{-1}$)
d	Additional transport distance (km)
e_{dry}	Energy required to dry woodchips ($\text{MJ}\cdot[\text{kg-water-removed}]^{-1}$)
f_k	Ratio of bio-fuel yield per unit feed at bio-fuel facility k
$f_{r,k}$	Petrol-diesel production ratio at bio-fuel facility k

f_{SMR}	Ratio of hydrogen production from methane
h	Annual quantity of available forest residues ($m^3 \cdot yr^{-1}$)
l_{CH_4}	Lower heating value of methane ($MJ \cdot kg^{-1}$)
$l_{C_3H_8}$	Lower heating value of propane ($MJ \cdot kg^{-1}$)
l_{ODW}	Lower heating value of oven-dry wood ($MJ \cdot kg^{-1}$)
m_{meth}	Mass ratio of methanol added to bio-oil
m_{WS}	Mass fraction of bio-oil that is water soluble
n_r	Number of relocations for each mobile facility during operation lifetime
n_{staff}	Number of staff required at each mobile facility
$o_{bf,k}$	Operation and maintenance percentage of bio-fuel facility k
o_{mob}	Operation and maintenance percentage of mobile facilities
o_{tank}	Operation and maintenance percentage of stainless steel tank
s_{mob}	Size of mobile facilities (ODTPD)
$s_{ref,k}$	Reference size of bio-facility k (TPD)
$s_{ref,tank}$	Reference size of stainless steel tank
x_i	Mobile facility mass yield ratio for product i
y	Harvest operation lifetime (yr)
y_i	Mobile facility energy yield ratio for product i
z	Moisture content of forest residues (% wt)
z_{ODW}	Moisture content of oven-dry wood (% wt)
$C_{i,bf}$	Cost i relating to bio-fuel facilities
$C_{i,mob}$	Cost i relating to mobile facilities
C_p	Cost of process p ($\$ \cdot yr^{-1}$)
$C_{tran,fix,j}$	Annual fixed cost of transportation for commodity j ($\$ \cdot yr^{-1}$)
$C_{tran,var,j}$	Annual variable cost of transportation for commodity j ($\$ \cdot yr^{-1}$)
CRF	Capital recovery factor
$\overline{D}_j$	Average annual transport distance of commodity j (km)
D_j	Total annual transport distance of commodity j (km)

$\overline{D}_{F,B}$	Average annual transport distance from logging fields to bio-fuel facility (km)
$\overline{D}_{F,M}$	Average annual transport distance from logging fields to mobile facilities (km)
$\overline{D}_{M,B}$	Average annual transport distance from mobile facilities to bio-fuel facility (km)
E_{dry}	Annual energy required to dry woodchips (GJ·yr^{-1})
$E_{i,gross}$	Total annual energy content of mobile facility product i (GJ·yr^{-1})
$E_{j,net}$	Total annual energy content of commodity j for bio-fuel production (GJ·yr^{-1})
E_{FR}	Annual energy content of forest residue resource (GJ·yr^{-1})
$F_{kg,j,k,m}$	Quantity of fuel m produced from bio-fuel facility k using feedstock commodity j (kg)
H_{mob}	Quantity of available forest residues within distributed collection region (m^3)
$LCB_{j,k,m}$	Levelised cost of bio-fuel m produced at bio-fuel facility k using commodity feedstock j ($·GJ^{-1})
LDC_j	Levelised delivered cost of commodity j ($·GJ^{-1})
M_{diesel}	Annual consumption of diesel at mobile torrefaction facility (tonne·yr^{-1})
$M_{i,gross}$	Annual quantity of mobile facility product i (tonne·yr^{-1})
$M_{j,feed}$	Annual quantity of commodity j used as bio-fuel feedstock (tonne·yr^{-1})
$M_{j,net}$	Annual quantity of commodity j transported to bio-fuel facility (tonne·yr^{-1})
$M_{truck,j}$	Load of truck transporting commodity j (tonne)
$M_{BC,excess}$	Annual quantity of excess bio-char not added to bio-slurry (tonne·yr^{-1})
$M_{BC,net}$	Annual quantity of bio-char added to bio-slurry (tonne·yr^{-1})
M_{CH_4}	Annual quantity of methane required for SMR (tonne·yr^{-1})
$M_{C_3H_8}$	Annual quantity of propane required to assist drying woodchips (tonne·yr^{-1})
M_{GT}	Annual quantity of available forest residues in GT (tonne·yr^{-1})
M_{H_2O}	Annual quantity of water removed from woodchips (tonne·yr^{-1})
$M_{H_2,UG}$	Annual quantity of hydrogen required for upgrading (tonne·yr^{-1})
M_{ODT}	Annual quantity of available forest residues in ODT (tonne·yr^{-1})

N_{grid}	Number of distributed collection regions when using mobile facilities
N_{mob}	Number of mobile units required to process an annual harvest h
N_{tank}	Number of liquid storage tanks required at bio-fuel facility
NPV_j	Net present value of all costs expended to deliver commodity j (\$)
$NPV_{j,k,m}$	Net present value of all costs expended to produce bio-fuel m at bio-fuel facility k using commodity feedstock j (\$)
R	Radius of harvest region (km)
$S_{bf,j,k}$	Size of bio-fuel facility k using commodity feedstock j (TPD)
V_j	Annual volume of commodity j delivered to bio-fuel facility (m^3)
$V_{j,bf}$	Maximum storage volume of commodity j at bio-fuel facility (m^3)
$V_{j,mob}$	Maximum storage volume of commodity j at each mobile facility (m^3)
X_{BO}	Fraction of gross bio-oil production used for electricity generation

Greek

Note: all lower case symbols represent values or data input into the model and all upper case symbols represent values or data calculated by the model

β	Electricity demand of mobile facilities (GJ·ODT^{-1})
γ_{H_2}	Ratio of hydrogen required per unit bio-oil feed for upgrading
ζ_{max}	Maximum bio-char loading in bio-slurry (%wt)
η_{dry}	Efficiency of drying woodchips
η_{gen}	Efficiency of electricity generator
κ	Cost scaling factor
ρ_j	Density of commodity j (kg·m^{-3})
$\rho_{C_3H_8}$	Density of propane (kg·m^{-3})
ρ_D	Density of diesel (kg·m^{-3})
ρ_{H_2O}	Density of water (kg·m^{-3})
ρ_{ODW}	Density of oven-dry wood (kg·m^{-3})
$\sigma_{bf,k}$	Capacity factor of bio-fuel facility k

σ_{mob}	Maximum capacity factor of mobile facilities
τ	Tortuosity of road network
φ	Density of available forest residues ($m^3 \cdot km^{-2}$)
$\Upsilon_{BO,SR}$	Fraction of bio-oil to be steam reformed during upgrading
Z	Bio-char loading in bio-slurry (%wt)

Subscripts

bf	Relating to bio-fuel facility
i	Mobile facility product i (syngas, bio-oil, bio-char, or torrefied wood)
j	Commodity j for bio-fuel production (woodchip, bio-oil, bio-slurry, or torrefied wood)
k	Bio-fuel facility k (FT, WGS, UG or SR)
kg	Kilogram
lab	Labour
m	Bio-fuel m (petrol, diesel or hydrogen)
m^3	Cubic metres
$meth$	Methanol
mob	Relating to mobile facility
p	Process p (e.g. piling, chipping, loading)
ref	Reference value
$relocate$	Relating to the relocation of mobile facilities
$tank$	Relating to bio-oil/bio-slurry storage tank
$wage$	Wage of mobile facility employees
BC	Bio-char
BO	Bio-oil
BS	Bio-slurry
CH_4	Methane
C_3H_8	Propane
D	Diesel
FR	Forest residue

FT	Gasification and Fischer-Tropsch facility
H	Hydrogen
$O\&M$	Operation and maintenance
P	Petrol
S	Syngas
SMR	Steam methane reformation facility
SR	Bio-oil steam reformation facility
TW	Torrefied wood
UG	Upgrading bio-oil facility
WC	Woodchip
WGS	Water gas shift facility
WS	Water soluble

1 Motivation

1.1 Climate change, forest residues and bio-fuels

Climate change concerns and government policies aimed at reducing greenhouse gas emissions from fossil fuels continue to contribute to an increasing demand for fuels from biomass sources ('bio-fuels'). The extent to which bio-fuels mitigate climate change by reducing greenhouse gas emissions compared against fossil fuels is a subject of debate, particularly when land use changes are considered in lifecycle analyses [1]–[5]. However, bio-fuels produced from waste wood, such as forest or mill residuals, can reduce net carbon emissions whilst avoiding controversy related to land use change as they are a by-product of the forest industry [6].

Forest residuals, in particular, have considerable potential for increased utilisation for bio-fuel production - at present, most are burned on-site at the end of commercial forestry operations. However, forest residues suffer from low spatial and energy densities, which hinder their use as a biomass resource. Typically, forest residues are spread-out over wide areas of land, thus large distances are travelled for collection and delivery to bio-fuel production facilities. If forest residues are transported in their raw form or as woodchips, truck capacity is limited by volume rather than weight and, as a result, more delivery trips are required than if the truck were transporting a more energy dense substance at full weight capacity [7]. The combination of low spatial and energy densities of biomass results in high transport costs which, in turn, elevate the final bio-fuel production cost.

One proposed method of reducing the cost of delivering a forest residue resource is to implement a network of distributed biomass conversion facilities near the location of forest residues [8]. These conversion facilities convert raw biomass to a more energy dense substance, which is then transported longer distances to a centralised bio-fuel production facility. Mobile facilities are of particular interest as forest residues are not consistently available at the same location for long periods of time. Mobile distributed conversion facilities ('mobile facilities') can be moved from a depleted region and relocated to a region with abundant forest residues. Relocating mobile facilities reduces transport distances of raw biomass material.

Two processes that are suited for mobile facilities are fast pyrolysis and torrefaction ([9], [10]). These are both forms of pyrolysis, which is the thermal decomposition of materials in the absence of oxygen. Fast pyrolysis involves high heating rates and short reaction times producing primarily a liquid bio-oil product [11]. Torrefaction occurs at lower temperatures than fast pyrolysis and the principal product is a solid char-like substance known as torrefied wood [12]. The energy and mass densities of the liquid and solid products are typically higher than that of forest residues or woodchips.

Upon delivery to a bio-fuel facility, the products of mobile facilities can be used directly as feedstock for bio-fuel production. All are suited for gasification ([11], [13]), which produces syngas that can be used to synthesise petrol or diesel via Fischer-Tropsch reactions, or produce hydrogen via water gas shift reactions. Alternatively, the bio-oil product of fast pyrolysis may be upgraded to produce petrol and diesel, or can undergo steam reformation to produce hydrogen.

Therefore, implementing mobile facilities introduces new pathways for bio-fuel production using a forest residue resource. No literature has been identified that investigates harvesting a forest residue resource using multiple mobile facilities, or the subsequent cost of bio-fuel production when implementing a network of mobile facilities.

1.2 Objective

The objective of this study is to investigate the technical and economic implications of producing bio-fuels when using a network of mobile facilities to deliver a forest residue resource to a bio-fuel facility. A model is created that considers the production of petrol and diesel (for use in present day fuel infrastructure), or hydrogen (which may be a prominent fuel in the near future). The two main outputs of the model are: (i) a levelised delivered cost of feedstock to a bio-fuel facility, and (ii) a final levelised cost of bio-fuel production. The model results are compared against current bio-fuel production methods to determine the feasibility of implementing bio-fuel production pathways using mobile facilities.

1.3 Outline

The study is divided into five Chapters. Chapter 2 provides background on forest residue resources, mobile facility processes and bio-fuel production processes. Chapter 3 describes the model constructed to analyse bio-fuel production pathways when implementing mobile facilities to harvest a forest residue resource. Chapter 4 presents model results and a discussion of the technical and economic feasibility of implementing mobile facilities. Conclusions and recommendations of further work are made in Chapter 5.

2 Background

This Chapter contains background information on forest residue resources, mobile facilities, and bio-fuel production facilities.

Characteristics of forest residue resources vary depending on location, forest type (tree species) and logging industry practices [14], [15]. This study considers a forest residue resource originating from a temperate forest region. No particular geographic location or logging practice is assumed, which would limit the scope of the study, and therefore a general description of forest residue resources is provided in Section 2.1.

Fast pyrolysis and torrefaction are processes suited to mobile application and are discussed in Section 2.2. The discussion includes technical information about each process, as well as information on associated products and commodities derived from these processes, which can be used as feedstock for bio-fuel production. The current status of mobile facilities is also addressed, with focus on companies based in North America.

The bio-fuel production processes considered in this study are gasification followed by either Fischer-Tropsch synthesis or water gas shift reactions, and upgrading or steam reformation of bio-oil. Fischer-Tropsch and water gas shift processes are selected because these are mature processes that are currently available and applicable to a wide range of feedstock. Upgrading and steam reformation of bio-oil are areas of current research ([16]–[19]) and, although no large scale facilities are known to be operating, these processes are included as they relate directly to the use of mobile fast pyrolysis facilities. Background information on each bio-fuel production process is addressed in Section 2.3.

2.1 Forest residues

The forest residue resource considered in this study is a by-product of conventional logging operations, and has been identified as a biomass resource with potential for increased utilisation [14], [15], [20]. Forest residues are tree tops and limbs, and other off-cuts, that are removed during roundwood harvest and discarded within the logging fields. They are either left scattered across logged areas or piled at the roadside, where they may be burnt to prevent forest fires at a later time.

Forest residues typically have a moisture content between 23 and 50 % ([21], [22]), resulting in lower heating values ranging between 14 and 8 MJ kg^{-1}, respectively [23]. Forest residues also have an ash content of up to 3%wt due to higher portions of bark in the wood, and may become contaminated with soil and other impurities during collection processes [24].

The volume of forest residues that are produced during logging varies, but is approximately 20% of the logged roundwood volume [14], [15]. Forest residue recovery is influenced by biophysical, technical, and economic factors. The biophysical resources that contribute to forest growth (e.g. topography, climate geology, and hydrology) impact the ecologically sustainable level of harvesting forest residues, and thus provide a baseline for forest residue recovery (some jurisdictions define a proportion of forest residues that should be retained) [14]. Additionally, it may only be technically possible to recover 41 - 75% of forest residues [25], and the cost-effectiveness of recovery will depend on a range of economic factors, such as market demand for resource utilisation and marginal costs of recovery [26]–[28], that are outside the scope of this study.

Units used to measure quantities of forest residues varies in the literature. A volume may be stated in cubic metres or, alternatively, a mass may be provided for wet (green) or dry tonnes of residues. The stated quantity of resource will depend on the moisture content of forest residues when using units of cubic metres (m^3) or green tonnes (GT). Therefore, a unit of oven-dry tonnes (ODT), corresponding to a moisture content of approximately 10%wt, is often used as standard to allow comparison between different feedstock types. However, moisture content and volume are important factors when considering the delivery of a biomass resource and therefore this study uses cubic metres to quantify forest residue resources. Table 2-1 provides conversion factors between units for a forest residue moisture content of 50%wt. See Section 3.1 for details.

Table 2-1 Conversion factors between units used to measure forest residue resource quantities (moisture content 50%wt).

m^3 per green tonne	1.62
green tonne per oven-dry tonne	1.61
m^3 per oven-dry tonne	2.61

2.2 Mobile facility processes

2.2.1 Fast pyrolysis

Pyrolysis is the thermal decomposition of materials in the absence of oxygen [29]. The products of pyrolysis reactions comprise solid char, liquid bio-oil and syngas, which is a mixture of hydrogen, carbon monoxide, carbon dioxide, and methane. The relative quantity and composition of each product depend on operating conditions, such as reaction temperature, residence time, use of catalysts, as well as the feedstock type.

To obtain a high liquid product yield, fast pyrolysis is used. Fast pyrolysis requires temperatures of 500 - 650°C and feed particles less than 3 mm in diameter [29], [30]. The feed particles are resident in the reactor for 2 to 3 seconds, and the vapours produced are condensed into bio-oil. High bio-oil yields of up to 80 wt% can be achieved [31].

There are many types of reactor systems that perform fast pyrolysis including fluid bed, circulating fluid bed, auger, rotating cone and ablative, of which the first three have a strong technical grounding and are most attractive for commercial development [32]. Auger pyrolysis has been selected as the reactor for this study because it has been suggested as an option for mobile facilities [10].

Auger fast pyrolysis requires a feed composed of granules less than 3 mm in diameter with a moisture content of approximately 10%. The feed particles are passed into the reactor where they are indirectly heated to approximately 500°C within 1 second, and the vapours produced are rapidly condensed into bio-oil. The feed system and reactor contain a screw conveyor to enable the process to run continuously (Figure 2-1). It is possible for the non-condensable syngas to be recycled within the reactor to provide process energy, and the solid char exits the reactor vessel for collection [10].

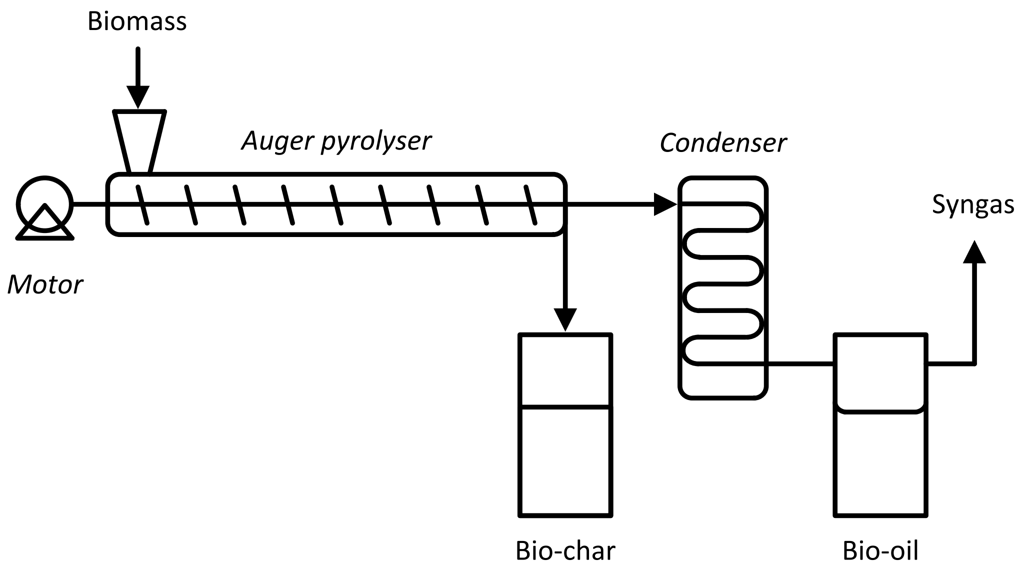


Figure 2-1 Typical auger reactor setup [33].

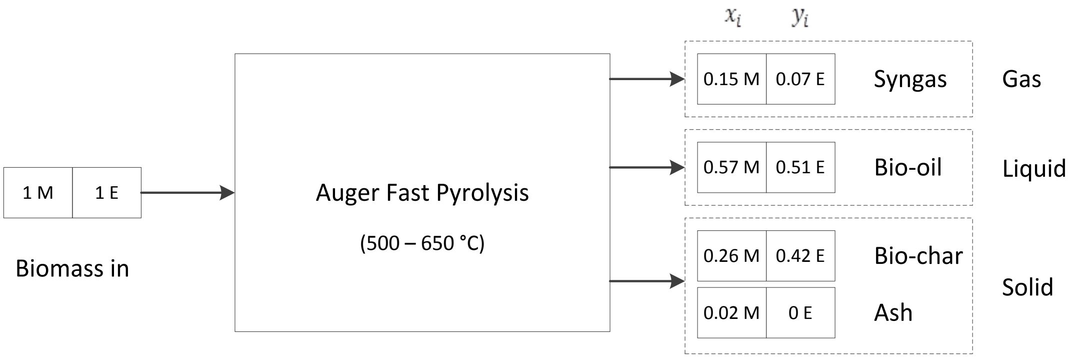


Figure 2-2 Overview of auger fast pyrolysis and process yields [10]. The energy content ratios for each product have been calculated to ensure typical lower heating values are maintained (syngas 8 $\mathrm{MJ \cdot kg^{-1}}$; bio-oil 16.2 $\mathrm{MJ \cdot kg^{-1}}$; bio-char 19 $\mathrm{MJ \cdot kg^{-1}}$).

The typical yield of bio-oil tends to be lower for auger reactors compared to fluid bed reactors as the vapours spend more time in the reactor vessel and secondary thermal break-down reactions occur (in contact with the solid char) reducing the quantity of vapours that condense into bio-oil [11]. The yields of auger pyrolysis used in this study are 57%wt bio-oil, 26%wt char and 15%wt syngas (Figure 2-2). Ash is assumed to comprise 2%wt of the products, and exits the reactor along with the solid char.

It is possible for the electrical and thermal energy requirements of a mobile fast pyrolysis facility to be supplied using fractions of the pyrolysis products. Thermal demands can be met using syngas, and electrical demands can be met by using bio-oil to power a generator. In cases of high initial moisture content, propane may be required for sufficient drying of biomass [10].

No mobile fast pyrolysis facilities have yet been commercialised, although there are a number of companies working on designs, such as Agri-Therm (Ontario, Canada) and Renewable Oil International (ROI) (Alabama, United States). ROI has manufactured a 5 oven-dry tonne per day (ODTPD) mobile facility and a 15 ODTPD fixed facility, and has plans to construct larger facilities [34], [35]. A 50 ODTPD mobile auger fast pyrolysis design by ROI was the focus of a recent study and is the subject of this analysis [10]. This 50 ODTPD facility is permanently mounted on two 16 metre lowboy trailers, for ease of mobilisation.

2.2.1.1 Bio-oil

Fast pyrolysis liquid, known as bio-oil, has a lower heating value of 14 to 19 MJ kg^{-1} and a density of approximately 1200 kg m^{-3} [11], [36]. The properties of the bio-oil are strongly influenced by the feed used for the fast pyrolysis process. Bio-oil is often dark-brown in colour, and is a free-flowing heterogeneous mixture composed primarily of oxygenated hydrocarbons and water. The reactive oxygenated compounds such as acids, ethers, esters, aldehydes, ketones and alcohols cause undesirable properties including high viscosity, low pH, immiscibility with fossil fuels, thermal instability and a tendency to polymerize under exposure to air [11], [37]. Therefore, removing the oxygen content of bio-oil, in a process known as upgrading, is often required although it is possible to use raw bio-oil as fuel in a diesel or flex fuel generator [10].

Bio-oil is often stored in stainless steel tanks due to the corrosive nature of the liquid [8]. Secondary reactions within the bio-oil can occur over time in a process known as aging, which results in increased viscosity and in some cases, phase separation. The aging process is accelerated by the presence of fine char within the liquid, but can be reduced by the addition of alcohols such as ethanol or methanol [11]. Downstream options for utilisation of bio-oil include: electricity generation, bio-fuel production via gasification or upgrading, steam reformation to hydrogen, and production of chemicals.

2.2.1.2 Bio-slurry

Char produced from the fast pyrolysis reaction can be added to bio-oil up to 20%wt to form a bio-slurry mixture that is flowable [38], [39]. Even low quality bio-oils, which are prone to phase separation and contain char and ash contaminates, are amenable to bio-slurry preparation. Adding bio-char to the bio-oil can allow up to 90% of the energy content of the pyrolysis products to be contained in the bio-slurry [40], making bio-slurry an attractive energy carrier for biomass. The density and energy content of bio-slurry varies depending on the char loading in the mixture, but is approximately 1300 kg m^{-3} and 30 MJ kg^{-1} respectively for a slurry containing 20%wt char. Bio-slurry can be easily pumped into high pressurised gasifiers or other processing reactors to generate electricity or produce bio-fuels [38].

2.2.2 Torrefaction

Torrefaction is a mild pyrolysis process that requires temperatures of 200 - 300°C to decompose the hemicellulose fraction of wood, creating a charcoal-like substance known as torrefied wood [12]. The process begins with initial drying of the woodchips to a moisture content of approximately 10%. Torrefaction occurs when the temperature rises above 200°C. The heating rate of the process remains relatively low (<50°C per min) [13]. Traditionally residence times are up to one hour, although at temperatures of 250 - 280°C it has been shown that residence times as low as 8 minutes can provide torrefied wood with desirable fuel characteristics and grindability [13].

Figure 2-3 shows typical mass and energy balances of the torrefaction process. In general, 70% of the mass remains in the solid product, which contains up to 90% of the input biomass energy. The syngas produced by torrefaction can be used to meet thermal demands, depending on the reactor configuration. Propane may be required to assist with drying biomass, and an external electricity supply may be required to power the process.

Commercial development of torrefaction has not yet been achieved, although auger torrefaction technology has proved a more popular reactor choice for development

[41]. In North America, auger torrefaction technology has been designed and built at North Carolina State University. Using this technology, Agri-Tech Producers, LLP (South Carolina, United States) has recently been granted a patent and has plans to design mobile torrefaction facilities (Hopkins and Burnette, "Autothermal and mobile torrefaction devices," US Patent 8 304 590, April 3, 2009). Integro Earth Fuels, also based in North Carolina, has constructed a 100 ODTPD fixed site pilot facility in Gramling, South Carolina [42]. Renewable Fuel Technologies are a California-based company that have begun designs for a 25 ODTPD mobile torrefaction facility [9].

No mobile torrefaction facilities are currently available, thus the technical parameters for torrefaction used in this study have been taken from the literature [13], [43]. A 50 ODTPD facility is assumed with the same initial cost as a mobile fast pyrolysis facility of an equivalent size, given that auger technology is used in both.

2.2.2.1 Torrefied wood

Torrefied wood has a higher energy density than raw biomass feedstock due to the removal of water [43]. The mass density of torrefied wood is lower than raw biomass feedstock, typically 180 - 300 kg m^{-3}, as the porosity is increased compared to that of the initial biomass. Torrefied wood is also more brittle than raw biomass, resulting in decreased mechanical strength, making it easier to grind or pulverise [43]. The chemical properties of torrefied wood are similar regardless of the source wood [13], and typical lower heating values range between 18 - 23 MJ kg^{-1}. This uniformity of product is an

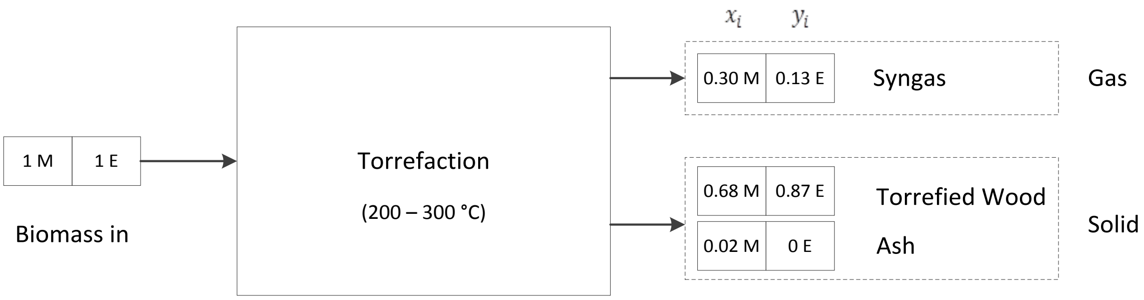


Figure 2-3 Overview of torrefaction and process yields [13]. The energy content ratios for each product have been calculated to ensure a typical lower heating values are maintained (syngas 8 MJ·kg^{-1}; torrefied wood 22.9 MJ·kg^{-1}).

advantage for downstream processes using torrefied wood as an input, such as combustion or gasification. Furthermore, torrefied wood is hydrophobic and therefore more suitable for long term storage than fresh woodchips as fungal degradation is less likely [44].

2.3 Bio-fuel production processes

Woodchips, bio-oil, bio-slurry and torrefied wood are all suited for gasification [11], [13]. Gasification produces syngas that can be used to synthesise petrol or diesel via Fischer-Tropsch reactions, or hydrogen via the water gas shift. Alternatively, bio-oil from fast pyrolysis may be upgraded to produce petrol or diesel, or can undergo steam reformation to produce hydrogen.

2.3.1 Gasification

Gasification is the conversion of carbon-based feedstock into large quantities of gaseous product and small amounts of char and ash [45]. It requires high temperatures between 500 - 1400°C, and may be performed at pressures of 0.1 - 3.3 MPa [46]. The produced gas is cleaned to remove particulates, tars, alkali compounds, sulphur compounds, nitrogen compounds and other contaminants to yield a clean syngas consisting of carbon monoxide, hydrogen, carbon dioxide, water, and methane [47].

Syngas is a 'platform chemical' that can be used for many different purposes, including Fischer Tropsch synthesis of liquid fuels (Section 2.3.2) and hydrogen production via the water gas shift (Section 2.3.3) [38]. Principal reactions (using methane as an example) that occur during gasification to produce syngas are outlined in Equations 2.1 to 2.7:

Reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{2.1}$$

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \tag{2.2}$$

Combustion:

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2 \tag{2.3}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{2.4}$$

Water gas shift:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2.5}$$

Carbon:

$$CH_4 \rightarrow C + 2H_2 \tag{2.6}$$

$$2CO \rightarrow C + CO_2 \tag{2.7}$$

Reforming reactions (Equation 2.1 and 2.2) are endothermic and require an input of energy provided by concurrent exothermic reactions of partial oxidation (Equation 2.3) or complete combustion (Equation 2.4). The water gas shift reaction (Equation 2.5) is mildly exothermic, and can assist in producing a hydrogen rich syngas under particular reactor conditions. Carbon is also produced during gasification (Equation 2.6 and 2.7).

The three main types of gasification processes are fixed bed, fluidized bed and entrained flow gasifiers [48]. Gasification is an endothermic process and heat may be provided directly (by combustion of the gasification mixture) or indirectly (from an external source - usually a hot solid such as sand or olivine circulating between the gasifier and the char combustor). Each type of gasification process may use steam, air and/or oxygen as a gasification agent to promote conversion. Direct gasification usually uses high pressure air or oxygen, and indirect gasification usually uses steam [48].

This study assumes an entrained flow indirectly heated gasification process designed by Battelle Columbus Laboratory (BCL), commercially known as Silvagas (Figure 2-4). This gasification process was selected as it is applicable to, and has been studied for, biomass based feeds and there is technical and cost information of the process available in the literature [49], [50]. The Silvagas process uses hot sand fluidised by steam to indirectly heat the carbonaceous feedstock to provide the thermal energy required for gasification [46]. The hot sand and char are separated from the gaseous stream into a char combustor where the sand is re-heated and re-circulated back into the gasification reactor. This gasification process produces high quality syngas with minimal nitrogen content [46].

Gasification of bio-oil, bio-slurry or torrefied wood requires a similar process to that of woodchip gasification [51]–[53]. Feeding liquid into a gasification reactor is typically easier than using a feed-hopper technique often used for woodchip feeds [11],

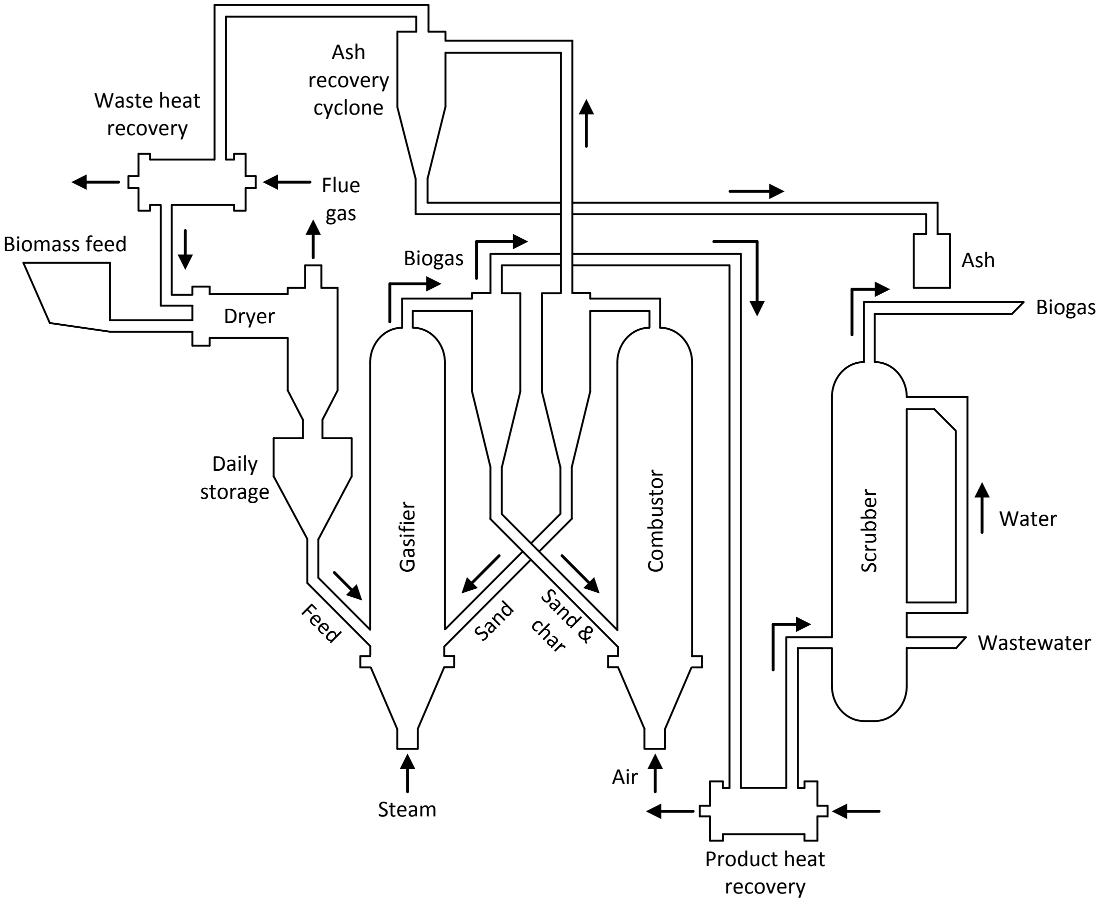


Figure 2-4 Schematic of BCL (Silvagas) gasification reactor [55].

and is an advantage of bio-oil and bio-slurry feeds. In addition, syngas quality is likely to be superior from gasification of bio-oil as many metals and minerals found in raw biomass, which can cause catalyst performance issues, are deposited in the char produced by fast pyrolysis reactions [54]. Gasification of torrefied wood is also found to produce improved syngas quality due to the lower moisture content of torrefied wood [53].

2.3.2 Fischer-Tropsch reactions

Synthetic hydrocarbon fuels can be produced from syngas via Fischer-Tropsch (FT) synthesis reactions. Pressures of 2 - 4 MPa are required [49], and different products are produced when reactions occur at different temperatures. Low temperature synthesis (180 - 250 °C) produces primarily waxes and diesel, and high temperature synthesis

(300 - 350 °C) produces alkenes and petrol [49]. The fuel mixture that is produced requires distillation to separate out petrol and diesel products [49].

The stoichometry of all FT reactions can be represented using two basic reaction equations to describe the production of alkanes (Equation 2.8) and alkenes (Equation 2.9) [56]:

$$nCO + (2n+1)H_2 \leftrightarrow C_nH_{2n+2} + nH_2O \tag{2.8}$$

$$nCO + 2nH_2 \leftrightarrow C_nH_{2n} + nH_2O \tag{2.9}$$

Fischer-Tropsch processes have been used since the 1920s, notably in Germany during WWII and also in South Africa during the Apartheid era, although reactor design and catalyst choice have been refined in recent years [57]. Iron and cobalt are typically selected as catalysts for current commercial FT operations [57].

Product yield and composition vary depending on the process conditions. The yields used in this study are taken from the literature. Petrol and diesel production via gasification and FT synthesis is assumed 5.17%wt and 7.79%wt of the initial biomass feed, respectively [49].

2.3.3 Water gas shift reactions

Syngas from gasification can undergo water gas shift reactions to increase the concentration of hydrogen present within the syngas. The water gas shift combines carbon monoxide and water to form hydrogen and carbon dioxide. It is usually performed in two steps - a high temperature water gas shift (300 - 450 °C) and a low temperature water gas shift (200 °C) [58]. Once the syngas has been subject to water gas shift reactions, it is purified to yield hydrogen gas. Typical yields of hydrogen from gasification and water gas shift reactions are between 70 - 80 kg_{H_2} per tonne of oven-dry biomass feed [48].

2.3.4 Upgrading bio-oil

Bio-oil produced by fast pyrolysis can be upgraded to produce petrol and diesel. This process consists of three steps: hydrotreating, hydrocracking and distillation [16]. Hydrotreating removes oxygen from the compounds in the bio-oil mixture, which

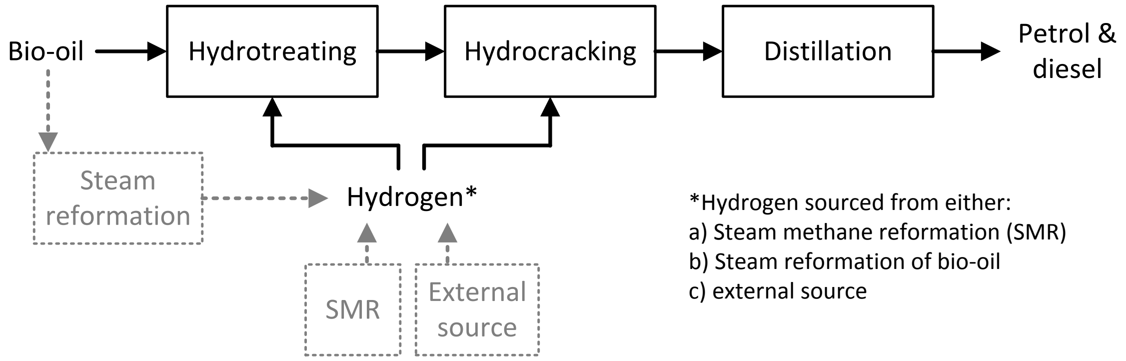


Figure 2-5 Bio-oil upgrading processes and hydrogen source options.

is followed by hydrocracking long chain hydrocarbons to shorter chain molecules. The products are distilled into diesel and petrol fractions (Figure 2-5).

Hydrogen is required for the hydrotreating and hydrocracking stages. Hydrogen may be delivered to an upgrading facility from an external source, or it may be produced on-site by steam reformation of natural gas or by steam reforming a fraction of the initial bio-oil feed (Section 2.3.5). Upgrading bio-oil to petrol and diesel has only been demonstrated at the laboratory or small engineering development scale, but a recent study performed a techno-economic analysis of a commercial scale facility [16]. Yields of petrol and diesel from upgrading are approximately 31.35%wt and 1.65%wt of the bio-oil feed, respectively [16].

2.3.5 Steam reformation of bio-oil

Approximately 60 - 80%wt of bio-oil is soluble in water [17]. This aqueous fraction can be steam reformed to produce hydrogen in a similar process used to steam reform methane [18]. However, reforming the aqueous fraction of bio-oil is presented with various challenges, most of which are related to coke formation on the surface of catalysts. Adding a solvent, such as methanol, can alleviate these issues, and typically a 10%wt methanol blend is prepared before reformation [19].

Steam reformation of bio-oil has only been demonstrated at laboratory scales (e.g. [59]–[61]), although a recent study provided a techno-economic model of a large scale facility [19]. The maximum stoichiometric yield of hydrogen that can be produced from steam reformation of bio-oil is 17.2%wt [62]. Steam reformation of a bio-oil methanol blend (10%) yields approximately 14.7%wt hydrogen [19].

2.4 Summary

This Chapter has provided background information on forest residues, fast pyrolysis and torrefaction processes and products, and bio-fuel production processes.

Forest residues are the tree tops and branches from roundwood logging operations. The quantity and availability of a forest residue resource depends on biophysical factors, tree species, logging industry practices, residue recovery methods, residue retention regulations, and competition between industries for access to forest residues.

Fast pyrolysis produces syngas, bio-oil and bio-char. The bio-oil may be used directly as a feedstock for bio-fuel production, or it may be combined with bio-char to produce a bio-slurry that contains a larger fraction of the initial energy content of a forest residue resource. Torrefaction produces syngas and torrefied wood. Bio-oil, bio-slurry and torrefied wood can be used as a feedstock for bio-fuel production processes.

Woodchip, bio-oil, bio-slurry and torrefied wood are all suitable as feedstock for gasification, which produces syngas that can undergo Fischer-Tropsch or water gas shift reactions to produce petrol and diesel, or hydrogen fuels respectively. The bio-oil product of fast pyrolysis may also be upgraded to produce petrol and diesel or steam reformed to produce hydrogen.

The following Chapter introduces the model constructed to investigate the technical and economic impacts of (i) harvesting a forest residue resource using a network of mobile facilities, and (ii) producing bio-fuels using the products of mobile facilities as feedstock.

3 Methods

This chapter presents a model for the production of bio-fuels from a forest residue resource. The model contains three main sections: definition of a forest residue resource (Section 3.1), collection and delivery of a forest residue resource to a bio-fuel facility plant gate (Section 3.2), and production of bio-fuels at a bio-fuel facility (Section 3.3). The model tracks both mass and energy flows of the forest residue resource through to bio-fuel production.

Four pathways of delivering a forest residue resource to a bio-fuel facility plant gate are considered: (i) woodchips (ii) bio-oil (iii) bio-slurry and (iv) torrefied wood. Furthermore, two point-of-delivery scenarios are included in the model to account for situations when a bio-fuel facility is either located within or at a distance from the forested region (Section 3.2.1). Four bio-fuel production processes are considered: (i) gasification and Fischer-Tropsch synthesis (ii) gasification and water gas shift reactions (iii) upgrading of bio-oil and (iv) steam reformation of bio-oil. Thus, the model incorporates the entire system of bio-fuel production from collection of forest residues to the synthesis of petrol and diesel, or hydrogen products. The main outputs of the model are a levelised delivered cost of forest residue resource to bio-fuel facility, and a final levelised cost of bio-fuel production. Levelisation converts a series of varying payments into a financially equivalent annuity.

Products of mobile facilities and *commodities* are two terms used throughout the description of the model and also in later Chapters. *Products* of mobile facilities are gross quantities of products from mobile facility processes. *Commodities* are net quantities of mobile facility products that can be used as feedstock for bio-fuel production.

Note: All lower case symbols in Equations represent values or data input into the model and all upper case symbols represent values or data calculated by the model.

3.1 Defining a forest residue resource

The model is based upon the amount of a forest residue resource that is available for bio-fuel production. An annual supply of available forest residues (m^3), h, is input by the user. The moisture content of the forest residues, z, and the density of oven-dry wood, ρ_{ODW}, allow the model to calculate the annual forest residue resource in terms of green tonnes (GT), M_{GT}, and oven-dry tonnes (ODT), M_{ODT}, using Equations 3.1 and 3.2:

$$M_{GT} = \frac{h}{10^3}\left(\frac{z - z_{ODW}}{\rho_{H_2O}} + \frac{(1-z) + z_{ODW}}{\rho_{ODW}}\right)^{-1} \tag{3.1}$$

$$M_{ODT} = M_{GT}(1 - z + z_{ODW}) \tag{3.2}$$

where ρ_{H_2O} is the density of water and z_{ODW} is the moisture content of oven-dry wood. The annual energy content, E_{FR}, within the forest residue resource is then calculated using Equation 3.3:

$$E_{FR} = M_{ODT} l_{ODW} \tag{3.3}$$

where l_{ODW} is the lower heating value of oven-dry wood.

The extent of the forest residue harvest region is determined by both the volume of forest residues to be collected during the harvest operation lifetime and the spatial density of the available residues, φ. The spatial density of forest residues is assumed to be constant across the land surface, and the harvest region is assumed to be circular (e.g. [63], [64]). Thus, the radius of the harvest region, R, is calculated using Equation 3.4:

$$R = \sqrt{hy/\varphi\pi} \tag{3.4}$$

where y is the lifetime of the harvest operation.

3.2 Feedstock collection and delivery to bio-fuel facility

Once the forest residue resource has been defined, the model contains four pathways of delivering the resource to a bio-fuel plant gate (Figure 3-1). The point-of-delivery can be selected as a bio-fuel facility either within or outside of the forest residue harvest region (Figure 3-2), as discussed in Section 3.2.1. The model for harvesting and transporting the forest residue resource to a bio-fuel facility as woodchips, bio-oil, bio-slurry or torrefied wood is presented in Section 3.2.2. Technical mobile facility calculations are provided in Section 3.2.3, and all financial calculations related to the delivery of resource to a bio-fuel plant gate are provided in Section 3.2.4.

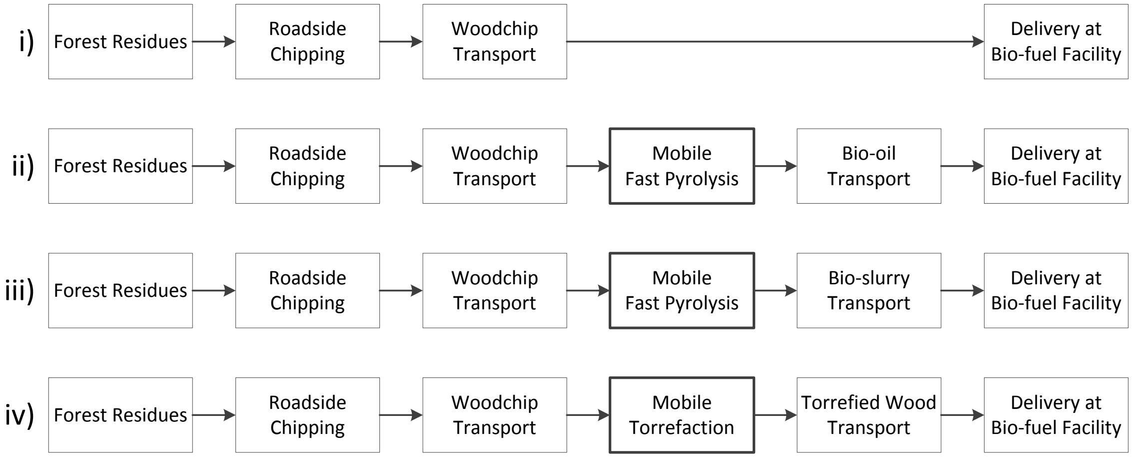


Figure 3-1 Four pathways for delivering a forest residue resource.

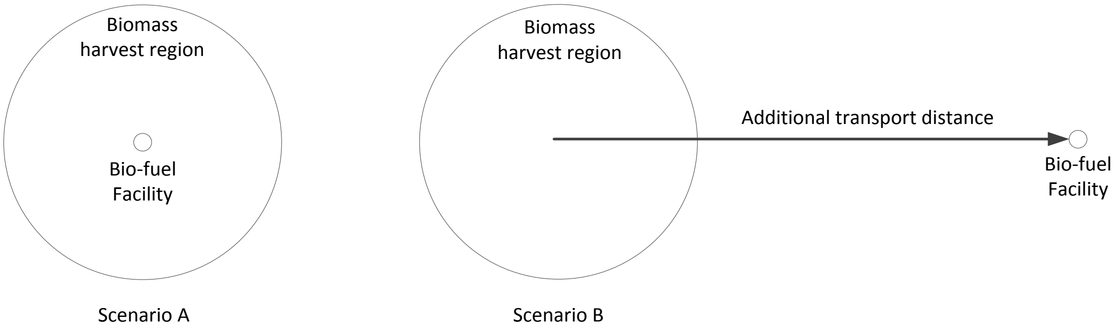


Figure 3-2 Point-of-delivery scenarios.

3.2.1 Point-of-delivery scenarios

Two point-of-delivery scenarios are considered in this study (Figure 3-2). In scenario A, the forest residue resource is delivered to a bio-fuel facility located at the centre of a biomass harvest region. This scenario models a situation where a bio-fuel facility is located within the forested region to purposefully use the local resource. In scenario B, feedstock is delivered to a bio-fuel facility outside of the harvest region, requiring greater transport distances. This scenario models a situation where a bio-fuel facility located at a settlement outside the forested region is the point-of-delivery.

3.2.2 Harvest and transport

Harvest and transport models are important components of determining the cost of delivering a biomass resource to a bio-fuel facility. Models in the literature range from simple continuous models applicable to idealised situations (e.g. [65]), to those incorporating geographical information systems (GIS) that require details of landscape attributes and road networks (e.g. [66]). This study implements a discrete transport model (with no specific geographical setting) similar to those used in the literature (e.g. [7], [63]), with modifications to account for the use of mobile facilities. The harvest and transport model is described in relation to woodchip delivery in Section 3.2.2.1, and pathways involving the use of mobile facilities in Section 3.2.2.2.

3.2.2.1 Woodchip delivery

The conventional method for utilising forest residues as a biomass feedstock requires transporting woodchips directly from the logging fields to a bio-fuel facility. In this process, residues are piled at the roadside where they are chipped directly into a chip truck, which delivers the woodchips to their destination.

The model does not include an in-depth representation of piling and chipping forest residues, such as evaluating machine hours and system productivity, as these vary depending on the equipment used [21]. Therefore the model considers only the cost of piling and chipping forest residues as discussed in Section 3.2.4.1.

The transport model is based upon the assumption that the harvest region is circular (Figure 3-3a). The average annual transport distance from logging fields to a

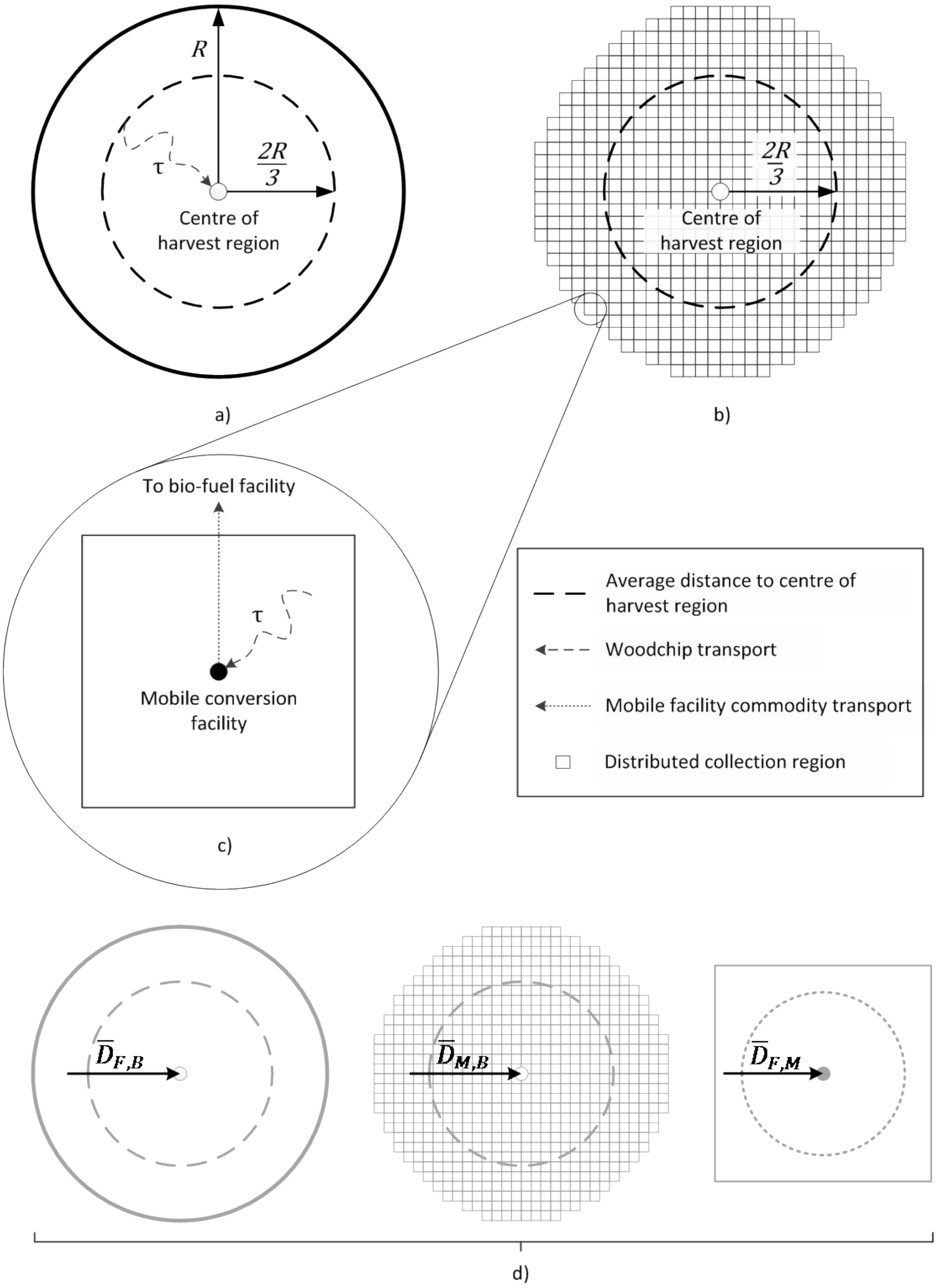


Figure 3-3 a) Harvest and transport model for delivering a conventional woodchip feedstock. b) Overview of harvest grid for harvest and transport model when implementing mobile facilities. c) A distributed collection region with mobile facility at the centre. d) Average transport distances (scenario A).

bio-fuel facility, $\overline{D}_{F,B}$, is calculated using Equation 3.5 (scenario A) or Equation 3.6 (scenario B), depending on the point-of-delivery to a bio-fuel facility:

$$scenario\ A \qquad \overline{D}_{F,B} = \tau\,(2R/3) \tag{3.5}$$

$$scenario\ B \qquad \overline{D}_{F,B} = \tau\big((2R/3) +\ d\big) \tag{3.6}$$

where τ is a tortuosity factor to account for the winding of roads (usually ranging between 1.2 and 3 [63]), and d is an additional transport distance to account for the point-of-delivery being located at a distance from the harvest region. The average annual distance woodchips are transported, $\overline{D}_{WC}$, is equal to the average annual transport distance from logging fields to bio-fuel facility, i.e.:

$$\overline{D}_{WC} = \overline{D}_{F,B} \tag{3.7}$$

The total annual transport distance travelled by woodchip delivery trucks will depend on whether the truck load is limited by weight or volume of woodchips (Appendix A), and is calculated using Equation 3.14 (Section 3.2.2.2).

3.2.2.2 Bio-oil, bio-slurry or torrefied wood delivery

Implementing distributed mobile facilities results in either bio-oil, bio-slurry or torrefied wood delivered to the bio-fuel facility, depending on the mobile facility process selected. Forest residues are chipped into chip trucks and transported to the nearest mobile facility. Preparation of the woodchip feed is followed by either fast pyrolysis or torrefaction, and the associated commodity that is produced is transported to the bio-fuel facility.

The transport model used when implementing mobile facilities is shown in Figure 3-3b and Figure 3-3c. The size of the entire harvest region is defined using Equation 3.4. Smaller square harvest regions are then assumed for distributed collection of forest residues. The number of distributed collection regions depends on the number of mobile facilities required to process the annual harvest, and also the number of times each facility is relocated over the lifetime of the harvest operation. The layout of the distributed collection regions is assumed such that no overlap occurs, thus representing a gridded version of the entire harvest region. The number of distributed collection regions, N_{grid}, is calculated using Equation 3.8:

$$N_{grid} = N_{mob}(1 + n_r) \tag{3.8}$$

where N_{mob} is the number of mobile facilities required to meet an annual harvest and n_r is the number of times each mobile facility is relocated over the lifetime of the harvest operation. The number of mobile facilities required varies depending on the annual harvest because the size of the mobile facilities is fixed. A larger annual harvest will demand more mobile facilities. The number of mobile facilities required, N_{mob}, is calculated using Equation 3.9:

$$N_{mob} = \left(\frac{M_{ODT}}{s_{mob}\sigma_{mob}}\right) \div 365 \tag{3.9}$$

where s_{mob} is the size of the mobile facilities (50 ODTPD) and σ_{mob} is the maximum capacity factor of the mobile facilities.

The grid details all the distributed collection regions that will be harvested over the operation lifetime. Each distributed collection region is only occupied once during the operation lifetime.

When harvesting forest residues within a distributed collection region, the average distance from any point in the square collection region to the mobile facility at the centre, $\overline{D}_{F,M}$, is calculated using Equation 3.10:

$$\overline{D}_{F,M} = \frac{1}{6}\tau\sqrt{H_{mob}/\varphi}\left(\sqrt{2} + \ln\left(1 + \sqrt{2}\right)\right) \tag{3.10}$$

where H_{mob} is the amount of available forest residues within the distributed collection region to be harvested whilst the mobile facility is at that location, defined using Equation 3.11:

$$H_{mob} = \frac{Total\ harvest\ over\ operation\ liftime}{Number\ of\ mobile\ locations} = \frac{hy}{N_{grid}} \tag{3.11}$$

When mobile facilities are implemented, the average annual delivery distances of woodchips, $\overline{D}_{WC}$, or mobile facility commodity j, $\overline{D}_j$, are shown by Equations 3.12 and 3.13:

$$\overline{D}_{WC} = \overline{D}_{F,M} \tag{3.12}$$

$$\overline{D}_j = \overline{D}_{M,B} \approx \overline{D}_{F,B} \tag{3.13}$$

where $\overline{D}_{M,B}$ is the average annual transport distance between mobile facilities and the bio-fuel facility (assumed to be equal to the average annual distance from logging fields to the bio-fuel facility, $\overline{D}_{F,B}$, due to the uniform grid of mobile facility locations).

The commodities produced by fast pyrolysis or torrefaction are transported using B-train trucks, assuming mobile facilities are located on sites with road networks adequate for larger vehicles. Once the forest residue resource in one grid location has been depleted, the mobile facility is relocated to an un-harvested grid location.

The total annual transport distance, D_j, of each commodity, j, (woodchips, bio-oil, bio-slurry or torrefied wood) is calculated using Equation 3.14:

$$D_j = 2\overline{D}_j \frac{M_{j,net}}{M_{truck,j}} \tag{3.14}$$

where $M_{j,net}$ is the annual mass of commodity j to be transported (Section 3.2.3.4), and $M_{truck,j}$ is the actual load carried by a truck, which depends on whether trucks are limited by weight or volume (Appendix A).

3.2.3 Mobile facilities

Mobile facility product yields are calculated in terms of mass and energy (Section 3.2.3.1). Some of the products of mobile facility processes are used for drying of woodchips (Section 3.2.3.2) and electricity generation (Section 3.2.3.3), and these requirements are calculated on an energy basis. The net amount of products available as a commodity feedstock for bio-fuel production are discussed in Section 3.2.3.4. Storage requirements at mobile facilities, to maintain a continuous production process, are addressed in Section 3.2.3.5.

3.2.3.1 Mobile facility gross product yields

The annual gross quantity of product i from mobile facilities (syngas, bio-oil, bio-char or torrefied wood) is calculated in terms of mass, $M_{i,gross}$, and energy, $E_{i,gross}$, using Equations 3.15 and 3.16:

$$M_{i,gross} = x_i M_{ODT} \tag{3.15}$$

$$E_{i,gross} = y_i E_{FR} \tag{3.16}$$

where x_i and y_i are the mass and energy product ratios provided in Figure 2-2 and Figure 2-3 (Pages 7 and 10). Net quantities of commodities available for bio-fuel production are discussed later in Section 3.2.3.4.

3.2.3.2 Drying

For both fast pyrolysis and torrefaction, the produced syngas is used to dry woodchips at the mobile facility. The amount of energy required for drying is calculated based on the initial moisture content of biomass and the efficiency of the dryer [67]. The annual amount of water removed from woodchips, M_{H_2O}, is calculated using Equation 3.17:

$$M_{H_2O} = M_{GT} - M_{ODT} \tag{3.17}$$

The annual energy required to dry woodchips, E_{dry}, is calculated using Equation 3.18:

$$E_{dry} = \frac{e_{dry} M_{H_2O}}{\eta_{dry}} \tag{3.18}$$

where e_{dry} is the energy required to evaporate one tonne of water from woodchips (which is based on the energy required to raise the moisture in the wood from 25°C to 100°C and the latent heat of water at 100°C) and η_{dry} is the drying efficiency [68].

If the annual energy content of produced syngas is not sufficient for the drying of woodchips, the annual amount of propane imported to mobile facilities, $M_{C_3H_8}$, is calculated using Equation 3.19:

$$M_{C_3H_8} = \frac{E_{dry} - E_{S,gross}}{l_{C_3H_8}} \tag{3.19}$$

where $l_{C_3H_8}$ is the lower heating value of propane.

3.2.3.3 Electrical demands

Mobile fast pyrolysis facilities generate electricity using a portion of the produced bio-oil. The fraction of bio-oil product used for electricity generation, X_{BO}, is calculated using Equation 3.20:

$$X_{BO} = \frac{(\beta M_{ODT})/\eta_{gen}}{E_{BO,gross}} \tag{3.20}$$

where β is the electricity demand per oven-dry tonne of woodchip feed and η_{gen} is the efficiency of the generator.

Mobile torrefaction facilities are powered by a diesel generator. The electrical demand of a mobile torrefaction facility is assumed the same as a mobile fast pyrolysis facility, although it is likely to be lower as no grinding of woodchips or condensation unit is required. The diesel generator is sized to meet electrical requirements and is fueled from on-site diesel storage available at logging sites. The annual amount of diesel consumed at each mobile facility is calculated on a linear scale using consumption rates of a 200kW generator (Appendix A) [69]. The total diesel consumption of all mobile facilities is then calculated.

3.2.3.4 Mobile facility net product yields (commodities)

The quantities of commodities produced at mobile facilities available as a feedstock for bio-fuel production are calculated as follows. The amount of bio-oil available for bio-fuel production depends on the electrical requirements of mobile facilities. The net quantity of a bio-oil commodity in terms of mass, $M_{BO,net}$, and energy, $E_{BO,net}$, are calculated using Equations 3.21 and 3.22:

$$M_{BO,net} = M_{BO,gross}(1 - X_{BO}) \tag{3.21}$$

$$E_{BO,net} = E_{BO,gross}(1 - X_{BO}) \tag{3.22}$$

The quantity and properties of a bio-slurry commodity depend on the amount of bio-oil available as well as the bio-char loading of the slurry. The bio-char loading of the bio-slurry, Z, is calculated using Equation 3.23:

$$Z = \frac{M_{BC,gross}}{M_{BO,net} + M_{BC,gross}} \tag{3.23}$$

However, if the bio-char loading is above the maximum value of 20%wt, the model will reduce the amount of bio-char added to the bio-slurry, and some excess bio-char will remain. The annual amount of excess bio-char, $M_{BC,excess}$, is calculated using Equation 3.24:

$$M_{BC,excess} = M_{BC,gross} - \left(\frac{\zeta_{max} M_{BO,net}}{1 - \zeta_{max}}\right) \tag{3.24}$$

where ζ_{max} is the maximum bio-char loading of a bio-slurry (20%wt).

The net annual amount of bio-char added to the bio-slurry is calculated using Equation 3.25:

$$M_{BC,net} = M_{BC,gross} - M_{BC,excess} \tag{3.25}$$

Therefore, the net annual quantity of bio-slurry delivered to the bio-fuel facility in terms of mass, $M_{BS,net}$, and energy, $E_{BS,net}$, is calculated using Equations 3.26 and 3.27:

$$M_{BS,net} = M_{BO,net} + M_{BC,net} \tag{3.26}$$

$$E_{BS,net} = E_{BO,net} + \left(\frac{M_{BC,net}}{M_{BC,gross}}\right) E_{BC,gross} \tag{3.27}$$

The density of the bio-slurry, ρ_{BS}, is calculated on a linear scale between 1100 kg·m^{-3} (0% bio-char loading) and 1300 kg·m^{-3} (30% bio-char loading) provided from referenced data [38].

The net quantity of torrefied wood that is delivered to a bio-fuel facility is equal to the gross quantity produced (because torrefied wood is not used to meet any system requirements at mobile torrefaction facilities) as shown by Equations 3.28 and 3.29:

$$M_{TW,net} = M_{TW,gross} \tag{3.28}$$

$$E_{TW,net} = E_{TW,gross} \tag{3.29}$$

3.2.3.5 Storage at mobile facilities

To maintain a continuous fast pyrolysis or torrefaction process a constant supply of woodchips is required. Therefore a storage pile of woodchips at the mobile facility site is necessary. Three days worth of storage for woodchips is assumed to allow for holidays or weekends when woodchip transport may not occur [70].

Storage of mobile facility products is also required, and three days storage is assumed. Bio-oil or bio-slurry product is stored in stainless steel tanks [8], and torrefied wood product is stored in piles.

The maximum storage volume required for commodity j at each mobile facility, $V_{j,mob}$, is calculated using Equation 3.30:

$$V_{j,mob} = \frac{3}{365}\left(\frac{M_{j,net} \cdot 10^3}{\rho_j N_{mob}}\right) \tag{3.30}$$

where ρ_j is the density of commodity j.

3.2.4 Costs of feedstock collection and delivery

The model includes financial calculations to produce a levelised cost of collecting and delivering the forest residue resource to a bio-fuel plant gate ('levelised delivered cost') using each of the four delivery pathways. The levelised delivered cost is calculated on an energy basis to provide an equal comparison for each delivery pathway.

The total delivered cost of the forest residue resource to a bio-fuel facility plant gate can be divided into three parts: costs of collecting a forest residue resource, costs relating to mobile facilities, and costs of transportation. Collection costs of a forest residue resource relate to purchasing, piling and chipping forest residues (Section 3.2.4.1). Mobile facility costs include purchasing and operating the mobile facilities, as well as storage requirements (Section 3.2.4.2). Transport costs relate to the hauling of woodchips and mobile facility commodities (Section 3.2.4.3).

3.2.4.1 Costs of forest residue resource

The costs of collecting a forest residue resource are the same for each delivery pathway regardless of mobile facility implementation. The annual cost of process p (purchasing, piling or chipping forest residues), C_p, is calculated using Equation 3.31:

$$C_p = c_p M_{GT} \tag{3.31}$$

where c_p is the unit cost of process p. (The purchase cost of forest residues is a fee for removal of fuels from the logging field [49]).

3.2.4.2 Mobile facility costs

When woodchips are delivered directly to a bio-fuel facility, no mobile facilities are required and mobile facility costs are equal to zero. Implementing mobile facilities incurs costs associated with the purchase and operation of the facilities.

The size of mobile facilities remains fixed regardless of the annual harvest of forest residues. The capital cost incurred for all mobile facilities, C_{mob}, is calculated using Equation 3.32:

$$C_{cap,mob} = c_{mob} N_{mob} \tag{3.32}$$

where c_{mob} is the reference cost for a single mobile facility. For mobile torrefaction facilities, the cost of a diesel generator is also added to the capital cost.

The annual operation and maintenance cost for all mobile facilities, $C_{O\&M,mob}$, is calculated using Equation 3.33:

$$C_{O\&M,mob} = o_{mob} C_{cap,mob} \tag{3.33}$$

where o_{mob} is a fixed operation and maintenance percentage of capital expenditure.

The annual cost of purchasing propane to assist with drying at mobile facilities, $C_{C_3H_8,mob}$, is calculated using Equation 3.34:

$$C_{C_3H_8,mob} = c_{C_3H_8} \left(\frac{M_{C_3H_8} \cdot 10^3}{\rho_{C_3H_8}} \right) \tag{3.34}$$

where $c_{C_3H_8}$ is the dollar per litre cost of propane.

The annual cost of purchasing diesel for electricity generation at mobile torrefaction facilities, $C_{diesel,mob}$, is calculated using Equation 3.35:

$$C_{diesel,mob} = c_{diesel}\left(\frac{M_{diesel} \cdot 10^3}{\rho_D}\right) \tag{3.35}$$

where c_{diesel} is the doller per litre cost of diesel, M_{diesel} is the annual consumption of diesel, and ρ_D is the density of diesel.

The annual labour costs for all mobile facilities, $C_{lab,mob}$, is calculated using Equation 3.36:

$$C_{lab,mob} = n_{staff} c_{wage,mob} N_{mob} \tag{3.36}$$

where n_{staff} is the number of staff required at each mobile facility and $c_{wage,mob}$ is the annual wage of each employee.

Storage of woodchips and torrefied wood at mobile facilities is assumed to be free, as the cost of maintaining open air storage is deemed negligible. Storing bio-oil or bio-slurry incurs costs associated with purchasing and maintaining a stainless steel tank at each mobile facility. The capital cost of all stainless steel tanks for commodity j (bio-oil or bio-slurry), $C_{tank,mob,j}$, is calculated using Equation 3.37:

$$C_{tank,mob,j} = N_{mob} c_{ref,tank}\left(\frac{V_{j,mob}}{s_{ref,tank}}\right)^{\kappa_{tank}} \tag{3.37}$$

where $s_{ref,tank}$ and $c_{ref,tank}$ are the reference size and cost of a stainless steel tank, respectively, and κ_{tank} is the cost scaling factor.

The annual maintenance costs of stainless steel tanks, $C_{O\&M,tank,mob}$, is calculated using Equation 3.38:

$$C_{O\&M,tank,mob} = o_{tank} C_{tank,mob} \tag{3.38}$$

where o_{tank} is a fixed operation and maintenance percentage of capital expenditure.

The costs of relocating mobile facilities are distributed evenly throughout the operation lifetime of harvesting forest residues (i.e. the time period between relocations is constant). All mobile facilities are assumed to relocate at the same time. The cost of one relocation of all mobile facilities, $C_{relocate,mob}$, is calculated using Equation 3.39:

$$C_{relocate,mob} = N_{mob} c_{relocate} \tag{3.39}$$

where $c_{relocate}$ is the cost of relocating a single mobile facility.

3.2.4.3 Transport costs

For each commodity (i.e. woodchips, bio-oil, bio-slurry or torrefied wood), there is a fixed cost of transportation and a variable hauling cost. The fixed cost is associated with loading and unloading of trucks. The variable hauling cost depends on truck capacities, the amount of each commodity to be transported, and transport distances as provided by the transport model detailed in Section 3.2.2.

The annual fixed costs of transportation for commodity j, $C_{tran,fix,j}$, are calculated using Equation 3.40:

$$C_{tran,fix,j} = c_{tran,fix,j} M_{j,net} \tag{3.40}$$

where $c_{trans,fix,j}$ is the unit cost of loading and unloading commodity j.

The annual variable cost of transportation for commodity j, $C_{tran,var,j}$, is calculated using Equation 3.41:

$$C_{tran,var,j} = c_{tran,var,j} D_j \tag{3.41}$$

where $c_{tran,var,j}$ is the unit hauling cost for commodity j.

No road building costs are included in the model as collection and delivery of forest residues is assumed to occur at existing logging sites, which have road access that has been funded by the lumber industry.

3.2.4.4 Levelised delivered cost

For each delivery pathway, all costs spanning the operation lifetime of harvesting and delivering forest residues are brought to present day value, totaled, and annualised. The levelised delivered cost of commodity j, LDC_j, is calculated using Equation 3.42:

$$LDC_j = \frac{CRF \times NPV_j}{E_{j,net}} \tag{3.42}$$

where CRF is the capital recovery factor, and NPV_j is the net present value of all costs expended to deliver commodity j.

3.2.5 Summary

Section 3.2 has provided technical and financial calculations that are performed by the model up to the point of delivering either woodchips, bio-oil, bio-slurry or torrefied wood to a bio-facility plant gate. The first main output of the model, a levelised delivered cost of forest residue feedstock, has been described. Section 3.3 continues the description of the model, providing calculations used to simulate the production of bio-fuels from the commodities delivered to the bio-fuel facility.

3.3 Bio-fuel facilities and production

The model considers bio-fuel production from each of the four commodities (woodchip, bio-oil, bio-slurry and torrefied wood) delivered to the bio-fuel facility plant gate (Figure 3-4). All are suited for gasification, followed by Fischer-Tropsch or water gas shift reactions. Bio-oil may also be used as a feedstock for upgrading or steam reformation processes.

The sizing of bio-fuel facilities and the quantity of bio-fuels produced depend on the amount of commodity feedstock delivered to the bio-fuel facility. The model sizes facilities appropriately and calculates annual bio-fuel production from each bio-fuel production process as outlined in Sections 3.3.1 and 3.3.2, respectively. Financial calculations provide a levelised cost of bio-fuel production (including all aspects of harvesting a forest residue resource), as discussed in Section 3.3.3.

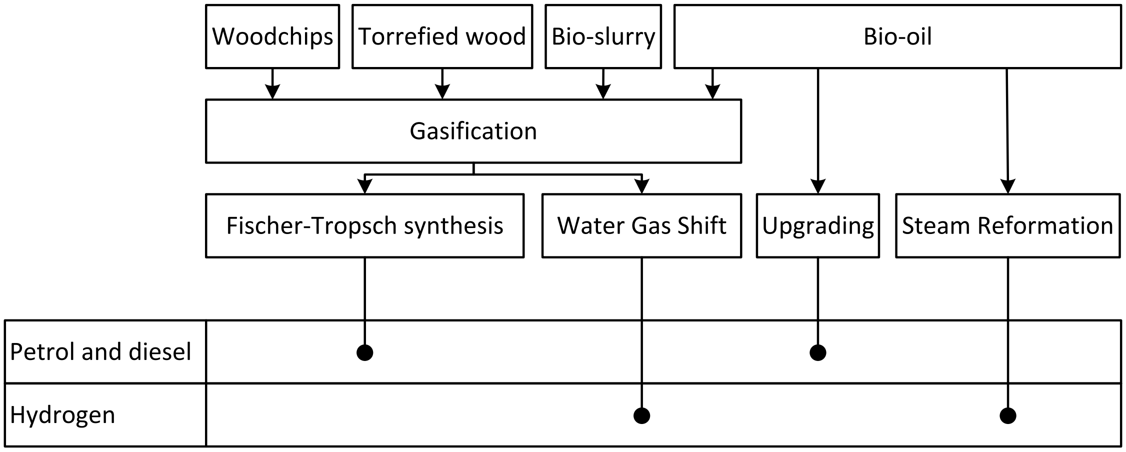


Figure 3-4 Bio-fuel production options.

3.3.1 Bio-fuel facilities

3.3.1.1 Feedstock handling and storage

Storage requirements at bio-fuel facilities depend on feedstock reliability, the size of the bio-fuel facility, and risk management requirements imposed by project investors and bio-fuel customers [70]. Greater storage is required for larger facilities as, in addition to requiring more feedstock, larger facilities require greater investments and therefore carry more risk, which means their storage capacities are disproportionally larger that smaller facilities to maintain the production process. If feedstock reliability is low, greater storage is required to ensure continuous production processes. Studies in the literature typically consider two to four weeks of feedstock reserve for large bio-energy facilities [70].

The type of storage employed at a bio-fuel facility depends on the feedstock characteristics, available storage space and the capital available for storage facilities. If storage space is limited, or if woodchips arrive with a low moisture content, woodchips may be stored in hoppers, bins, silos or bunkers. This study assumes green woodchips are stored in large open uncovered piles on top of a base of concrete pads, which is significantly less expensive.

Bio-oil and bio-slurry are stored in stainless steel tanks [8]. Methanol is added to bio-oil to prevent aging during longer term storage (10%wt) [19]. Torrefied wood is stored in open uncovered piles similar to green woodchips.

The model calculates two week reserve storage requirements at central facilities. The volume of storage of commodity j at the bio-fuel facility, $V_{j,bf}$, is calculated using Equation 3.43:

$$V_{j,bf} = \frac{14}{365}\left(\frac{M_{j,net} \cdot 10^3}{\rho_j}\right) \tag{3.43}$$

(Storage of bio-oil includes a methanol additive as part of the mixture, detailed in Section 3.3.1.3).

For liquid storage at central facilities, the number of stainless steel tanks required, N_{tank}, is calculated based upon instalments of 9,400 m^3 capacity stainless steel tanks [8].

3.3.1.2 Pre-treatment

Green woodchips and torrefied wood need to undergo pre-treatment processes before being input to gasification reactors. Green woodchips need to be screened to remove metal, stone and dirt, before being dried and ground down to finer particles [70]. Torrefied wood only needs to be ground to finer particles. The model does not include an in-depth representation of pre-treatment processes, such as evaluating energy requirements of each process, as these vary depending on the equipment used [21]. Therefore the model considers only the cost of pre-treatment processes provided in the literature, as discussed in Section 3.3.3.1.

3.3.1.3 Sizing of bio-fuel facilities

Bio-fuel facilities are sized depending on the amount of commodity feedstock available for bio-fuel production processes. After commodities have been delivered to the bio-fuel facility, the quantity of feedstock for bio-fuel production processes changes during storage or pre-treatment processes. The quantity and properties of bio-oil are altered when methanol is added, and the mass of woodchips is reduced after drying. The mass quantities of commodity j used directly as feedstock for bio-fuel production processes, $M_{j,feed}$, are outlined in Equations 3.44 to 3.47:

$$M_{WC,feed} = M_{ODT} \tag{3.44}$$

$$M_{BO,feed} = (1 + m_{meth})M_{BO,net} \tag{3.45}$$

$$M_{BS,feed} = M_{BS,net} \tag{3.46}$$

$$M_{TW,feed} = M_{TW,net} \tag{3.47}$$

where m_{meth} is the mass ratio of methanol added to bio-oil (10%wt).

The size (tonne per day) of bio-fuel facility k using commodity feedstock j, $S_{bf,j,k}$, is calculated using Equation 3.48:

$$S_{bf,j,k} = \left(\frac{M_{j,feed}}{\sigma_{bf,k}}\right) \div 365 \tag{3.48}$$

where $\sigma_{bf,k}$ is the capacity factor of bio-fuel facility k.

3.3.2 Bio-fuel production

When bio-fuels are produced via methods using gasification processes, all feeds are assumed to be different forms of oven-dry woodchips (i.e. they would yield the same ultimate analysis results) and so the same product yield ratios, f, are used [13], [54]. This is because no conversion factors from bio-oil, bio-slurry or torrefied wood to bio-fuels via gasification and Fischer-Tropsch or water gas shift reactions have been identified in the literature. Bio-fuel production from bio-oil via upgrading or steam reformation are available in the literature, and are used in the model.

All bio-fuel production ratios are provided in terms of mass. Further calculations in the model provide conversion to litres, gallons and gigajoules of bio-fuel produced and are detailed in Appendix A.

3.3.2.1 Fischer-Tropsch

Fischer-Tropsch synthesis yields petrol and diesel. The total annual quantity (kg) of petrol produced from commodity feedstock j, $F_{kg,j,FT,P}$, is calculated using Equation 3.49:

$$F_{kg,j,FT,P} = f_{FT} f_{r,FT} M_{j,feed} \cdot 10^3 \tag{3.49}$$

where f_{FT} is the ratio of bio-fuel yield per unit feed and $f_{r,FT}$ is the petrol-diesel production ratio.

The total annual quantity (kg) of diesel produced from commodity feedstock j, $F_{kg,j,FT,D}$, is calculated using Equation 3.50:

$$F_{kg,j,FT,D} = f_{FT}\left(1 - f_{r,FT}\right) M_{j,feed} \cdot 10^3 \tag{3.50}$$

3.3.2.2 Water gas shift

The water gas shift yields hydrogen as a product. The total annual quantity (kg) of hydrogen produced from commodity feedstock j, $F_{kg,j,WGS,H}$, is calculated using Equation 3.51:

$$F_{kg,j,FT,H} = f_{WGS} M_{j,feed} \cdot 10^3 \tag{3.51}$$

where f_{WGS} is the ratio of hydrogen production per unit feed.

3.3.2.3 Bio-oil upgrading

Bio-oil upgrading yields petrol and diesel as products. Hydrogen is required for the process, which may be derived from steam methane reformation (SMR), steam reformation of a fraction of the bio-oil feed, or from an external hydrogen source.

The annual amount of hydrogen required by the upgrading process, $M_{H_2,UG}$, is calculated using Equation 3.52:

$$M_{H_2,UG} = \gamma_{H_2} M_{BO,feed} \tag{3.52}$$

where γ_{H_2} is the ratio of hydrogen required per unit bio-oil feed [16], [71], [72].

If SMR is selected as the method for producing hydrogen, the annual amount of methane consumed, M_{CH_4}, is calculated using Equation 3.53:

$$M_{CH_4} = \frac{M_{H_2,UG}}{f_{SMR}} \tag{3.53}$$

where f_{SMR} is the ratio of hydrogen production from natural gas. The annual methane consumption is used to size the SMR facility at the bio-oil upgrading facility.

If a portion of the bio-oil feed is used to produce hydrogen for upgrading, the fraction of bio-oil feed to be steam reformed, $\Upsilon_{BO,SR}$, is calculated using Equation 3.54:

$$\Upsilon_{BO,SR} = \frac{\gamma_{H_2}}{\gamma_{H_2} + m_{WS} f_{SR}} \tag{3.54}$$

where m_{WS} is the percentage of bio-oil that is water soluble and f_{SR} is the ratio of hydrogen production from steam reformation of the aqueous fraction of bio-oil. The annual mass fractions of bio-oil to be either upgraded or steam reformed are then calculated, and two combined facilities (bio-oil upgrading and bio-oil steam reformation) are sized using Equation 3.48.

No production processes or storage capacities are assumed if hydrogen is sourced externally. Instead, the hydrogen is provided at a cost per kilogram (Section 3.3.3.2).

The total annual quantity (kg) of petrol produced from upgrading bio-oil, $F_{kg,BO,UG,P}$, is calculated using Equation 3.55:

$$F_{kg,BO,UG,P} = f_{UG} f_{r,UG} M_{BO,feed} \cdot 10^3 \tag{3.55}$$

where f_{UG} is the ratio of bio-fuel yield per unit feed and $f_{r,UG}$ is the petrol-diesel production ratio.

The total annual quantity (kg) of diesel produced from upgrading bio-oil, $F_{kg,BO,UG,D}$, is calculated using Equation 3.56:

$$F_{kg,BO,UG,D} = f_{FT}\left(1 - f_{r,FT}\right)M_{BO,feed} \cdot 10^3 \tag{3.56}$$

3.3.2.4 Bio-oil steam reformation

Steam reformation of bio-oil yields hydrogen as a product. The total quantity (kg) of hydrogen produced from steam reformation of bio-oil, $F_{kg,BO,SR,H}$, is calculated using Equation 3.57:

$$F_{kg,BO,FT,H} = f_{SR} m_{WS} M_{BO,feed} \cdot 10^3 \tag{3.57}$$

where m_{WS} is the mass ratio fraction of bio-oil that is water soluble, as only the aqueous fraction of bio-oil is suitable for steam reformation.

3.3.3 Costs of bio-fuel production

The costs of producing bio-fuels discussed in this Section are those related to bio-fuel facilities and bio-fuel production processes only. Costs associated with feedstock collection and delivery to the bio-fuel facility are discussed earlier in Section 3.2.4.

3.3.3.1 Storage and pre-treatment

Woodchip and torrefied wood are assumed to be stored in open-air piles [70], [73]. The annual cost of this storage method for commodity j (woodchip or torrefied wood), $C_{pile,bf,j}$, is calculated using Equation 3.58:

$$C_{pile,bf,j} = c_{pile} V_j \tag{3.58}$$

where c_{pile} is the cost per cubic metre to store commodity j, and V_j is the annual volume of commodity j delivered to the bio-fuel facility.

Bio-oil and bio-slurry are stored in stainless steel tanks. The capital cost of the storage equipment, $C_{tank,bf}$, is calculated based on the number of tanks installed, N_{tank},as shown in Equation 3.59:

$$C_{tank,bf} = c_{ref,tank} N_{tank} \tag{3.59}$$

where $c_{ref,tank}$ is the reference cost of a stainless steel tank.

The annual operation and maintenance costs of the stainless steel tanks, $C_{O\&M,tank,bf}$, is calculated using Equation 3.60:

$$C_{O\&M,tank,bf} = o_{tank} C_{tank,cent} \tag{3.60}$$

where o_{tank} is the fixed operation and maintenance percentage of the capital expenditure.

The annual cost of methanol, $C_{meth,bf}$, added to bio-oil is calculated using Equation 3.61:

$$C_{meth,bf} = c_{meth} m_{meth} M_{BO,net} \cdot 10^3 \tag{3.61}$$

where c_{meth} is the dollar per kilogram price of methanol.

Feed preparation for woodchips consists of screening for metals and other impurities, drying and grinding. Feed preparation for torrefied wood only requires grinding. The costs associated with these processes are considered additional capital costs due to the additional equipment required at the bio-fuel facility (costs are provided in Appendix B) [49], [50]. This equipment is not required for liquid feedstock, and therefore these additional costs are not included when bio-oil or bio-slurry feedstock are used. The pre-treatment capital cost is added to the bio-fuel facility capital cost and scaled as necessary depending on the bio-fuel facility size (Section 3.3.3.2).

3.3.3.2 Capital, operating and maintenance costs

The capital cost of bio-fuel facility k utilising commodity j as feedstock, $C_{cap,bf,j,k}$, is calculated using Equation 3.62:

$$C_{cap,bf,j,k} = c_{ref,k} \left(\frac{S_{bf,j,k}}{s_{ref,k}} \right)^{\kappa} \tag{3.62}$$

where $c_{ref,k}$ is the cost of a bio-fuel facility of reference size $s_{ref,k}$ (tonne per day), and κ is the cost scaling factor.

If woodchip or torrefied wood is used as a feedstock, the capital reference cost includes feed preparation equipment. For woodchip feedstock this requires screening, drying and grinding equipment. For torrefied wood feedstock only a grinder is required. These additional costs are added to the reference capital cost of the bio-fuel facility, and are therefore subject to operation and maintenance costs as well [49].

Equation 3.62 is also used to calculate the capital cost of SMR facilities (when hydrogen is produced from methane at a bio-oil upgrading facility), except that annual methane consumption (M_{CH_4}) is used for scaling costs rather than annual feedstock requirements (S_{bf}).

When upgrading uses hydrogen sourced from bio-oil steam reformation, Equation 3.62 is used to calculate the capital cost of both an upgrading facility and steam reformation facility separately. These costs are combined to produce a total capital cost (no cost savings other than labour are assumed through co-location of facilities).

The fixed operation and maintenance cost of bio-fuel facility k utilising commodity feedstock j, $C_{O\&M,bf,j,k}$, is calculated using Equation 3.63:

$$C_{O\&M,bf,j,k} = o_{bf,k} C_{cap,bf,j,k} \tag{3.63}$$

where $o_{bf,k}$ is a fixed operation and maintenance percentage of capital expenditure.

Additional operating costs that are calculated by the model are those related to the purchase of methane or hydrogen when upgrading bio-oil. The annual cost of purchasing methane for steam reformation to hydrogen, $C_{CH_4,bf}$, is calculated using Equation 3.64:

$$C_{CH_4,bf} = c_{CH_4} l_{CH_4} M_{CH_4} \tag{3.64}$$

where c_{CH_4} is the dollar per GJ cost of methane and l_{CH_4} is the lower heating value of methane.

The cost of purchasing hydrogen directly from an external source, $C_{external\text{-}H_2,bf}$, is calculated using Equation 3.65:

$$C_{external\text{-}H_2,bf} = c_{external\text{-}H_2} M_{H_2,UG} \cdot 10^3 \tag{3.65}$$

where $c_{external\text{-}H_2}$ is the dollar per kilogram cost of hydrogen from an external source.

The labour costs for the bio-fuel facilities are based on the size of the bio-fuel facility. For a bio-fuel facility size of 2000 TPD, fifty operating and four administrative staff with an hourly wage of \$40 and \$64, respectively, is assumed. The number of administrative workers is assumed constant for all plant sizes. For every increase or decrease in size of bio-fuel facility by 100 TPD, one more or one less operating worker is required, respectively [49].

3.3.3.3 Levelised cost of bio-fuel production

For each bio-fuel production route (Figure 3-4), all costs spanning the operation lifetime of harvesting forest residues and producing bio-fuels are brought to present day value, totaled, and annualised. These costs include those calculated in Section 3.2. The levelised cost of producing bio-fuel m from commodity feedstock j at bio-fuel production facility k in terms of mass (kg), $LCB_{kg,j,k,m}$, is calculated using Equation 3.66:

$$LCB_{kg,j,k,m} = \frac{CRF \times NPV_{j,k,m}}{F_{kg,j,k,m}} \tag{3.66}$$

where CRF is the capital recovery factor, $NPV_{j,k,m}$ is the net present value of all costs expended to deliver commodity j to bio-fuel facility k and produce bio-fuel m, and $F_{kg,j,k,m}$ is the total quantity (kg) of bio-fuel m produced.

The levelised cost of producing bio-fuels can be calculated in terms of mass (Equation 3.66), volume or energy content of the final fuels. To provide comparison between bio-fuel production routes in later Chapters, the levelised cost of bio-fuel production may be referred to in dollars per GJ, dollars per litre, or dollars per kilogram of fuel.

3.3.4 Summary

Section 3.3 has provided technical and financial calculations that model the production of bio-fuels from woodchip, bio-oil, bio-slurry or torrefied wood feedstock. The second main output of the model, a levelised cost of bio-fuel production, has been described. Section 3.4 describes the analyses that are performed using the model described in Section 3.1 to Section 3.3 to investigate bio-fuel production when using mobile facilities to deliver a forest residue resource to a bio-fuel facility.

3.4 Analysis performed

This Section outlines the analyses that are performed using the model described in Section 3.1 to Section 3.3. All feedstock delivery pathways and bio-fuel production routes are examined. There are four delivery pathways considered, and a total of twelve routes for bio-fuel production - eight bio-fuel production routes via gasification of feedstock, and four bio-fuel production routes specific to a bio-oil feedstock (Figure 3-4). Each time the model is run, results for all four delivery pathways and all twelve routes for bio-fuel production are obtained.

Initially, a base analysis is performed using the model (Section 4.1). For this analysis, an annual harvest of 1.717 million m^3 (equivalent to 2000 ODT) of forest residues is input (which is a standard base annual harvest used by other studies in the literature) and delivery scenario A is selected. The spatial density of forest residues assumed for the base analysis is 65 m^3 km^{-2}, which is consistent with temperate forest data used in other studies (e.g. [49]). The base analysis therefore considers a harvest region of 528,308 km^2 over a 20 year harvest operation. The forest residues are modelled with an initial moisture content of 50%, and an oven-dry wood bulk density and LHV of 500 kg m^{-3} and 18 MJ kg^{-1}, respectively. Base analysis results are validated against results in the literature and a comparison of delivered feedstock costs, bio-oil production costs, and bio-fuel production costs is provided.

A sensitivity study is then performed to examine the key factors that influence model results (Section 4.2). All input parameters are varied individually by plus and minus 50% of their original value, and the impact on levelised delivered cost of feedstock (LDC) and levelised cost of bio-fuels (LCB) are recorded. Parameters that influence both the LDC and LCB by less than 10% are not subject to further analysis.

Using the results of the sensitivity study, key parameters (those that produce more than 10% variation in LDC or LCB results) are used to identify topics for further analysis. Other issues relating to forest residue resource volumes and characteristics, mobile facilities, and point-of-delivery scenarios are also studied, providing extensive investigation into LDC and LCB results. Results specific to levelised delivered costs of feedstock (LDC) are provided in Section 4.3, and results relating to levelised cost of bio-fuels (LCB) are provided in Section 4.4.

3.5 Summary

Chapter 3 has provided a description of the model constructed to investigate the technical and economic impact of producing bio-fuels when using mobile facilities to deliver a forest residue resource to a bio-fuel facility.

The model contains three main sections: definition of a forest residue resource, collection and delivery of a forest residue resource to a bio-fuel facility plant gate, and production of bio-fuels at a bio-fuel facility. The two main outputs of the model are a levelised delivered cost of forest residue resource to a bio-fuel facility plant gate, and a final levelised cost of bio-fuel production. The analyses performed using the model have been described and the results of these analyses are provided next in Chapter 4.

4 Results and Discussion

This Chapter provides results and discussion for analyses performed using the model outlined in Chapter 3, and is divided into four Sections. In Section 4.1, base analysis results are presented and validated against existing results in the literature. A sensitivity study is then performed in Section 4.2 to determine key parameters of the model that influence results. A study of feedstock collection and delivery to bio-fuel facilities is presented in Section 4.3, examining in depth each of the four delivery pathways used to deliver a forest residue resource to a bio-fuel facility (Figure 3-1). Finally, Section 4.4 provides a detailed analysis of bio-fuel production costs via each of the bio-fuel production facilities considered in this study (Figure 3-4), using feedstock from each of the four delivery pathways.

Throughout this Chapter, costs of individual processes (from harvesting of forest residues up to bio-fuel production) may be grouped into the categories shown in Table 4-1, for ease of discussion.

Table 4-1 Cost categories.

biomass	all costs related to the purchase, piling and chipping of forest residues
mobile	all costs related to the purchase, operation and labour requirements of mobile facilities, including on-site storage
transport	all costs related to the transport of woodchips and mobile commodities
central	all costs related to the purchase, operation and labour requirements of the bio-fuel facility, including on-site storage
hydrogen	all costs related to the production or purchase of hydrogen necessary for the bio-oil upgrading process

4.1 Base analysis

The base analysis, described in Section 3.4, uses input values provided in Appendix B. Results of the base analysis are discussed in terms of levelised delivered cost of feedstock (Section 4.1.1) and levelised cost of bio-fuel (Section 4.1.2), before validating model results against results available in the literature (Section 4.1.3).

4.1.1 Levelised delivered cost

Results for levelised delivered cost of feedstock (LDC) for the base analysis are shown in Table 4-2. The LDC of woodchips is 7.97 $ GJ^{-1} while the LDC for bio-oil, bio-slurry and torrefied wood are 18.20 $ GJ^{-1}, 13.03 $ GJ^{-1} and 8.58 $ GJ^{-1}, respectively. The annual average transport distance is 273 km. Approximately 80% of the total LDC for woodchip delivery is due to transport costs. Implementing mobile facilities reduces the impact of transport costs to less than 40% of the total LDC for mobile facility pathways, yet for this size of annual harvest the costs of implementing mobile facilities outweigh the reduction in transport costs.

Delivering woodchips ensures that all of the energy content of forest residues are delivered to the bio-fuel facility. When delivering bio-oil, bio-slurry or torrefied wood the total energy delivered to the bio-fuel facility is reduced due to the energy requirements of the mobile facilities, which use a fraction of the biomass energy content to meet thermal or electrical demands. Fast pyrolysis facilities use 12.4% of the produced bio-oil for electricity generation for the facility. Furthermore, the energy content of the char product of fast pyrolysis is not available for bio-fuel production when only bio-oil is delivered. Some of the char is transported when a bio-slurry is produced, although the configuration of the fast pyrolysis reactor in this study yields excess char that cannot be added to the bio-slurry due to a maximum char loading of 20%. Therefore, the total energy delivered by bio-oil, bio-slurry and torrefied wood is 45%, 65% and 87% of the initial forest residue energy content, respectively. This reduced quantity of energy delivered to the bio-fuel facility increases the LDC of each commodity.

Table 4-2 Breakdown of levelised delivered cost (LDC) for base harvest.

Cost component (Table 4-1)	woodchip		bio-oil		bio-slurry		torrefaction	
	$ GJ^{-1}	%[a]	$ GJ^{-1}	%[a]	$ GJ^{-1}	%[a]	$ GJ^{-1}	%[a]
biomass								
purchase, piling & chipping	1.67	20.9	3.70	20.3	2.56	19.6	1.92	22.4
mobile								
feed preparation	-	-	3.74	20.6	2.58	19.8	0.00	0.0
purchase & maintenance	-	-	3.83	21.0	2.65	20.3	2.19	25.5
labour	-	-	2.71	14.9	1.88	14.4	1.41	16.4
relocation	-	-	0.01	0.0	0.00	0.0	0.00	0.0
storage	-	-	0.04	0.2	0.03	0.2	0.00	0.0
transport								
woodchip delivery	6.30	79.1	1.61	8.8	1.11	8.5	0.84	9.8
product delivery	-	-	2.56	14.1	2.22	17.0	2.22	25.9
total	7.97	100.0	18.20	100.0[b]	13.03	100.0[b]	8.58	100.0

[a] Percentage of total LDC

[b] Rounded values do not sum to 100.0%

4.1.2 Levelised cost of bio-fuel

Results for levelised cost of bio-fuel (LCB) for the base analysis are shown in Figure 4-1. The net present value of all costs expended for each bio-fuel production route is similar, between $1.0 - 1.3 billion (Figure 4-1a). However, when the quantity or energy content of bio-fuels produced from each process is taken into account, the results for LCB vary significantly (Figure 4-1b).

Bio-fuels produced via gasification and Fischer-Tropsch synthesis (petrol and diesel) are most expensive, for any feedstock. The variation between Fischer-Tropsch (FT) bio-fuel production costs using different feedstock is due to the quantity of each feedstock delivered to the bio-fuel facility for a given harvest (as mentioned in Section 4.1.1). The LCB from FT synthesis is 41.75 $ GJ^{-1} (1.42 $ litre^{-1}), 66.76 $ GJ^{-1} (2.28 $ litre^{-1}), 60.54 $ GJ^{-1} (2.06 $ litre^{-1}) and 52.92 $ GJ^{-1} (1.80 $ litre^{-1}) for woodchip, bio-oil, bio-slurry and torrefied wood feedstock, respectively.

Upgrading bio-oil to produce petrol and diesel yields a lower LCB than FT bio-fuels, regardless of the source of hydrogen required for upgrading. Upgrading

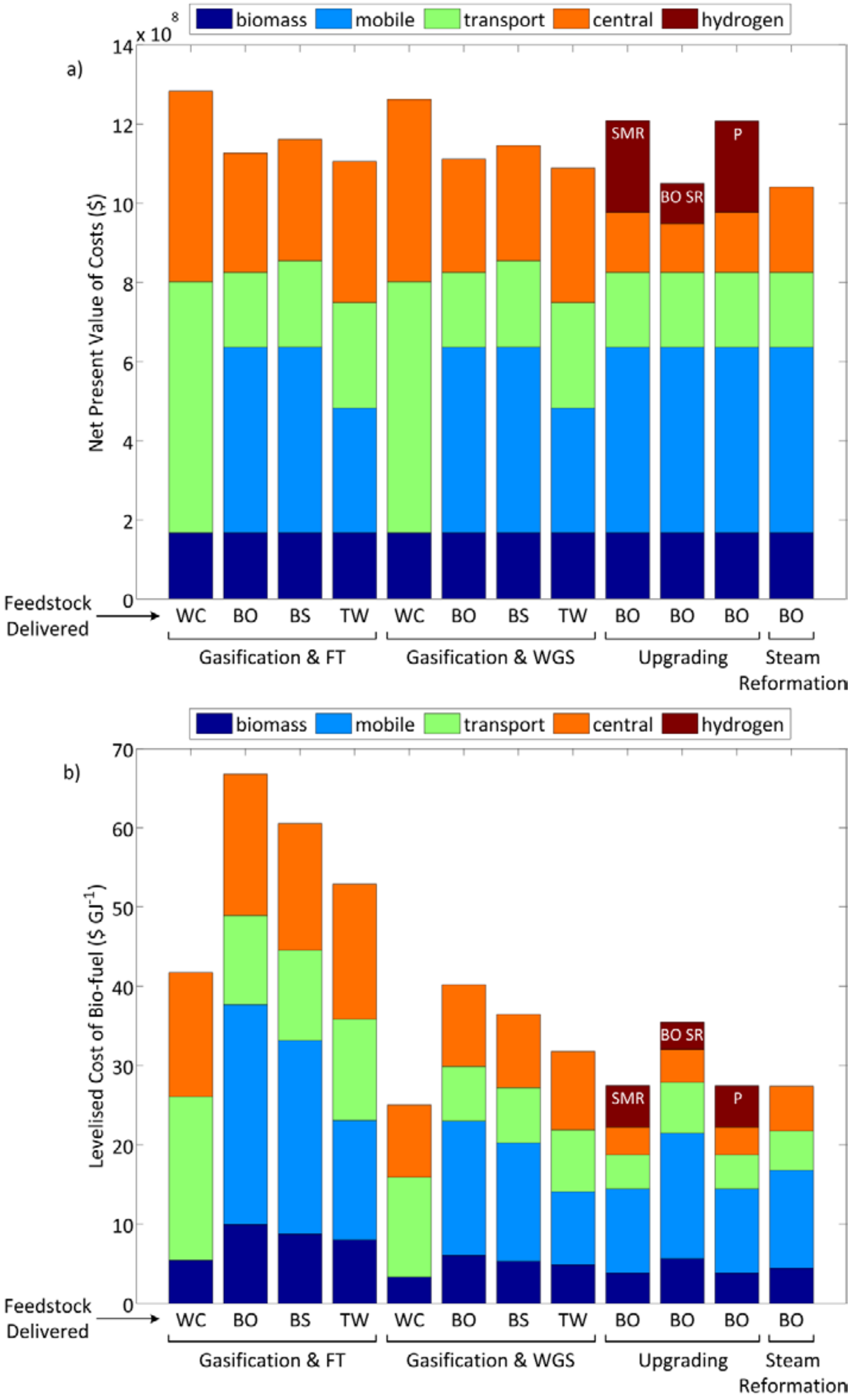


Figure 4-1 a) Net present value of costs for all bio-fuel production routes. b) Levelised cost of bio-fuel for all bio-fuel production routes. [Base harvest (1.717 million m^3); SMR: Steam methane reformation; BO SR: Bio-oil steam reformation; P: Purchased hydrogen ($1.5 kg^{-1})].

bio-oil using hydrogen produced by steam reforming a fraction of the bio-oil feed requires less overall expenditures (Figure 4-1a), but less bio-fuel is produced resulting in a higher LCB compared to other hydrogen sources (Figure 4-1b). The LCB from bio-oil upgrading is 27.48 \$ GJ^{-1} (0.88 \$ $litre^{-1}$), 35.46 \$ GJ^{-1} (1.14\$ $litre^{-1}$) and 27.46 \$ GJ^{-1} (0.88 \$ $litre^{-1}$) when using hydrogen sourced from SMR, bio-oil steam reformation and purchased hydrogen (1.5 \$ kg^{-1}), respectively.

Hydrogen produced via gasification and water gas shift (WGS) of woodchip feedstock provides the lowest LCB of all bio-fuel production routes (Figure 4-1b). Hydrogen production via gasification and WGS for other feedstock types is more expensive due to reduced quantities of feedstock available from mobile facilities for bio-fuel production. The LCB from gasification and WGS is 25.06 \$ GJ^{-1} (3.01 \$ kg^{-1}), 40.21 \$ GJ^{-1} (4.83 \$ kg^{-1}), 36.45 \$ GJ^{-1} (4.37 \$ kg^{-1}) and 31.81 \$ GJ^{-1} (3.82 \$ kg^{-1}) for woodchip, bio-oil, bio-slurry and torrefied wood feedstock, respectively.

Hydrogen production via steam reformation of bio-oil has a levelised cost of 27.42 GJ^{-1} (3.29 \$ kg^{-1}).

4.1.3 Validation

The model presented in Chapter 3 consists of a series of components and processes, each of which is based on methods used by other studies in the literature. Together, these components and processes model the delivery of a forest residue resource to a bio-fuel facility using mobile facilities, as well as bio-fuel production. Validating outputs of the model ensures that combining model components and processes still yields reasonable results.

Table 4-3 provides a comparison of model results to those available in the literature. None of the results in the literature are specifically related to bio-fuel production from forest residues when using mobile facilities. Therefore, an absolute comparison cannot be made, although it is useful to show that the model does provide results within a reasonable range suggested by other studies.

Table 4-3 Validation of the model against results available in the literature.

Subject of validation	Model	Literature	Reference(s)
Delivered woodchip feedstock cost ($\$\cdot GT^{-1}$)	70.27	15 - 75 [a]	[35], [48]
Delivered bio-oil feedstock cost ($\$\cdot litre^{-1}$)	0.33	0.30 - 0.58[b]	[10], [19]
Delivered bio-slurry feedstock cost ($\$\cdot litre^{-1}$)	0.30	0.12 - 0.15[c]	[39]
Bio-oil production cost using mobile pyrolysis facilities ($\$\cdot litre^{-1}$)	0.28	0.25[d]	[74]
Torrefied wood production cost ($\$\cdot tonne^{-1}$)	196.85	68.07 - 95.29[e]	[13], [43]
Woodchip gasification and Fischer-Tropsch: petrol and diesel fuel production cost ($\$\cdot litre^{-1}$)	1.42	0.76 - 2.40	[49]
Bio-oil gasification and Fischer-Tropsch: petrol and diesel fuel production cost ($\$\cdot litre^{-1}$)	2.28	0.40 - 0.89[f]	[75], [76]
Bio-slurry gasification and Fischer-Tropsch: petrol and diesel fuel production cost ($\$\cdot litre^{-1}$)	2.06	1.73[g]	[56]
Woodchip gasification and water gas shift: hydrogen fuel production cost ($\$\cdot kg_{H_2}^{-1}$)	3.01	2.80 - 5.40	[48]
Bio-oil upgrading: petrol and diesel fuel production cost ($\$\cdot litre^{-1}$)			
Hydrogen sourced from SMR	0.88	0.48 - 0.92	[16], [74]
Hydrogen sourced from bio-oil steam reformation	1.14	1.80	[71]
Purchased hydrogen ($\$1.5\ kg_{H_2}^{-1}$)	0.88	0.90	[71]
Bio-oil steam reformation: hydrogen fuel production cost ($\$\cdot kg_{H_2}^{-1}$)	3.29	3.12[b]	[19]

Model results correspond to an annual harvest of 1.717 million m^3 (2000 ODTPD equivalent) of forest residues. [a] values provided in ODT are converted to GT for comparison using conversion factors in Table 2-1. [b] values are for bio-oil produced from larger scale fixed distributed fast pyrolysis facilities [c] values are for bio-slurry produced from larger scale (500 ODTPD) fixed distributed fast pyrolysis facilities. [d] value is for a larger mobile fast pyrolysis facility (100 ODTPD) [e] values are for larger scale fixed torrefaction facilities, and do not include feedstock costs. [f] values are for larger scale fixed distributed fast pyrolysis facilities providing bio-oil feedstock. [g] values are for bio-slurry sourced from larger scale fixed facilities.

4.2 Sensitivity study

A sensitivity study is performed on all input parameters to determine key factors that significantly influence model results. All parameters are varied individually by plus and minus 50% of their original input value, and the impact on levelised delivered cost (LDC) and levelised cost of bio-fuels (LCB) is recorded. Parameters that influence LDC or LCB results by more than 10% are discussed in Sections 4.2.1 and 4.2.2, respectively. Tables detailing the results of the sensitivity study can be found in Appendix C.

4.2.1 Levelised delivered cost

Parameters that significantly influence LDC results (produce more than 10% variation in LDC results) can be grouped into the following categories: mobile facility capital cost; densities of commodities; transport factors; mobile facility electrical and drying requirements; and initial moisture content of forest residues.

Mobile facility capital cost significantly influences LDC results as any change in cost is multiplied by the number of installations, and operation and maintenance costs of mobile facilities are also impacted, which are calculated as a percentage of capital cost.

The density of each commodity (woodchip, bio-oil, bio-slurry, or torrefied wood) proves significant as this is used to determine how much of the commodity can be loaded into a single truck (within the weight limit of the vehicle). Thus, the density of a commodity is more important when trucks are limited by volume rather than weight. The LDC of woodchips is particularly sensitive to the density of woodchips.

All transport parameters input to the model, except fixed costs (loading and unloading), are found to be significant by the sensitivity study. Truck volumes impact woodchip and torrefied wood LDC values more than those for bio-oil and bio-slurry delivery. Bio-oil and bio-slurry are impacted by truck weight limits, because liquid loads are limited by weight rather than volume. The tortuosity factor and haul cost factors influence the LDC of woodchip and torrefied wood significantly (but not bio-oil or bio-slurry) as both woodchip and torrefied wood delivery require greater total transport distances.

The efficiency of the electricity generator at mobile fast pyrolysis facilities is a significant parameter for fast pyrolysis pathways because this affects how much bio-oil is consumed by the electricity generator and thus the net quantity of bio-oil available as a commodity or for bio-slurry production. The woodchip dryer efficiency is significant for all mobile facilities as this determines how much syngas is used for the drying of woodchips. When the dryer has a low efficiency, propane requirements increase if there is not sufficient syngas for drying, which increases LDC results. The cost of propane also proves important for mobile fast pyrolysis facilities (which produce less syngas than mobile torrefaction facilities).

The initial moisture content of forest residues is a significant parameter for two reasons. First, increased moisture content of forest residues increases the drying requirements at mobile facilities. Second, moisture content determines how much wood content there is within a volume of forest residues i.e. increasing moisture content within a fixed volume of a forest residue resource results in a decreased wood content (Equation 3.1). Therefore, because a volume of forest residues is input to the model, the total energy content of the forest residue resource is less when the moisture content is increased, resulting in higher LDC values (Equation 3.42).

4.2.2 Levelised cost of bio-fuel

Parameters that significantly influence LCB results (produce more than 10% variation in LCB results) can be grouped into the following categories: density of woodchips; density of torrefied wood; transport factors; mobile facility electrical and drying requirements; initial moisture content of forest residues; bio-fuel facility capital cost; discount factor; and bio-fuel production factors.

The densities of woodchip and torrefied wood, drying and electrical requirements of mobile facilities, and the initial moisture content of forest residues are significant parameters for LCB results for the same reasons explained in Section 4.2.1.

Bio-fuel facility capital cost influences LCB results significantly as it is a large expenditure and also impacts the operation and maintenance costs of bio-fuel facilities, which are calculated as a percentage of capital cost.

The discount rate input to the model, which reflects interest rates, inflation and other financial risk, is used in financial calculations (in particular for calculating the net present value of future costs) and significantly impacts the levelised cost of bio-fuels for all delivery pathways and bio-fuel production routes. The influence of the discount factor is not major for LDC results, but is more apparent when dealing with large costs associated with the operation and maintenance of bio-fuel facilities.

Parameters that influence the quantity of bio-fuel produced from any feedstock influence LCB results most significantly. A reduction in the quantity of bio-fuel produced will result in a higher LCB (Equation 3.66).

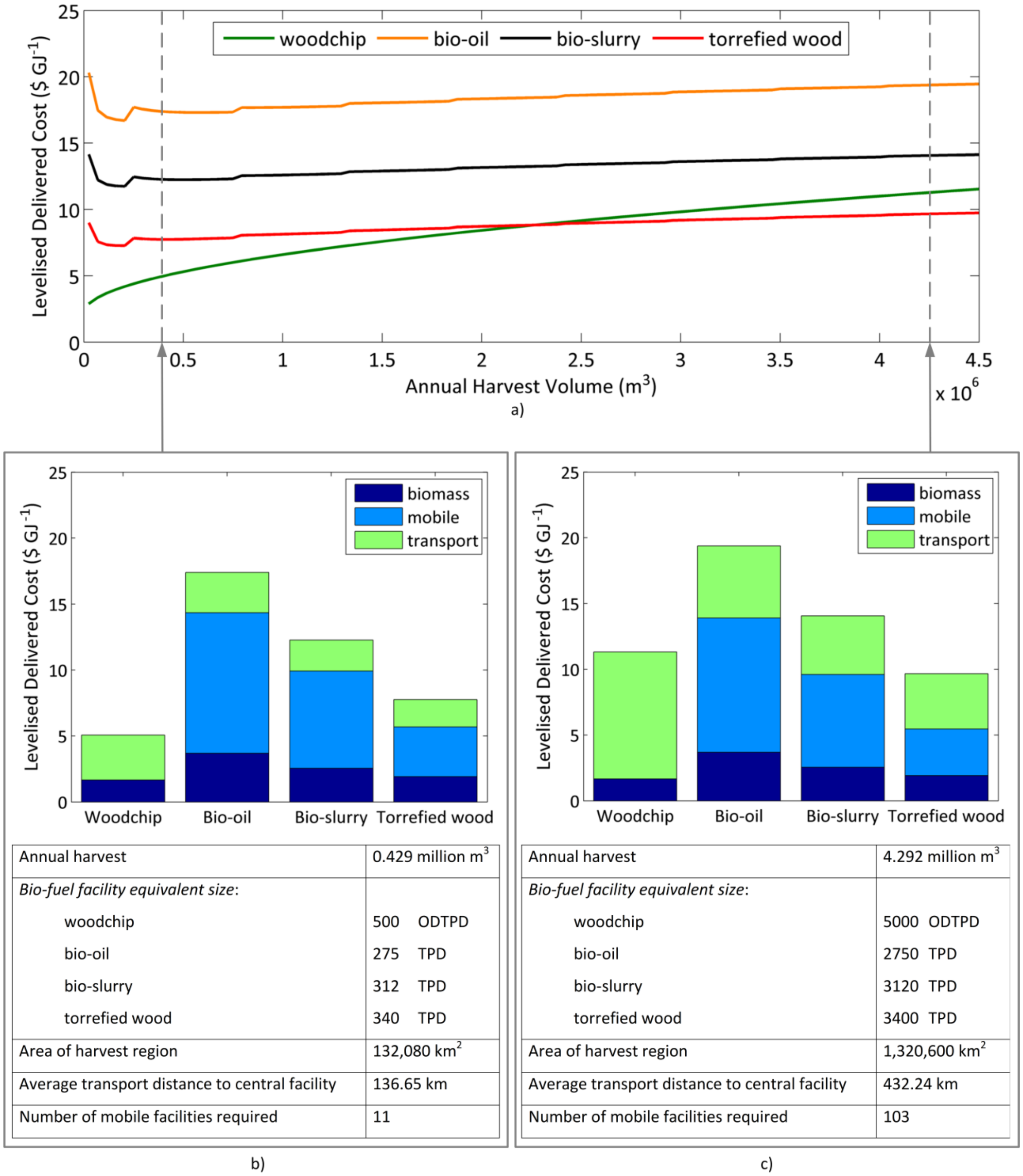
4.3 Feedstock collection and delivery

This Section presents further results for each pathway used to deliver a forest residue resource to a bio-fuel facility (Figure 3-1). Levelised delivered costs are provided for a range of forest residue harvest volumes and spatial densities (Section 4.3.1 and Section 4.3.2). Initial moisture content of forest residues and commodity transport factors are studied in more detail, given their influence on LDC results as shown by the sensitivity study (Section 4.3.3 and Section 4.3.4). Relocation of mobile facilities is investigated (Section 4.3.5), and results are examined for a range of point-of-delivery distances (scenario B), modelling a situation where the bio-fuel facility is located at a distance from the forested region (Section 4.3.6).

Note: Results shown throughout this Section relate to bio-fuel facilities located at the centre of the forested region (scenario A), except when discussing point-of-delivery distances in Section 4.3.6.

4.3.1 Annual volume of forest residues

Figure 4-2 shows how the levelised delivered cost (LDC) for each delivery pathway varies with annual harvest volume of forest residues. Above a harvest of approximately 2.3 million m^3 per year it becomes more economical to implement mobile torrefaction facilities. The number of mobile facilities required increases with annual harvest volume (the size of the mobile facilities is fixed). However, the cost reduction provided on conventional woodchip transport direct to a bio-fuel facility means implementing mobile torrefaction facilities reduces the total LDC of resource. The



Annual harvest	0.429 million m^3
Bio-fuel facility equivalent size:	
woodchip	500 ODTPD
bio-oil	275 TPD
bio-slurry	312 TPD
torrefied wood	340 TPD
Area of harvest region	132,080 km^2
Average transport distance to central facility	136.65 km
Number of mobile facilities required	11

b)

Annual harvest	4.292 million m^3
Bio-fuel facility equivalent size:	
woodchip	5000 ODTPD
bio-oil	2750 TPD
bio-slurry	3120 TPD
torrefied wood	3400 TPD
Area of harvest region	1,320,600 km^2
Average transport distance to central facility	432.24 km
Number of mobile facilities required	103

c)

Figure 4-2 a) Levelised delivered cost over a range of annual harvest volumes. b) Cost components **(**Table 4-1**)** for a bio-fuel facility of size 500 ODTPD (woodchip equivalent). c) Cost components for a bio-fuel facility of size 5000 ODTPD (woodchip equivalent). The quantity of commodity delivered to the bio-fuel facility after conversion processes at mobile facilities is less than when delivering woodchips, and so the bio-fuel facility size required for each possible feed is also provided in Figure 4-2b and Figure 4-2c.

minimum LDC of commodities when using a mobile facility network (for both fast pyrolysis or torrefaction) occurs at an annual forest residue harvest of approximately 200,000 m^3, which requires the use of only five mobile facilities. However, the average transport distance to the bio-fuel facility for this size of harvest is only 93 km, and conventional woodchip delivery is the lowest cost pathway.

Figure 4-2b and 4-2c show LDC results partitioned into three cost components (biomass, mobile, and transport as discussed in Table 4-1) for annual harvests of 0.429 and 4.292 million m^3 (500 and 5000 ODTPD woodchip equivalent). As the annual harvest increases, a larger portion of the LDC of woodchips is due to transport. The portion of LDC attributed to transport is considerably smaller for pathways using mobile facilities. Therefore, the LDC of resource for mobile facility pathways increases at a lower rate than woodchip delivery as greater volumes of forest residues are harvested.

4.3.2 Forest residue spatial density

The spatial density of forest residues affects the LDC of woodchips more than pathways using mobile facilities (Figure 4-3). Varying the spatial density between 30 and 100 m^3 km^{-2} results in a +34.2% and -14.1% change in LDC for woodchip delivery, respectively. The LDC of commodities from mobile facilities varies by a maximum and minimum of +12.1% and -5.0% over the same spatial density range. Mobile torrefaction facilities provide the lowest cost delivery pathway when the average spatial density of a forest residue resource is below 47 m^3 km^{-2} (for an annual harvest of 1.717 million m^3).

4.3.3 Initial moisture content

Moisture content of forest residues impacts the feed preparation energy requirements of mobile facilities. Each mobile fast pyrolysis facility requires 1855 litres of propane per day when the initial moisture content is 50%. This quantity of propane accounts for approximately 20% of the LDC for bio-oil or bio-slurry commodities. For the configuration of the mobile facilities assumed in this study, no propane is required to dry woodchips at mobile fast pyrolysis facilities when the initial moisture content of the forest residues is below 37%. Each mobile torrefaction facility produces enough syngas to meet drying requirements when initial moisture content is 50%, and propane is only

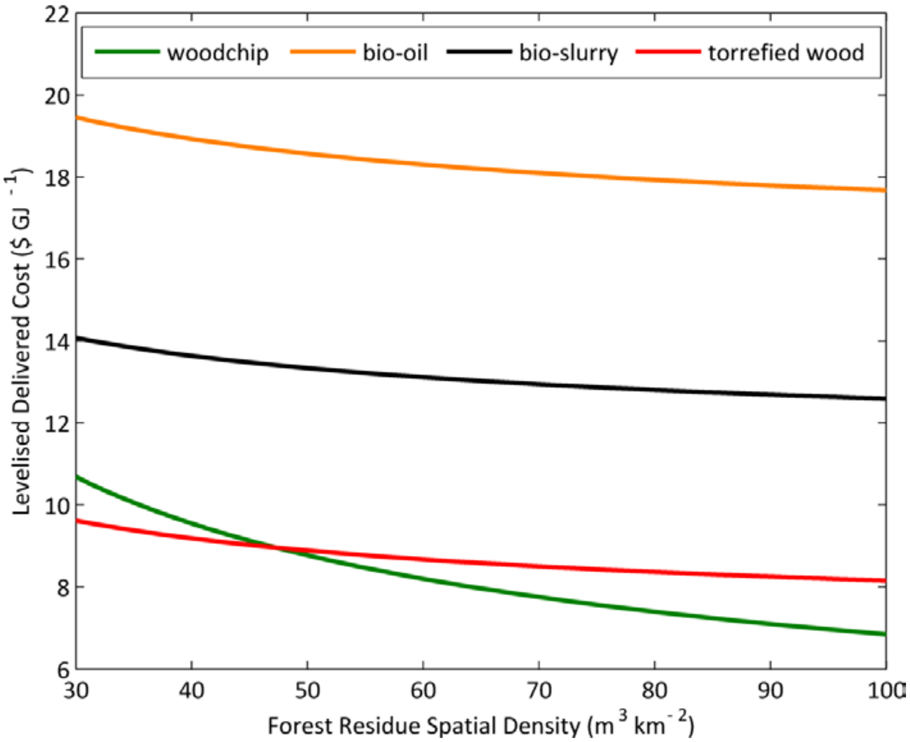


Figure 4-3 Levelised delivered costs for a range of forest residue spatial densities.

required to meet drying energy requirements when the moisture content is over 52%. The effect of initial moisture content on LDC is shown in Figure 4-4a.

Propane requirements are also determined by the efficiency of the dryer at mobile facilities. Figure 4-4b shows how propane requirements change when the efficiency of the dryer is 52% (min value), 72% (base value) and 89% (max value) over a range of initial moisture content.

4.3.4 Transport

The sensitivity study showed that transport parameters used in the model significantly influenced LDC results. Table 4-4 shows how LDC results vary for each delivery pathway for an annual harvest of 1.717 million m^3 (2000 ODTPD woodchip equivalent) when different haul cost factors are used. Table 4-4 also includes LDC results for when smaller straight trucks are used for mobile facility commodity delivery, which may be necessary when road conditions are not suitable for large B-train vehicles.

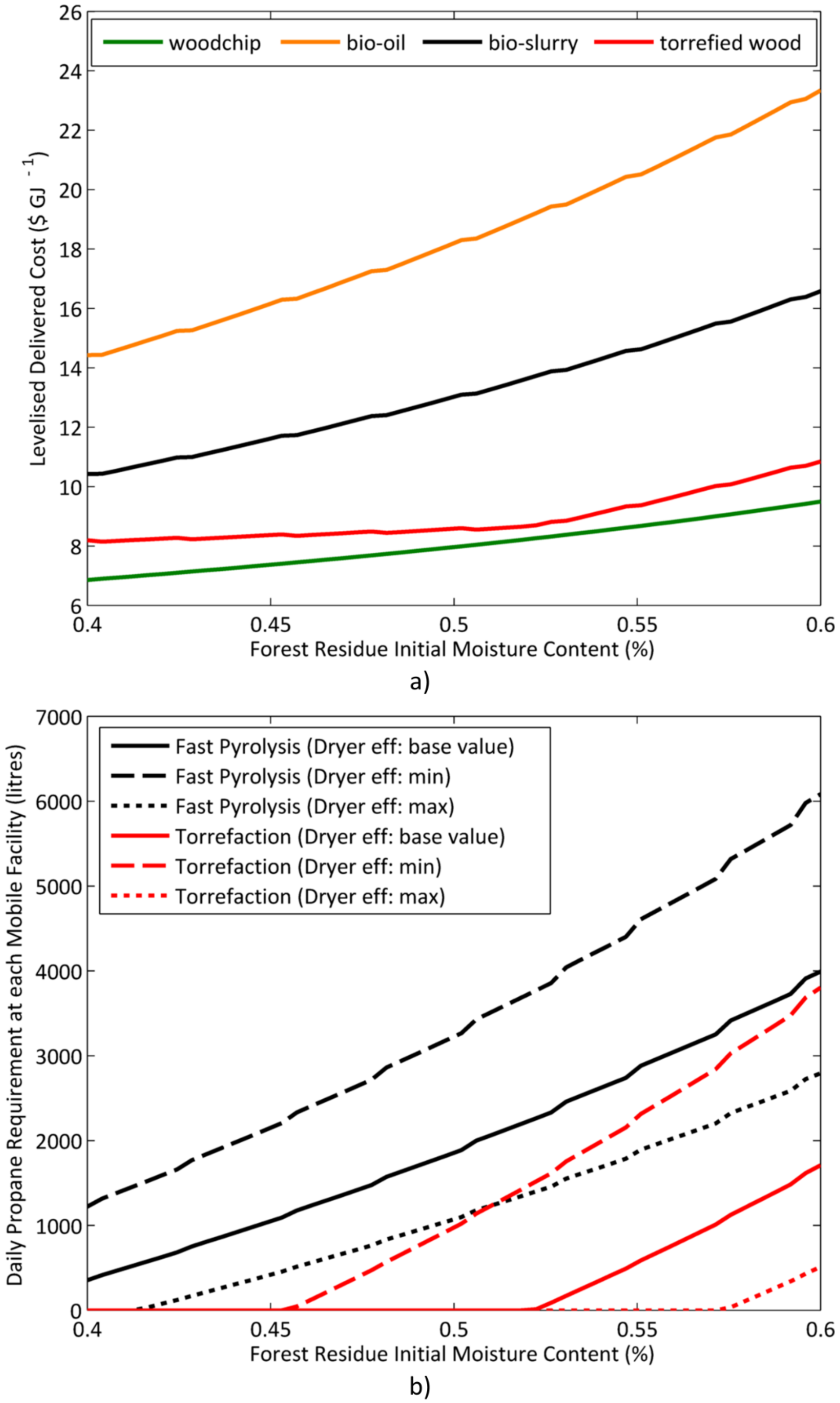


Figure 4-4 a) Levelised delivered costs for a range of initial moisture content of forest residues. b) Daily propane requirements at mobile facilities for a range of drying efficiencies and initial moisture content of forest residues (minimum efficiency 52%; maximum efficiency 89%).

Table 4-4 Levelised delivered costs for a range of truck types and haul costs.

	Truck haul cost ($ km^{-1})				
	1.0	1.5	2.0	2.5	3.0
Truck type	Total Levelised Delivered Cost ($ GJ^{-1})				
Woodchip					
Straight truck[a]	6.04	**7.97**	9.89	11.81	13.74
Bio-oil					
Straight tanker[b]	17.79	18.70	19.61	20.52	21.44
B-train tanker[c]	16.86	17.31	17.75	**18.20**	18.64
Bio-slurry					
Straight tanker[b]	12.68	13.47	14.25	15.04	15.83
B-train tanker[c]	11.87	12.26	12.64	**13.03**	13.41
Torrefied wood					
Straight truck[a]	8.86	9.99	11.11	12.23	13.36
B-train truck[d]	7.40	7.79	8.19	**8.58**	8.97

[a]Straight truck: Volume 70 m^3, Weight limit 22.5 tonnes [7] [b]Straight tanker: Volume 30 m^3, Weight limit 30.5 tonnes [77] [c]B-train truck: Volume 200 m^3, Weight limit 62.5 tonnes [78] [d]B-train tanker: Volume 60 m^3, Weight limit 62.5 tonnes [79]. Bold values indicate results when base analysis values are used (Section 4.1).

Results show that if the haul cost for woodchip delivery is as low as 1 $ km^{-1}, woodchip delivery will be the lowest cost pathway for delivery of a forest residue resource regardless of other vehicle types or haul cost factors used for other commodity delivery (for the ranges shown in Table 4-4). If the haul cost for woodchip delivery is as high as 3 $ km^{-1}, then torrefied wood is the lowest cost delivery pathway, when either straight trucks or B-train trucks are used. The LDC of bio-slurry may also be less expensive than woodchip delivery (at 3 $ km^{-1}) depending on the vehicle type used and the haul cost of bio-slurry delivery, although torrefied wood remains the lowest cost pathway. Bio-oil is the most expensive delivery pathway, and the LDC of bio-oil is not below that of woodchip delivery, even when the haul cost of woodchips is 3 $ km^{-1}.

However, Table 4-4 (as well as the results of the sensitivity study) demonstrates that the LDC of mobile facility commodities are less influenced by haul cost factors than woodchip delivery. This is because transport requirements are reduced when mobile facility pathways are used for delivery of a forest residue resource. For the same reason, decreasing the size of truck used to transport mobile commodities imparts small variation of LDC results, especially for liquid commodities.

The tortuosity factor used in the model is akin to the nature of the road network (the windiness of roads). This factor was found to be significant in the sensitivity study. Results of varying the tortuosity factor can be inferred from Table 4-4 - total transport costs are calculated by multiplication of both the tortuosity factor and haul cost factor (see Equations in Section 3.2.2). For example, doubling the haul cost factor is analogous to doubling the tortuosity factor, provided the other factor is held constant.

4.3.5 Relocation of mobile facilities

One advantage of using mobile facilities suggested in the literature is relocation of facilities. The levelised delivered cost, when using both types of mobile facility, is lowest when the facilities are relocated approximately 210 times (i.e. marginally under once per month for a 20 year operation). Relocating more frequently than this results in commodity transport cost savings being offset by the cost of continuously relocating each mobile facility. The average woodchip transport distance to each mobile facility is 9.60 km, 2.76 km and 1.96 km when mobile facilities are relocated 19 (annually), 240 (monthly) and 480 (every two weeks) times over the 20 year operation, respectively. The associated levelised delivered cost for a mobile torrefaction facility is 8.58 \$ GJ^{-1}, 8.45 \$ GJ^{-1} and 8.48 \$ GJ^{-1} (Figure 4-5).

4.3.6 Point-of-delivery

Figure 4-6 shows how the levelised delivered cost varies when the bio-fuel facility is located at an additional transport distance from the forest harvest region (scenario B) for an annual harvest of 1.717 million m^3 (equivalent to delivering 2000 ODTPD woodchips). Woodchip delivery is the lowest cost pathway for additional distances under approximately 50 km (base value haul costs). For greater distances, torrefied wood is the lowest cost pathway for delivering the forest residue resource. Bio-slurry is a less costly delivery pathway than woodchips at distances above 360 km, although the delivered cost of torrefied wood is still lower. Further analysis shows that if

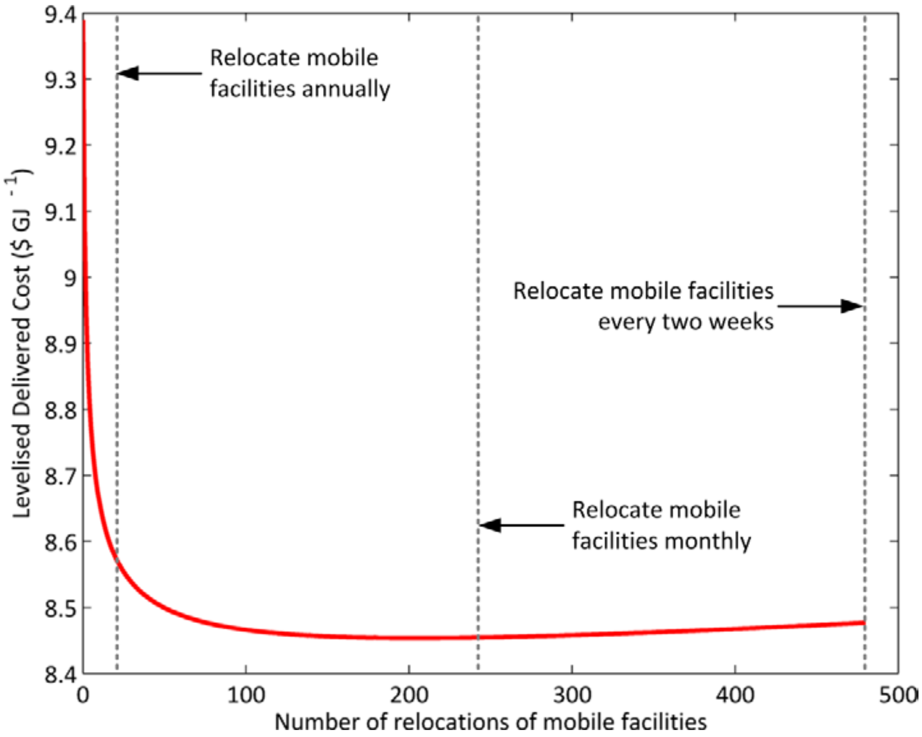


Figure 4-5 Variation in levelised delivered cost of torrefied wood when relocating mobile torrefaction facilities.

woodchip haul costs are as low as 0.85 \$ km^{-1}, delivering woodchips is the lowest cost pathway for additional distances up to at least 500 km.

Figure 4-7 shows the lowest cost delivery pathway for a range of annual harvests and additional transport distances. Bio-oil is always the most expensive pathway for delivering the forest residue resource (for the analysis range considered) followed by bio-slurry. Torrefied wood is a less costly pathway than both bio-oil and bio-slurry, and is also less costly than woodchips depending on the annual harvest volume and additional transport distance required. In Figure 4-7, implementing mobile torrefaction facilities is shown to be the lowest cost delivery pathway (for any annual harvest volume) when the point of delivery requires additional transport distances of more than 250 km. When there is no additional transport requirement, torrefied wood is the lowest cost delivery pathway when annual harvests are above 2.25 million m^3.

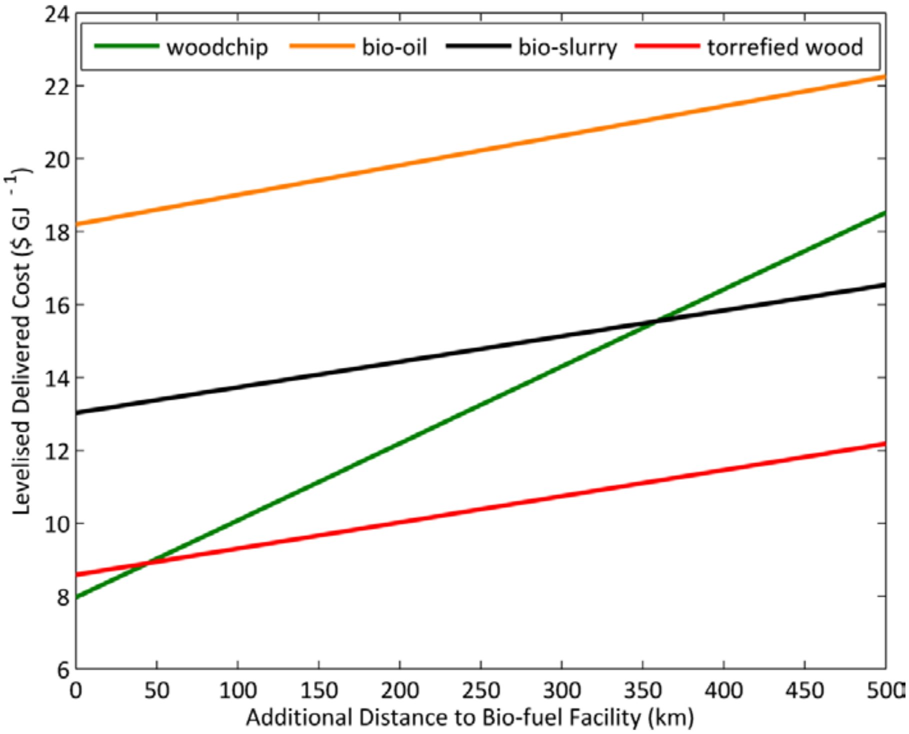


Figure 4-6 Levelised delivered cost when additional transport distances to a bio-fuel facility are required (scenario B; annual harvest of 1.717 million m^3).

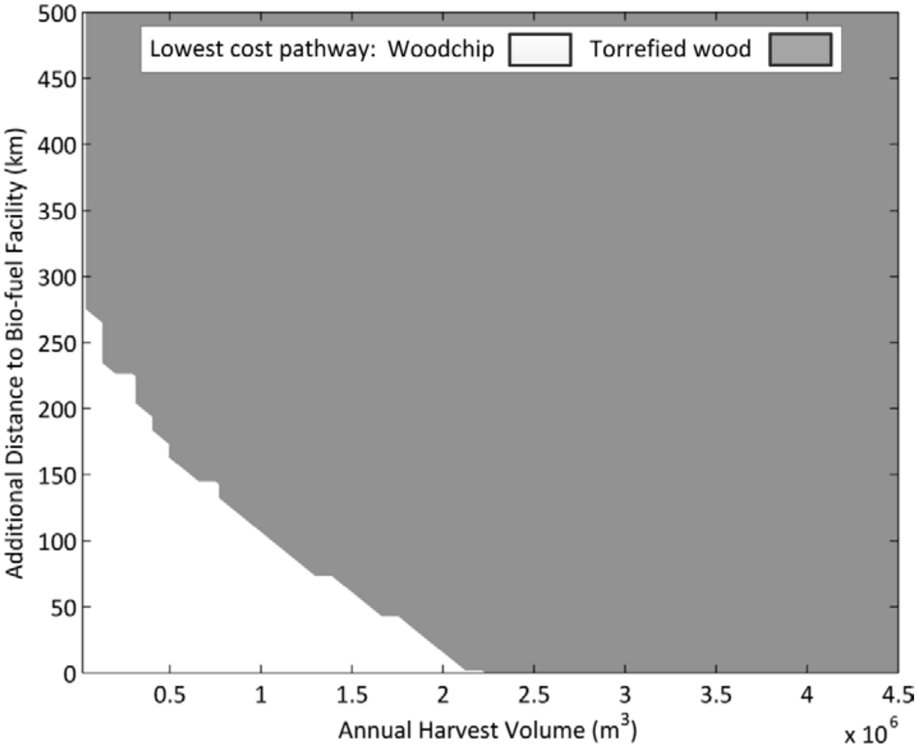


Figure 4-7 Visualisation of lowest cost delivery option for a range of harvest volumes and additional transport distances.

4.4 Bio-fuel production

This Section presents results for each bio-fuel production route using feedstock from each feedstock delivery pathway, where applicable (Figure 3-4). Petrol and diesel fuel production (Section 4.4.1) is analysed separately from hydrogen production (Section 4.4.2). Analysis includes levelised costs of bio-fuel production for a range of forest residue harvest volumes, which provides insight into optimal harvest volumes for each bio-fuel production route. The effect of additional transport distances is also examined for when the bio-fuel facility is located outside of the forested region (scenario B), and finally the effect of bio-fuel production parameters on bio-fuel costs are discussed further, given their influence on LCB results as highlighted in the sensitivity study.

Note: Results shown throughout this Section relate to bio-fuel facilities located at the centre of the forested region (scenario A), except when discussing point-of-delivery distances in Section 4.4.1.2 and Section 4.4.2.2.

4.4.1 Petrol and diesel

4.4.1.1 Optimal harvest volumes

Figure 4-8 shows how the levelised cost of bio-fuel (LCB) for petrol and diesel fuels varies with the annual harvest volume of forest residues, for both Fischer-Tropsch (FT) and upgrading bio-fuel production routes.

LCB results all follow the same trend: for small annual harvest volumes the LCB is high because there are large expenditures for the bio-fuel facility, yet the quantity of fuel produced is small; for large annual harvest volumes the LCB is high because, although more fuel is produced and economies of scale reduce the cost of the bio-fuel facility (per tonne feed), transport costs are high due to harvesting forest residues over an increasingly large area. There is an optimum low cost of bio-fuel production between these two regions.

The minimum cost of FT bio-fuels produced from a woodchip feedstock occurs at an annual harvest of 992,000 m^3 forest residues (equivalent to a 1160 ODTPD bio-fuel

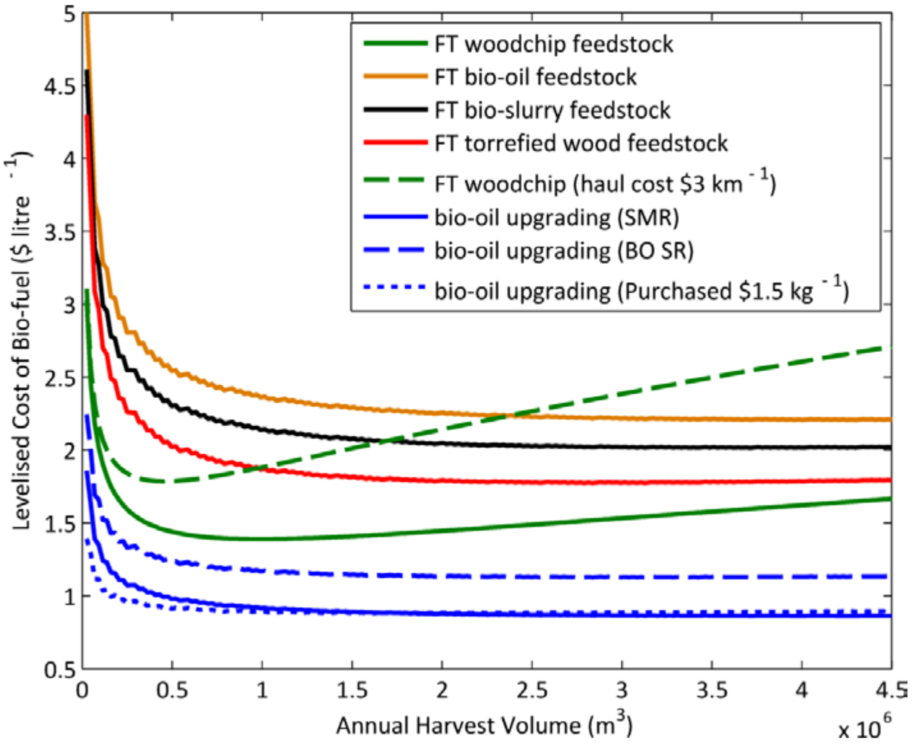


Figure 4-8 Levelised cost of bio-fuel (petrol and diesel) for a range of annual harvest volumes.

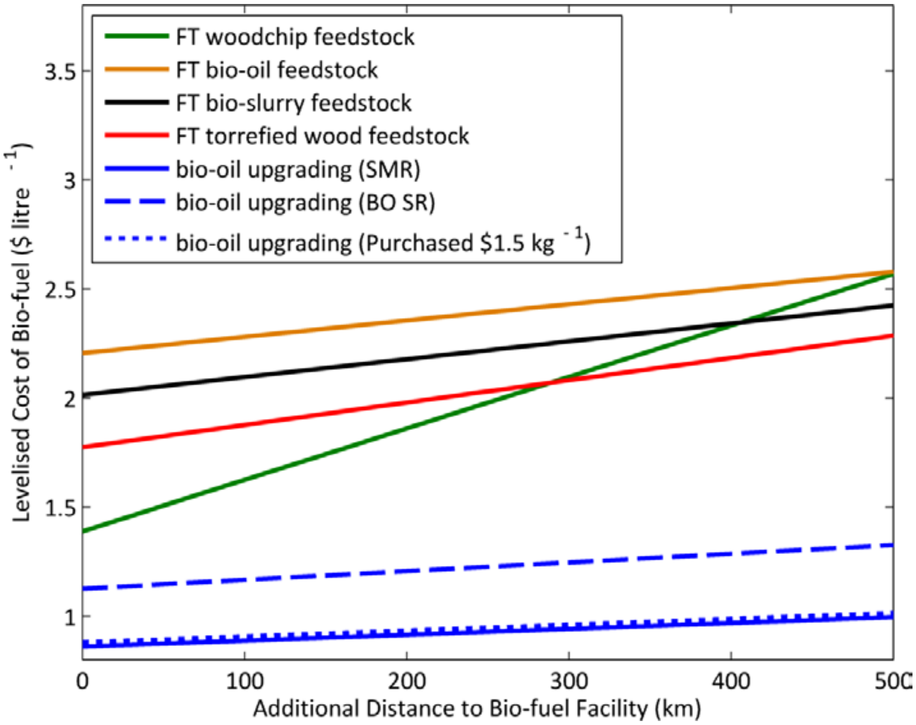


Figure 4-9 Levelised cost of bio-fuel (petrol and diesel) for optimally sized bio-fuel facilities when additional transport distances to a bio-fuel facility are required (scenario B).

facility), and the LCB is 1.39 \$ litre^{-1}. Transport requirements are reduced for delivery pathways using mobile facilities, therefore minimum LCB results for bio-fuel facilities using bio-oil, bio-slurry or torrefied wood occur at larger annual harvest volumes (i.e. larger bio-fuel facilities). Optimum sizes of FT facilities using either bio-oil, bio-slurry or torrefied wood feedstock occur for harvests of 4.30 million m^3 (2750 TPD), 3.71 million m^3 (2700 TPD), and 2.84 million m^3 (2250 TPD), respectively. For bio-fuel production via gasification and FT synthesis, woodchip feedstock provides the lowest LCB. However, if woodchip haul costs increase, torrefied wood feedstock becomes the lowest cost option, for larger annual harvests. For example, if haul costs of woodchips increases to 3 \$ km^{-1}, torrefied wood feedstock produces the lowest LCB results for annual harvests above approximately 1 million m^3, as shown in Figure 4-8.

Bio-fuel production costs via bio-oil upgrading are lower than those produced via FT synthesis, and are less influenced by annual harvest volume as mobile fast pyrolysis facilities reduce transport requirements of bio-oil feedstock delivery. The minimum LCB occurs at 4.30 million m^3 (2750 TPD), 3.13 million m^3 (2000 TPD) and 1.96 million m^3 (1250 TPD) for bio-oil upgrading facilities using hydrogen sourced from SMR, bio-oil steam reformation and purchased hydrogen (1.5 \$ kg^{-1}), respectively. The minimum LCB for producing bio-fuels via upgrading is 0.86 \$ litre^{-1} when using SMR for the hydrogen source.

The cost of purchasing or producing hydrogen for upgrading bio-oil affects final bio-fuel production costs. The effect of purchased hydrogen prices (1.5 - 6 \$ kg^{-1}) are shown in Table 4-5. If SMR is used to produce hydrogen from methane, the price of methane has little effect on LCB - a 50% change in methane price results in a 3.6% change in LCB, according to sensitivity study results. However, the capital and operating costs of a SMR facility play a larger role in dictating LCB results. Similarly, when hydrogen is sourced from a bio-oil steam reformation facility, the LCB of upgrading is influenced by the capital and operating costs of the steam reformation facility. However, the largest impact on LCB results for upgrading occurs when bio-fuel production parameters are varied (i.e. the hydrogen requirement for upgrading bio-fuels, or hydrogen yields from steam reformation of bio-oil). These are discussed further in Section 4.4.1.3.

Table 4-5 Levelised costs of bio-fuels via upgrading bio-oil using hydrogen purchased from an external source.

Hydrogen purchase price ($ kg^{-1})	LCB at optimum harvest ($ $litre^{-1}$)
1.5	0.88
3	1.05
4.5	1.22
6	1.39

4.4.1.2 Point-of-delivery

Figure 4-9 shows how LCB results for petrol and diesel vary as the additional distance to the bio-fuel facility from the forested region is increased from 0 to 500 km (scenario B). To compare minimum bio-fuel production costs for each bio-fuel production route, LCB results shown in Figure 4-9 are for optimally sized bio-fuel facilities (Section 4.4.1.1). The optimal size of bio-fuel facility for each bio-fuel production route does not change with additional transport distance because additional transport distances are independent of the annual harvest volume of forest residues.

For a Fischer-Tropsch bio-fuel facility, woodchip feedstock produces the lowest cost bio-fuels for distances up to 290 km. For distances greater than 250 km, torrefied wood feedstock produces the lowest cost bio-fuels for a FT bio-fuel facility. Upgrading bio-oil provides the lowest LCB result of all petrol and diesel production routes for all additional transport distances. The final cost of bio-fuel does not increase substantially with distance because bio-oil transportation is inexpensive (compared to woodchip or torrefied wood commodities).

4.4.1.3 Bio-fuel production parameters

Parameters that influence bio-fuel production via Fischer-Tropsch synthesis are the quantity of bio-fuels produced per tonne feed, and also the fraction of bio-fuel that is petrol or diesel. There are numerous variables throughout gasification and FT synthesis (e.g. temperature, pressure, use of catalysts) that can influence the quantity of bio-fuel produced, which are beyond the scope of this study. These variables have been grouped into one parameter for bio-fuel production (Section 3.3.2), and has been applied to all feedstock types. The effect of this parameter is not complex - if a smaller amount of bio-fuel is produced per tonne feedstock the LCB increases (Equation 3.66), and vice versa. The fraction of either petrol or diesel produced by Fischer-Tropsch synthesis does impact LCB results as significantly. For example, a FT bio-fuel production facility optimally sized for woodchip feedstock will produce bio-fuels between a LCB of 1.27 $ litre^{-1} to 1.48 $ litre^{-1} as the fraction of fuel ranges from 100% petrol to 100% diesel, respectively. Producing 100% petrol or diesel is not practical at FT facilities, although this result demonstrates the impact of this variable in the model.

Parameters that influence bio-fuel production via bio-oil upgrading are the quantity of bio-fuels produced per tonne feed, the fraction of bio-fuel that is petrol or diesel and, when a portion of the bio-oil feed is steam reformed to produce the hydrogen required for upgrading, the quantity of hydrogen required per tonne bio-oil feed and the hydrogen yield of bio-oil steam reformation.

The parameters that influence the total quantity and fractions of petrol or diesel products from upgrading are set up in the model with the same architecture as those for FT synthesis. However, the reference for upgraded fuels produces 95% petrol and 5% diesel (as opposed to 40% petrol and 60% diesel in Fischer-Tropsch synthesis). Furthermore, bio-fuel yields via bio-oil upgrading are subject to variation as this study has assumed that bio-oil methanol mixtures yield similar quantities of bio-fuels to when pure bio-oil is upgraded.

The hydrogen requirement of upgrading only influences the quantity of bio-fuels produced when upgrading uses hydrogen sourced from steam reformation of the bio-oil feed (when hydrogen is produced from SMR or purchased, the quantity of bio-fuel product remains the same although the size and cost of the SMR facility, or hydrogen purchase expenses, may change). For upgrading using hydrogen sourced from steam reformation of bio-oil, LCB results can vary due to steam reformation yields as well as upgrading hydrogen requirements (Figure 4-10). Results are more sensitive to the hydrogen yield of bio-oil steam reformation, and the LCB can increase from 0.90 $ litre^{-1} to 1.20 $ litre^{-1}.

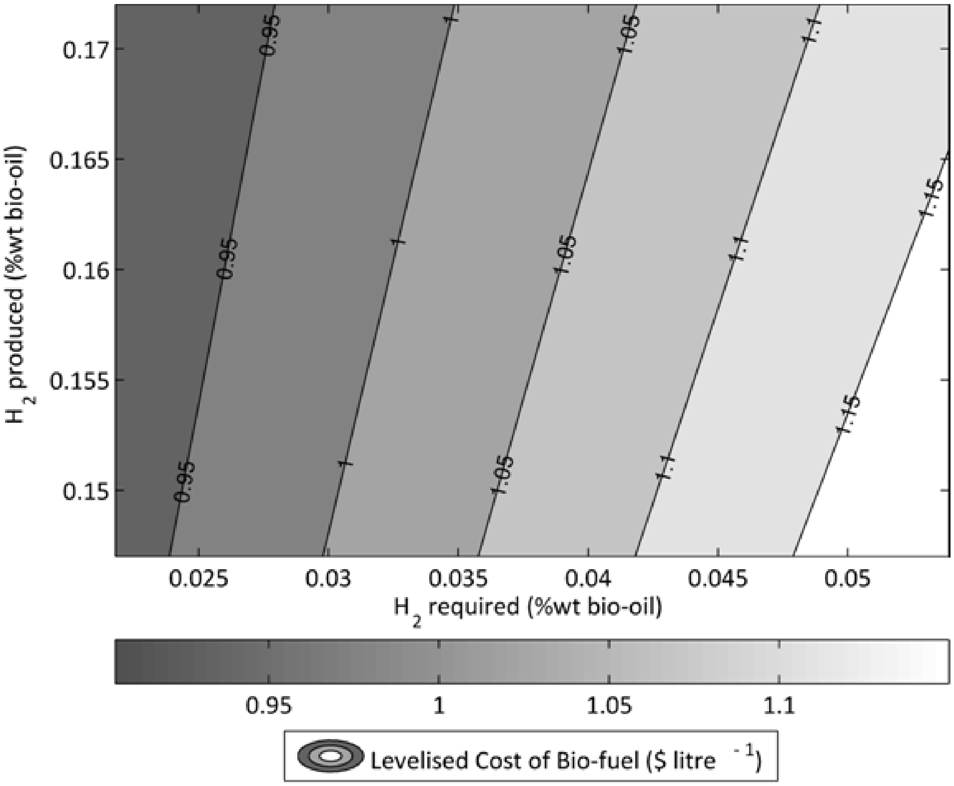


Figure 4-10 Levelised cost of bio-fuel (petrol and diesel) for ranges of hydrogen requirements for upgrading and hydrogen production from bio-oil steam reformation provided in the literature.

4.4.2 Hydrogen

4.4.2.1 Optimal harvest volumes

Figure 4-11 shows how the levelised cost of bio-fuel (LCB) for hydrogen varies with the annual harvest volume of forest residues, for bio-fuel production routes of gasification followed by water gas shift reactions and bio-oil steam reformation. The minimum LCB of hydrogen produced from gasification and water gas shift (WGS) of a woodchip feedstock occurs for an annual harvest of 947,000 m^3 forest residues (equivalent to a 1100 ODTPD bio-fuel facility), and the LCB is 2.92 \$ kg^{-1}. Optimum sizes of gasification and WGS facilities using either bio-oil, bio-slurry or torrefied wood feedstock occur for harvests of 4.01 million m^3 (2560 TPD) , 3.42 million m^3 (2490 TPD), 2.84 million m^3 (2250 TPD), respectively. For hydrogen production via gasification and WGS, woodchip feedstock provides the lowest LCB. However, as haul

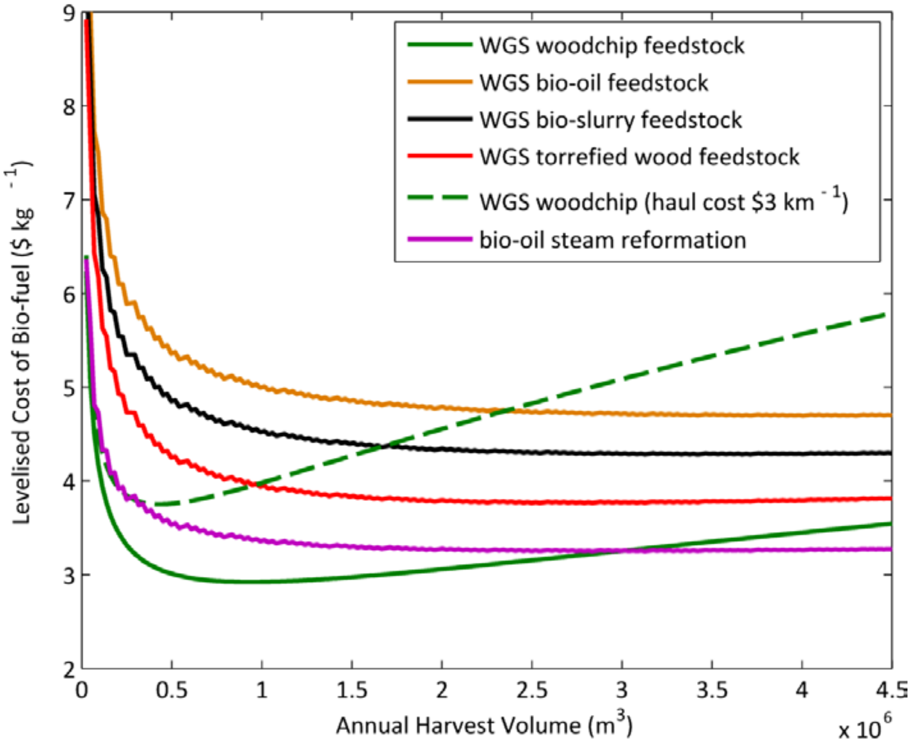


Figure 4-11 Levelised cost of bio-fuel (hydrogen) for a range of annual harvest volumes.

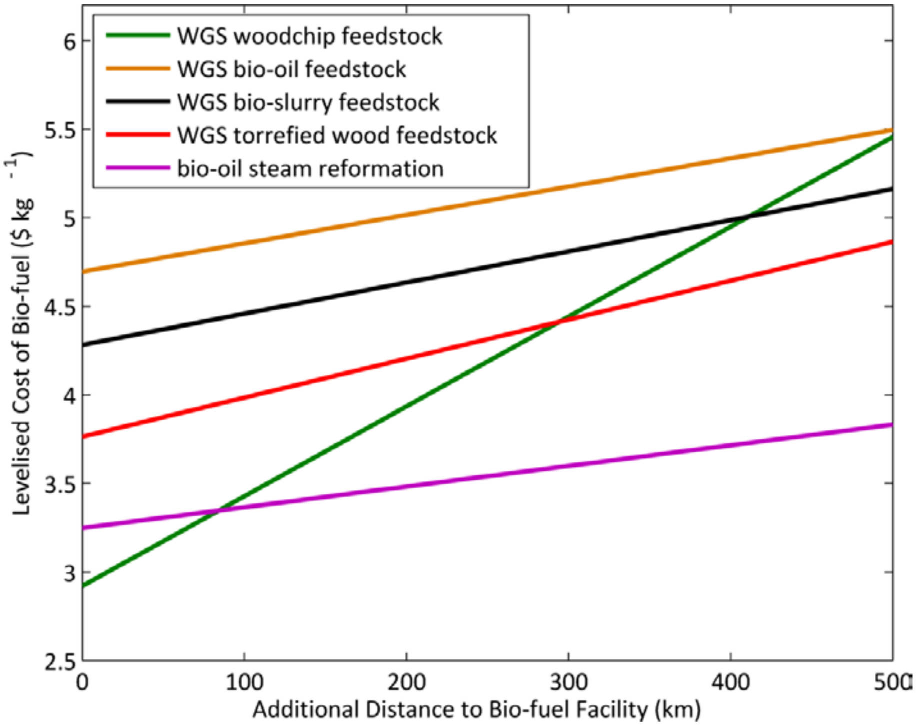


Figure 4-12 Levelised cost of bio-fuel (hydrogen) for optimally sized bio-fuel facilities when additional transport distances to a bio-fuel facility are required (scenario B).

costs increase, torrefied wood feedstock becomes the lowest cost option, for larger annual harvests.

Hydrogen production costs via steam reformation of bio-oil are competitive with those of gasification and WGS of a woodchip feedstock. LCB results for steam reformation of bio-oil are less influenced by annual harvest volume, as mobile fast pyrolysis facilities reduce transport requirements of feedstock delivery. The minimum LCB occurs at an annual harvest of 2.84 million m^3 (1810 TPD), and the cost of hydrogen production is 3.25 \$ kg^{-1}.

4.4.2.2 Point-of-delivery

Figure 4-12 shows how LCB results for hydrogen production vary as the additional distance to the bio-fuel facility from the forested region is increased from 0 to 500 km (scenario B). To compare minimum bio-fuel production costs for each bio-fuel production route, LCB results shown in Figure 4-12 are for optimally sized bio-fuel facilities (Section 4.4.2.1).

For a gasification and WGS bio-fuel facility, woodchip feedstock produces the lowest cost hydrogen for distances up to 295 km. For larger distances, torrefied wood feedstock produces the lowest cost hydrogen. Steam reformation of bio-oil produces lowest LCB results of all hydrogen bio-fuel production routes for all additional transport distances above 85 km.

4.4.2.3 Bio-fuel production parameters

Hydrogen production yield via gasification and WGS varies depending on the set up of the gasification reactor and also the conditions of the water gas shift reactions. For an optimally sized gasification and WGS facility utilising woodchip feedstock the levelised cost of hydrogen varies between 2.74 \$ kg^{-1} and 3.22 \$ kg^{-1} as the production yield parameter is varied between maximum and minimum values available in the literature.

Hydrogen production via steam reformation is still in development, although implementing production rates from the literature produces LCB results between 3.14 \$ kg^{-1} and 3.25 \$ kg^{-1}, for an optimally sized bio-oil steam reformation facility.

4.5 Other considerations

4.5.1 Forest residue resource

The model presented in this study provides an analysis of using mobile facilities to harvest a general forest residue resource. However, biomass is a spatially and temporally dependent resource, and further considerations are necessary when examining particular geographic regions. Transport distances, hauling costs and sites available for mobile facilities require knowledge of the availability and location of the forest residue resource, as well as the local road network. These considerations would also prove useful when investigating the impact and cost savings possible from the relocation of mobile facilities.

4.5.2 Market demand and marginal costs

The market demand, or competition, for forest residue resources may impact the quantity of resource available for bio-fuel production. As the demand for forest residues increases the purchase price of forest residues will likely increase, and industries that can harvest the resource for lowest costs will be in the best position for securing the resource. In this respect, competition for forest residues is generally not a concern of physical availability but instead an economic matter, in which demand change from one user can cause significant price changes for other users [27].

The marginal cost of using forest residue resources may reduce the extent to which the resource is utilised. The marginal cost of harvesting residues increases at a faster pace than the marginal cost of roundwood [28]. Therefore, harvesting large volumes of forest residues for large size bio-fuel facilities may not occur. Rather, supply may switch to roundwood when feedstock costs of roundwood are cheaper than that of forest residues. At this point, however, the bio-fuel sector starts to infringe on the supply of roundwood used by the logging industry and there is increased competition between industries.

On the other hand, mobile facilities reduce the marginal cost of a forest residue resource as they reduce transport requirements, which is an important factor of marginal costs [27]. Therefore, mobile facilities may allow greater penetration of forest residue resources that are largely unused due to high marginal costs [28]. Integrating forest residue recovery (and mobile facility use) with existing logging industry could alleviate negative consequences of competition between bio-fuel and logging sectors. The costs of harvesting forest residues are expected to decrease as labour and equipment could be shared.

4.5.3 Mobile facility configurations

The mobile facility configurations used in this study for fast pyrolysis and torrefaction represent those in the literature. This study has not examined the influence of varying mobile facility configurations (i.e. varying product yields produced by each process). This would likely require experimental data and/or detailed process simulation, as the quantity and characteristics of the products, as well as the thermal and electrical requirements of the mobile facility are expected to change for each different set up.

Configuration of mobile facilities for optimal product yields would be beneficial for decreasing the levelised delivered cost of mobile facility products. Ensuring sufficient syngas is produced to meet drying and thermal requirements of the facilities would remove the costs of purchasing propane. However, increasing syngas production would likely decrease the yield of other products to be delivered to the bio-fuel facility, thus increasing the levelised delivered cost. Essentially, the optimum set up of mobile facilities would ensure that all thermal and electrical demands are met, whilst also producing maximum yields of products that will be used as feedstock at bio-fuel facilities.

4.5.4 Sustainability of bio-fuel production from forest residues

Utilisation of any biomass resource requires a sustainable approach that encompasses environmental, social and economic issues [80]. One fundamental concept of environmental sustainability is to ensure a lasting supply of resource (i.e. harvest rates should not exceed the regeneration rates) [81]. In terms of a forest residue resource this means that, in conjunction with other logging activities, the rate at which forests are harvested should not exceed forest regeneration rates. This issue is generally managed by policies such as annual allowable cuts, which limit the amount of logging that can occur within a specific region each year. However, removal of forest residues from logging sites raises concerns related to soil productivity and biodiversity, that could affect the growth rate of new forest [82]. If forest residues are removed as woodchips, then the majority of nutrients within the wood will be removed as part of the woodchip feedstock. When mobile facilities are implemented, it has been proposed that solid products of mobile facilities (e.g. bio-char) could be re-distributed back into soils at forestry sites as an option for soil remediation after removal of forest residues (e.g. [83]). However, any redistribution of products to the logging fields would incur additional costs.

Social aspects of sustainability have not been addressed in this study, as they are very dependent on the region or country in which such bio-fuel production systems would be implemented.

The cost analysis presented in this study provides a starting point to discuss economic issues related to the use of mobile facilities and utilisation of forest residue resources, yet insight into sustainable economic growth would require details of regional and national markets of both resource extraction and alternative fuel options (e.g. fossil fuels), which are also temporally and location dependent.

In general, continuous examination of bio-energy systems should be performed to ensure that no adverse environmental effects arise from forest residue removal at logging sites, and social and economic factors should be investigated for regions where forest residue resources are to be utilised.

4.5.5 Initiating use of mobile facilities

Since mobile facilities are not commercially available and are still subjects of research, it is unlikely that the first use of mobile facilities will be on a large scale, as the risk of purchasing multiple mobile facilities at one time to meet an entire harvest requirement of a bio-fuel facility is high. However, results show that small numbers of mobile facilities do not generally create lower delivered feedstock costs compared to conventional woodchip delivery, and, in addition, bio-fuel facilities using feedstock from mobile facility pathways produce lowest cost fuels for large annual harvests (which would require many mobile facilities to meet harvest requirements). Thus, one question is whether a gradual introduction of mobile facilities can be economically viable. This study does not provide results that can provide a complete answer to this question, although the feasibility would likely depend on the end use of the forest residue resource and the availability of existing infrastructure that could make use of mobile facility commodities as feedstock (which may not be bio-fuel facilities).

For small scale implementation to be economically feasible, transport distances need to be large (over 250 km according to the results of this study). Therefore, mobile facilities would be most favourable for harnessing forest residue resources that are too far from existing facilities that would use such resources to justify conventional woodchip delivery. Mobile facilities would initially be suited to existing infrastructure that could make use of the commodities they produce without needing major changes to current operations. For instance, mobile facilities could produce either bio-slurry or torrefied wood to be co-fired with coal at existing power stations [13], [39]. Over time, additional mobile facilities could be purchased to access greater volumes of forest residues and the destination of mobile facility commodities may switch to a bio-fuel facility purpose-built to access feedstock from mobile facility delivery pathways.

4.6 Summary

This Chapter has provided results and discussion of the use of mobile facilities in harvesting a forest residue resource for bio-fuel production.

Of the four pathways considered to deliver a forest residue resource to a bio-fuel facility, woodchip delivery is the lowest cost option when annual harvests are small or transport distances are short. Implementing mobile facilities becomes economically attractive for larger harvests or when additional transport distances are required.

Reductions in levelised delivered cost for mobile facility pathways depend on (i) the purchase and operating costs of the mobile facilities (ii) the energy content of the products of mobile facilities (i.e. the conversion efficiencies of the mobile facilities), and (iii) the cost reductions of transportation when compared to conventional woodchip transport. Torrefied wood is the lowest cost pathway of delivering a forest residue resource when using mobile facilities, and is competitive with woodchip delivery at larger harvests and transport distances.

Levelised delivered costs are particularly sensitive to densities of commodities delivered to bio-fuel facilities, transport factors, and, when mobile facilities are implemented, mobile facility capital costs, thermal and electrical demands of mobile facilities, and the initial moisture content of forest residues.

Results for levelised cost of bio-fuels show that there are optimal harvest volumes (bio-fuel facility sizes) for each bio-fuel production route, which yield minimum bio-fuel production costs. These occur primarily as the benefit of economies of scale for larger bio-fuel facilities competes against increasing transport costs for large harvest volumes. Optimal harvest volumes are larger for bio-fuel production routes that use feedstock sourced from mobile facilities, as mobile facilities reduce total transport requirements.

Petrol and diesel production costs are lowest for bio-fuel production routes that upgrade bio-oil feedstock, even though the levelised delivered cost of bio-oil is highest compared against other delivery pathways. This is mainly because greater quantities of bio-fuels are produced from the upgrading process, compared to Fischer-Tropsch synthesis. The levelised cost of bio-fuels produced via Fischer-Tropsch synthesis are lowest for woodchip feedstock, unless haul costs or transport distances are large, in which case torrefied wood feedstock provides the lowest cost of bio-fuel.

Hydrogen production via steam reformation of bio-oil is competitive with gasification and water gas shift processes for hydrogen production, particularly for larger annual harvest of forest residues. Hydrogen production costs from gasification and WGS processes are lowest for woodchip feedstock, unless transport costs are high, when torrefied wood feedstock becomes the lowest cost option. Levelised costs of bio-fuels are particularly sensitive to bio-fuel facility costs and bio-fuel production parameters.

If a bio-fuel facility is located outside of the forested region, bio-fuel production processes that use mobile facility commodities as feedstock provide lowest cost bio-fuels as the additional transport distance is increased.

This study has provided an analysis of the use of mobile facilities to harvest a forest residue resource for bio-fuel production. Mobile facility implementation for bio-fuel production in a specific region or country will require detailed information of the local forest residue resource, local resource and fuel markets, and local infrastructure.

Extensive research into environmental, social and economic issues relevant to the specific region is also necessary to ensure a sustainable supply of bio-fuels.

The following Chapter presents concluding remarks from this study as well as suggestions for further work.

5 Conclusions

The objective of this study was to investigate the technical and economic implications of producing bio-fuels when using a network of mobile facilities to deliver a forest residue resource to a bio-fuel facility. To meet this objective, this study has developed a general model for examining the use of mobile facilities to deliver a forest residue resource for bio-fuel production.

Analyses investigated the levelised delivered cost of a forest residue resource using four pathways to deliver the resource as either woodchip, bio-oil, bio-slurry or torrefied wood. The levelised cost of bio-fuels was calculated for bio-fuel processes using each type of feedstock. Bio-fuel production processes analysed in this study were gasification followed by either Fischer-Tropsch synthesis or water gas shift reactions, and upgrading or steam reformation of bio-oil.

Results show that implementing a network of mobile facilities will reduce the energy content of forest residues delivered to a bio-fuel facility as mobile facilities use a fraction of the biomass energy content to meet thermal or electrical demands. The total energy delivered by bio-oil, bio-slurry and torrefied wood is 45%, 65% and 87% of the initial forest residue energy content, respectively. Nonetheless, implementing mobile facilities is economically feasible when large transport distances are required. Transport costs are reduced to less than 40% of total levelised delivered costs when mobile facilities are implemented, compared against 80% of costs for conventional woodchip delivery, for annual harvests of 1.717 million m^3 (equivalent to 2000 ODTPD). Torrefied wood is the lowest cost pathway of delivering a forest residue resource when using mobile facilities. Cost savings occur against woodchip delivery for annual forest residue harvests above 2.25 million m^3 or when transport distances greater than 250 km are required.

The minimum cost of petrol and diesel production is 0.86 \$ litre^{-1} when bio-oil is upgraded using hydrogen sourced from SMR. The optimum size of this facility is 2750 TPD and requires an annual harvest of 4.30 million m^3. The minimum cost of hydrogen production is 2.92 \$ kg^{-1} via the gasification of a woodchip feedstock and subsequent water gas shift reactions. The optimum size for this facility is 1100 ODTPD and requires an annual harvest of 947,000 m^3.

The sensitivity study performed has shown important parameters that significantly impact results:

- initial moisture content of forest residues
- mobile facility capital cost
- mobile facility electrical and drying requirements
- densities of commodities (woodchip, bio-oil, bio-slurry and torrefied wood)
- transport factors (truck volumes, haul costs, and tortuosity factors)
- bio-fuel facility capital cost
- bio-fuel production factors (bio-fuel yields per unit feedstock)

This study has provided a general analysis of mobile facility use in delivering a forest residue resource for bio-fuel production. Mobile facility implementation for bio-fuel production in a specific region or country will require detailed information of the local forest residue resource, local resource and fuel markets and also extensive research into environmental, social and economic issues relevant to the specific region to ensure a sustainable supply of bio-fuels. To this end, recommendations of further work extending this research are presented below.

5.1 Recommendations

The following recommendations offer both improvements to the model presented in this study and topics of further research, which could enhance the findings of this study and/or provide useful techniques to assist in the application of the model to specific regions of interest:

- use experimental data or detailed process modelling to examine mobile facility product yields and characteristics for different mobile facility configurations
- update financial data for mobile torrefaction facilities if and when it becomes available in the literature

- investigate the extent to which mobile facilities could be integrated with current logging practices
- extend the model framework to include the use of geographical information systems (GIS) software (e.g. [66]), which could:
    - allow for definition of a forest residue resource that includes spatial and temporal variations
    - provide detailed road network information to enhance calculations of transport distances and costs
    - determine suitable sites for mobile facility locations, which in turn will provide more accurate results for cost savings that may occur through relocation of facilities
    - determine optimal sites and sizes for bio-fuel facilities
    - include social and economic factors when considering utilisation of forest residue resources and also locations of mobile and bio-fuel facilities

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Appendix A: Additional calculations

Converting forest residue volume to mass

For a given volume of green wood, h :

$$h = V_{H_2O} + V_{ODW} \tag{A.1}$$

where V_{H_2O} and V_{ODW} are the volume of water and oven-dry wood within the total volume, respectively. If the green wood has a moisture content, z, defined as a percentage mass of the green wood, then Equation A.1 becomes:

$$h = \frac{(z - z_{ODW})M_{GT} \cdot 10^3}{\rho_{H_2O}} + \frac{\big(1 - (z - z_{ODW})\big)M_{GT} \cdot 10^3}{\rho_{ODW}} \tag{A.2}$$

where z_{ODW} is the moisture content of oven-dry wood, ρ_{H_2O} is the density of water and ρ_{ODW} is the density of oven-dry wood. A factor of 10^3 is introduced as M_{GT} is provided in tonnes rather than kilograms. Rearranging, Equation A.2 becomes:

$$M_{GT} = \frac{h}{10^3}\left(\frac{z - z_{ODW}}{\rho_{H_2O}} + \frac{(1 - z) + z_{ODW}}{\rho_{ODW}}\right)^{-1} \tag{3.1}$$

Weight and volume limits of trucks

Equation A.3 is used to determine if trucks that transport commodity j are limited by weight or by volume:

$$x = \big(\rho_j \times v_j\big)/w_j \tag{A.3}$$

where ρ_i is the density of commodity j (either woodchip, bio-oil, bio-slurry, or torrefied wood), and v_j and w_j are the volume and weight limit of the truck used to carry commodity j, respectively.

If $x < 1$, then the limiting factor is volume and if $x > 1$ the limiting factor is weight.

Bio-fuel quantity conversions

Equations A.4 and A.5 detail the conversion between mass (kg) and volume (litre) or energy content (GJ) of bio-fuel m produced from commodity feedstock j at bio-fuel production facility k, respectively:

$$F_{litre,j,k,m} = \frac{F_{kg,j,k,m}}{\rho_m} \cdot 10^3 \tag{A.4}$$

$$F_{GJ,j,k,m} = \frac{F_{kg,j,k,m}}{l_m} \cdot 10^{-3} \tag{A.5}$$

where ρ_m is the density of bio-fuel m (not applicable for hydrogen) and l_m is the lower heating value of bio-fuel m.

Diesel consumption at mobile torrefaction facilities

Diesel consumption at mobile torrefaction facilities is based on a 200 kW generator, which is capable of meeting maximum electrical demands of the mobile facility. However, depending on the capacity of the mobile torrefaction facility, electrical demands may decrease and diesel consumption will reduce. The rate at which diesel is consumed in based on data shown in Figure A-1.

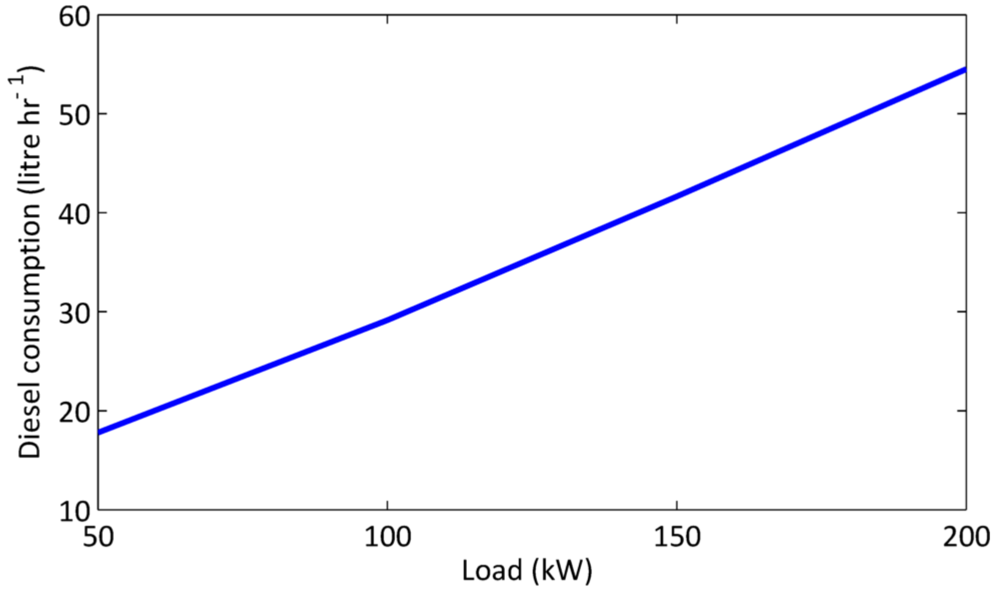

Figure A-1 Diesel consumption rates for a 200 kW generator. [Data taken from [69]].

Appendix B: Input data

All costs are in 2012 US$.

Forest residue resource

Table B-1 Forest residue resource input data (technical)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Annual volume of biomass	h	$m^3 \cdot yr^{-1}$	User defined	-	-
Density of forest residues	φ	$m^3 \cdot km^{-2}$	65	-	[84]
Initial moisture content of forest residues	z	%	50	40 - 60	[8], [70]
Moisture content of oven-dry wood (12% moisture)	z_{ODW}	%	12	-	[8]
Density of oven-dry wood (12% moisture)	ρ_{ODW}	$kg \cdot m^{-3}$	500	400 - 865	[8]
Density of water	ρ_{H_2O}	$kg \cdot m^{-3}$	1000	-	-
Density of woodchips	ρ_{WC}	$kg \cdot m^{-3}$	300	220 - 350	[7], [8]
Energy required to dry woodchips	e_{dry}	$MJ \cdot kg_{H_2O}^{-1}$	2.572	-	[68]
Lower heating value of oven-dry wood (12% moisture)	l_{ODW}	$MJ \cdot kg^{-1}$	18	18 - 21	[23], [70]

Table B-2 Forest residue resource input data (financial)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Purchasing forest residues cost	$c_{purchase}$	$\$ \cdot GT^{-1}$	3.22	-	[49]
Piling forest residues cost	c_{piling}	$\$ \cdot GT^{-1}$	1.64	-	[85]
Chipping forest residues cost	$c_{chipping}$	$\$ \cdot GT^{-1}$	13.73	-	[21]

Transport

Table B-3 Transport input data (technical)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Woodchip truck volume	$v_{truck,WC}$	m^3	70	-	[7]
Woochip truck weight limit	$m_{truck,WC}$	tonne	21.5	-	[7]
Liquid B-train tanker volume	$v_{truck,liq}$	m^3	60	-	[79]
Liquid B-train tanker weight limit	$m_{truck,liq}$	tonne	62.5	-	[78]
Torrefied wood truck volume	$v_{truck,TW}$	m^3	200	-	[78]
Torrefied wood truck weight limit	$m_{truck,TW}$	tonne	62.5	-	[78]
Road tortuosity	τ	-	1.5	1.2 - 3	[63]
Additional transport distance	d	km	User defined	-	-

Table B-4 Transport input data (financial)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Woodchip loading and unloading	$c_{tran,fix,WC}$	$\$\cdot GT^{-1}$	5.83	-	[86]
Woodchip hauling	$c_{tran,var,WC}$	$\$\cdot km^{-1}$	1.5	-	[87], [88][a]
Bio-oil loading and unloading	$c_{tran,fix,BO}$	$\$\cdot tonne^{-1}$	5.55	-	[79]
Bio-oil hauling	$c_{tran,var,BO}$	$\$\cdot km^{-1}$	2.5	2.04 - 3.16	[88]
Bio-slurry loading and unloading	$c_{tran,fix,BS}$	$\$\cdot tonne^{-1}$	5.55	-	[b]
Bio-slurry hauling	$c_{tran,var,BS}$	$\$\cdot km^{-1}$	2.5	2.04 - 3.16	[88]
Torrefied wood loading and unloading	$c_{tran,fix,TW}$	$\$\cdot tonne^{-1}$	5.83	-	[c]
Torrefied wood hauling	$c_{tran,var,TW}$	$\$\cdot km^{-1}$	2.5	2.04 - 3.16	[88]

[a] trucking costs in British Columbia are on average 5% higher than in Alberta [88]

[b] assumed the same as bio-oil loading and unloading

[c] assumed the same as woodchip loading and unloading

Mobile facilities

Table B-5 Mobile facility input data (technical)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Mobile facility size	s_{mob}	ODTPD	50	-	[10]
Maximum capacity factor	σ_{mob}	%	87.5	-	[10]
Electricity requirement	β	GJ·ODT^{-1}	0.3448	-	[10]
Diesel generator size	s_{gen}	kW	200	-	-
Diesel consumption rate	r_{diesel}	litre·hr^{-1}	55		[69]
Bio-oil electricity generator efficiency	η_{gen}	%	30	-	[10]
Biomass dryer efficiency	η_{dry}	%	72	54 - 89	[68]
Staff required per facility	n_{staff}	-	3	-	[10]
Density bio-oil	ρ_{BO}	kg·m^{-3}	1100	1100 - 1300	[11], [36], [38]
Bio-oil aqueous fraction	m_{WS}	%wt	70	60 - 80	[17]
Density bio-slurry (30% char loading)	ρ_{BS}	kg·m^{-3}	1300	-	[38]
Bio-slurry maximum char loading	ζ_{max}	%wt	20	-	[38]
Density torrefied wood	ρ_{TW}	kg·m^{-3}	250	180 - 300	[43]
Stainless steel tank reference size	$s_{ref,tank}$	m^{-3}	9400	-	[8]
Density propane	$\rho_{C_3H_8}$	kg·m^{-3}	493	-	[89]
LHV bio-char	l_{BC}	MJ·kg^{-1}	30	28 - 31	[38], [90]
LHV bio-oil	l_{BO}	MJ·kg^{-1}	17	-	[29]
LHV syngas	l_S	MJ·kg^{-1}	8	7.7 - 10	[91], [92]
LHV torrefied wood	l_{TW}	MJ·kg^{-1}	20	18 - 23	[13]
LHV propane	$l_{C_3H_8}$	MJ·kg^{-1}	46.35	-	[93]

Table B-6 Mobile facility input data (financial)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Capital cost (per facility)	c_{mob}	$million	3.669	-	[10]
Operation and maintenance	o_{mob}	%capital	1.5	-	[10]
Cost per facility relocation	$c_{relocate}$	$	866	-	[10]
Staff wage	$c_{wage,mob}$	$·yr^{-1}	120,765	-	[10]
Diesel generator cost	$c_{gen,mob}$	$	50,000	-	[94], [95]
Stainless steel tank reference cost	$c_{ref,tank}$	$million	1.0	-	[8]
Stainless steel tank maintenance	o_{tank}	%capital	2	-	-
Stainless steel tank cost scaling factor	κ_{tank}	-	0.65	-	[79]
Diesel purchase price	c_{diesel}	$·litre^{-1}	0.85	-	[96]
Propane purchase price	$c_{C_3H_8}$	$·litre^{-1}	0.7	-	[97]

Bio-fuel facilities

Table B-7 Bio-fuel facility input data (technical)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Gasification and Fischer-Tropsch facility reference size	$s_{ref,FT}$	ODTPD	2000	-	[49]
Gasification and Fischer-Tropsch facility bio-fuel production	f_{FT}	%wt feed	12.96	-	[49]
Gasification and Fischer-Tropsch facility bio-fuel production ratio (petrol /diesel)	$f_{r,FT}$	-	0.4	-	[49]
Gasification and water gas shift facility reference size	$s_{ref,WGS}$	ODTPD	2000	-	[48], [49]
Gasification and water gas shift facility bio-fuel production	f_{WGS}	%wt feed	7.5	6.8 - 8.0	[48]
Upgrading bio-oil facility reference size	$s_{ref,UG}$	TPD	1500	-	[16]
Upgrading bio-oil facility bio-fuel production	f_{UG}	%wt feed	33	-	[16]
Upgrading bio-oil facility bio-fuel production ratio (petrol/diesel)	$f_{r,UG}$	-	0.95	-	[16]
Upgrading bio-oil facility hydrogen requirement	γ_{H_2}	%wt bio-oil	5	2.18 - 5.39	[16], [71], [72]
SMR facility for hydrogen production	$s_{ref,SMR}$	$\mathrm{kg_{CH4}\cdot day^{-1}}$	74,400	-	[16]
SMR hydrogen production	f_{SMR}	$\mathrm{\%wt_{CH4}}$	0.44	-	[16]
Steam reformation of bio-oil facility reference size	$s_{ref,SR}$	TPD	1198	-	[19]
Steam reformation of bio-oil facility bio-fuel production	f_{SR}	%wt bio-oil (WS)	14.7	14.7 - 17.2	[19]
Quantity of methanol added to bio-oil	m_{meth}	%wt bio-oil	10	-	[19]
Density diesel	ρ_D	$\mathrm{kg\cdot m^{-3}}$	856	-	[98]
Density petrol	ρ_P	$\mathrm{kg\cdot m^{-3}}$	737	-	[98]
Density methanol	ρ_{meth}	$\mathrm{kg\cdot m^{-3}}$	791.3	-	[99]
Density bio-oil/methanol blend (10%wt methanol)	$\rho_{BO\text{-}meth}$	$\mathrm{kg\cdot m^{-3}}$	1040	-	[100]
LHV diesel	l_D	$\mathrm{MJ\cdot kg^{-1}}$	41.66	-	[98]
LHV petrol	l_P	$\mathrm{MJ\cdot kg^{-1}}$	43.47	-	[98]
LHV hydrogen	l_H	$\mathrm{MJ\cdot kg^{-1}}$	120	-	[98]
LHV methane	l_{CH_4}	$\mathrm{MJ\cdot kg^{-1}}$	47.79	-	[98]
Build time	t_b	yr	0	-	-

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Operation lifetime	t_{op}	yr	20	-	-
Capacity factor (all bio-fuel facilities)	σ_{bf}	%	90	-	-

Table B-8 Bio-fuel facility input data (financial)

Data	Symbol	Unit	Value	Cited Range	Reference(s)
Gasification and Fisher-Tropsch facility reference cost	c_{FT}	\$million	269.02	-	[49]
Gasification and Fischer-Tropsch facility operation and maintenance	$o_{bf,FT}$	%	6	-	[49]
Gasification and water gas shift facility reference cost	c_{WGS}	\$million	255.15	255 - 370	[48], [49]
Gasification and water gas shift facility operation and maintenance	$o_{bf,WGS}$	%	6	-	[49]
Feed preparation equipment: Screening (2000 TPD bio-fuel facility)	c_{screen}	\$million	1.90	-	[68]
Feed preparation equipment: Rotary dryer (2000 TPD bio-fuel facility)	c_{dry}	\$million	9.43	-	[68]
Feed preparation equipment: Grinding (2000 TPD bio-fuel facility)	c_{grind}	\$million	12.10	-	[68]
Upgrading bio-oil facility reference cost	c_{UG}	\$million	138.34	-	[16]
Upgrading bio-oil facility operation and maintenance	$o_{bf,UG}$	%	2	-	[16]
SMR facility for hydrogen production reference cost	c_{SMR}	\$million	95.94	-	[16]
SMR facility for hydrogen production operation and maintenance	$o_{bf,SMR}$	%	2	-	[16]
Steam reformation of bio-oil facility reference cost	c_{SR}	\$million	155.00	-	[19]
Steam reformation of bio-oil facility operation and maintenance	$o_{bf,SR}$	%	4	-	-
Open air pile storage	c_{pile}	$\$\cdot m^{-3}$	1.31	-	[73]
Cost of methanol	c_{meth}	$\$\cdot kg^{-1}$	0.53	-	[101]
Cost of natural gas	c_{CH_4}	$\$\cdot GJ^{-1}$	5.24	-	[102]
Cost of hydrogen from external source	$c_{external\text{-}H_2}$	$\$\cdot kg^{-1}$	5	1.5 - 10	[71], [103]

Appendix C: Sensitivity study results

Table C-1 Sensitivity study results for levelised delivered cost

(-) signifies result change of less than 10%

Input parameter	Woodchip		Bio-oil		Bio-slurry		Torrefied Wood	
	-50%	+50%	-50%	+50%	-50%	+50%	-50%	+50%
	Percentage change in Levelised Delivered Cost							
Bio-oil density	-	-	11.0	-	-	-	-	-
Mobile facility reference cost	-	-	-10.5	10.5	-10.2	10.2	-11.6	11.6
Volume of mobile product transport truck	-	-	-	-	-	-	22.9	-
Density of torrefied wood	-	-	-	-	-	-	22.9	-
Weight limit of mobile product transport truck	-	-	12.2	-	14.7	-		
Char loading of bio-slurry	-	-	-	-	18.4	-16.1	-	-
Mobile facility electricity generator efficiency	-	-	14.2	-	13.7	-	-	-
Cost of propane	-	-	-10.3	10.3	-	-	-	-
Haul cost factor of B train trucks	-	-	-	-	-	-	-11.5	11.5
Haul cost factor of woodchip truck	-36.3	36.3	-	-	-	-	-	-
Woodchip density	72.5	-	-	-	-	-	-	-
Volume of woodchip truck	72.5	-	-	-	-	-	-	-
Tortuosity factor	-36.3	36.3		-	-	-	-12.8	12.8
Dryer efficiency	-	-	45.5	-15.2	43.9	-14.6	45.3	-
Initial moisture content of forest residues	-28.7	67.6	-29.1	101.7	-28.1	98.3	-9.5	107.3

Table C-2 Sensitivity study results for levelised cost of bio-fuel (Gasification and Fischer-Tropsch bio-fuel production route)

(-) signifies result change of less than 10%

Input parameter	Woodchip		Bio-oil		Bio-slurry		Torrefied Wood	
	-50%	+50%	-50%	+50%	-50%	+50%	-50%	+50%
	Percentage change in Levelised Cost of Bio-fuel							
Volume of mobile product transport truck	-	-	-	-	-	-	15.5	-
Density of torrefied wood	-	-	-	-	-	-	17.3	-
Bio-oil upgrading hydrogen requirement	-	-	-	-	-	-	-	-
Weight limit of mobile product transport truck	-	-	-	-	10.9	-	-	-
Reference cost of bio-fuel facility	-15.8	15.8	-12.6	12.6	-13.2	13.2	-14.6	14.6
Haul cost factor of woodchip truck	-22.7	22.7	-	-	-	-	-	-
Volume of woodchip truck	45.3	-	-	-	-	-	-	-
Mobile facility electricity generator efficiency	-	-	12.0	-	11.7	-	-	-
Woodchip density	48.4	-	-	-	-	-	-	-
Aqueous fraction of bio-oil	-	-	-	-	-	-	-	-
Bio-hydrogen produced from bio-oil steam reformation	-	-	-	-	-	-	-	-
Tortuosity factor	-22.7	22.7	-	-	-	-	-	-
Discount factor	-	10.3	-10.6	12.0	-10.4	11.7	-12.1	13.6
Bio-fuel production factor	100.0	-33.3	100.0	-33.3	100.0	-33.3	100.0	-33.3
Dryer efficiency	-	-	33.3	-11.1	32.3	-10.8	30.7	-
Initial moisture content of forest residues	-21.4	49.5	-23.2	78.3	-22.7	76.3	-	77.2

Table C-3 Sensitivity study results for levelised cost of bio-fuel (Gasification and water gas shift bio-fuel production route)

(-) signifies result change of less than 10%

Input parameter	Woodchip		Bio-oil		Bio-slurry		Torrefied Wood	
	-50%	+50%	-50%	+50%	-50%	+50%	-50%	+50%
	Percentage change in Levelised Cost of Bio-fuel							
Volume of mobile product transport truck	-	-	-	-	-	-	15.8	-
Density of torrefied wood	-	-	-	-	-	-	17.6	-
Bio-oil upgrading hydrogen requirement	-	-	-	-	-	-	-	-
Weight limit of mobile product transport truck	-	-	-	-	11.0	-	-	-
Reference cost of bio-fuel facility	-15.3	15.3	-12.1	12.1	-12.7	12.7	-14.0	14.0
Haul cost factor of woodchip truck	-23.0	23.0	-	-	-	-	-	-
Volume of woodchip truck	46.1	-	-	-	-	-	-	-
Mobile facility electricity generator efficiency	-	-	12.0	-	11.8	-	-	-
Woodchip density	49.2	-	-	-	-	-	-	-
Aqueous fraction of bio-oil	-	-	-	-	-	-	-	-
Bio-hydrogen produced from bio-oil steam reformation	-	-	-	-	-	-	-	-
Tortuosity factor	-23.0	23.0	-	-	-	-	-	-
Discount factor	-	10.0	-10.5	11.9	-10.2	11.5	-11.9	13.5
Bio-fuel production factor	100.0	-33.3	100.0	-33.3	100.0	-33.3	100.0	-33.3
Dryer efficiency	-	-	33.7	-11.2	32.8	-10.9	31.1	-
Initial moisture content of forest residues	-21.7	50.0	-23.4	79.1	-22.9	77.1	-	78.2

Table C-4 Sensitivity study results for levelised cost of bio-fuel (Upgrading bio-oil bio-fuel production route)

(-) signifies result change of less than 10%

Input parameter	SMR		BO SR		Purchase	
	-50%	+50%	-50%	+50%	-50%	+50%
	Percentage change in Levelised Cost of Bio-fuel					
Volume of mobile product transport truck	-	-	-	-	-	-
Density of torrefied wood	-	-	-	-	-	-
Bio-oil upgrading hydrogen requirement	-	-	-17.5	17.2	-	-
Weight limit of mobile product transport truck	-	-	-	-	-	-
Reference cost of bio-fuel facility	-	-	-	-	-	-
Haul cost factor of woodchip truck	-	-	-	-	-	-
Volume of woodchip truck	-	-	-	-	-	-
Mobile facility electricity generator efficiency	11.1	-	12.4	-	10.4	-
Woodchip density	-	-	-	-	-	-
Aqueous fraction of bio-oil	-	-	34.2	-11.6	-	-
Bio-hydrogen produced from bio-oil steam reformation	-	-	34.2	-11.6	-	-
Tortuosity factor	-	-	-	-	-	-
Discount factor	-11.2	12.7	-10.8	12.1	-	-
Bio-fuel production factor	100.0	-33.3	100.0	-33.3	100.0	-33.3
Dryer efficiency	31.1	-10.4	35.7	-11.9	31.1	-10.4
Initial moisture content of forest residues	-21.6	72.9	-24.4	83.0	-20.7	71.2

Table C-5 Sensitivity study results for levelised cost of bio-fuel (Steam reformation of bio-oil bio-fuel production route)

(-) signifies result change of less than 10%

Input parameter	Bio-oil	
	-50%	+50%
	Percentage change in Levelised Cost of Bio-fuel	
Volume of mobile product transport truck	-	-
Density of torrefied wood	-	-
Bio-oil upgrading hydrogen requirement	-	-
Weight limit of mobile product transport truck	-	-
Reference cost of bio-fuel facility	-	-
Haul cost factor of woodchip truck	-	-
Volume of woodchip truck	-	-
Mobile facility electricity generator efficiency	12.4	-
Woodchip density	-	-
Aqueous fraction of bio-oil	100.0	-33.3
Bio-hydrogen produced from bio-oil steam reformation	100.0	-33.3
Tortuosity factor	-	-
Discount factor	-10.3	11.6
Bio-fuel production factor	100.0	-33.3
Dryer efficiency	36.1	-12.0
Initial moisture content of forest residues	-24.5	83.6