High Value Sustainable Renewable Fuels and Bio-Products from Forest Residues in Ireland

A report for the Sustainable Energy Authority of Ireland

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Abstract

Irish energy infrastructure remains heavily dependent on imported fossil fuels, even more so in transport sector than heat or electricity. While there has been considerable development in electrifying light vehicles, little to no advancements have been made in decarbonizing heavy-duty vehicles (HDVs) that are major contributors to overall CO_2 emissions. Forest residues are an underutilized bioresource in Republic of Ireland (ROI) that can potentially become a sustainable source of advanced biofuels to decarbonize HDVs and help meet binding energy targets. However, development of forest bioenergy is constrained due to lack of significant market, difficulty of extraction, wide geographical distribution, and low energy value. This problem can be solved by increasing the fuel quality and consequently densifying biomass into biofuels using thermochemical technologies. Throughout the work it has been made clear that numerous advancements have been made in utilizing thermochemical technologies to produce advanced biofuels for application in hard to abate sector like HDVs. However, most studies displayed lower production cost of advanced biofuels due to large economies of scale and lacked documentation on supply and distribution of gaseous advanced biofuels such as bio-CNG (biomass derived compressed natural gas) from gasification of forest residues. For a small country like ROI that has relatively low and widely dispersed forest cover has led to high prices and consequently lower market demand for forest residues. To produce competitive advanced biofuels under these conditions it was important to not only design an optimized supply chain for feedstock but also to identify the size and location of markets that can enhance their decarbonisation potential at a scale possible in Ireland. Therefore, this work utilized existing studies on thermochemical technologies to design optimized supply chains of advanced biofuels for decarbonisation of HDVs in the regional context of ROI. Through results this study 1) displayed a framework for designing optimized supply chains of forest residue based advanced biofuels, 2) showed novel circular economy approach of using indigenous forestry residues to completely offset diesel demand of HDVs operating in the forestry sector, and 3) evaluated both economic and environmental competitiveness of advanced biofuels supply chains with fossil-based counterparts.

Dissemination of Research

Archived Conference Articles

- Rai A., Dominic Joyce., Monaghan R.F.D. Towards design of a nationwide biorefining network for forest residues in Ireland European Biomass Conference and Exhibition Proceedings 2019 (27^{th} EUBCE).
- Rai A., Dominic Joyce., Monaghan R.F.D. Cost estimation of biorefining network for forest residues in Ireland Pyroliq conference proceedings 2019.
- Rai A., Dominic Joyce., Monaghan R.F.D. Running on residues: An optimized bio-CNG supply chain for heavy-duty timber fleets MIT A+B Applied Energy Symposium Proceedings 2020.

Journal Articles (In preparation)

- Rai A., Dominic Joyce., Monaghan R.F.D. Running on residues: An optimized bio-CNG supply chain for heavy duty timber fleets (Chapter 3)
- Rai A., Monaghan R.F.D. Techno-economic assessment of crude bio-oil production from forest residues and effects of biochar valorisation as activated carbon (Chapter 4)
- Rai A., Monaghan R.F.D. Residue to biofuel: an environmental sustainability analysis of supply chains (Chapter 5)

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Contents

1 Introduction

1.1 Global Climate Change and Energy targets

Currently climate change due to anthropogenic greenhouse gas emissions caused by human activities is one of the biggest threats faced by the world. In business-as-usual scenarios, world energy consumption is estimated to increase by 28% between 2015 to 2040, leading to a consequential increase of CO_2 emissions by 34% from 33.9 to 42.7 billion tonnes [1]. In 2014, the International Panel on Climate Change (IPCC) identified the energy sector as the most polluting and showcased key pathways for its intensive decarbonization via increasing efficiency, employing circular economy concepts and replacing existing polluting technologies with electrification, hydrogen, biofuels and carbon capture [2]. In response to the ever-increasing energy demand and aiming to prevent further rise in global temperatures, the European Union (EU) took the initiative to aggressively curb GHG emissions and become carbon neutral by 2050. The initial target of 40% GHG emissions reduction in 2030 was raised to 55% by 2030 and 100% by 2050 as highlighted by the European Green Deal (EGD) established in 2019. Global renewable energy infrastructure has rapidly evolved over last few decades resulting in increasing renewable energy share in domestic and industrial energy sectors. However, the transport sector which is responsible for one-third of global energy demand and one-sixth of global GHG emissions has the lowest share of renewable energy [3]. Heavy duty vehicles (HDVs) remain a hard to abate sector, which is heavily dependent on diesel and gasoline. There was a significant decline in diesel and gasoline usage during the Covid-19 pandemic, but according to the International Energy Agency (IEA) the global road transport demand for gasoline and diesel will rebound from 46.7 million barrels/day (mb/d) in 2020 to 50.5 mb/d in 2050 with diesel accounting for 60% share [4]. The IEA also predicted that demand for biofuels will increase from 1.9 mb/d to 5.7 mb/d, accounting for 5.2% of total liquid fuel demand in 2050 [4]. However, in order to achieve sustainable development goals (SDGs) biofuels should account for a 14% share in 2050 [4].

1.2 Biomethane - Potential in the transport sector

When compared to diesel, natural gas, either compressed or liquefied, is often shown as having certain GHG reduction benefits. Heavy duty vehicles showed 2-12% reduction in GHG emissions with natural gas compared to diesel [5]. However, the GHG reduction is limited due to lower efficiencies of gas engines, methane leakage and the fact that natural gas is still a fossil fuel [6]. In fact, in some cases the GHG emissions from some natural gas heavy duty vehicles can be higher than diesel [7], [8].

'Biomethane', a gaseous fuel produced from organic matter via Anaerobic Digestion (AD) or thermal decomposition (Gasification), shares similar properties with natural gas and can therefore easily replace natural gas or diesel in the transport sector [9]. Several researchers have argued that biomethane presents an effective strategy for curbing GHG emissions from the transport sector and achieving renewable energy targets set by the EGD (EU Green Deal) [10]. The EU has committed to achieve a specific sub-target of 3.5% renewable energy in transport sector from advanced biofuels that will be double counted [11]. 'Advanced biofuels' term refers to liquid or gaseous biofuels made from materials listed in Part A of Annex IX from RED II. This list includes industrial and domestic biowaste, agricultural and forest residues, among other waste biomass that avoid creating an additional demand for land [11]. Biomethane produced from thermal decomposition of waste biomass is an advanced biofuel that will be double-counted towards both the 3.5% sub-target and 14% overall transport energy target [12]. Therefore, biomethane has a key role to play in decarbonization of hard to abate road transport sector such as HDVs [4]. This potential for decarbonization of HDVs with biomethane has reignited interest in biomethane upgrading and compression, resulting in a consequential increase in biomethane distribution infrastructure. As of 2018, use of CNG vehicles have significantly evolved in countries like Italy, Germany, Sweden and Netherlands whereas countries like Belgium, ROI , UK among others have projected up to 50-100% increase in CNG vehicles and refuelling infrastructure by 2030 [13], [12]. Renewable gas (biomethane/Bio-CNG) is compatible with existing CNG refuelling infrastructure meaning it can facilitate faster GHG emission reductions with limited additional investment.

ROI has started developing infrastructure to facilitate deployment of biomethane in transport sector by installing CNG network (The Causeway project). Resource assessment by [14] showed that ROI has potential of producing 10.18 PJ/a of biomass derived synthetic natural gas (bio-SNG/Biomethane) from gasification of waste/residue biomass. This indicated that ROI has potential to replace 6.6% diesel demand of HDVs with advanced biofuels [14]. While several recent studies in ROI have focused on potential of MSW [15], little to no studies have been conducted on deployment of forest residues based advanced biofuels.

1.3 Decarbonization - role of advanced biofuels in ROI

The EU Renewable Energy Directive mandated that renewable energy sources for transport

(RES-T) should contribute up to 10% of final energy consumption in 2020. Ireland managed to successfully achieve its RES-T target (10.2% vs 10%) [16]. However, transport sector remains largest contributor of CO_2 emissions due to high dependency on diesel. Although electrification of the transport sector has helped in medium term, it is still limited to private car and light commercial sectors whereas, electrification of HDVs still remains a challenge [17]. As the transport sector is still heavily reliant on fossil fuels the reduction in CO_2 emissions has been small [16]. In this context, increasing the contribution of liquid and gaseous biofuels is a potentially viable option for Ireland to avoid missing new 2030 RES-T and overall 2050 targets [17].

The biofuel sector has rapidly developed since its introduction. Drop-in biofuels that require no change to existing fuel supply infrastructure can be produced using several methods, which include (1) oleochemical pathways such as the hydroprocessing of oil seeds and animal fat, (2) biochemical pathways that involve biological conversion and upgrading of energy crops and lignocellulosic biomass (sugarcane or starch), and (3) thermochemical pathways that convert forest and agricultural residues to syngas & bio-oil for further upgrade to liquid and gaseous fuels [18]. Oleochemical and biochemical pathways are technically more mature and remain the main supply routes of commercial biofuels. However, this pathway is constrained due to high cost of feedstock, the undesirable use of arable land for energy production, and competition with food and other industries [4]. In addition to the thermochemical pathway being less susceptible to this constraint, it can also produce higher yields of biofuel [19]. However, much needs to be done in terms of technical and economic characterizations, design of feedstock supply chains and product routes to market, and calculation of overall environmental impact.

1.4 Forest residues - status quo and future potential in the Irish bioeconomy

During timber harvesting, trees are delimbed and cross-cut into specified dimensions. Branches with diameter < 7cm and out-of-specification stems that are defective, undersize, or uneven are left on the forest floor. This material is termed ‘forest residues’ or ‘brash’. A recent study focused on residue extraction from sites that are sensitive to environmental damage concluded that 70% of forest residues could be extracted from a given site in the best-case scenario, i.e. causing little soil damage and nutrient loss [20]. Ireland uses a mechanized system for gathering and bundling forest residues in to cylindrical bales, which facilitates easier handling, transporting and storage of forest residue bundles [21]. However, brash bundling occurs only in small geographically specific locations that supply bundles to combined heat and power

(CHP) plants within 50 km of forest locations, as a low-cost fuel for heat and electricity application. According to the Sustainable Energy Authority of Ireland (SEAI) 2018 report, 393 CHP units used natural gas and oil as primary fuel, producing up to 327 MW_e, whereas only 3 CHP units used biomass for heat and electricity generation in 2017, producing 5.5 MW_e [20]. The low quality and low density of forest residues poses a great challenge in large-scale mobilization of forest residues to CHP units. Ireland has a comparative advantage in terms of its biomass resources as underlined by the *National Bioeconomy Statement* released in 2018 [22]. The increasing interest in the bioeconomy is palpable and the government is poised to capitalize on it. The statement further illustrates in Value Chain 10, which is *"the use of forest residues to produce bio-products beyond conventional direct heat and power applications, by incorporating advanced conversion technologies"* [22]. Therefore, it is necessary to introduce an advanced conversion technology in Irish sector that will potentially initiate large-scale utilization of waste forest residues, affecting the Irish energy sector and helping in reduction of GHG emissions.

1.5 Research Motivation

As discussed previously the potential of forest residues is constrained by lack of significant market, difficulty of extraction, wide geographical distribution, and low energy value. This problem can be solved by increasing the fuel quality and consequently densifying biomass into biofuels using thermochemical conversion pathways. The EU Renewable Energy Directive also favours 'second generation' or advanced biofuels from lignocellulosic and waste resources over first-generation biofuels such as energy crops and oil seeds due to sustainability concerns. Therefore, large-scale mobilization of forest residues can significantly increase the biomass contribution in the energy mix. This will not only contribute to Ireland's renewable transport targets but also help in mitigating GHG emissions, as production and utilization of biofuels can be potentially carbon neutral. However, there has been little to no work done on deployment of forest residue-based biofuels production in Ireland. Therefore, the motivation for this work is to study different supply chain scenarios of forest residue-based biofuels to provide a sustainable and cost-effective supply and distribution of them to the market. A techno-economic assessment will help determine capital and operational costs of establishing a biorefining infrastructure in Irish premise. Life cycle assessment will track GHG emissions associated with production and utilization of advanced biofuels.

1.6 Research Aim and Objectives

The aim of this research is (1) to investigate ROI's potential to mobilize forest residue as feedstock to produce transportation grade biofuels for decarbonization of heavy-duty vehicles, (2) to optimize overall biofuel production costs by locating and sizing a centralized biorefinery with minimum transport cost of feedstock and biofuels distribution and (3) to determine the environmental impact of economically-optimal biofuel supply chains.. The outcomes of this research are new and are of interest to several audiences. Firstly, policymakers interested in the mobilisation of indigenous residues as renewable heavy-duty transport fuel. Secondly, industrial researchers, interested in investing in biofuel production to pursue decarbonization of trucking fleets and valorisation of residues. Finally, academic researchers, interested in the novel combination of techno economic assessment, GIS modelling and optimization that can be applied to any geographical region.

The overall aims are achieved by meeting technical research objectives, which are:

1. To conduct an initial economic analysis of state-of-the-art forest residues to transportation grade biofuels technologies. Three primary thermochemical technologies are assessed for their suitability to produce biofuels to replace diesel in heavy-duty vehicles. Technologies with potential to produce competitive biofuels are used for objective 2 and 3.
2. To design regional nationwide supply and distribution chains of forest residue-based biofuels and apply optimization techniques to minimize transport cost of feedstock and biofuel distribution. Optimal biofuel supply chain designs are used for objective 3.
3. To conduct a comprehensive techno-economic assessment on two optimal biofuel supply chains: (i) bio-CNG from gasification, and (ii) crude bio-oil and biochar from non-catalytic fast pyrolysis. Differently from objective 1, bio-CNG infrastructure and distribution costs are investigated for the gasification scenario. While for pyrolysis scenario co-processing of crude bio-oil at an existing oil refinery with valorisation of biochar is explored. Economically optimal biofuel production pathways are used for objective 4.
4. To perform environmental impact assessments of economically optimal biofuel pathways to investigate their greenhouse gas emissions.

1.7 Report Overview

This section provides an overview of all chapters enclosed in this report.

Chapter 1 (this chapter) provides a general overview of background for the research. It covers the global issues of climate change and highlights the need to mobilize low-carbon emission technologies for offsetting diesel fuel demand in heavy-duty vehicles. The research objectives and report outline are also provided in this chapter.

Chapter 2 investigates the potential of three state-of-the-art thermochemical technologies for conversion of forestry to commercially competitive drop-in biofuels for offsetting diesel demand of heavy-duty vehicles. Although there are several studies focusing on biofuels production from forestry residues via thermochemical pathway in various countries, Ireland has yet to explore these pathways. The economic competitiveness of thermochemical pathways are determined by calculating the minimum fuel selling price (MFSP) of biofuels.

Chapter 3 explores a circular economy approach where timber fleets that transport merchandisable timber from forest to sawmill are selected as suitable end users that could maximize the diesel offsetting impact of bio-CNG. A combined economic and spatial modelling technique is used to locate and size feedstock, hypothetical bio-CNG demand, filling stations and biorefinery. A techno-economic model calculates net present value (NPV) and levelised cost of bio-CNG ($LCOB_{cng}$), which is compared with incumbent wholesale price of diesel including carbon taxes.

Chapter 4, in a similar fashion to chapter 3, presents combined economic and spatial modelling to optimally locate a pyrolysis biorefinery for production of crude bio-oil with biochar or activated carbon as by-product. Crude bio-oil is transported to an existing oil refinery, Whitegate in Cork, for co-processing. Levelised cost of bio-oil is used to compare its competitiveness with fossil-based counterparts. NPV is used to compare the profitability of co-producing biochar and activated carbon.

Chapter 5 presents an environmental sustainability analysis of economically optimal biofuel production scenarios to determine their greenhouse gas emissions.

Chapter 6 provides concluding remarks based on the results obtained, the advancement of the state-of-the-art on forest residue to biofuels, as well as an outline of suggested future developments of the research.

2 Preliminary techno-economic assessment of thermochemical technologies

2.1 Chapter Overview

Currently, the main product from forestry sector of Ireland is timber logs made from stems of spruce trees, which constitute up to 60-75% of the total tree volume. The remaining 25-40%, which consists of branches, stems of diameter <7cm, stumps, and deformed trees, typically called forest residues or brash, are left on the forest floor due to their lack of large-scale demand in Irish market. Recent studies have shown the use of forest residues as feedstock for producing high-value bio-products such as liquid and gaseous biofuels. In this study, three scenarios involving state-of-the-art thermochemical technologies, namely gasification, pyrolysis, and hydrothermal liquefaction (HTL) for biofuel production, were assessed for their potential to produce diesel-grade fuel in Ireland. The gasification scenario produces biomass-derived compressed natural gas (Bio-CNG), pyrolysis and HTL produced biofuels that were converted to litres of diesel equivalent (LDE). The techno-economic assessment calculates capital investment, operational cost, and minimum fuel selling price (MFSP), which was found to be 0.83 €/LDE, 1.4 €/LDE, and 1.2 €/LDE for gasification, pyrolysis, and HTL respectively at maximum biorefinery capacity of 700 dt/day. To evaluate the level of incentivization required to achieve parity with diesel, current carbon tax of 26 €/t CO_2 was increased to 80 and 160 €/t CO_2.

2.2 Introduction

With increasing concerns regarding global temperature rise and climate change, it has become necessary to improve and develop both existing and novel sources of sustainable energy production technologies. Several recent studies show that biomass is the most versatile resource to produce value-added chemicals, energy carriers or direct-use energy, to reduce global dependency on fossil-based products. Biorefining can be termed as a set of techniques for converting biomass into highly valuable biochemicals and biofuels. Biorefining technologies can be broadly classified into (1) biochemical, which biologically converts biomass into bio-ethanol, (2) catalytic conversion, which requires acid-catalysed reactions to produce levulinic acid, (3) oleochemical, which involves hydroprocessing of oilseeds and animal fats, and (4) thermochemical, that converts biomass into biofuels/energy carriers [23]. The choice of biorefining technology primarily depends on the quantity and quality of biomass used as feedstock. Lignocellulosic biomass such as forest residues are required to be treated at high temperatures to release chemical energy, and therefore are a more suitable feedstock for thermochemical technologies that operate at high temperatures (400-850 °C) with or without oxygen as reported in [18] and [19]. Thermochemical conversion of biomass typically produces biofuels and byproducts that are very potent energy carriers and if upgraded can be used as a transportation fuel.

The EU Renewable Energy Directive mandated that renewable energy sources for transport (RES-T) should contribute up to 10% of final energy consumption in 2020 [4]. Although Ireland was able to achieve RES-T targets (10.2% vs 10%), the transport sector remains heavily dependent on fossil fuels. This poses a huge challenge for achieving not only future RES targets but also GHG emissions targets. SEAI's 2021 Energy in Ireland report highlights that the energy use for transport sector was down by 26% due to COVID-19 restrictions [25]. The report showed that aviation and private cars sectors had highest reductions in energy use, by 64 % and 21% respectively whereas, heavy duty vehicles (HDVs) sector accounted for lowest reduction of 9 % in 2020. This resulted in reduction of final consumption of transport fuel such as petrol and diesel. However, diesel remained the largest fuel type used with a share of 70% followed by gasoline (15%), jet kerosene (10%) and liquid biofuels (4%). Despite this large reduction in energy use, transport sector was responsible for largest share of CO_2 emissions at 31%. Three things are clear from the report: firstly, HDVs had highest energy use in transport sector, secondly diesel had the highest share in final fuel consumption and lastly transport sector has highest overall CO_2 emissions. To address these three challenges, it is necessary to develop a sustainable source of renewable fuel to reduce dependency on diesel for HDVs. However, it is acknowledged that there is no single solution to decarbonize the transport sector, requiring multiple alternative fuels to work in tandem for different modes of transport. Electrification of transport sector has significant impact in medium term for light vehicles but has not been able to effectively decarbonize heavy road transport, freight and aviation industries. Especially decarbonizing HDVs has always been a hurdle for electrification technologies due to their higher driving range, charging time, and load capacity [26]. In this context, increasing the contribution of liquid and gaseous biofuels derived from biomass is a potentially viable option for Ireland to avoid missing 2030 RES-T targets. The EU Renewable Energy Directive favours second-generation biofuels from lignocellulosic and waste resources over first-generation biofuels such as energy crops and oil seeds due to sustainability concerns. Biofuels from wastes such as forest residues can diversify the available feedstock for fuel and energy generation in ROI [27]. The Republic of Ireland (ROI) has 14% land forest coverage.

Forestry activity is currently primarily dedicated to timber log harvesting. Ireland produces up to 800,000 m^3a^{-1} of forest residues, defined as tree-top to 7 cm in diameter, majority of which is left on the forest floor as highlighted by [28]. [14] showed that Ireland has the potential to supply up to 2.5 PJa^{-1} renewable energy from forest residues in 2019. During resource assessment, it was found that maximum biorefinery capacity that can be achieved using all forest residues is approximately 700 dt/day, assuming their complete recovery and no loss during handling and transportation. Therefore, this study focuses on evaluating thermochemical technologies, which could allow use of forest residues to produce competitive drop-in biofuels for HDV in Ireland.

2.3 Motivations and Objectives

Transport sector being the largest consumer of energy also had lowest share of renewable fuels and highest energy related emissions in 2020 in ROI. If Ireland aims to achieve new ambitious 2030 and 2050 targets, it is essential to decarbonize transport sector and reduce dependency on diesel as transportation fuel. Ireland's forestry sector produces significant quantities of residues that when fully utilized will contribute to achieving RES-T and GHG emissions targets. Thermochemical technologies being most suitable for forestry residues can be potentially used to convert forest residues to produce drop-in fuels to replace diesel. Although there are several studies focusing on biofuels production from forestry residues via thermochemical pathway in various countries, Ireland has yet to explore these pathways. Hence, this chapter focuses on evaluating suitable thermochemical pathways for biofuel production from forest residues in Ireland using minimum fuel selling price (MFSP) as an economic indicator.

The objectives of this study are:

1) To conduct a literature review on thermochemical pathways for biofuels production
2) To evaluate the economic performance of thermochemical pathways
3) To compare MFSP and diesel price with increasing carbon tax to show the level of incentive required to produce competitive biofuel.

2.4 Methodology

Literature review was conducted to study techno-economic assessment methodology employed by researchers in order to evaluate the economic competitiveness of state-of-the-art thermochemical technologies suitable for forest residues. Following section discusses the process design, technical and economic parameters of thermochemical pathways. Techno economic assessment methodology studied from literature review were modified by actualizing all costs to current year of study (2019) and adjusting the economic parameters to Ireland's case study. Figure 2.1 shows process design of three thermochemical technologies explored in this study.

2.4.1 Thermochemical technologies state of the art

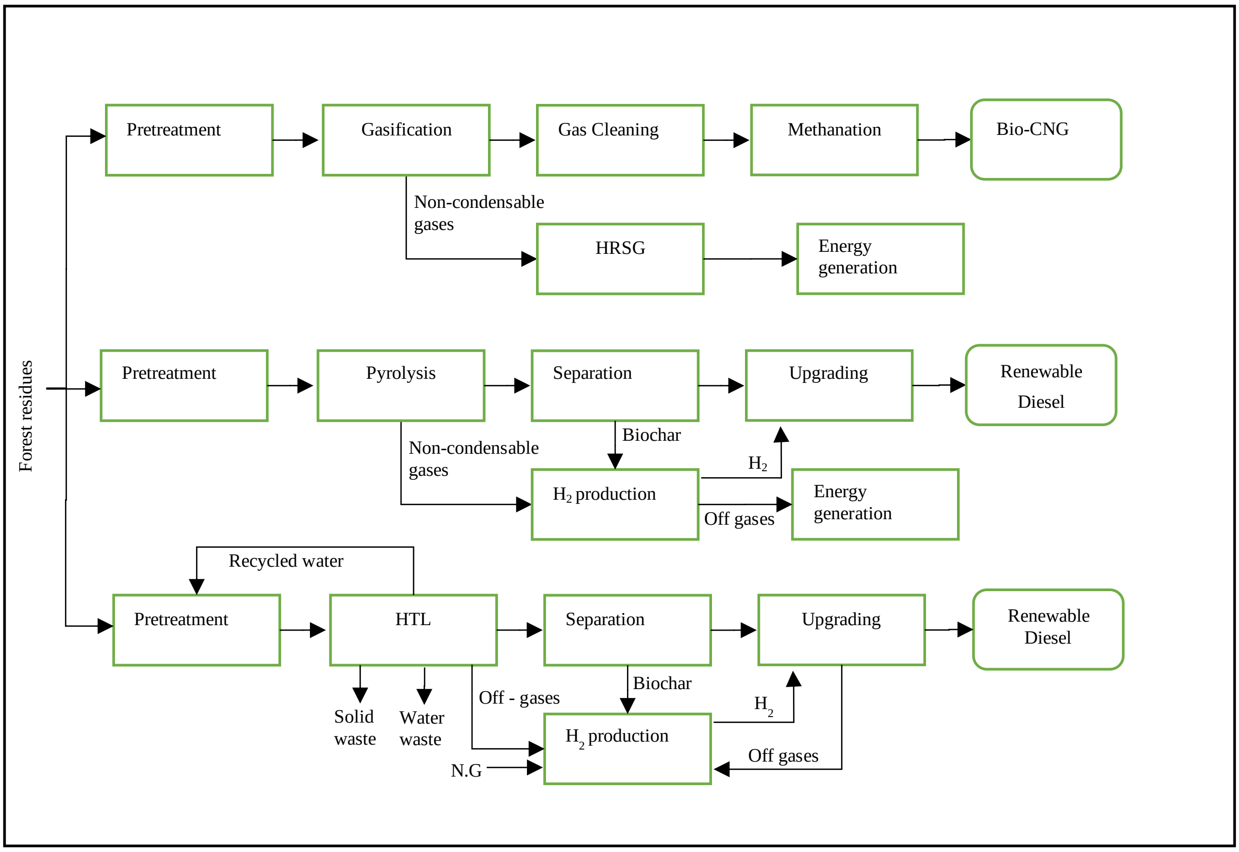

Figure 2.1: Process design scenarios of gasification, pyrolysis and HTL scenario

Gasification converts biomass into a synthetic gas (syngas) and solid residues (ash) at high temperature in the presence of air, steam and/or oxygen. Syngas can be converted into a variety of energy products such as biomass-derived synthetic natural gas (bio-SNG), methanol, dimethyl ether, synthetic gasoline and diesel via the Fischer-Tropsch (FT) process [29]. For large-scale production of bio-SNG, indirect and direct fluidized bed gasification (FBG) are most common. [30] conducted a comprehensive study of different process alternatives for bio-SNG production. The study showed that biomass to bio-SNG efficiency of indirect FBG can be up to 63%. [31] studied improvements that can be made in syngas processing of GoBiGas and revealed that a potential 29% of capital investment can be reduced if olefin hydration and hydrodesulphurisation units are combined, pre-reformer section is eliminated and methanation section is modified. They also converted all aromatic compounds to bio-SNG, increasing overall efficiency from 64.8% to 71.1% [31]. A pseudo-equilibrium thermodynamic model used by [14] showed similar efficiency of 62.1% with 99.6% CH_4 and 0.44% H_2 product molar compositions. [14] used the process design of Gothenburg Biomass Gasification otherwise known as GoBiGas and showed that an additional heat recovery system can produce net electricity of 0.13 MW/MW_{SNG} produced.

Unlike gasification, pyrolysis of forest residues has not yet been investigated in Ireland. Pyrolysis converts biomass to syngas, bio-oil and carbon-rich char at moderate to high temperature in a non-oxidizing environment. The relative product quantities depend on feedstock heating rate, final temperature, and residence time. Fast pyrolysis is most suitable for maximizing bio-oil yields [18]. It involves thermochemical decomposition of biomass into liquid (bio-oil, 64 wt.%), solid (bio-char, 14 wt.%) and gaseous (non-condensable gases, 22 wt.%) at elevated temperatures ranging between 450 – 650 °C and at a short residence time of 2 seconds [32]. Depending on what the desired pyrolysis product is, by-products are burned to produce all required energy for plant processing [18]. Bio-oil is a low-quality fuel due to high oxygen content and chemical instability. Therefore, it must be upgraded to synthetic gasoline or diesel-like fuels. The most widely used bio-oil upgrading technology is hydroprocessing, which involves a two-stage hydrogen treatment step. First hydrodeoxygenation (HDO) selectively removes oxygen by catalytically reacting bio-oil with hydrogen over nickel-molybdenum or cobalt-molybdenum catalyst. Hydrocracking then decomposes heavy aromatics into lighter aromatics and aliphatic compounds. A techno-economic performance analysis conducted by [33] for biofuel production from forest residues in UK showed that 37 wt.% of bio-oil is hydrocracked into gasoline and diesel products, which is comparable to other studies for similar setup [34], [35].

Hydrothermal liquefaction does not require drying of feedstock, unlike gasification and pyrolysis, as water plays an important role in the conversion process. At high temperature, it acts as a catalyst in disintegrating organic material. Although HTL is still at an early stage of technological development when compared to pyrolysis, the elimination of energy- and cost-intensive drying is an advantage. Akin to pyrolysis, the main products from HTL technology are also syngas, bio-char and bio-oil, followed by hydrotreatment of bio-oil. [36] conducted a techno-economic analysis on HTL biofuel production from woody biomass describing two case scenarios: (1) a state of technology (SOT) case with HTL experimental data, and (2) a goal case that considered future improvements and technologically advanced conversion. The result showed that for SOT case, MFSP that can be achieved was 1.15 $/LGE (Liter Gasoline-Equivalent). For the goal case 0.65 $/LGE could potentially be achieved in future, indicating that HTL has potential to be an economically viable source of transportation fuel. [37]

conducted a similar study in British Columbia, Canada for a biorefinery producing 100 million litres of HTL biofuel per year in three different scenarios of feedstock delivery. The study concluded that forest residues chipped onsite and then transported to the biorefinery showed lowest MFSP at 0.89 $/LGE. Table 2.1 shows economic parameters used in referenced study to calculate the MFSPs for each scenario and Table 2.2 shows all the operating parameter for three thermochemical technologies..

Table 2.1: Tehno-economic review on thermochemical technologies

Conversion Technology	**Capacity (dt/day)**	**Feedstock**	**Product**	**TCI** M€	**OC** M€/a	**MFSP** €/MWh	**Ref**
Gasification	650	Forest residue	Bio-SNG	121.16	53.62	83.12	[14]
	660	Forest residue	Bio-SNG	91.2	64.7	68	[31]
Pyrolysis	2000	Wood residue	Gasoline & Diesel	380.03	137.06	1.30 €/ LDE	[38]
	72	Forest residue	Gasoline & Diesel	19.09	7.36	1.62 €/ LDE	[33]
HTL	2000	Woody biomass	Gasoline & Diesel	455.68	66.7	1.045 €/ LDE	[36]
	1500	Forest residue	Gasoline & Diesel	240	57.8754	0.82 €/ LDE	[37]

Table 2.2: Technical parameters of thermochemical processes

Technical comparison	Pyrolysis	HTL	Gasification
Feedstock requirement			
Moisture content (wt.%)	<10 [18]	No requirement [18]	10-20 [18]
Particle size	<3 mm [18]	< 3 mm [18]	<50-60 mm[18]
Reaction parameters			
Pressure (MPa)	0.101 [18]	10-25 [18]	2-7 [18]
Temperature	400-500 °C [18]	280-370 °C [18]	600-1000 °C [18]
Product upgrading	Hydrotreatment [38]	Hydrotreatment [37]	Methanation [39]

Main product	Renewable Diesel [18]	Renewable Diesel[18]	Bio-CNG
By-products (wt.%)	No byproducts, Bio-char is gasified for H_2 production and/or burned for process heat and electricity generation [38]	No byproducts, Off-gases and Natural gas are used for H_2 generation [37]	Excess electricity
HHV of Upgraded biofuel	38.6 MJ/L [38]	37.9 MJ/L [37]	39.8 MJ/m^3 [39]
Biomass to biofuel efficiency (wt.%)	16 [38]	26 [37]	62.1 [39]
Overall energy efficiency (%)	40 [38]	62 [37]	70 [39]

2.4.2 Techno economic assessment

2.4.2.1 Total Capital Investment

The total capital investment for each scenario was estimated by first calculating total purchased equipment cost (TPEC) of all major equipment used for conversion to biofuel. The TPEC for all equipment used in scenarios were sourced from various literature as shown in Table 2.3 and Table 2.4. The equipment sizes and costs were scaled down using cost-size relationship shown by Eq. (1)

$$C_N = C_0 * \left({S_N}/{S_0} \right)^n * IF \quad (1)$$

Where C_0 is base equipment cost for base scale S_0, C_N is new equipment cost for new scale S_N, n is scaling factor and IF is installation factor. Table 2.5 summarizes calculation of total capital investment for each scenario.

Table 2.3: Equipment cost for pyrolysis and HTL scenario

Capacity 2000 DT/day	
Pyrolysis TPEC sourced from [38]	M€
Pretreatment	12.20
Pyrolysis	63.83

Gases combustion	6.95
Upgrading	102.32
Hydrogen production	70.40
Storage and Water cooling	2.25
HTL TPEC sourced from [36]	M€
Biomass conditioning	26.10
HTL reactor system	83.26
Upgrading (hydrotreating)	90.02
Upgrading (hydrocracking)	0.00
Hydrogen plant	22.34
Utilities	35.01
Missing equipment	25.72

Note: The base cost is actualized to 2019 using conversion factor 1.11 $\$/€_{2019}$ and $CEPCI_{2019}$ = 607.5

Table 2.4: Cost inventory of gasification process sourced from [39]

Equipment	Base cost (M€) C_0	Scaling factor, SF	Base scale, S_0	Unit	Installation factor, IF
Grinding	0.153	1	2140	tdry/day	2.47
Drying	0.321	0.7	1100	tdry/day	2.47
Gasification Section	9.20	0.72	100	MWth of biomass(LHV)	2.47
Ceramic filter	2.22	0.7	500	MWth of biomass(HHV)	2.47
Oil Scrubber	18.0	0.65	135	497 Nm3/h	1
Compression of raw Syngas	5.31	0.7	5.44	MWe	1.32
Olefin hydrator	0.00311	0.67	65.77	t/h	2.47
HDS unit	0.00311	0.67	65.77	t/h	2.47
CO_2 and H2S removal	18.5	0.65	12.62	kg/s of eq. CO_2	2.47
ZnO guard-bed	0.0271	1	8	Nm3/s	3
WGS unit	0.383	0.56	44.66	kg/s	1
Pre-reformer	49.1	0.6	1277	kmol/h reformed	1
Methanation	0.0395	0.67	149.69	kg/s 1st reactor	2.47

Note: All unit costs were actualized to 2019 using conversion factor 1.11 $\$/€_{2019}$

Table 2.5: Total Capital Investment calculations

	[b] **Gasification**	[b] **Pyrolysis**	[b] **HTL**
Total installed cost (TIC)	2.47[a]/X[a] *TPEC	2.47[a]/X[a] *TPEC	2.47[a]/X[a] *TPEC
Indirect cost (IC)	21.9%*TIC	25%*TIC	62%*TPEC
Fixed capital investment (FCI)	TIC + IC	TIC + IC	TIC + IC
Project Contingency	N/A	15%*TIC	N/A
Working Capital (WC)	N/A	5%*FCI	20%* FCI
TCI	TIC+IC	FCI+PC+WC	FCI+WC

Note: N/A indicates that the particular cost was not included in respective literature.

[a] 2.47 is installation factor generally used for thermochemical technologies, X is individual factor that varies with specific equipment

[b] The method for TCI calculations was taken from Ref [39], [38], [37] respectively

2.4.2.2 Operational expenditure

The operating cost of biorefinery is typically divided in to two parts, variable operating cost (OC_{var}) and fixed operating cost (OC_{fixed}). The fixed operating cost included property tax, insurance, labour cost and plant overheads that were taken as percentage factor of *TCI* for gasification, pyrolysis and HTL from [39], [38], [37] as shown in Table 2.6 . Variable operating cost includes cost of feedstock, catalysts, utilities, chemicals and waste disposal. Table 2.6 also shows unit cost of parameters that were modified for this case study. For transportation cost since an optimum site for biorefinery is still unknown, the transportation distance was assumed to be 50 km for all scenarios. Total operating cost was calculated using Eq. (2)

$$OC_{Total} = TCI * \left(\frac{OC_{Fixed}}{100}\right) + ((m_{FR} * P_{FR} + E_{used} * P_E + m_{C\&A} * P_{C\&A} + m_{Utilities} * P_{Utilities}) * OH) \quad (2)$$

Where, m_{FR}, $m_{C\&A}$, $m_{Utilities}$ and are the mass flow of forest residues, chemicals, Utilities in t/hr, E_{used} is electricity used and P_{FR}, P_E, $P_{C\&A}$, $P_{Utilities}$ are delivered cost of forest residue, price of electricity, chemicals and other utilities as listed in Table 2.6.

Table 2.6: Parameters for calculating total operating cost for all scenarios

	Pyrolysis	HTL	Gasification
Fixed OC	25%*TCI[a]	15%*TCI[a]	13%*TCI[a]
Feedstock delivery cost (€/t_{db}) [b] [40]	125	125	125
Catalyst and chemicals	84 €/kg	34.25 €/kg	12.8 % of OC_{var}
Cooling water	0.24 €/t	-	-
Electricity cost (€/MWh) [b] [41]	101	101	101
Natural Gas (€/MWh) [b] [41]	N/A	74.1	N/A
Operating hours(OH)	7500	7500	7500
Transport Distance (km)	50	50	50

Note:

[a] Fixed Operating cost was calculated using Ref; [39] , [38] & [37] for pyrolysis, HTL and gasification scenarios respectively.

[b] The unit cost for delivered feedstock, electricity and natural gas were modified to Ireland's case study.

2.4.2.3 Minimum Fuel Selling Price

The MFSP for each scenario was calculated using discounted cash flow rate of return (DCFROR) analysis. This method calculates MFSP of biofuels by assuming net present value (NPV) to be zero to find the breakeven point [42]. The DCFROR considers biofuel as the only product for each biorefinery scenario. Table 2.7 gives information about major assumptions made to calculate economic parameters. All calculations were performed in Excel.

Table 2.7: Levelised cost of biofuel calculations

Parameters	**Assumptions**
Debt/Equity	**0/100%**
Plant life time (N)	20 years
Internal rate of return (i)	10%
Income tax rate (ITR)	30%
Construction period	1 year

Eq. (4) calculates biofuel revenues (B_{Rev}) in M€/year when NPV = 0

$$B_{Rev} = \frac{OC_{Total}\,(1-ITR)+ROI}{(1-ITR)} \quad (4)$$

Where, ROI is return of investment in M€/year calculated by Eq. (5)

$$ROI = \frac{i*(1+i)^N}{(1+i)^N-1} * TCI \quad (5)$$

Where, i is internal rate of return and *N* is project lifetime. The MFSP is calculated using Eq. (6)

$$LCOB = \frac{B_{Rev}}{B_{Produced}} \quad (6)$$

Where, $B_{Produced}$ is biofuel produced in L/year for gasification, pyrolysis and HTL. To maintain a consistent comparison with incumbent petroleum transportation fuel in Ireland i.e. diesel, the MFSP (€/L) was converted in to litre diesel-equivalent $MFSP_{LDE}$ i.e. €/LDE using Eq. (7)

$$LCOB_{LDE} = \frac{LCOB_{Fuel}*Diesel\ HHV}{Final\ product\ HHV} \quad (7)$$

It is important to note that in case of HTL and pyrolysis the final product yield consists of % distribution of gasoline, diesel, jet fuel and heavy oil that have respective HHV 34, 37.4, 38.6, and 41.1 MJ/L therefore, HHV of biofuel mix is 37.9 MJ/L as reported by [37] . HHV of diesel is assumed to be 38.6 MJ/L. For mitigation of global warming impact Irish government has introduced carbon tax in 2009, which was 26 €/t in 2019 [43]. Carbon tax is levied based on life cycle GHG emissions of a fuel. The life cycle GHG emissions for diesel is assumed to be 0.09 kg/MJ (3.19 kg/L) as reported by [18].

2.5 Results

2.5.1 Model validation

The techno-economic model created in this study based on literature review was validated by getting results on same scales as shown in [39], [38] and [37]. The result of model validation was satisfactory. The difference in *TCI* was mainly due to difference in currency rate (1.12 $/€$_{2019}$ in this study) and cost index ($CEPCI_{2019}$ = 639.8). HTL and pyrolysis showed major differences in *OC* mainly due to lower feedstock cost which is 84 and 62.1 €/dt in [38] and [39] work respectively as opposed to 105 €/dt in this study. Figure 2.2 shows results of model validation with literature.

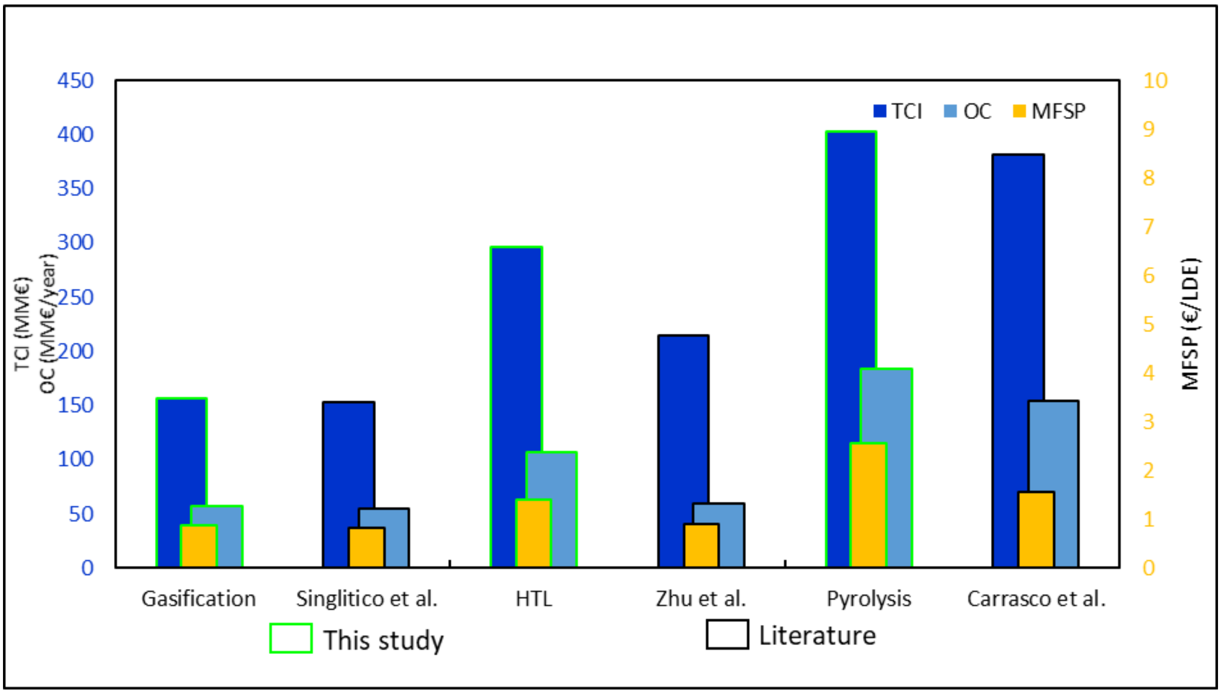

Figure 2.2: Validation of techno-economic model with results reported by [39], [38] and [37]

2.5.2 Techno-economic assessment results

Table 2.8 provides a summary of major costs for establishing a 700 dt/day thermochemical biorefinery that uses all forest residues in ROI. The *TCI* is dominated by installed equipment cost, which accounts for about 50% for all scenarios. Figure 2.3 shows detailed installed equipment cost for all scenarios. The higher *TCI* for HTL and pyrolysis can be attributed to upgrading process as it accounts for the highest contribution in total installed equipment.

Table 2.8: Techno-economic assessment results for a biorefinery scenarios

	Gasification	**Pyrolysis**	**HTL**
TCI (M€)	157	230	243
OC (M€/a)	57	62	48
$B_{Revenue}$ (M€/a)	66	81	74
MFSP(€/L)	0.21	1.80	1.3
$MFSP_{LDE}$(€/L)	0.84	1.4	1.26

The in-situ hydrogen production for pyrolysis makes up for 27% of *TIC*, which is much higher than HTL scenario (8%) that uses natural gas reforming for hydrogen generation. For gasification scenario equipment for gasification reactor (conversion stage) accounted for highest contribution to *TCI* followed by methanation and energy generation. Compared to other scenarios HTL technology had higher *TCI* as it operates at high pressure and require more expensive shell and tube reactor design.

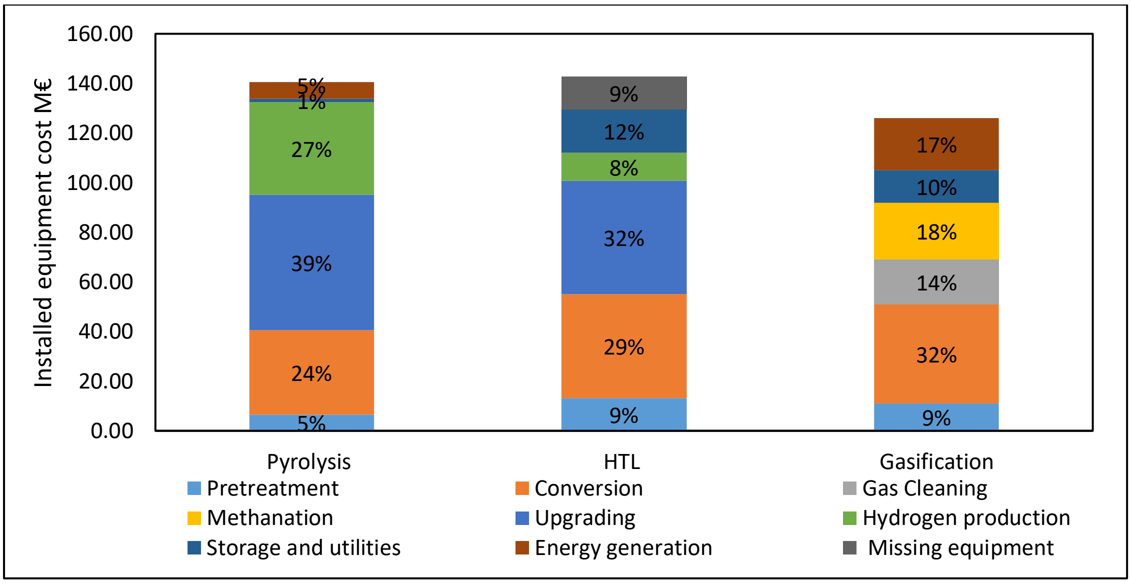

Figure 2.3: Results for total installed equipment cost of each scenario

Figure 2.4 shows a breakdown of OC_{total} for each scenario. Pyrolysis had highest OC_{total} followed by Gasification and HTL scenario. The fixed cost of pyrolysis scenario includes operating labour, maintenance, and overheads. OC_{fix} of pyrolysis was highest as it requires maintenance of more equipment (upgrading and H_2 generation) than other scenarios. It is evident from the graph that *VC* is highly dependent on feedstock cost, which accounted for highest contribution towards OC_{total} for all scenarios. Therefore, it is vital to procure feedstock at lower cost to bring down OC_{total}.

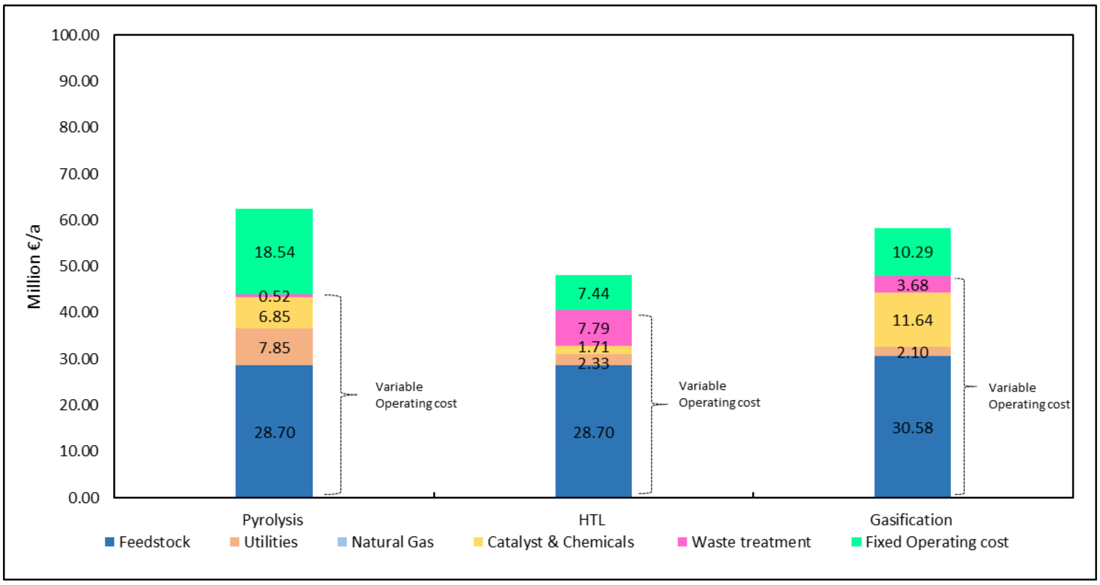

Figure 2.4: Total Operating cost of each scenario

The annual catalyst and utilities cost for Pyrolysis and Gasification accounts for significant expenditure. Pyrolysis scenario had highest requirement of utilities (18% of total *VC*) and Gasification had highest cost for catalyst & chemicals accounting for 24% of total *VC*. HTL scenario had lowest catalyst and utilities cost (4% of total *VC*) but the waste treatment process amounts to a significant value towards total OC (19% of *VC*). Therefore, lowering the cost of utilities and catalyst by installing heat recovery systems and using catalyst with longer life can decrease the OC_{total} for pyrolysis and gasification scenario. The production of biofuels from forest residue presented in this study has MFSP of 1.42, 1.26 and 0.83 €/LDE for pyrolysis, HTL and Gasification scenario for a 700 dt/day capacity biorefinery. Table 2.7 shows breakdown of all annual cost contributing towards the MFSP of biofuels for each scenario. The MFSP of bio-CNG in €/LDE for Gasification scenario is 71% and 51 % lower than MFSP of biofuels from Pyrolysis and HTL respectively. This is mainly due to higher biomass to biofuel conversion efficiency of Gasification scenario as compared to the other two scenarios shown in Table 2.2. Gasification scenario also benefits from using heat recovery system that produces net electricity, which lowers the MFSP by 18%. As expected, MFSP indicates highest sensitivity towards feedstock cost, which is evident from

Table 2.9, as it has highest contribution towards MFSP in each scenario.

Table 2.9: Contribution of total annual cost of biofuel production towards the MFSP for each

scenario

	Pyrolysis (€/L of product)	%Contribution to MFSP	HTL (€/L of product)	%Contribution to MFSP	Gasification (€/L of product)	%Contribution to MFSP
Fixed Operating	0.41	29.2%	0.13	10.3%	0.03	15.4%
Utilities	0.18	12.4%	0.04	3.1%	0.01	3.1%
Net electricity	-	-	-	0.0%	-0.04	-18.0%
Catalyst and Chemicals	0.15	10.8%	0.03	2.3%	0.04	17.4%
Waste treatment	0.01	0.8%	0.14	10.4%	0.01	5.5%
Feedstock	0.64	45.2%	0.50	38.4%	0.10	45.8%
Capital depreciation	0.10	7.0%	0.13	10.2%	0.04	18.7%
Return on Investment (ROI)	0.23	15.9%	0.09	6.8%	0.03	12.0%
Average tax	0.08	5.9%	0.25	18.9%	-	-
MFSP	1.80	100%	1.30	100%	0.22	100%
MFSP (LDE)	1.42		1.26		0.83	

Figure 2.5 presents a comparison between diesel wholesale price with carbon tax and MFSP of scenarios explored in this study. The wholesale prices of diesel was assumed to be 0.6 €/L (2019) without carbon tax. Although MFSP of Gasification scenario was much lower than Pyrolysis and HTL, bio-CNG is still not competitive with diesel at current carbon tax in Ireland (26 €/tCO_2, 2019). At current quantities of forest residues in Ireland (700 dt/day), diesel price with carbon tax was 24%, 46% and 53% lower than the MFSP Gasification, HTL and pyrolysis scenario respectively. Therefore, under current circumstances, biofuel production using forest residues is not economically competitive with diesel.

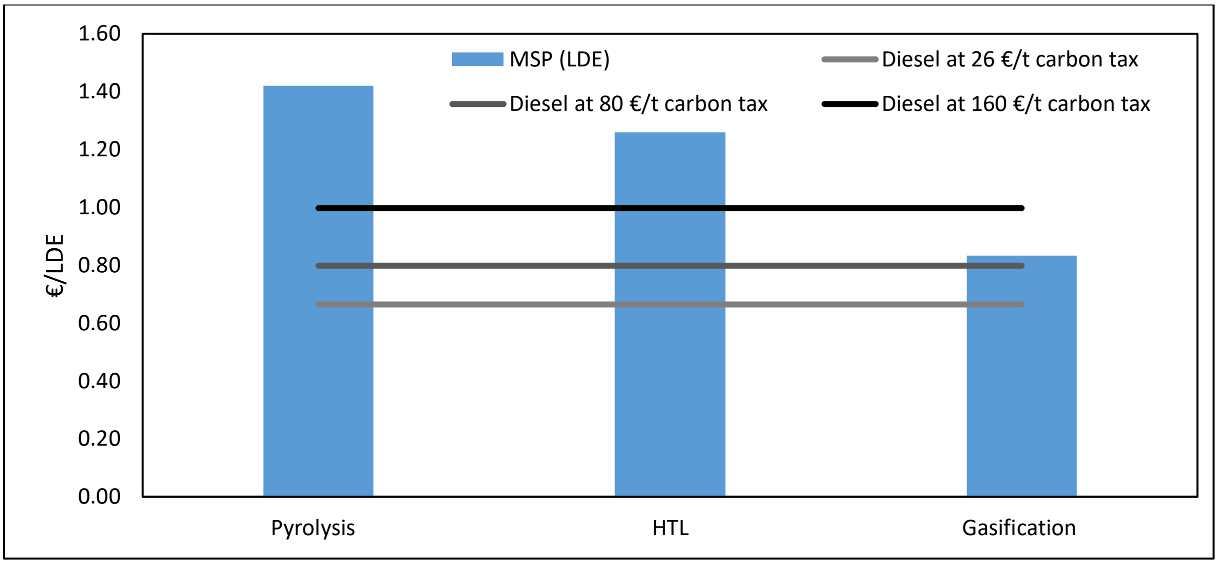

Figure 2.5: MFSP comparison with incumbent diesel fuel wholesale price and carbon tax

However in order to showcase the level of incentivization needed to make forest residue based biofuel competitive this study assumed carbon tax to increase from 26 €/dt to 80 €/t and 160 €/t. Figure 2.5 also shows the impact of increasing carbon tax on price of diesel price. The gap between wholesale price of diesel and MFSP decreases significantly with addition of higher carbon tax. However, only the MFSP of bio-CNG from gasification scenario came close to achieving parity with diesel price at 80 €/t CO_2 and becomes 17% lower at 160 €/t CO_2. The gap between MFSP of Pyrolysis, HTL scenario and diesel is reduced by 30% and 25% respectively at 160€/t CO_2 but neither could be cost competitive with diesel. It is important to note that pyrolysis in this study has been considered to not produce any by-products, as 50% of char is gasified for upgrading process and remaining is used for process energy. Biochar is an excellent energy carrier/ by-product that can generate additional revenue; therefore its valorisation can significantly improve competitiveness of Pyrolysis scenario with other thermochemical technologies. At maximum capacity, only Gasification-produced bio-CNG has the potential to achieve parity with diesel price at 80 €/t CO_2 carbon.

2.6 Conclusions

This study presented and compared the techno-economic results of three state-of-the-art thermochemical technologies using DCFROR method. The analysis provided insights on *TCI*, OC_{total} and MFSP of a biorefinery operating with three different thermochemical technologies namely Gasification, Pyrolysis and HTL at 700 dt/day capacity in Ireland using forest residues as feedstock. HTL and pyrolysis had higher *TCI* due to installation of expensive equipment and upgrading of biofuel. The *OC* was highly dependent on feedstock cost for all scenarios. Pyrolysis and Gasification scenarios had higher *OC* due to their higher dependency on utilities, catalyst and chemicals. As MFSP was dependent on biomass conversion efficiency, gasification, having the highest efficiency, showed lowest MFSP 0.83€/LDE. Pyrolysis and HTL MFSPs were 71% and 51% higher than Gasification scenario. Even with 26 €/t CO_2 carbon tax, the wholesale price of diesel was significantly lower than MFSP of the Gasification scenario. The gap between diesel price and MFSP of bio-CNG was significantly reduced when current carbon tax on diesel (26 €/t CO_2) was raised to 80 €/t CO_2. Whereas increasing it to 160 €/t CO_2 resulted in diesel price being 17% higher than MFSP of the Gasification scenario. Unlike Gasification, MFSPs of Pyrolysis and HTL scenario could not break even with diesel even at higher carbon taxes. However, Pyrolysis scenario should be further explored with biochar as a by-product. As biochar has high energy content, valorising it will increase the biomass to biofuel energy efficiency of pyrolysis scenario which can enhance its competitiveness with fossil-based counterparts. Although Gasification scenario had lowest MFSP, capital and operating cost will increase if the cost of bio-CNG distribution and utilization is added. This might adversely affect the MFSP of bio-CNG calculated in this study.

Chapter 3 will focus on designing supply chain for bio-CNG to identify an optimal biorefinery size and location. The cost of bio-CNG infrastructure (CNG filling stations, product distribution and cost of CNG vehicles) required for bio-CNG utilization in ROI will also be explored.

3 GIS–based supply chain for bio-CNG in Ireland

3.1 Chapter Overview

The European Union (EU) is focused on achieving carbon neutrality by 2050 as underlined in the European Green Deal. This requires a comprehensive lowering of carbon emissions in the road transport sector, which has historically proved difficult in Ireland. EU countries such as Germany, France and Italy have shown considerable growth in production of renewable gas from biomass for road transport in the past decade. Ireland, however, has fallen behind in effectively decarbonizing the heavy-duty road transport sector. The Irish forestry sector produces 800,000 m^3 a^{-1} of forest residue that is left on the forest floor due to a lack of a compelling business case for its use. This quantity of unused forest residue can potentially be mobilized as biomass feedstock for high-value biofuels beyond traditional heat and power applications, which for various reasons have proven uneconomical in Ireland. Chapter 2 focused on a comparative techno-economic assessment of three thermochemical technologies, namely pyrolysis, hydrothermal liquefaction and gasification; showed that with the available resources, biomass-derived compressed natural gas (bio-CNG) produced by gasification, methanation and upgrading is a potentially viable route to decarbonize transportation of heavy-duty trucks in Ireland. The focus of this chapter is to design a supply and distribution network for bio-CNG to replace diesel demand of forestry timber hauling fleets. A combined economic and spatial modelling technique presented by Singlitico et al. for supply chain of bio-SNG from forest residue is used as a reference for this study [39]. Spatial models have been built based on a *location-allocation* algorithm for locating and sizing forest residues, hypothetical demand for bio-CNG, and the residues-to-fuel biorefinery. An economic model calculates net present value (NPV) and levelised cost of bio-CNG ($LCOB_{cng}$), which is compared with incumbent wholesale price of diesel including carbon taxes.

3.2 Introduction

Global perspective over alternative sustainable biofuels for transportation have dramatically changed over past few decades due to raising environmental and societal impacts of fossil fuels. Europe's new economy decarbonisation framework – European Green Deal shows Europe's desire to become carbon neutral by 2050 [26]. Many EU countries with Germany in the lead are looking to expand on the potential of renewable gas (biomethane, bio-CNG) as alternative renewable fuels for transport sector in order to reduce their dependency on fossil fuels [44].

France in particular had highest growth rate for biomethane plant reaching a total of 67 installed plants in 2020 [45]. [12] Discusses the potential of biomethane as a transport fuel for heavy duty vehicles (HDVs) in the transport sector of Europe and states that by 2030 a total of 20 bcm/yr biomethane production is expected.

Ireland's transport sector accounted for nearly 40 % total energy related emissions in 2020 [26]. It is acknowledged that there is no single solution to decarbonize the transport sector, requiring multiple alternative fuels to work in tandem for different modes of transport. Effectively decarbonizing heavy duty fleets has always been a hurdle for electrification technologies due to their higher driving range, load capacity and charging time [26]. Renewable gaseous fuel can be potentially used in heavy-duty transport sector to drastically reduce the associated carbon emissions. Gas networks Ireland, Ireland's gas grid operator aims to facilitate the renewable gas industry by installing 70 CNG filling stations by 2028 [46]. Ireland's forestry sector produces residues that are largely unused by European standards. A circular economy approach can therefore be taken which uses forestry residues to produce bio-CNG to replace diesel used by forestry fleets. Currently the main product from the forestry sector in the Republic of Ireland (ROI) is timber logs from stems of spruce trees. Forest harvesting activities leave by-products in the form of forest residues, otherwise called "brash", on the forest floors. Although the previous study showed gasification as a suitable technology for Ireland, it did not consider geographical heterogeneity in feedstock cost, supply of resources to biorefinery, and demand of bio-CNG in Ireland. To further evaluate this concept of bio-CNG production from forest residues, a supply-distribution chain was needed, that is one of the objectives of analysis shown in this paper.

3.3 Motivation and Objectives

Bio-CNG produced by upgrading and compressing biogas has seen gradual increase in its application in the transport sector due to the need to replace fossil fuels such as diesel and petrol [10]. While typically produced via anaerobic digestion, bio-CNG can also be produced via gasification of woody feedstock and subsequent methanation [47]. Use of forest residues, which does not impinge on food supply, avoids food versus fuel concerns, opens a route to valorise an under-used residue. Forestry in Ireland is undergoing rapid expansion to nearly double forested area by 2035. Current forestry activities in Ireland produce up to 800,000 m^3a^{-1} of forest residues, defined as treetop to 7 cm in diameter, majority of which is left on forest floor as highlighted by [14]. This unused potential of forest residues can be mobilised to produce transport grade fuel for HDVs, as electrification of these vehicles, especially in remote regions, has proven difficult [48]. [39] provided an insight on using spatial modelling for economic optimization of bio-SNG (biomass-derived synthetic natural gas) supply chains from forest residues to inject into the Irish gas grid with 1-4 plant configuration scenarios. The study found that for a small country like Ireland, a single plant configuration produces lowest cost bio-SNG. Most of the biofuels used in the transport sector of Ireland were imported in 2015 [49]. [50] showed that indigenous renewable gaseous fuel such as bio-methane would be more beneficial to use in the transport sector rather than injected into a gas grid, provided the resources are in close proximity to the biorefinery. Timber fleets that transport merchandisable timber from forest to sawmill are suitable end users that could maximize the diesel offsetting impact of bio-CNG, by creating a circular economy and minimize the distribution cost of bio-CNG. Currently due to no demand for bio-CNG in Ireland and a lack of distribution infrastructure, it has to date been difficult to fully evaluate the economic benefits of bio-CNG in Ireland. A complete supply chain will require the size and locations of forestry residues, biorefinery, hypothetical demand of bio-CNG and filling stations.

Therefore, the objectives of this study are:

(1) To assess the potential demand of bio-CNG from timber fleets and optimally locate bio-CNG filling stations,

(2) To design a complete biorefinery supply and distribution network of bio-CNG by optimally locating a forest residue based biorefinery in Ireland and,

(3) To calculate the levelised cost and NPV of bio-CNG production by conducting techno-economic assessment of the designed supply chain.

3.4 Methodology

This study focuses on calculateng economic indicators such as $LCOB_{cng}$ and NPV by locating the biorefinery based on relative locations of forest residues and hypothetical demand of bio-CNG from timber hauling fleets. Therefore, it can be divided in to two parts: (1) design of a biorefinery supply and distribution network (BSDN), and (2) techno-economic assessment of biorefinery. The siting and sizing of locations in BSDN are done by using the ArcGIS *Location-Allocation* feature [51].

Several studies in the recent year have used spatial and mathematical optimization models in conjunction to design least cost (optimized) supply chains, which optimally locates biorefinery considering a large array of biomass supply and demand locations. [52] used spatial optimization to analyse the impact of four cost reduction strategies for biofuel production. [53]

used location-allocation to optimally locate anaerobic digesters maximizing biogas production in the UK. [54], in their research for locating a biomethane plant in Finland, used location-allocation to consider the wide distribution of biomass with an aim of minimizing transport distance to conversion facility and maximize biomass recovery. The most recent study using this methodology was conducted by [39] to optimally site and size a biorefinery producing bio-SNG for gas grid injection in Ireland. This study expands on the spatial model design of [39] by introducing a bio-CNG distribution chain in the form of filling stations. Economic and thermodynamics of the biorefinery was also taken from [39] with some modifications such as updated quantity of resource, cost of compressor and storage unit. Figure 3.1 shows a flow chart of BSDN method adopted for current study, which includes three location-allocation models described below in sections.

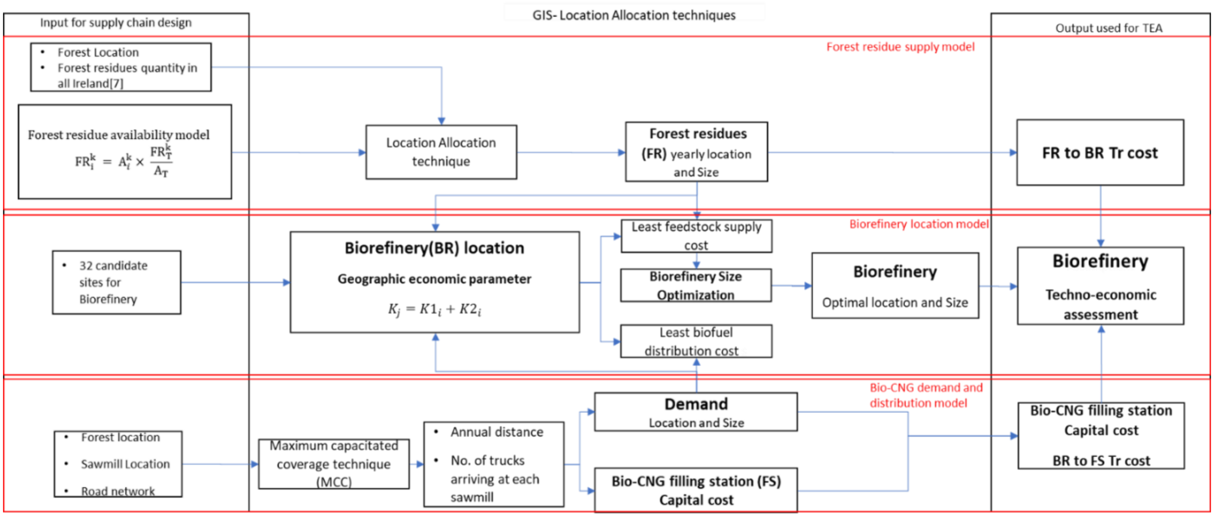

Figure 3.1: Flow chart for the integrated location allocation model in Biorefinery supply distribution network (This model is explored in detail from section 3.3.1.1 to 3.3.1.4)

3.4.1 Biorefinery optimal location and size

Initially this model places 32 equidistant biorefinery candidate sites *j* on the map and calculates an economic parameter called biorefinery location index K_j for each candidate location *j*. This parameter identifies the transport cost of delivering all forest residues $m_{FR,i}$ from forest location *i* and distributing all bio-CNG, $m_{bio-CNG,i}$ to bio-CNG filling station location *i* from each candidate location *j* calculated by Eq. (1) in units of €.

$$K_j = Trcost_{ij;m_{FR,i}} + Trcost_{ij;m_{bio-CNG,i}} \tag{1}$$

The candidate location with lowest cost of transporting both forest residues and bio-CNG to filling stations is selected. $Trcost_{ij}$ is transportation cost calculated by Eq. (2)

$$Trcost_{ij} = m_{FR/biocng,i}(Trcost_{Fix} + Trcost_{var} * dist_{ij}) \tag{2}$$

Where, $m_{FR/bio\text{-}CNG}$ is mass of forest residue and bio-CNG at location *i* and $Trcost_{fix}$ is fixed transport cost 4.96 €/t [39], $Trcost_{Var}$ is variable transport cost 0.11 €/km [39] and $dist_{ij}$ is distance from *i* to *j* calculated from location allocation model as shown in Figure 3.1. The candidate biorefinery site with lowest K_j indicates an optimal location, which has lowest unit cost of collecting forest residues and distributing bio-CNG to filling stations and thus is selected as location for biorefinery. Once a location of biorefinery is selected Eq. (8) is replaced by Eq. (3), where forest residues at location *i* is assigned to biorefinery location j only if the transport cost of forest residue $Trcost_{ij;m_{FR,i}}$ falls in an acceptable range i.e. less than $Trcost_{ij;m_{FR,i}\,Max}$. In other words all the expensive forest residues at location *i* are iteratively removed until t $LCOB_{bio\text{-}CNG}$ is minimized.

$$\sum_{j \in J} y_{ij} = \begin{cases} 1 & Trcost_{ij;m_{FR,i}} < Trcost_{ij;m_{FR,i}\,Max} \\ 0 & Trcost_{ij;m_{FR,i}} \geq Trcost_{ij;m_{FR,i}\,Max} \end{cases} \text{ for all } i \in I \tag{3}$$

3.4.2 Forest residue supply chain model

Ireland's forestry sector is mainly focused on harvesting timber, which is primary product of forest operations. Each forest property undergoes steps of planting/replanting, thinning, and clear-felling[55]. All planted properties are allowed to fully grow for approximately 35 years with occasional intermediate thinning before they are clear-felled and subsequently replanted for next cycle [55]. Although thinning operations generate some forest residues their quantity in Ireland is assumed too small and dispersed to be extracted from the forest floor [56]. Therefore, only forest residues produced during clear-felling operations are considered for this study. As forest residues are by-products that are produced during these operations, their available quantity and locations are dependent on property's timber harvesting schedule. Therefore, Eq. (4) is used to calculate the harvesting year of each forest property by iteratively adding 35 years to planting year until their value was ≥ 2020. This study considers year 2020 as the base year for all calculations.

$$P_{Hk} = P_{Pk} + 35, \; where\; P_{Hk} \geq 2020 \tag{4}$$

Where, P_{Hk} is the property harvest year, P_{Pk} is property plantation year. The All Ireland Roundwood Forecast provides an annual projection of all size category timber availability including forest residues from 2016-2035 [28]. The public and private forest property location data was sourced from Coillte, Ireland's state forestry agency, along with each property's planting year. Once harvesting schedule was acquired for each property, forest residues availability of year from roundwood forecast was distributed in forest properties to be harvested in same year, proportional to forest cover (area covered by the forest) using Eq. (5)

$$\mathrm{FR}_{\mathrm{i}}^{\mathrm{k}} = \mathrm{A}_{i}^{\mathrm{k}} \times \frac{\mathrm{FR}_{\mathrm{T}}^{\mathrm{k}}}{\mathrm{A}_{\mathrm{T}}} \tag{5}$$

Where, i is forest locations, k is scheduled year of harvest

- $\mathrm{FR}_{\mathrm{i}}^{\mathrm{k}}$ = Quantity of forest residues in property i in the year k
- $\mathrm{A}_{\mathrm{i}}^{\mathrm{k}}$ = Area of property i
- $\mathrm{FR}_{\mathrm{T}}^{\mathrm{k}}$ = Sum of all forest residues in Ireland in year k
- A_{T} = Sum area of all forest properties in Ireland

3.4.3 Bio-CNG demand and distribution model

We assume that sawmills could serve as suitable locations for bio-CNG fuelling stations. Bio-CNG demand and distribution model is designed to allocate yearly harvested timber to the nearest sawmills and convert the diesel demand for transporting timber to sawmills into hypothetical bio-CNG demand. To solve this, a location allocation solver that operates on Hillsman theory, *Maximum Capacitated Coverage model* (MCC) is used [57]. Three geospatial datasets; location of forest (origin points) with annual quantity of timber to be hauled by fleets , location of the sawmills that are end users of this timber (demand points), and detailed road network with major and minor roads to provide distance between any two given points as shown in Table 3.1. The mathematical formulations of this solver are listed in Table 3.3, where Eq. 6 is the objective function and Eq. 6-11 are constraints to which the objective function must adhere to give an optimum solution.

- I = The set of forest locations with annual timber availability (1…, i) (origin)
- J= The set of sawmill locations with annual timber requirement (1…, j) (destination)
- S= the service area covering standard facility
- $\mathrm{d_{ij}}$ = travel distance between origin and destination
- $\mathrm{a_i}$ = amount of timber in the forest location i
- p = total number of sites with timber demand
- $\mathrm{c_j}$ = total amount of timber supplied annually to sawmills by state forestry agency

This model allocates forest timber to nearest sawmill with unfulfilled timber requirement. If timber demand at the nearest sawmill is already met, the forest timber will be allocated to next closest sawmill with unfulfilled timber requirement. It is evident from Eq. 9 that all the timber available annually in forest is allocated to at least one timber demand location. The model gives distance d_{ij} travelled annually from each origin *i* to destination *j*, which is used to calculate diesel equivalent bio-CNG demand B_{total} created by timber hauling fleets at sawmill *j*, using Eq. 12.

$$B_{total} = (D_{TT} + D_{TFR} + D_{TB}) * \mathrm{f_{cons}} \quad (12)$$

Where, B_{total} is total demand of bio-CNG by timber fleets in kg, D_{TT}, D_{TFR}, and D_{TB} are transportation distance of timber to sawmills, forest residue to biorefinery and bio-CNG to filling stations respectively as shown in Table 3.2. f_{cons} is constant fuel consumption rate of bio-CNG heavy duty vehicles, 0.31 L/km [58]. Initially 5 Locations with highest bio-CNG demands are selected as filling stations and total annual refuelling distance trucks at neighbouring locations must travel are calculated in ArcGIS. More locations are added iteratively to decrease annual refuelling distance until the change in annual refuelling distance becomes insignificant.

This section will estimate capital cost for building bio-CNG filling stations. The components of a bio-CNG filling stations are compressor (for dispensing bio-CNG at 250 bar), gas dispenser (for dispensing gas into end user's vehicle) and high-pressure multi-storage (for storage of high-pressure gas). [15] in their study of strategic framework for bio-CNG infrastructure, showed that cost and size of a bio-CNG filling stations are directly dependent on a number of important factors such as; frequency of natural gas vehicles (NGV) refuelling at stations, refuelling time and the quantity of bio-CNG used by NGV. The locations with highest number of trucks per day, which consequently had highest bio-CNG demand, are selected as locations for bio-CNG filling stations. Eq. 12 & 13, which was taken from [15], calculates capital investment required for bio-CNG infrastructure. It should be noted that cost for pipe installation to connect filling stations to gas grid was also included in [15] which was not considered in this study as it is assumed that bio-CNG will be transported by trucks.

$$C_{FS} = 273{,}648 \ln(\mathrm{n}) + 491{,}859 \quad (13)$$

$$n_{i,j} = \frac{D_{i,J}}{NVW} \quad (14)$$

Where,

- C_{FS} = Capital cost of the bio-CNG filling station (in €)
- $n_{i,j}$ = number of trucks arriving for refuelling per day at
- $D_{i,j}$ is weight of demand at location *i* or j
- *NVW* is net vehicle weight, 30 tonnes [26]

Table 3.1: Description of data inputs used for design of supply and distribution chain of bio-CNG

		Attributes Used	
Input type	Input	Forest residues supply	Bio-CNG distribution model
Geospatial data	Forest residue location [33]	Yes, Forest location, harvesting schedule and area covered by the forest	Yes, same as resource mapping
	Sawmill location [33]	No	Yes, Sawmill location and total annual quantity of timber supplied by Coillte to each sawmill
	Road network [59]	No	Yes, Distance travelled by timber fleets in order to supply timber to sawmills
Excel Table	All Ireland Roundwood forecast [28]	Yes, Annual availability of forest residues (tip-7 cm, 7-13cm) produced by Coillte	Yes, Annual availability of merchantable timber (13-20 cm, 20+ cm) produced by Coillte

Table 3.2: Bio-CNG demand by trucks transporting timber, forest residue and bio-CNG

Bio-CNG demand	Description
$D_{TT} = \left(\sum_{k=1}^{n}\sum_{i=1}^{m} d_{ik}\right)$	where *i* is timber location and *k* is sawmill
$D_{TFR} = \left(\sum_{j=1}^{n}\sum_{i=1}^{m} d_{ij}\right)$	where *i* is forest residue location and *j* is biorefinery
$D_{TB} = \left(\sum_{j=1}^{n}\sum_{l=1}^{m} d_{jl}\right)$	where *j* is biorefinery and *l* is filling station

Table 3.3: Mathematical formulation of MCC model used for sizing and siting of bio-CNG demand in sawmills

Description	Function
Objective function Multi-objective function to maximize the amount of demand covered and simultaneously minimize total distance travelled between origin and destination	Maximize $z = \sum_{i\in I}\sum_{j\in J_i} a_i\ y_{ij} - \sum_{i\in I}\sum_{j\notin J_i} d_{ij}\ a_i y_{ij}$ (6)
1st constraint, to ensure all demands allocated to sawmills does not exceed the maximum limit of timber supplies by state forestry agency	$\sum_{i\in I} a_i\ y_{ij} \leq c_i x_j$ for all $j \in J$ (7)
2nd Constraint, specifies total number of sawmills to be located	$\sum_{j\in J} x_j = p$ (8)
3rd constraint, each origin is assigned to a destination	$\sum_{j\in J} y_{ij} = 1$ for all $i \in I$ (9)
4th constraint, to indicate that the decision variable x_j is a non-negative integer	$x_j = 0,1,2,\dots,p$ for all $j \in J$ (10)
5th constraint, restrict the continuous decision variable y_{ij}, which ranges from 0 to 1	$y_{ij} = (0,1)$ for all $i \in I$ (11)

3.4.4 Levelised Cost of bio-CNG and Net Present Value

The objective of technoeconomic model is to estimate $LCOB_{cng}$ and NPV to compare the economic competitiveness of bio-CNG versus incumbent diesel fuel. This biorefinery follows similar thermodynamic and economic model as described by [39] with some modifications such as cost of compressing bio-SNG into bio-CNG, bio-CNG storage and distribution to filling stations. Mathematical equations are presented and described below.

$LCOB_{cng}$ is calculated using Eq. (16) in unit €/kg and converted to litre diesel equivalent (€/LDE) using Eq. (17)

$$LCOB_{cng} = \frac{\sum_{y=0}^{LT} \frac{\mathrm{CF_{out,y}}}{(1+DR)^y}}{\sum_{y=0}^{LT} \frac{\mathrm{m_{bio-CNG}}}{(1+DR)^y}} \quad (16)$$

$$LCOB_{cng}\left(\frac{€}{LDE}\right) = LCOB_{cng} * \frac{HHV_{diesel}}{HHV_{bio-CNG}} \quad (17)$$

HHV for diesel and bio-CNG is 38 MJ/L and 9.3 MJ/L respectively. NPV is calculated using Eq. (18), *DR* is discount rate and *y* is project life time, both are listed in Table 3.5, CF_{in} is cash flow in calculated by Eq. (19) and CF_{out} is cash flow out, calculated by Eq. (20).

$$NPV = \sum_{y=0}^{LT} \frac{\mathrm{CF_{in,y}} - \mathrm{CF_{out,y}}}{(1+DR)^y} \quad (18)$$

$$\mathrm{CF_{in}} = \frac{\mathrm{E_{DAF,F}} * \eta_{\mathrm{bio-CNG}}}{3.6} * (\mathrm{P_{bio-CNG}} + \mathrm{Inc_{bio-CNG}}) + \frac{(\mathrm{E_{El,out}} - \mathrm{E_{El,in}})}{3.6} * (\mathrm{Inc_{El}}) \quad (19)$$

Where $E_{DAF,F}$ El_{out} El_{in} are in units GJ per annum, $\eta_{bio-CNG}$ is the conversion efficiency which is 65%, $P_{bio-CNG}$, $Inc_{bio-CNG}$ is price of bio-CNG 71€/MWh, incentive for biofuel 108 €/MWh [60] and Inc_{El} is electricity incentive. The Irish Renewable Energy Feed-in-Tariff for electricity production from biomass sources has values between 90 to 160 €/MWh, so a mean value of 125 €/MWh is used for Inc_{El} [61].

$$\mathrm{CF_{out}} = Capex + Opex + Trex \quad (20)$$

Where *Capex* is total capital expenditure calculated by Eq. (21).

$$Capex = C_{BR} + C_{TFS} \quad (21)$$

The total capital expenditure includes cost for both biorefinery (C_{BR}) and filling stations (C_{TFS}). All the capital cost is allocated to year 0. Capital cost of biorefinery C_{BR} is calculated using Eq. (22) which also includes cost of compressors and storage tanks for bio-CNG according to the size shown in Table 3.4. The cost of compressors and storage units was taken from [62]. EC_0 is purchased equipment cost, S_0 is base scale, *SF* is scaling factor, *IF* is installation factor.

$$C_{BR} = \left(\sum EC_0 * \left({S_N}/{S_0}\right)^{SF} * IF\right) * \left(1 + \frac{IC}{100}\right) \quad (22)$$

The total capital cost of filling station C_{TFS} is calculated using Eq. (13) & (23).

$$C_{TFS} = \mathrm{N} * C_{FS} \quad (23)$$

N is the number of filling stations. Total operation expenditure *Opex* is calculated by Eq. (24)

$$Opex = Opex_{fix} + Opex_{var} + Trcost \quad (24)$$

Where fixed operational cost is a percentage of total equipment cost given by Eq. (25) in units' Euro per annum.

$$Opex_{,fix} = C_{BR} * \frac{OC}{100} \quad (25)$$

Variable operation cost is calculated using Eq. (26), the inputs of which are given in Table 3.5.

$$Opex_{var} = \left(\frac{m_{FR} * P_{FR} + m_{C\&A} * P_{C\&A}}{1 - \sum \frac{VC}{100}} * 3600 + E_{used} * P_E\right) * O\mathrm{H} \quad (26)$$

Table 3.4: Cost inventory for calculation of installed equipment for bio-CNG production **[39]**

Equipment	Base cost (M€), C_0	Scaling factor, SF	Base scale, S_0	Units	Installation factor, IF
Grinding	0.153	1	2140	DT/day	2.47
Drying	0.321	0.7	1100	DT/day	2.47
Gasification	9.20	0.72	100	MW_{th} of biomass (LHV)	2.47
Ceramic filter	2.22	0.7	500	MW_{th} of biomass (HHV)	2.47
Oil Scrubber	18.0	0.65	135	497 Nm^3/h	1
Compression of raw Syngas	5.31	0.7	5.44	MW_e	1.32
Olefin hydrator	0.00311	0.67	65.77	t/h	2.47
HDS unit	0.00311	0.67	65.77	t/h	2.47
CO_2 and H_2S removal	18.5	0.65	12.62	kg/s of eq. CO_2	2.47
ZnO guard-bed	0.0271	1	8	Nm^3/s	3
WGS unit	0.383	0.56	44.66	kg/s	1
Pre-reformer	49.1	0.6	1277	kmol/h reformed	1
Methanation	0.0395	0.67	149.69	kg/s 1st reactor	2.47
Compressor [62]	0.48	1	310	gge/hr	1
Storage tank[62]	0.11	1	1560	Nm^3	1

Table 3.5: Parameters for calculation of ROI and Variable operation and maintenance cost of bio-CNG

Parameters	**Gasification**
Plant lifetime (y)	35 years
Discount rate (i)	10%
Fixed operating cost (OC)	8.39%
Variable Cost (VC)	13%
Feedstock price (€/t_{dry})	125
Electricity cost (€/MWh)	101
Operating hours (OH)	7500

The diesel wholesale price (excluding taxes) was 0.51 €/L taken from [63] with carbon tax levied based on life cycle GHG emissions of the fuel which for diesel is assumed to be 0.09 kg/MJ (3.19 kg/L) as reported by [18]. Ireland's Finance Act 2020 has prescribed a progressive increase of carbon tax by 7.5 €/t CO_2 from 2020 value (26 €/t CO_2) bringing the overall carbon tax to 100 €/t CO_2 by 2030[64]. Therefore, this study explores the effect of progressively increasing carbon tax (increment of 7.5 and 15 €/t CO_2) on the wholesale price of diesel. The sensitivity analysis was conducted by cost parameter (+ and – 30%) such as plant capacity, biofuel credit and prices of feedstock, electricity price and catalysts.

3.5 Results

3.5.1 Biorefinery supply and distribution network

Figure 3.2 shows two maps that visually represent biorefinery supply and distribution network. Location of the biorefinery shown in maps had lowest cost of transporting both forest residues from forests to biorefinery, and bio-CNG from biorefinery to filling stations. Therefore, it was selected as an optimal location as it gives the highest capacity for biorefinery at lowest feedstock and product transport cost.

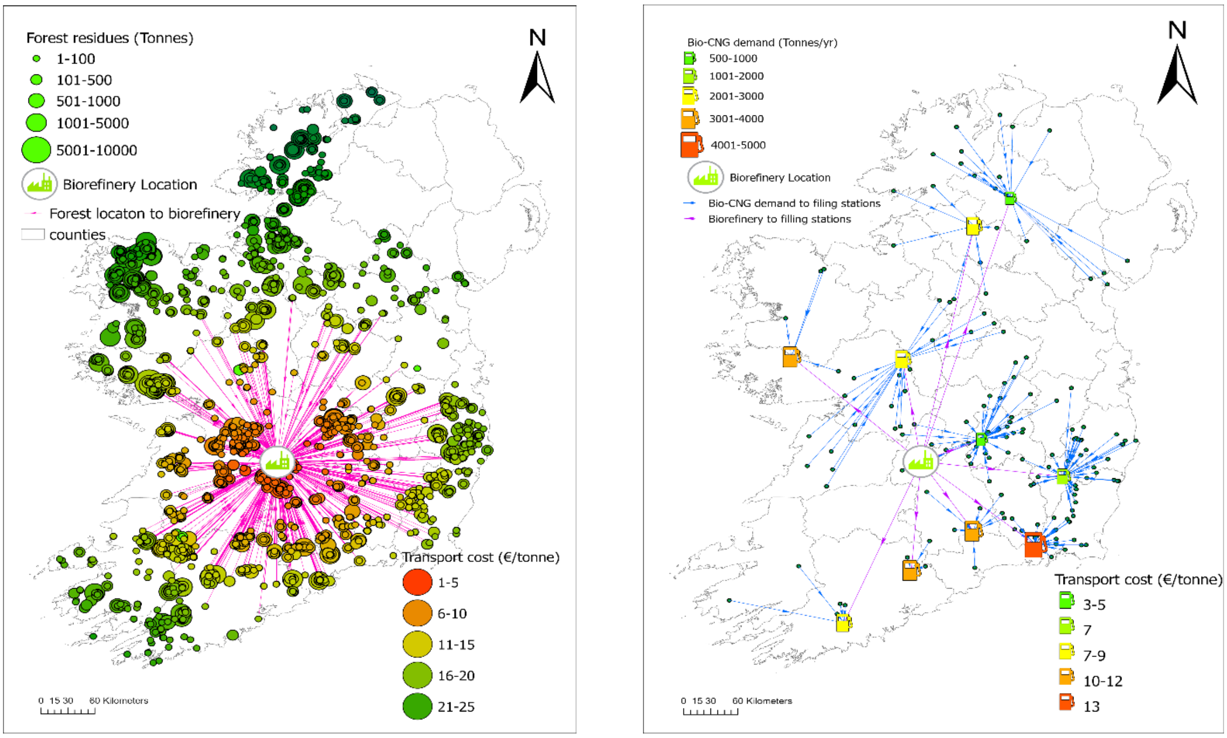

Figure 3.2: Map-1 quantity, location, and transport cost of forest residues to biorefinery; Map-2 quantity, location and transport cost of bio-CNG to 10 filling stations

If the capacity of biorefinery in unrestricted by mobilization constraints such as feedstock cost, all available forest residues are allocated to a single biorefinery location, resulting in a maximum capacity of 92 $MW_{bio\text{-}CNG}$ and $LCOB_{cng}$ of 1.18 €/LDE. Map-1 also illustrates locations and sizes of forest residues at different forest locations. It also shows the transport costs of forest residues to selected biorefinery location, ranging from 1 €/t for the closest forests, to 25 €/t for the farthest forest. Excluding the most expensive resources (21-25€/t) reduced biorefinery capacity to 75 $MW_{bio\text{-}CNG}$ and $LCOB_{cng}$ of 1.13 €/LDE. This shows that for capacities greater than 75 $MW_{bio\text{-}CNG}$ the transport cost of forest residues increases more steeply resulting in a lowest $LCOB_{cng}$ at this capacity. For clarity, exact road routes for transportation are not shown, but the straight line indicates which forest residues are allocated to the biorefinery. Map-2 in Figure 3.2, shows hypothetical demand of bio-CNG demand at large sawmill locations and its transport cost to filling stations. Bio-CNG filling station locations shown in Map-2 were selected from among the sawmill locations. 10 filling stations were chosen based on their higher demand of bio-CNG and proximity to other smaller bio-CNG demand locations. Map-2 gives more detail on the location and sizes of filling stations. A total of 239 trucks per day needs to be fuelled by the filling station with annual bio-CNG demand of 283501 MWh or 28 million LDE. Figure 3.3 shows the annual energy potential of forest residues, producible bio-CNG at full and optimized scale and demand of bio-CNG by forestry fleets. It is clear from the graph that all the bio-CNG demand can be met with the available feedstock size and 10 filling stations can cater to 100% bio-CNG demand of forestry fleets in Ireland with surplus bio-CNG that can meet up to 3.3% of HDVs energy demand according to SEAI 2021 report [65].

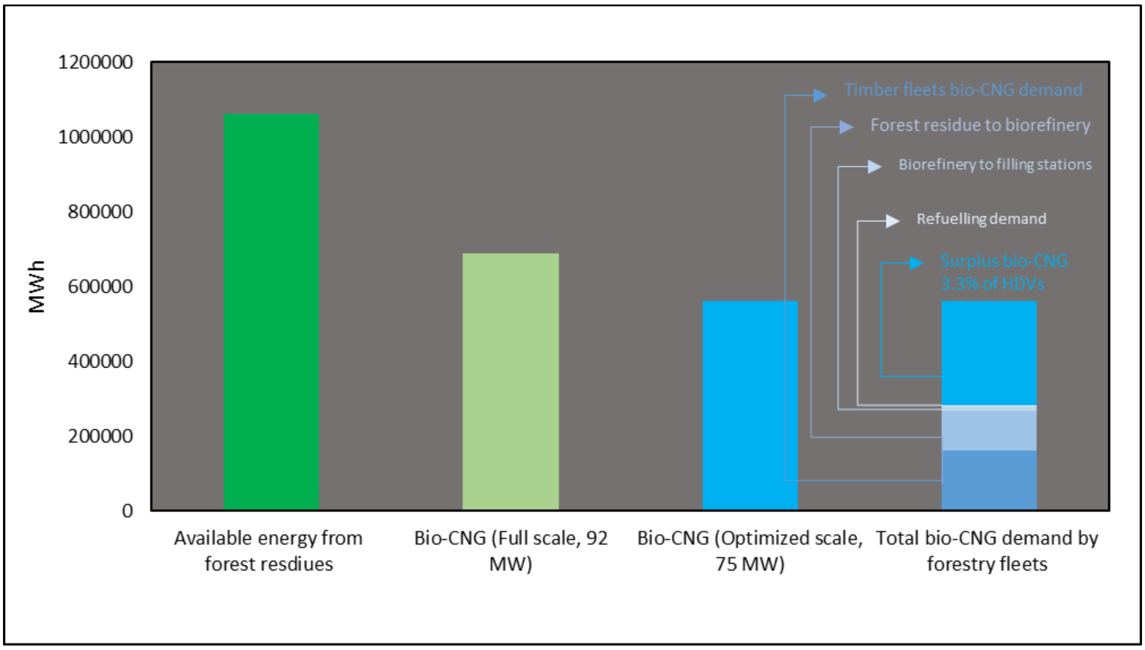

Figure 3.3: Annual energy potential of forest residues and bio-CNG demand of fleets

Table 3.6: Information on the selected locations of bio-CNG filling stations

Site	Location, County	No. of trucks refuelled per day	Capex of filling station (M€)
1	Dunmanway, Cork	36	1.8
2	Fermoy, Cork	20	1.3
3	Tramore, Waterford	44	2.1
4	Clonmel, Waterford	26	1.4
5	Tullow, Carlow	12	1.1
6	Durrow, Laois	13	1.1
7	Tuam, Galway	28	1.5
8	Headford, Galway	32	1.7
9	Enniskillen, Fermanagh	20	1.3
10	Omagh, Tyrone	8	1.1

3.5.2 Levelized cost of bio-CNG and Net present value

Figure 3.4, shows the techno-economic results and cost contribution towards Capex and Opex for two sizes of biorefinery, namely 92 $MW_{bio\text{-}CNG}$ (Full scale) and 75 $MW_{bio\text{-}CNG}$ (Optimized scale). Capex shown in the graph includes total capital cost of bio-SNG production from chapter 2, compression, storage and capital cost of 10 filling stations.

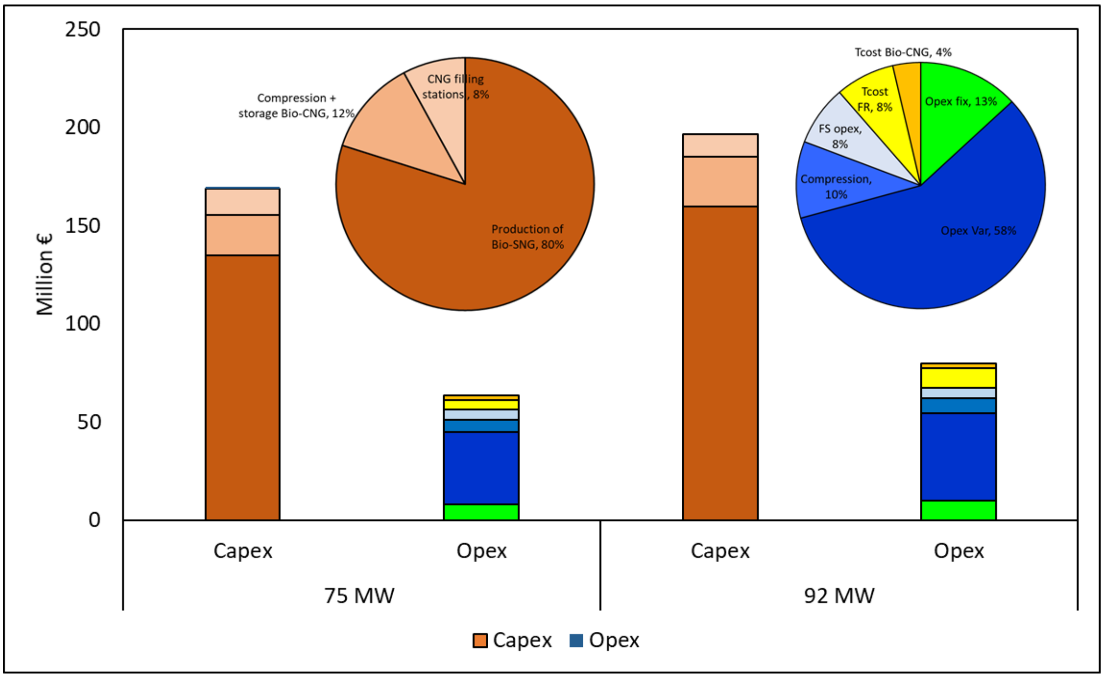

Figure 3.4: Techno-economic results showing Capex and Opex of two biorefinery size for bio-CNG production

Addition of high-pressure bio-CNG compressors, storage unit and filling stations resulted in 20% increase in total capital investment and 46% increase in total operating cost from the gasification scenario explored in Chapter 2. Higher operating cost was mainly attributed to electricity required for compression (0.028 $MW/MW_{bio\text{-}CNG}$), as shown by [66], transport cost of feedstock and operating cost of filling stations, which accounted for 10%, 8% and 8% contributions towards *Opex*, respectively. Figure 3.5 shows the $LCOB_{cng}$ in €/LDE for two biorefinery sized and compares them with wholesale prices of diesel with increasing carbon tax. At current rate of carbon tax (33.5 €/tCO_2, 2021) diesel price in units of €/L is 100% (92$MW_{bio\text{-}CNG}$) and 91% (75$MW_{bio\text{-}CNG}$) lower than $LCOB_{cng}$. However, when carbon tax in increased at a rate of 7.5 €/tCO_2 p.a. the gap between diesel and $LCOB_{cng}$ reduces significantly but it never breaks even. When carbon tax increment rate was assumed to be doubled (15

€/tCO$_2$ p.a.) LCOB$_{cng}$ of 75 MW$_{bio\text{-}CNG}$ biorefinery reaches parity with diesel prices in year 2035 and 2037 for 92 MW$_{bio\text{-}CNG}$ biorefinery size.

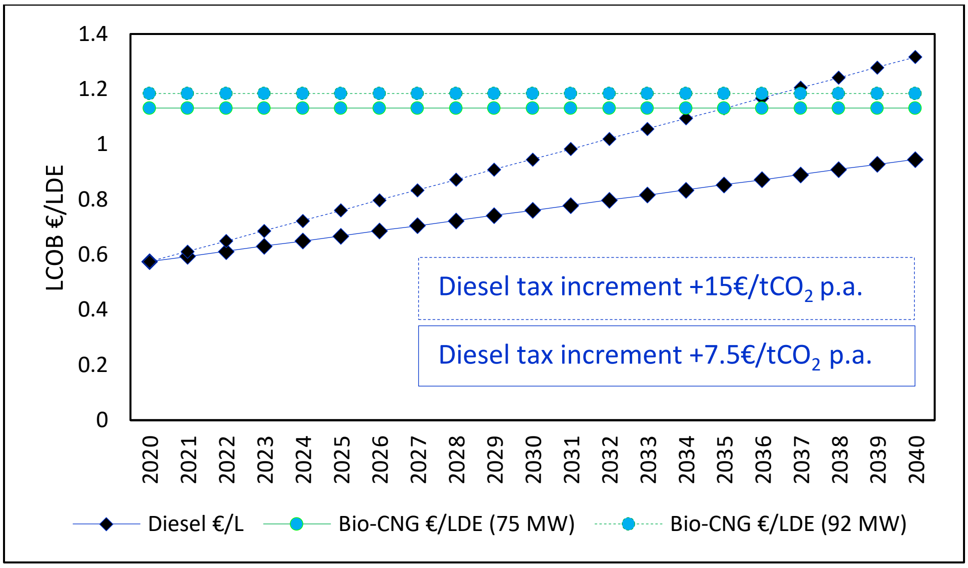

Figure 3.5: Comparison of LCOB$_{cng}$ with price of diesel (Including increments in carbon tax)

Figure 3.6 shows the results of profitability analysis. The NPV of the 92 MW$_{bio\text{-}CNG}$ bio-CNG biorefinery was calculated to be 486 M€ which is 57% higher than the NPV calculated in [39] for a single configuration bio-SNG plant (208.6 M€). This is mainly due to biofuel credit in the form of BOC that has a value of 108 €/MWh of 2nd generation biofuel. Which indicates that it is more profitable to produce and utilize bio-CNG due to its higher energy density and incentives.

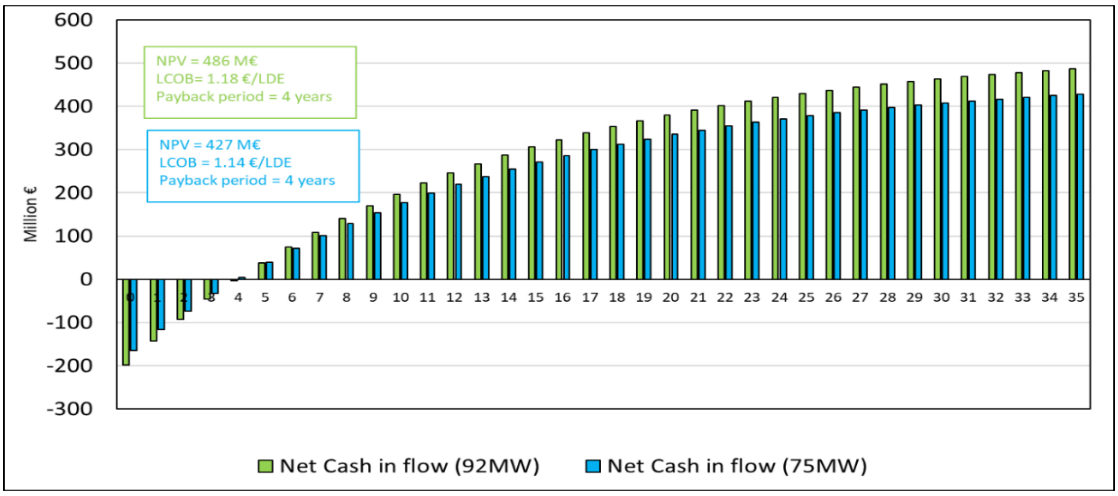

Figure 3.6: Results of profitability analysis

Figure 3.7 shows results of sensitivity analysis on $LCOB_{cng}$ and NPV. Sensitivity analysis was conducted by changing cost parameters by ±30% of their original value. NPV showed most sensitivity to changes in plant capacity and biofuel credit, and to a lesser extent, to feedstock price, total capital cost and operational costs. Variation in plant capacity (+ and –) of 30% would increase NPV to 783.6 M€ or decrease it to 86 M€. Similarly increasing the biofuel credit by 30% resulted in increased NPV (647 M€), whereas increasing the feedstock price resulted in decreased NPV (359 M€). As $LCOB_{cng}$ is independent of biofuel and electricity credit, changing their values had no effect on $LCOB_{cng}$. $LCOB_{cng}$ showed highest sensitivity to changes in plant capacity, feedstock price, total capital cost, compression operating cost and transport cost of forest residues respectively. As expected, variation in plant capacity (+ and –) of 30% would significantly reduce $LCOB_{cng}$ to 0.9 €/LDE or increase it to 1.5 €/LDE. Whereas, increasing feedstock cost, capital cost and other operational cost would negatively affect $LCOB_{cng}$ as shown in Figure 3.7. Therefore, it can be concluded that the most sensitive variables that affect both $LCOB_{cng}$ and NPV were plant capacity, biofuel credit, and feedstock price. Diesel prices have little to no impact on Levelised cost of bio-CNG as it was assumed that bio-CNG will be used for supply and distribution of Bio-CNG. However, changes in diesel prices were explored in the form of incremental taxes to determine the amount of incentive required in terms of diesel carbon tax for Bio-CNG to become economically competitive with diesel price gap between the prices of diesel and Bio-CNG, refer to Figure 3.5.

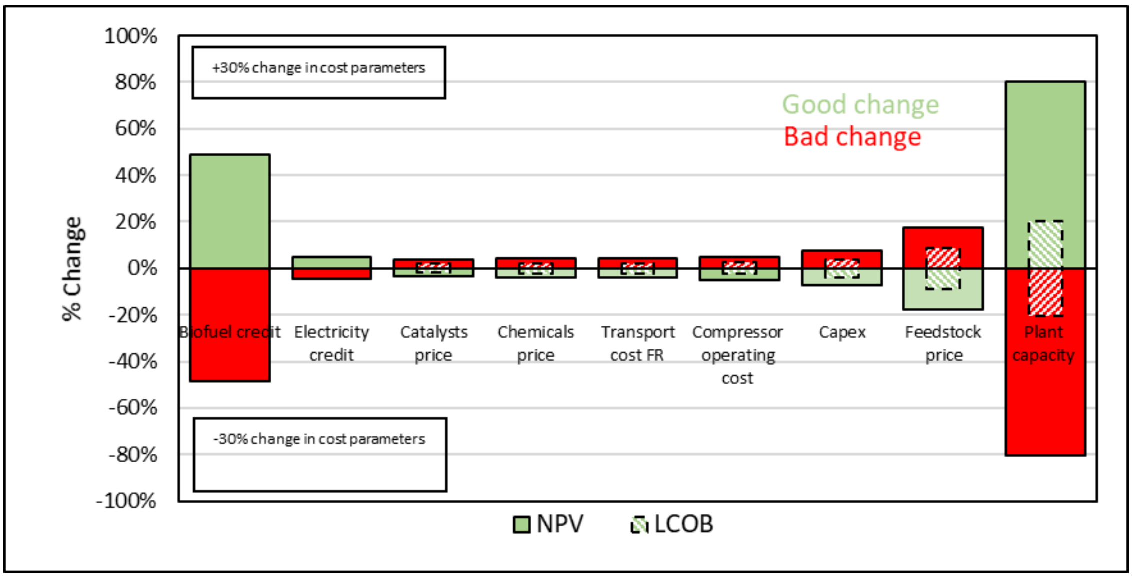

Figure 3.7: Sensitivity Analysis on $LCOB_{cng}$ and NPV based on ±30% change in cost parameters

3.6 Conclusions

This study presented a biorefinery supply and distribution network for a forest residue based biorefinery to produce bio-CNG. Using location-allocation algorithm in GIS environment, it evaluated the locations and size of forest residue, hypothetical bio-CNG demand and optimal maximum capacity of biorefinery in Irish context. $LCOB_{cng}$ and NPV was calculated to evaluate the techno-economic parameters of the supply and distribution network. An optimal location for a biorefinery with respect to location of resources and end demand was selected from candidate locations. Then lowest LCOBcng, which is determined by iteratively removing most expensive resources, indicated the optimal size of biorefinery to be 75 $MW_{bio\text{-}CNG}$. By using $LCOB_{cng}$ the competitiveness of bio-CNG system was compared with incumbent diesel prices. A sensitivity analysis was also conducted to evaluate the effect of changing cost variables on $LCOB_{cng}$ and NPV.

Results showed that the energy content of available forest residues is more than enough to meet the national bio-CNG demand of Ireland's timber hauling fleets with a single plant configuration of capacity 75 $MW_{bio\text{-}CNG}$. 100% of total bio-CNG demand can be practically met by placing 10 filling station at sawmill locations with the highest bio-CNG demand and proximity to other demand locations. Techno-economic analysis results showed that additional components such as bio-CNG compressors, storage unit and filling stations increased the capex by 20% and operational cost by 18%. If the capacity is unrestricted, biorefinery size can be up to 92 $MW_{bio-CNG}$ with the highest profitability (NPV,435 M€). This NPV for bio-CNG was 57% higher than NPV of bio-SNG indicating that it is more profitable to convert forest residues to bio-CNG for HDVs. However, unrestricted capacity adversely affects $LCOB_{cng}$ as feedstock transport cost increases steeply when it gets increasingly dispersed from the biorefinery location. When most expensive feedstock at the extremes of the island of Ireland were removed, the capacity significantly reduced to 75 $MW_{bio-CNG}$ but $LCOB_{cng}$ was only slightly reduced from 1.18 €/LDE to 1.13 €/LDE. The comparison of $LCOB_{cng}$ with diesel prices showed that at current carbon tax, bio-CNG produced is not yet cost-competitive with incumbent diesel for HDVs. However, doubling the yearly increment rate of carbon tax (from 7.5 to 15 €/tCO_2/year) resulted in $LCOB_{cng}$ reaching parity with diesel in 2035 and 2037 for the 75 $MW_{bio-CNG}$ and 92 $MW_{bio-CNG}$ biorefinery sizes, respectively. Sensitivity analysis showed that NPV was most sensitive to variations in plant capacity, biofuel credit and feedstock cost. $LCOB_{cng}$ showed most sensitivity towards feedstock cost and plant capacity. It can be concluded that bio-CNG production for replacement of diesel in HDVs is more profitable than producing bio-SNG for replacing natural gas in grid. But at current feedstock price, plant capacity and carbon tax, $LCOB_{cng}$ is still not competitive with diesel. Therefore, besides increasing carbon tax on diesel, more supportive policies and projects regarding bio-CNG to stimulate further technological advancement in bio-CNG infrastructure are required for it to become economically competitive with diesel in Ireland.

As this chapter focused on economic aspects of gasification scenario for producing diesel equivalent bio-CNG for HDVs, chapter 5 will explore the environmental benefits of replacing diesel with bio-CNG. Chapter 4 will expand on the pyrolysis scenario for production of hybrid diesel by co-processing upgraded pyrolysis bio-oil at an existing oil refinery. The effect of biochar valorisation will also be discussed in chapter 4.

4 Techno-economic assessment of crude bio-oil production from forest residues and effects of biochar valorisation as activated carbon

4.1 Chapter Overview

Pyrolysis of forest residues for production of upgraded bio-oil explored in chapter 2 showed least competitiveness with diesel wholesale prices due to higher capital and operational expenditure associated with upgrading pyrolysis bio-oil. However, several studies in recent years show that co-processing of crude bio-oil in oil refineries is a viable solution to avoid additional expenditure associated with standalone bio-oil upgrading. Crude bio-oil can be co-processed up to volume fractions of 5-10% with vacuum gas oil without any significant impact on quality and quantity of diesel produced at an existing oil refinery. Moreover, the excess biochar produced during pyrolysis can be sold to generate additional revenue, further bringing down the overall cost of production for biorefinery. Biochar has several desirable qualities such as high energy, carbon content and surface area, which makes it an attractive feedstock for production of activated carbon that has higher value than pyrolysis biochar. Therefore, this study will focus on conducting techno-economic assessment of a pyrolysis biorefinery co-producing crude bio-oil and biochar or activated carbon as by-product. The *location allocation* model in ArcGIS is used to design a supply and distribution network for a pyrolysis-based biorefinery. Crude bio-oil is transported to the only oil refinery in Ireland, located at Whitegate in Cork for co-processing. Economic indicators such as levelised cost of bio-oil is used to display and compare competitiveness of bio-oil with fossil-based counterparts. Net present value is used to compare the profitability of co-producing biochar with activated carbon.

4.2 Introduction

Pyrolysis is an attractive thermochemical technology due to its process simplicity, wide feedstock range and higher energy and mass yield of products [18]. Lignocellulosic biomass, such as forest residues, is converted to liquid, gas and solid phases using the pyrolysis technique, which is carried out at atmospheric pressure and high temperatures (400-500 °C) [67]. Non-condensable gases (NCG) are generally used for providing process energy for pyrolysis reactor [68], [38], whereas biochar has high energy and carbon content and can be utilized for generating process energy, upgrading bio-oil or for additional revenue [38], [69], [70]. Bio-oil is a complex mixture of water and organic compounds that has higher energy content than forest residues and is easier to handle and store [71]. However, it is still considered a low quality fuel as it is composed of highly reactive oxygenates that lead to low heating value, corrosivity, immiscibility and instability, which adversely affect its proper utilization as fuel [72]. These undesirable properties of crude bio-oil can be improved via downstream catalytic cracking or hydrodeoxygenation (HDO), which are commonly known as upgrading. Catalytic cracking eliminates oxygen from the vapours evolved during pyrolysis via formation of water, CO_2, and CO compounds resulting in much more stable bio-oil with less problematic oxygenates [73]. However, this upgrading process suffers from drawbacks such as significantly diminished oil yield, rapid catalyst deactivation and fact that the bio-oil is only partially deoxygenated [59]. Alternatively, bio-oil is almost completely deoxygenated using HDO, which is carried out at intermediate temperature (200-350°C) in the presence of pressurized hydrogen and heterogeneous hydrogenation catalyst [74], [75]. However, the HDO process requires significant quantities of hydrogen, resulting in higher operational cost [33]. HDO can also be carried out at milder condition, which consumes less hydrogen, reducing operational cost [76]. The techno-economics for in-situ upgrading of fast pyrolysis bio-oil using biochar was also discussed in Chapter 2.

It is obvious from the discussion above that upgrading is a complex process that not only significantly reduces pyrolysis bio-oil yield but also requires significant capital and operational expenditure. Several studies done in the past decade consider co-processing bio-oil at existing oil refineries that use similar upgrading techniques as a way of overcoming technical and economic barriers posed by standalone bio-oil upgrading [77], [72]. Co-processing bio-oil can be carried out at refineries with fluid catalytic cracking (FCC) and hydroprocessing techniques [78]. FCC is primarily used at oil refineries for processing heavy petroleum feeds into gasoline, diesel and other high quality fuels [79]. FCC is an advanced, flexible and widely used technique that can process even impure feedstocks with changes in catalyst and operating conditions, which makes it a suitable technique for upgrading bio-oil [80]. Moreover, co-processing bio-oil at oil refineries utilizes existing infrastructure for upgrading that can avoid additional capital and operational expenditure associated with conventional downstream upgrading techniques [81], [82]. This effectively enables the repurposing of existing fossil fuel infrastructure to renewables.

Traditionally, activated carbon (AC) is produced from charcoal. It has a wide range of application in chemical industries such as carbon catalyst or filtration units. Recent studies demonstrate other raw materials that can be used for production of AC, including bio-based feedstock such as coconut husk and wood [83], [84]. Biochar is a typical by-product of various thermochemical conversion pathways, such as fast pyrolysis, hydrothermal liquefaction, and gasification, that use bio-based feedstock. Biochar has desirable properties such as high carbon content and surface area, which make it an attractive precursor for solid carbon catalyst manufacturing [85]. However, chemical composition of raw biochar has several impurities such as Ca, K, P, Si, Mg, Na, Fe and Zn (typically known as biochar ash) that limit its application for production of AC [85]. Although these impurities can also exhibit catalytic activity that facilitates catalytic cracking and in-situ reforming of pyrolytic vapours to hydrocarbons and for hydrogen production [86]. For a biorefinery producing crude bio-oil for co-processing at an existing oil refinery, excess biochar becomes available for additional revenue generation. Today, physical and chemical methods are employed for conversion of biochar to AC. Acid washing is a typical chemical method used to remove mineral impurities from biochar. It is also necessary to increase the carbon content of biochar by removing hydrogen and oxygen that are responsible for formation of tar compounds [87]. Activation treatment is also performed to further increase the carbon content, surface area, porosity and active sites of biochar structure. Physical methods include exposing biochar to steam or CO_2 at high temperature (> 700 °C) [88].

4.3 Motivations and Objectives

As discussed in the previous section, fast pyrolysis of forest residues for production of crude bio-oil and biochar is an advantageous conversion pathway due to higher energy efficiency and mass yield of products when compared with other thermochemical technologies like hydrothermal liquefaction and Gasification. However, due to the undesirable qualities of bio-oil, it is difficult to handle and store, which necessitates bio-oil upgrading. Nevertheless, several studies have shown that upgrading process not only reduced the overall mass yield of bio-oil but also incurred additional capital and operational expense, which adversely affects the competitiveness of upgraded bio-oil with fossil-based counterparts such as diesel. The upgrading process can be circumvented by co-processing bio-oil at existing oil refineries. Ireland has only one major oil refinery, the Whitegate refinery, located in County Cork that uses imported crude oil for production of transportation fuel used domestically. Therefore, it could serve as a viable option for co-processing crude bio-oil that will not only help produce competitive crude bio-oil but will also increase the quantity of renewables in transportation fuel used for heavy duty vehicles (HDVs), which has proven to be hard to abate in Ireland and elsewhere, as discussed in previous chapters. However, to date, it has been difficult to evaluate potential of co-producing crude bio-oil and biochar from forest residues in ROI due to lack of data on CBO supply chain.

Therefore, the objectives of this study are:

1. To design a biorefinery supply and distribution network of crude bio-oil production from forestry residue.

2. To calculate economic indicators such as levelised cost and net present value of pyrolysis crude bio-oil production to compare its competitiveness with fossil-based counterparts.

3. To investigate and display effects of converting biochar to activated carbon on the economic indicators.

4.4 Methodology

4.4.1 Process description

The biorefinery scenarios explored in this study is based on non-catalytic pyrolysis scenario explored by [89]. The process flow sheet for biorefinery scenarios shown in Figure 4.1 can be divided in to six main sections, namely pretreatment, pyrolysis, product recovery, combustion, and steam and power generation for a biorefinery producing crude bio-oil (CBO) and biochar (BC) as by-products termed as CBO_{BC}. An additional activated carbon plant for CBO with activated carbon (AC) as by-product is considered in scenario 2 termed as CBO_{AC}. Information on mass and energy balance for each CBO scenario is given in Table 4.1. Pretreatment involves size reduction and drying of biomass to specified moisture content (MC from 40 to 8.28 wt%). Forest residues with MC 40% are first ground in a high-efficiency grinder with specific electricity requirement of 14 kWh/green tonne [38]. Ground biomass is then preheated through indirect contact with hot char and steam and through direct contact with flue gases before entering the pyrolysis reactor.

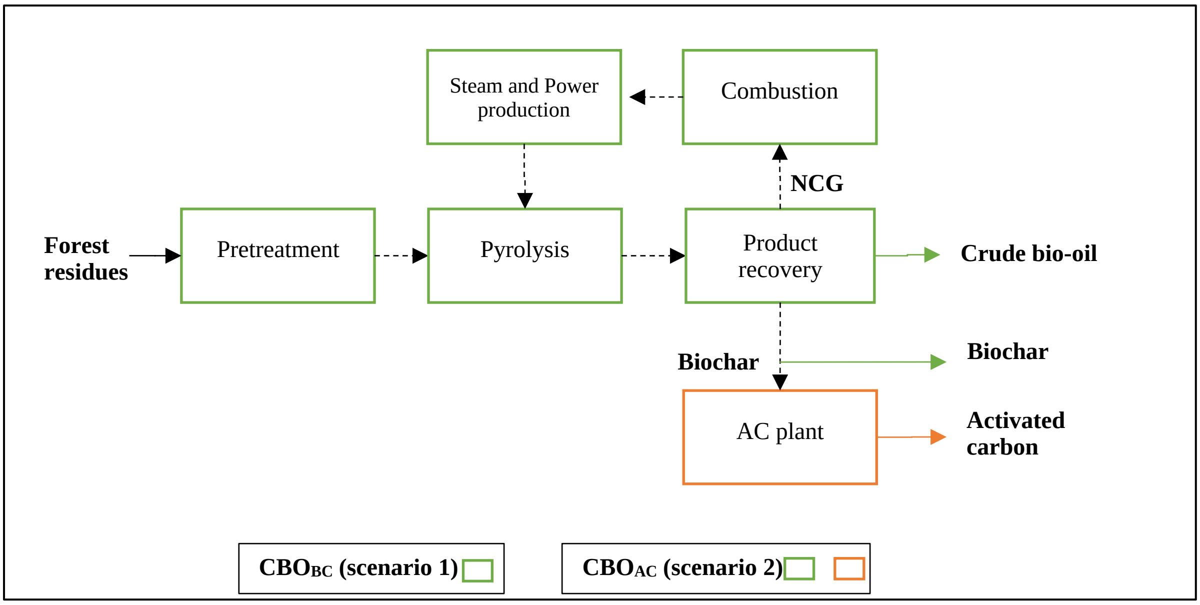

Figure 4.1: Process flow describing two biorefinery scenarios for production of crude bio-oil, biochar [89] and additional activated carbon plant [69]

The pyrolysis reactor operates at 500 °C and 1.013 bar. [89] showed that non-catalytic pyrolysis gives a product yield of 22.86 wt% bio-oil, 28.75 wt% char, 22.24% aqueous fraction and 26.05% non-condensable gases (NCG), as summarized in Table 4.1. The yield of bio-oil and char is dependent on factors such as residence time, reaction temperature and catalyst used during pyrolysis. [68] showed that catalytic pyrolysis of forest residues at 450 °C with CaO as catalyst can yield up to 34 wt% upgraded bio-oil and 26.0 wt% char yield. Furthermore, use of catalyst lowers the energy demand of the pyrolysis reactor due to exothermic formation of $CaCO_3$. After pyrolysis, solids and volatiles are first separated through a cyclone separator. The pyrolysis vapours are then condensed in a condenser train to separate bio-oil from NCG and aqueous fraction. NCG and 21 wt% of the char are combusted with preheated ambient air to meet the heat demand for the pyrolysis reactor [89]. The hot flue gases from the combustor are used for steam and power production, which is used to provide process energy for pyrolysis reactor.

Biochar is a common by-product of pyrolysis reactions. It has relatively high carbon content and surface area, making it suitable feedstock for activated carbon production, but it is generally used to meet the energy demand of the biorefinery [34], [90] or upgrading of bio-oil [38]. Recent studies have shown that it can be used to produce a wide range of high value products. Activated carbon is one such product that is produced by physical or chemical activation methods as shown by [85], [91]. Activated carbon has higher market value than biochar and therefore can potentially generate higher additional revenue. There is, however, a significant loss of biochar during the upgrading process. Studies displaying the economic impacts of biochar upgrading to activated carbon are scarce. [69] predicted the yield and surface area of activated carbon to be 0.2g_{BC}/g_{AC} biochar and 746 m^2/g respectively showing that conversion of BC to AC reduces by-product yield for CBO_{AC}. The additional capital and operational expenditure for the AC plant shown for the CBO_{AC} scenario was taken from [69].

Table 4.1:Mass and energy balance of pyrolysis biorefinery calculated using [28]

	Literature [89]	**This study**
Input		
Forest residues	813 dt/day, with 8.28% MC	779 dt/day, with 8.28% MC
Energy demand (includes, heating cooling and power)	1264 MWh/day	1129 MWh/day
Energy resources (NCG, 21% of biochar yield)	1080 MWh/day	960 MWh/day
Net Output		
Biochar	200 t/day	177 t/day
Bio-oil	176 t/day	178 t/day
Aqueous fraction	177 t/day	174 t/day
Surplus electricity	25 MWh/day	24 MWh/day
Energy efficiency	**63%**	**63%**

Table 4.2: Yield and higher heating values of components [89]

Components	Yield wt%	HHV, GJ/t
Forest residues	100	19.33
Bio-oil	22.86	26.3
Biochar	28.75	30
NCG	26.04	11.68
Aqueous fraction	22.34	-

4.4.2 Biorefinery supply and distribution network

The creation of the biorefinery supply and distribution network follows a similar method as shown in chapter 3. Using the *location allocation* technique in ArcGIS, forestry residues are allocated to the biorefinery location shown in Figure 4.2. It was observed in chapter 3 that transport cost associated with supply of forest residues to biorefinery had much higher impact on biorefinery economies than transportation cost of product distribution. Therefore, the location shown in the map was selected as optimal location for pyrolysis biorefinery as it gave lowest feedstock transport cost (see, Chapter 3).

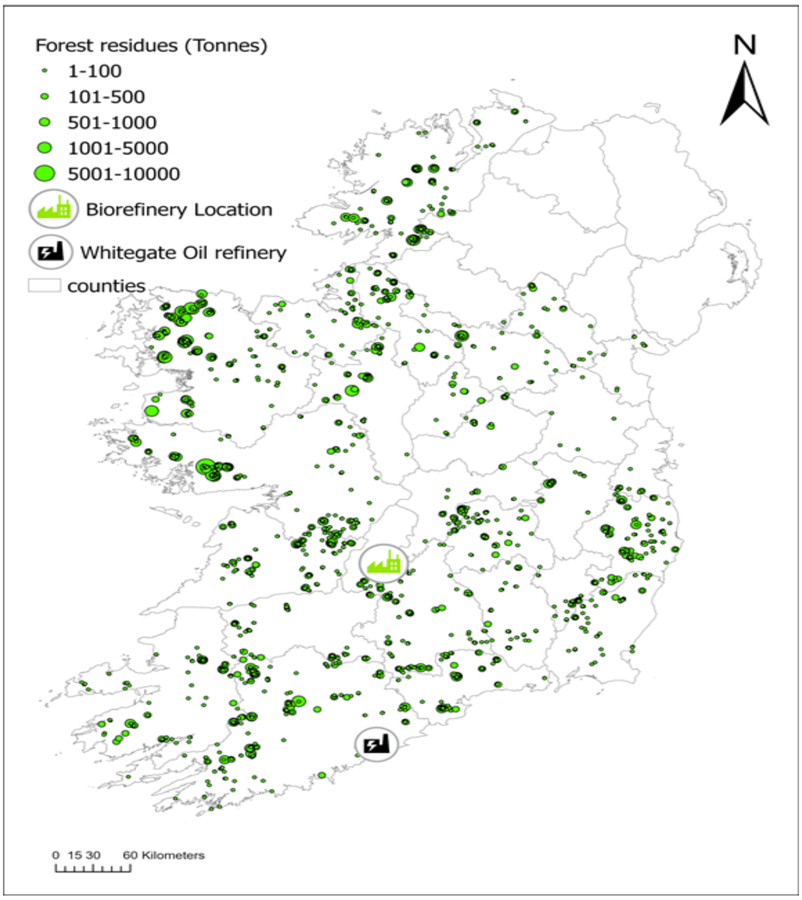

Figure 4.2: Map showing location of and size of forest residues, biorefinery and Whitegate oil refinery

Since this study investigated Ireland's potential for producing CBO, it was assumed that all forestry residues will be allocated to the biorefinery location. The only significant producer of diesel is Whitegate oil refinery in Cork. Therefore, it was assumed to be the destination of CBO for all scenarios explored in this study. Since no significant market for biochar or activated carbon was identified, for simplicity of economic comparison, a constant distance of 200 km from the biorefinery location was assumed to calculate their transportation costs.

Total transport cost is calculated using Eq (1) where, $m_{FR/BO/BC/AC}$ is the mass of forest residue (FR), bio-oil (BO), biochar (BC), or activated carbon (AC) at origin location i (forest locations for FR and biorefinery location for BO). $Trcost_{fix}$ is fixed transport cost 4.96 €/t [39], $Trcost_{Var}$ is variable transport cost 0.11 €/km [39] and $dist_{ij}$ is distance from i (origin) to j (destination) calculated from location allocation model as shown in Figure 4.2 . Destination j for FR is biorefinery and for BO is Whitegate oil refinery in Cork.

$$Trcost_{ij} = m_{FR/BO/BC/AC,i}(Trcost_{Fix} + (Trcost_{var} * dist_{ij}) \quad (1)$$

4.4.3 VGO and bio-oil demand at Whitegate oil refinery

Unlike electricity generation, which has multiple inputs but one output, oil refining has only one input, crude oil, and multiple outputs, gasoline, diesel, kerosene, and other heavy and light oils. In 2020, Whitegate oil refinery produced 1.3 Mtoe of diesel using crude oil [16]. Vacuum gas oil (VGO) is an intermediate produced by crude oil when it is cracked using FCC and consequent hydrotreatment (HDT) to multiple heavy and light oils [92]. Multiple studies in recent years show that VGO can be co-processed with fast pyrolysis bio-oil to produce gasoline and diesel. Up to 10 wt% of bio-oil can be co-processed with VGO without any significant changes in quality and quantity of gasoline and diesel [92]. [92] showed that approximately 21 wt% of VGO is converted to diesel while the rest is converted in to other light and heavy oils. Considering the diesel output of Whitegate oil refinery, 6.2 Mtoe of VGO would be required for 1.3 Mtoe of diesel production. With a 95:5 wt% ratio of VGO to bio-oil, about 0.31 Mtoe crude bio-oil is required to be co-processed for production of 1.3 Mtoe of diesel. However, at full capacity (779 dt/day FR), the modelled pyrolysis biorefinery has a throughput of 50 ktoe/a (0.05 Mtoe/a). This shows that at maximum capacity ROI has potential of replacing 0.8% of VGO with CBO, which would result in 0.2 Mtoe of hybrid diesel (95% VGO, 5% bio-oil) production.

4.4.4 Levelised Cost of Bio-oil and Net Present Value

This section describes the mathematical equations used to calculate LCOB and NPV for a pyrolysis biorefinery producing CBO_{BC} and CBO_{AC}.

$LCOE_{BR}$ was levelised cost of energy from biorefinery which is calculated using Eq. (2) in unit €/MWh and converted to $LCOB_{oil}$ using Eq. (3) in units €/L where E_{BO} is yearly energy out in units GJ/a

$$LCOE_{BR} = \frac{\sum_{y=0}^{LT} \frac{\mathrm{CF_{out,y}}}{(1+DR)^y}}{\sum_{y=0}^{LT} \frac{(net\ energy\ out)}{(1+DR)^y}} \quad (2)$$

$$LCOB_{oil} = \frac{\left(\frac{E_{BO}}{3.6} * LCOE_{BR}\right)}{Volume\ of\ BO_{yearly}} \quad (3)$$

$$NPV = \sum_{y=0}^{LT} \frac{\mathrm{CF_{in,y}} - \mathrm{CF_{out,y}}}{(1+DR)^y} \quad (4)$$

NPV was calculated by using Eq. (4) where $CF_{in,y}$ and $CF_{in,y}$ are yearly cash inflow and cash outflow, calculated by Eq. (5) and (6) respectively. *DR* is the discount rate as listed is Table 4.3, along with other major assumptions.

Table 4.3: Major assumptions for calculation of Levelised cost and NPV

Parameters	
Plant life time (y)	35 years
Operating hours/days (OH/days)	7500/312
Discount rate (*i*)	8%
Feedstock price (€/t_{dry})	125
Electricity price (€/MWh)	101
Electricity incentive (€/MWh), Inc_{EL}	125
Bio-oil selling price (€/t), P_{BO}	500
Bio-oil incentive for 2nd Gen biofuel (€/MWh), Inc_{BO}	108
Biochar selling price (€/t), P_{BC}	314
Activated carbon selling price (€/t), P_{AC}	4900

$$\mathrm{CF_{in}} = \frac{\mathrm{E_{BO}}}{3.6} * (\mathrm{P_{bio-oil}} + \mathrm{Inc_{bio-oil}}) + \frac{\mathrm{E_{BC/AC}}}{3.6} * \left(\mathrm{P_{BC/AC}}\right) + \frac{\mathrm{E_{El,out}}}{3.6} * (\mathrm{Inc_{El}}) \quad (5)$$

$$\mathrm{CF_{out}} = Capex + Opex + Trex \quad (6)$$

Capex is sum of total capital expenditure for the pyrolysis biorefinery and activated carbon plant given by Eq. (7). C_{AC} is calculated by scaling up AC plant to 163 t/day biochar input for this study as shown in Table 4.5.

$$Capex = C_{BR} + C_{AC} \quad (7)$$

C_{BR} is calculated by Eq. (8), where *WC* and *LC* are working capital and land cost as shown in Table 4.4.

$$C_{BR} = FCI_{BR} * \left(1 + \frac{WC}{100} + \frac{LC}{100}\right) \quad (8)$$

FCI_{BR} is the fixed capital invest for pyrolysis biorefinery, calculated by using Eq (9). Where EC_0 is installed equipment cost taken from Table 4.5, S_0 is base scale, S_N is new scale and SF is scaling factor. Where DC is direct cost that includes cost of warehouse site development and additional piping, IC is indirect cost that includes field expenses, construction fees, project contingency and other costs as listed in Table 4.4 .

$$FCI_{BR} = \left(\left(\sum EC_0 * \left({S_N}/{S_0}\right)^{SF}\right) * \left(1 + \frac{DC}{100}\right) * \left(1 + \frac{IC}{100}\right)\right) \quad (9)$$

Table 4.4: Parameters for calculating total capital cost of pyrolysis BR

Additional expenditure	%
Direct cost (DC)	13.3% of total installed equipment
Indirect cost (IC)	60% of total installed equipment
Working capital (WC)	5% of FCI_{BR}
Land cost (LC)	0.7% of FCI_{BR}

Table 4.5: Installed equipment cost for pyrolysis biorefinery

Equipment cost [1]	Installed Equipment cost (M€)[3]
Pretreatment	20.0
Pyrolysis	44.4
Product recovery	16.4
Combustion	2.4
Steam and Power production	6.5
HDT	9.3
Waste water treatment	6.4
Utilities	3.8
Storage	12.0
Activated carbon plant[3]	9.0

[1] Installed equipment cost for the pyrolysis biorefinery was sourced from [89], base scale S_0 was 745 dt/day and *SF* is 0.6
[2] Installed equipment cost were actualized using $CEPCI_{2021}$ (701) and 0.89 €/$\$_{2021}$
[3] Total capital cost for AC plant was sourced from [69], where base scale S_0 was 33 dt/day and *SF* is equal to 1.

Total operational expenditure, *Opex* in M€/a is sum of fixed, *variable Opex* of biorefinery, total annual transport cost for CBO_{BC} using Eq. (10) and an addition annual *Opex* of AC plant for CBO_{AC} as shown in Table 4.6.

$$Opex = Opex_{fix} + Opex_{var} + Opex_{AC} + Trcost \quad (10)$$

$Opex_{fix}$ is calculated by Eq. (11) where OC is 3% percentage of C_{BR}.

$$Opex_{,fix} = C_{BR} * \frac{OC}{100} \quad (11)$$

$Opex_{var}$ is calculated by Eq.(12) where m_{FR} is the mass flow of forest residues in units dt/hr, P_{FR} is the price of forest residues taken as 125 €/dt, *VC* is percentage of variable cost listed in Table 4.6.

$$Opex_{var} = \left(m_{FR} * P_{FR} \left(1 + \sum \frac{VC}{100}\right)\right) * OH \quad (12)$$

Table 4.6: Parameters for calculating variable operation cost BR and total operating cost for AC plant

Variable cost	% of Variable cost
Waste water treatment	0.74%
Process water	0.50%
50 wt% caustic soda (NaOH)	0.40%
BFW and cooling tower chemicals	0.22%
Ash disposal	0.06%
Operational expenditure of AC plant	40% of C_{AC}

4.5 Results

Figure 4.3 visually displays the calculated biorefinery supply and distribution network that minimizes forest residue transport costs. For clarity, exact road routes for transportation are not shown, but the straight line indicates which forest residues are allocated to the biorefinery. Location of the biorefinery shown in maps had lowest cost of transporting forest residues from forests locations to biorefinery.

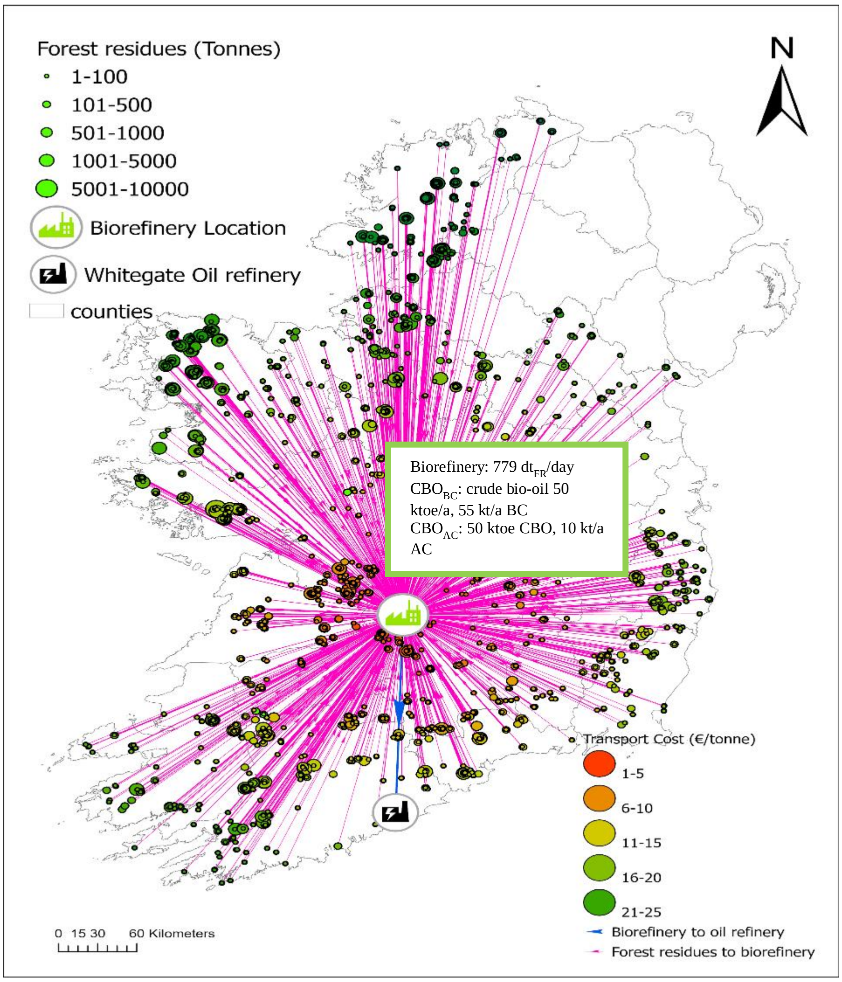

Figure 4.3: Results for biorefinery supply and distribution network of CBO_{BC} and CBO_{AC}

Therefore, it was selected as an optimal location as it gives the highest capacity for biorefinery at lowest feedstock transport cost, which had a more significant impact on economic indicators than bio-oil distribution. The biorefinery capacity is assumed to be unrestricted by mobilization constraints such as feedstock cost, thereby allocating all available forest residues to a single biorefinery location, resulting in a maximum capacity of 779 dt_{FR}/day. This biorefinery at maximum capacity can produce 50 ktoe of crude bio-oil and 55 kt of biochar for the CBO_{BC} scenario or 11 kt of activated carbon for the CBO_{AC} scenario. As discussed previously, at current size of feedstock CBO produced from pyrolysis biorefinery can replace 0.8% of VGO used at Whitegate oil refinery, which will result in 0.2 Mtoe of hybrid diesel (95% VGO, 5% bio-oil) production.

4.5.1 Techno-economic analysis results

4.5.1.1 Capital and Annual Operational Expenditure

Table 4.7 shows a summary of techno-economic results for CBO_{BC} and CBO_{AC} scenarios. Figure 4.4 shows a breakdown of total capital expenditure (*Capex*) of the 779 dt/day biorefinery producing crude bio-oil and biochar (CBO_{BC}) or activated carbon (CBO_{AC}) and compares it with capex of biorefinery producing only upgraded bio-oil (UBO, from chapter 2 corrected for 779 dt/day size). For UBO, the total installed cost accounted for 60% of capex, which included includes pretreatment, pyrolysis, and gas combustion also known an inside battery limit (ISBL), hydrogen production, upgrading and storage.

Table 4.7: Summary of results from techno-economic analysis for two pyrolysis biorefinery scenario

Techno-economic results	CBO_{BC}	CBO_{AC}
Capex (M€)	209.5	258.0
Opex (M€/a)	38.4	54.5
Revenue (M€/a)	41.3	42.3
LCOB (€/t)	580.0	865.0
NPV (M€)	330.9	185.2

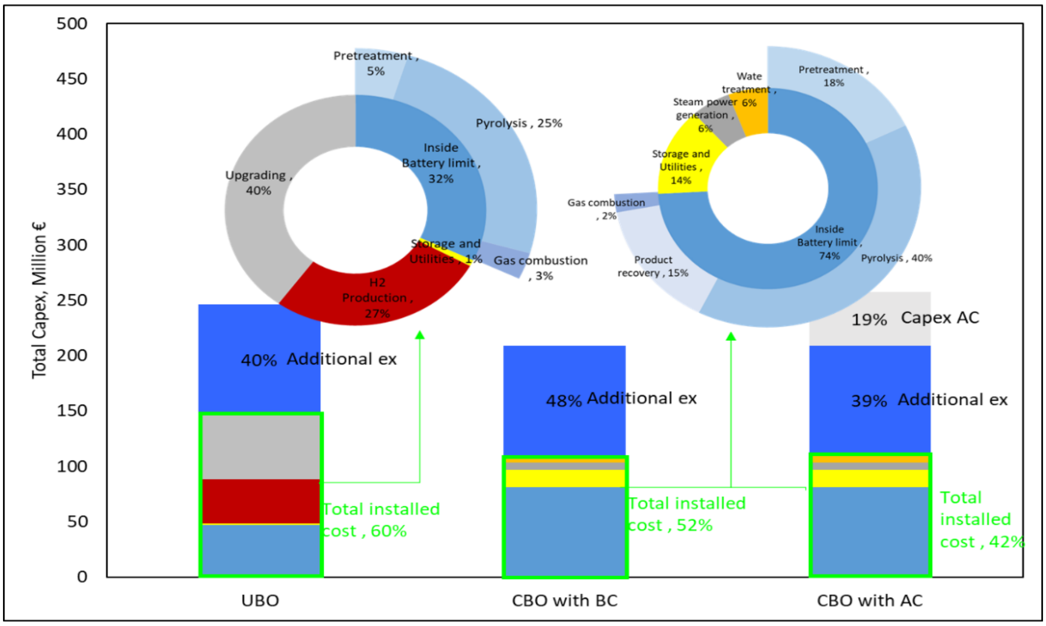

Figure 4.4: Total capital expenditure for biorefinery producing upgraded bio-oil (UBO), crude bio-oil with biochar (CBO_{BC}) or with activated carbon (CBO_{AC})

As discussed in chapter 2, the capital investment for the upgrading plant was significantly higher mainly due to the upgrading process and hydrogen production. [38] noted that, although production of bio-oil using pyrolysis is at commercial level, hydrogen production using biochar and consequent upgrading are at lab scale which means that the investment for these sub-processes can be expected to decrease overtime. Capex for CBO_{BC} and CBO_{AC} mainly consisted of total installed cost, additional expenditure (indirect, direct cost, working capital and land cost) and additional capex of AC plant (only for CBO_{AC}). The ISBL for both scenarios, accounting for 74% of total installed cost, was dominated by pyrolysis reactor (40%) followed by pretreatment (18%), product recovery (15%) and gas combustion (2%). Other installed equipment such as storage & utilities, steam & power generation and water & waste treatment accounted to 14%, 6% and 6% of total installed cost respectively. The total capex for CBO_{BC} scenario was 15% lower than upgraded bio-oil biorefinery, whereas addition of AC plant accounting for 19% of capex in CBO_{AC} resulted in 4.5% higher total capex than upgraded bio-oil biorefinery. This indicates that the scenario with activated carbon as by-product is most expensive in terms of total capex.

Figure 4.5 shows comparison and breakdown of total annual operating expenditure (*Opex*). The total fixed Opex, which included salaries, benefits & overheads, maintenance, insurance and taxes for CBO_{BC} and CBO_{AC}, was dependent on size of pyrolysis biorefinery and therefore, was slightly lower than fixed Opex calculated by [89] (10.21 M€, with 0.89 €/$\$_{2021}$). The total variable Opex included variable cost of pyrolysis biorefinery and total transport cost. The feedstock cost accounted for approximately 75% of total variable cost. The variable cost for the biorefinery was dominated by the feedstock cost, which was much higher than values reported by [89] mainly due to differences in feedstock cost (9.33 €/t_{dry} in [89] and 125 €/t_{dry} in this study). The total transport cost accounted for 23% of total variable cost, where the cost of transporting forest residues ($Trcost_{FR}$) accounted for 16.6%, transport of bio-oil ($Trcost_{BO}$) and biochar/activated carbon ($Trcost_{BC/AC}$) to Whitegate oil refinery accounted for 4.2% and 2.3%, respectively. The addition of an AC plant increased total *Opex* of CBO_{AC} by 34%. Total *Opex* of UBO was 49% and 10.9% higher than CBO_{BC} and CBO_{AC}, respectively, mainly due to the catalyst used for hydrotreating, hydrocracking and reforming during hydrogen production and upgrading process as reported by [38]. This shows that the *Opex* of UBO scenario is highest, even with addition of the AC plant Opex for CBO_{AC}.

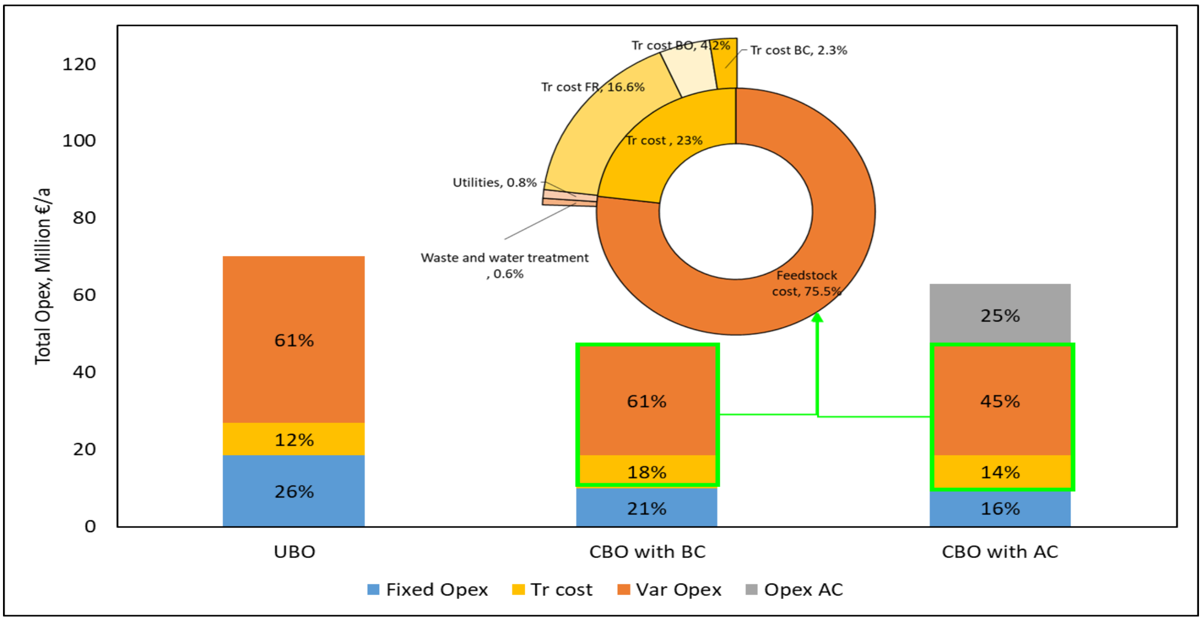

Figure 4.5: Total annual operating cost for CBO_{BC} & CBO_{BC} compared with UBO biorefinery

4.5.1.2 Levelized Cost of Bio-oil

Capex and *Opex* estimates were used to calculate the LCOB for each scenario. Figure 4.6 shows a comparison between LCOB for each scenario and their fossil-based counterparts. On an energy basis, upgraded bio-oil is closer to diesel (45 MJ/kg) and crude bio-oil is comparable to crude oil or VGO (25, 30 MJ/kg respectively). The market price of VGO was calculated by adding the crude oil distillation cost (13.81% of crude oil price) to the crude oil price [89]. LCOB for upgraded bio-oil was almost double the wholesale price of diesel, whereas the gap between CBO and crude oil/VGO was significantly lower. However, addition of an AC plant increased the gap between crude bio-oil and crude oil by twofold. The higher LCOB of UBO can be attributed to its superior quality that is associated with higher annual expenditure and lower bio-oil and biochar yield as shown previously. Co-producing bio-oil and high quality biochar increased not only the overall energy efficiency (63%) but also overall mass yield (89 wt%) [89] of pyrolysis process as opposed to UBO scenario (energy efficiency 40%, mass yield 16 wt%) [38]. This resulted in significant economic advantage for intermediate pyrolysis process co-producing crude bio-oil and biochar whereas co-producing AC had much lower yield (0.2 t_{AC}/t_{BC}), which reduced the overall efficiency and mass yield of pyrolysis process.

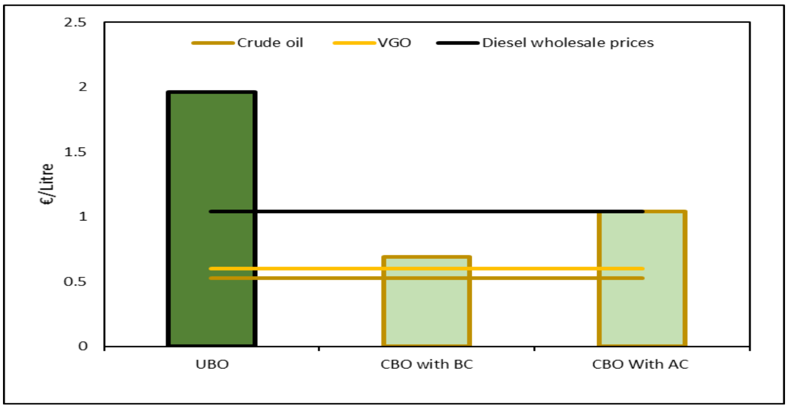

Figure 4.6: Levelised cost of bio-oil compared with their fossil-based counterparts

4.5.1.3 Net Present Value

Figure 4.7 shows and compares the results of net cash inflow for CBO_{BC} and CBO_{AC}. Net cash inflow includes revenue generated by bio-oil, bio-oil credit in the form of biofuel obligation certificate (BOC 108 €/MWh), sales of surplus electricity to the grid, and sales of biochar/activated carbon. The NPV for CBO_{BC} scenario (330.9 M€) was almost twice the NPV of CBO_{AC} (185.2 M€). This difference in NPV was primarily attributed to higher *Capex* and *Opex* associated with co-producing AC for CBO_{AC}. Although the selling price of AC (4.9 €/kg) considered in this study was much higher than that for biochar (0.31 €/kg), the revenue generated by co-products was also dependent on their final mass yield, which was much lower for AC when compared to BC.

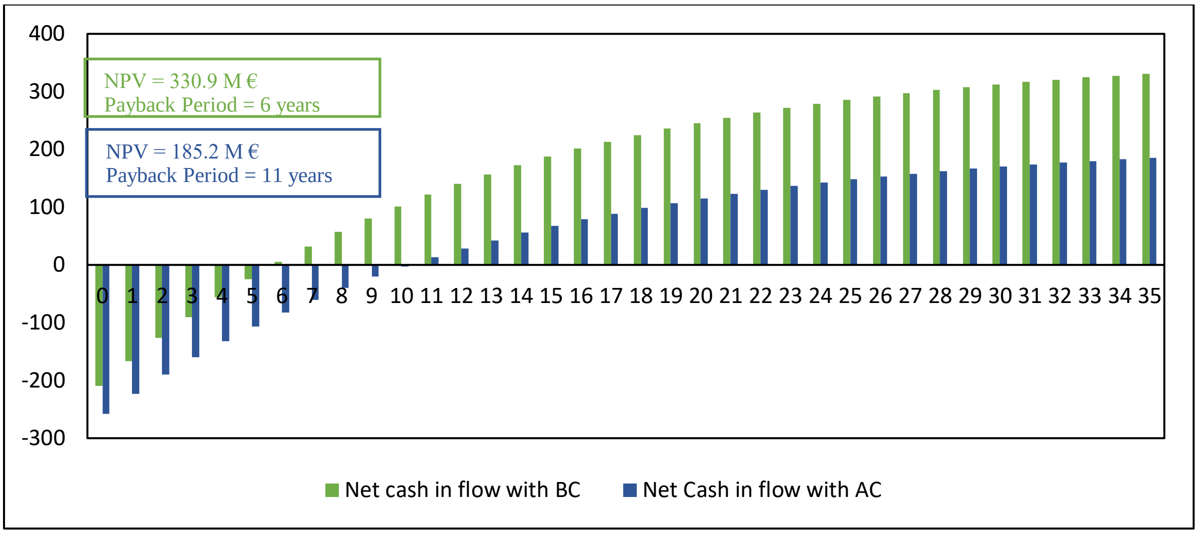

Figure 4.7: Net cash inflow and Net present value for biorefinery scenarios with crude bio-oil (main product) and biochar or activated carbon as co-products

4.5.2 Sensitivity Analysis

Figure 4.8, shows results of sensitivity analysis on LCOB and NPV for CBO_{BC} scenario. Sensitivity analysis was conducted by changing the cost parameters by ±30% of their original value. LCOB showed highest sensitivity to yield of biochar, bio-oil, and feedstock price. Increasing the yield of biochar and bio-oil by 30% lowered LCOB by 13% and 12%, respectively. Since LCOB is dependent on net energy output from biorefinery, it was slightly more sensitive to biochar yield than bio-oil mainly due to the higher energy content of biochar (30 MJ/kg). Decreasing feedstock price by 30% lowered the operational expenditure of the biorefinery, reducing LCOB by 13%. Feedstock price considered in this study was 125 €/t_{dry}. This is because, in current infrastructure of Irish forestry sector, extraction of forest residues is much more expensive than roundwood [40]. However, with investments in advanced forestry equipment and improvements in forest residue harvesting and extraction techniques, the price of forest residues can be reduced to 95 €/dt by 2030 [40]. Changes in the capital expenditure of biorefinery and plant capacity had ±8% and ±4% impact on LCOB respectively.

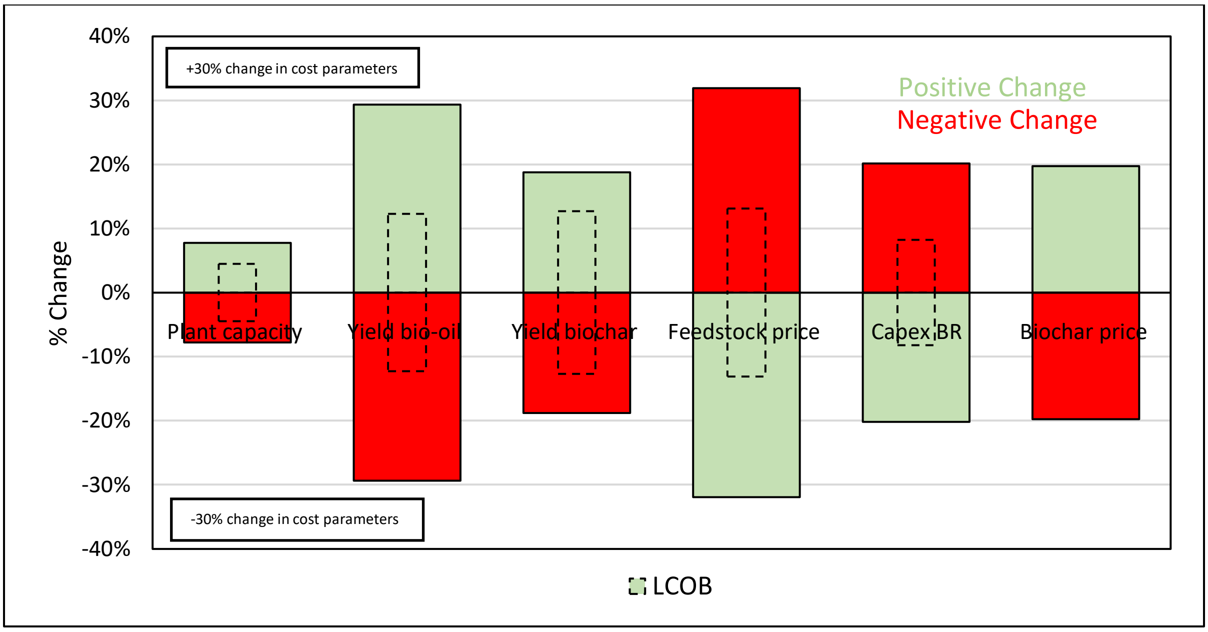

Figure 4.8: $LCOB_{cng}$ and NPV Sensitivity Analysis for CBO_{BC} scenario

NPV showed highest sensitivity to ±30% changes in feedstock cost and bio-oil yield. Decreasing cost parameters such as feedstock price and capex by 30% reduces cash outflow of the biorefinery, resulting in positive changes for NPV. Increasing bio-oil and biochar yield increases the cash inflow (revenue), resulting in positive changes in NPV. It is important to note that changing plant capacity should have more impact on NPV. However, at higher capacities, operational cost increases significantly due to higher feedstock cost, which balances cash inflow and outflow of the biorefinery. Therefore, it can be concluded from the sensitivity analysis that feedstock cost is the most dominant cost parameter for a pyrolysis biorefinery producing bio-oil and biochar.

4.6 Conclusions

This study presented a biorefinery supply and distribution network for co-producing crude bio-oil as well as biochar or activated carbon from forest residues. With an objective to evaluate Ireland's potential for producing crude bio-oil for co-processing at Whitegate oil refinery, all forestry residues were assumed to be allocated to a single biorefinery location, with a maximum capacity of 779 dt/day (8.28% MC) using the location allocation technique in ArcGIS. At current size of available feedstock (maximum capacity), the modelled biorefinery could produce 50 ktoe of bio-oil, as well as 55 kt of biochar or 11 kt of AC. Considering this production volume of bio-oil, it was determined that 0.8 wt% of VGO used at Whitegate oil refinery for diesel production can be replaced by crude bio-oil.

A techno economic model was developed to analyse capital and annual operational expenditure of co-producing bio-oil with BC or AC and upgraded bio-oil. CBO_{AC} had highest *Capex* (8% and 33% higher than UBO and CBO_{BC} scenarios) mainly due to additional expenditure for AC. UBO has highest *Opex* (8% and 26% higher than UBO and CBO_{BC}) primarily due to catalyst cost associated with hydrogen production from biochar and upgrading. The economical competitiveness of bio-oils was compared with their fossil counterparts (diesel for UBO and crude oil/VGO for CBO) using indicators such as levelised cost of bio-oil (LCOB). LCOB of CBO_{BC} was unsurprisingly lowest among the scenarios explored due to higher energy efficiency and mass yield. Addition of AC plant raised the LCOB of CBO_{AC} by 50%. LCOB of UBO was highest due to its superior quality that is associated with higher annual expenditure and lower bio-oil yield. LCOB of CBO_{BC} showed higher competitiveness with its fossil counterpart than UBO and CBO_{AC}. The profitability of biorefineries coproducing bio-oil with BC or AC were compared using NPV as an indicator. Although AC had higher selling price than BC, the NPV of CBO_{AC} was lower due to lower yield of AC as compared BC in CBO_{BC}. This resulted in an NPV of CBO_{AC} half of that of CBO_{BC}, indicates that at current size of feedstock available in ROI, it is more profitable to co-produce biochar than activated carbon. A sensitivity analysis was conducted on the LCOB and NPV of the CBO_{BC} scenario by changing significant cost parameter by ± 30%. It was observed that LCOB and NPV were most sensitive to changes in biochar yield, feedstock cost and bio-oil yield.

5 An environmental sustainability analysis of biofuel supply chains

5.1 Introduction

Current global energy infrastructure, which is primarily dependent on fossil fuels, has been proven to be unsustainable due to depleting resources, increasing energy demand and unprecedented climate change. To accommodate increasing energy demand while simultaneously curbing global temperature rise, residue to biofuel systems have been proven by several studies to be a viable alternative energy source [93]. Waste or residues are commonly perceived as low value by-products of crops or wood harvesting activities that are generally left in the field to provide nutrients to soil and prevent erosion. However, due to their high organic content it becomes appropriate to recover residues for producing bioenergy thereby providing an alternative energy source with significantly lower environmental impacts than convention fossil based resources [94], [50], [95]. Supply chains are increasingly becoming key enablers for the cost-effective and efficient large-scale mobilization of waste bioresources such as agricultural and forest residues [96]. However, it is important to address critical issues related to climate and sustainability effects of these residue to biofuel supply chain systems.

Life cycle assessment (LCA) is among the leading framework for evaluating and assessing environmental impacts of any product system, from feedstock production to final end use. Since the 2000s, LCA has received increasing attention to evaluate several bioenergy systems that utilize traditional biomass feedstocks such as crops, herbaceous plants and waste-based feedstocks such as municipal solid wastes [97], [98]. More recently, LCA studies have started focusing on non-traditional biomass feedstocks such as algae, seaweed and waste residues from harvesting activities [99], [100]. LCA is commonly divided in to attributional LCA (A-LCA) or consequential LCA (C-LCA) depending on system boundaries and the type of environmental impacts studied. A-LCA shows ‘potential environmental impacts that can be attributed to a product over its life cycle, i.e. upstream along the supply-chain of feedstock and downstream following the end use/disposal of products [101]. On the other hand, expanding the scope of study to include feedback effects of decisions made in the foreground (residue to biofuel system) and consequences in background systems (substituting fossil fuels) leads to C-LCA [101].

5.2 Motivations and Objectives

As biofuel supply chains move from concept to reality, there is a need to develop a systematic approach to assess their environmental impact. Recent work on advanced biofuel (Bio-SNG) supply chain design show that those optimized for techno-economic performance may not necessarily have optimized environmental impact [102]. It is therefore necessary to integrate methods for the design, sizing, and mapping/siting of supply chains with life cycle assessment (LCA), which is a state-of-the-art tool to determine environmental impact. This integrated approach must be applicable to a wide range of supply chain archetypes covering diverse bioresource and bioproduct categories. This work aims to provide a framework for environmental sustainability analysis of the two residue to biofuel supply chains previously identified. Therefore, the objectives of this work are:

1. To design a life cycle assessment framework biofuel supply chains.
2. To determine environmental impacts by calculating the global warming potential (GWP_{100}) of each supply chain scenario.

5.3 Methodology

The environmental sustainability of the residue to biofuel production system is assessed through the LCA methodology to analyse and compare their global warming potential fossil-based counterparts. Figure 5.1 shows an overview of LCA methodology employed in this study. LCA methodology is based on ISO 14040 [103] and 1SO 14044 [104] standards using OpenLCA [105] (open source software) with the Ecoinvent 3.4 database [106].

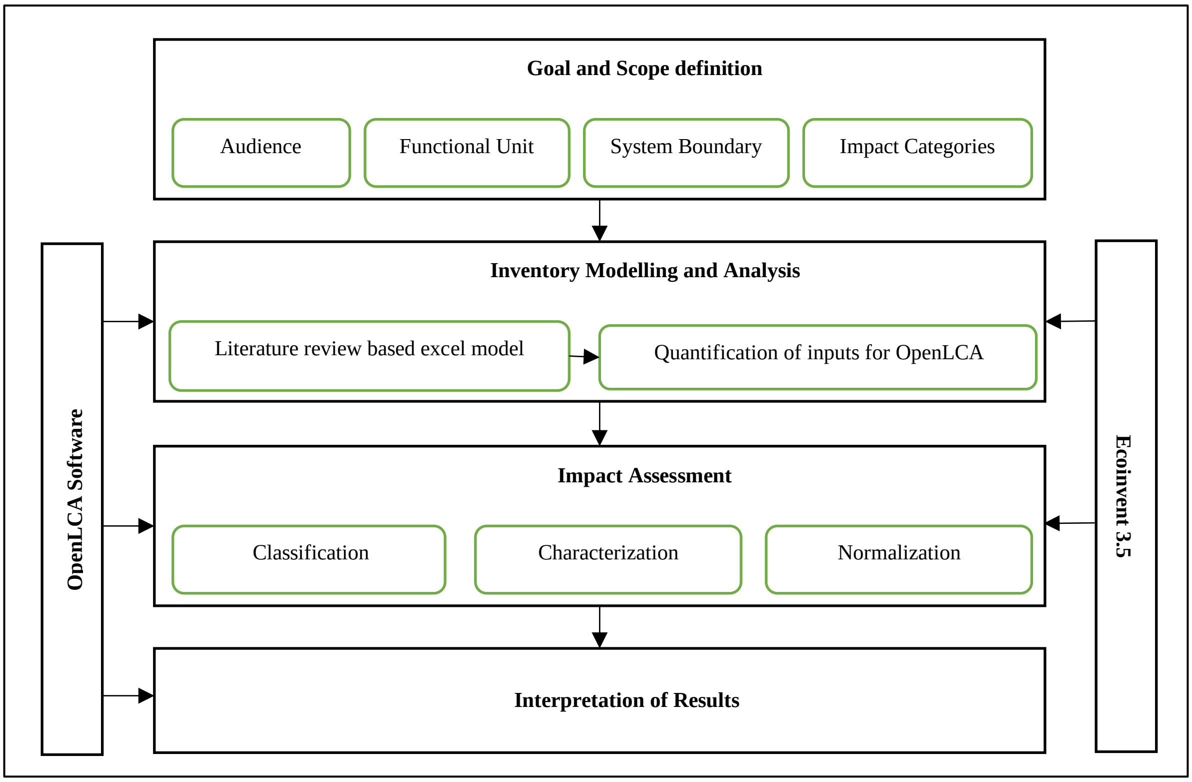

Figure 5.1: Life cycle assessment methodology description

5.3.1 Life cycle assessment goal and scope

In this study, the C-LCA approach was applied to evaluate the environmental impacts of the residue to biofuel supply chains as summarized in Table 5.1. The goal of this C-LCA is to assess environmental impact per unit of energy output. Therefore, the functional unit was set to 1 GJ of bio-CNG or crude bio-oil. Supply chain 1 uses forest residues for producing bio-CNG (biomass-derived compressed natural gas) at a hypothetical biorefinery location in ROI, as shown in Chapter 3. The end-users for bio-CNG are assumed to be timber fleets currently running on diesel. Therefore, production and end use of diesel was selected as the reference system for supply chain 1. For supply chain 2, forest residues are used to produce crude bio-oil (CBO) and biochar (BC) at a hypothetical biorefinery location shown in chapter 4. The end use of CBO is used for co-processing with crude oil/vacuum gas oil to produce hybrid diesel (95% VGO: 5% CBO) at Whitegate oil refinery in Cork. Therefore, production and end use of diesel was selected as reference system for supply chain 2.

Table 5.1: Summary of residue to biofuel supply chain archetypes

Supply chain	Supply chain 1	Supply chain 2
Feedstock	Forest residues also classified as unmarketable wood tip-7cm in diameter	Forest residues also classified as unmarketable wood tip-7cm in diameter
Conversion pathway	Gasification, gas cleaning, methanation and compression	Pyrolysis, biochar separation, co-processing with vacuum gas oil and hybrid diesel production
Final product & end use	Biomass-derived compressed natural gas (Bio-CNG) **End use** Transport fuel for forestry fleets	Pyrolysis Oil based Hybrid diesel **End use** Transport fuel for fleets Biochar as soil fertilizer
Reference system	Diesel production and combustion in forestry fleets	Gasoline and diesel produced from fossil-based resources (i.e. crude oil) and fuel combustion
Literature	[102]	[89]

5.3.2 System boundaries and LCA inventory

Table 5.2 provides a summary of all mass and energy inputs used to create life cycle inventory of supply chains.

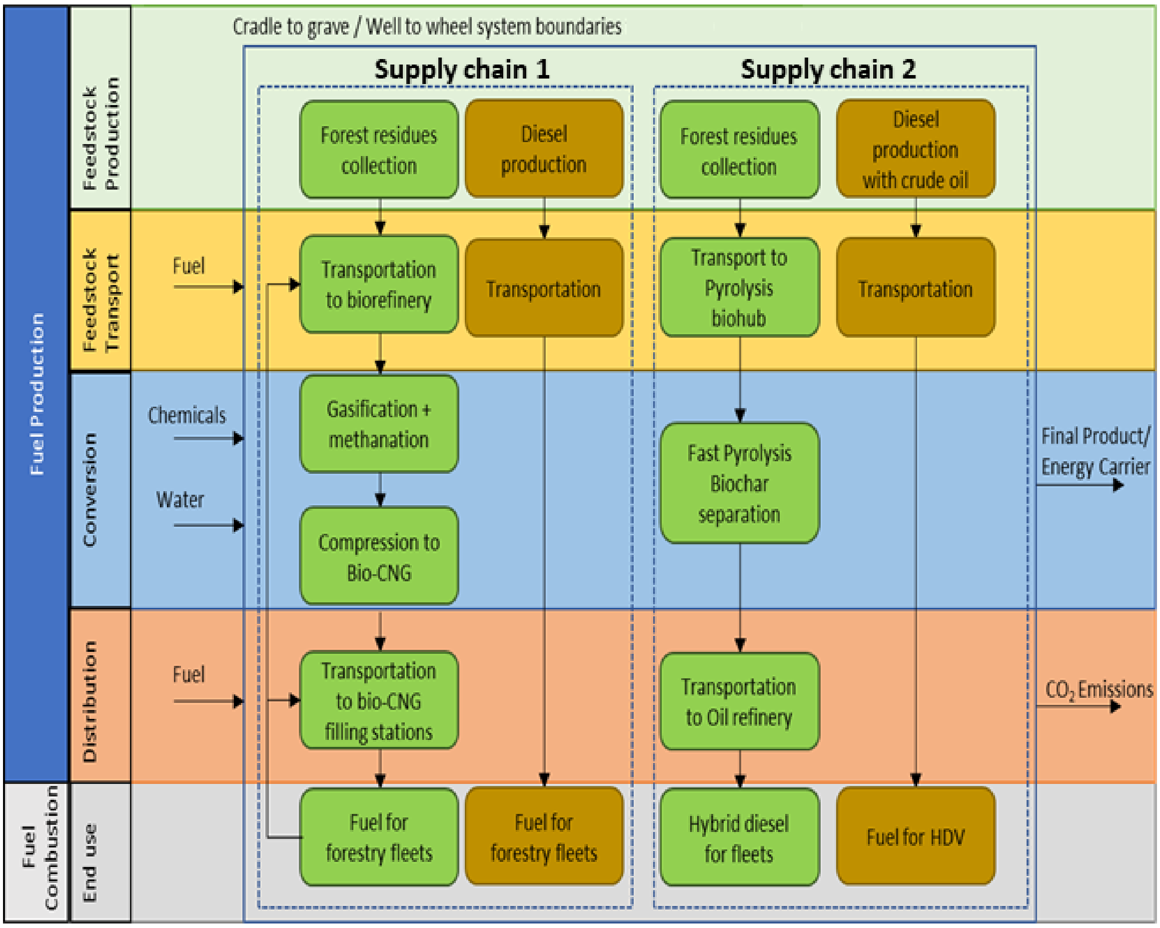

Figure 5.2: Well to wheel/ cradle to grave system boundaries for the residue to biofuel scenarios

In ROI, forestry residues (FR) are generally left on the forest floor to provide nutrients to the soil and prevent soil erosion by during timber harvesting activities. In this work it was assumed that forest residues will be left on the forest floor for two years to allow nutrient absorption by soil and natural drying of residues from 55% MC to 40% [108]. [109] showed that 0.187 GJ per dry tonnes of FR is required during cultivation, harvesting, and bundling of forest residues in ROI. Bundled FR is then transported to the supply chain location using EURO6 trucks able to transport 32 tonnes of FR with a gross vehicle weight of 46 tonnes for 6-axle articulated trucks [102]. At the supply chain, the forest residues are first converted to bio-SNG, which is modelled in a similar manner to [39], which was originally based on the GoBiGas process. The quantity of materials and chemicals, such as olivine used as bed material, $CaCO_3$ and K_2CO_3 used as activation agents, activated carbon used for H_2S removal from syngas and rape-seed oil methyl ester (RME) used for bio-SNG production were sourced from [102]. It is important to note that the bio-SNG model presented by [39] considers co-generation of electricity from heat-recovery steam generation (HRSG) system for on-site use with surplus sold to the electricity grid. In this study it was assumed that surplus electricity produced from HRSG system will be used for compression of bio-SNG to bio-CNG (200 bar) and the net surplus electricity will be sold to electricity grid, similar to [102]. Bio-CNG is then distributed to filling station locations in high-pressure tankers hauled by EURO6 trucks. Table 5.2 provides a summary of all mass and energy inputs for supply chain 1.

Table 5.2: Life cycle inventory

		Supply chain 1		**Supply chain 2**	
		LCA process	**Input quantity**	**LCA process**	**Input quantity**
Fuel Production	Feedstock Production	Biomass input: Dry kg/GJ bioCNG Energy for collection: MJ/dry tonne$_{FR}$	90 187	Biomass input: Dry kg/GJ CBO Energy for collection: MJ/dry tonne$_{FR}$	114.5 267
Fuel Production	Feedstock Transport	Forest to supply chain transportation average distance: km	140	Forest to supply chain average transportation distance: km	240
Fuel Production	Conversion	Energy: MJ/ GJ bio-CNG	324.8	Energy: MJ/ GJ CBO Drying	118
Fuel Production	Conversion	Chemicals(kg/GJ bioCNG) Calcium carbonate: Potassium carbonate: Olivine: Activated carbon: RME: Water:	1.58 0.016 0.91 0.03 1.47 91	Energy: MJ/ GJ CBO Pyrolysis	213
Fuel Production	Conversion	Electricity: MJ/ GJ bioCNG	40		
Fuel Production	Distribution	Supply chain to bio-CNG filling stations average distance: km	110	Supply chain to Oil Refinery average distance: km	120
Fuel Combustion	End Use	Distance driven in 1GJ fuel	Bio-CNG	Distance driven in 1GJ fuel Soil credits from biochar	Pyrolysis Oil Biochar

Differences arise during conversion, distribution, and end use stages of supply chain 1 and 2. For supply chain 2, forest residues are converted to crude bio-oil and biochar (by-product) using non-catalytic fast pyrolysis during the conversion stage. Table 5.2 shows the material and energy balances for conversion of forest residues to CBO and BC, sourced from [89]. The LCA model utilizes the system expansion method (also known as the substitution method) to substitute by-products outputs. It includes an assumption that the by-product will substitute an existing product on the market. The avoided burden associated with this substitution is subtracted from the total environmental burden associated with residue to biofuel system [110], [111]. In the case of biochar it was assumed to be returned to soil as a soil amendment for direct carbon sequestration [89].

5.4 Results

Table 5.3 shows the summary of LCA results for the supply chains. Net GWP_{100} shows net GHG emissions in units of kg CO_2-eq/GJ_{fuel}, which is the difference of fuel life cycle and biogenic emissions. The main source of GHG emissions for bio-CNG production (supply chain 1) was the conversion process of the fuel production phase. Bio-CNG was assumed to be used by forestry fleets during, feedstock transportation, product distribution, and end use stages; therefore, these life cycle stages of bio-CNG were assumed to be emitting biogenic CO_2. The main contributor to emissions in fuel production shown in Figure 5.3 is the conversion phase, accounting for 8.4 kg CO_2/GJ. This is due to the chemicals and electricity required during the conversion phase. Their respective contribution to emissions in fuel production are as follows: electricity for compression (38%), potassium carbonate (3%), rapeseed methyl ester (37%), activated Carbon (21%). The net GWP_{100} of diesel was 105 kg CO_2/GJ indicating a GHG reduction potential of 92% for supply chain 1.

Table 5.3: Summary of life cycle impact assessment results and GHG reduction potentials of the supply chains

Key impact factor	Bio-CNG	Hybrid diesel	Diesel
Net GWP_{100} (kg CO_2-eq/GJ_{fuel})	8.4	40.0	105.3
GHG savings relative to reference (kg CO_2-eq/GJ_{fuel})	96.9	65.3	0.0
GHG reduction potential (%)	92.0	62.0	0.0

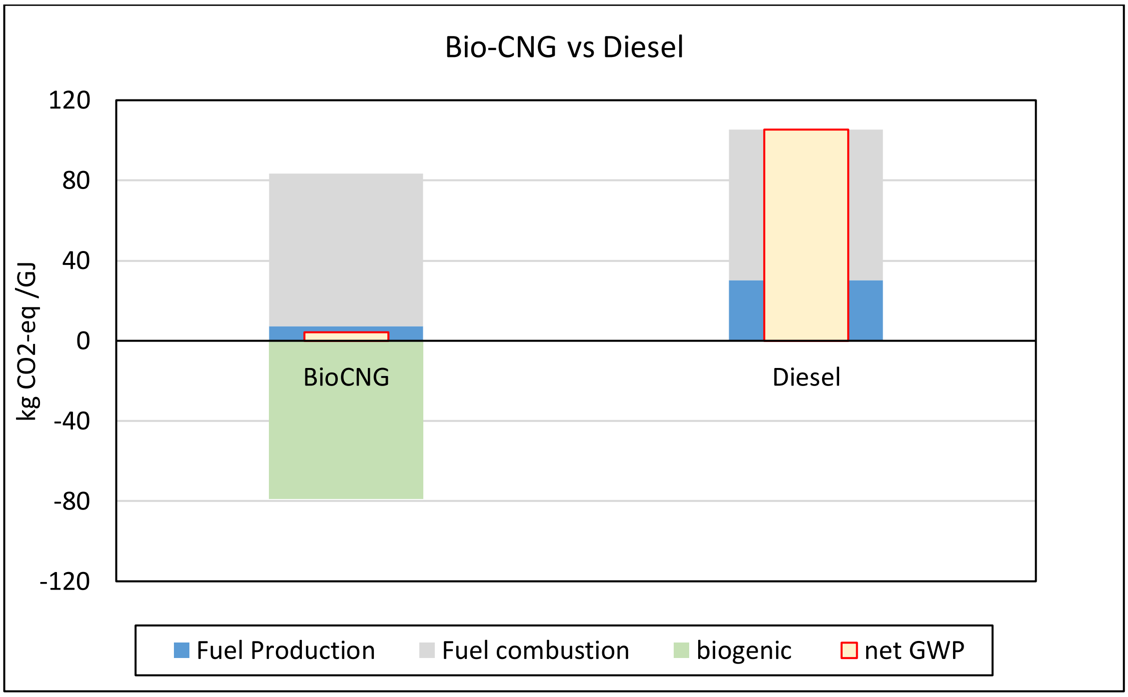

Figure 5.3: Net Global warming potential of bio-CNG and diesel (supply chain 1)

The contributions to net GWP_{100} of life cycle stages for production of CBO and end use of hybrid diesel as shown in Figure 5.4. During the fuel production stage, the processes responsible for positive GWP_{100} were forest residue collection (4.4%), FR transport (8.4%), pyrolysis (81%), bio-oil and biochar transport (6.1%) and end use of hybrid diesel. The positive

GWP_{100} during end use involves burning of hybrid diesel in HDVs. The negative GWP_{100} contribution was mainly due to biogenic CO_2 and biochar credit for direct application to soil. Biochar being rich in carbon content contributes to a significant reduction in net GWP_{100} of hybrid diesel when used as a soil fertilizer.

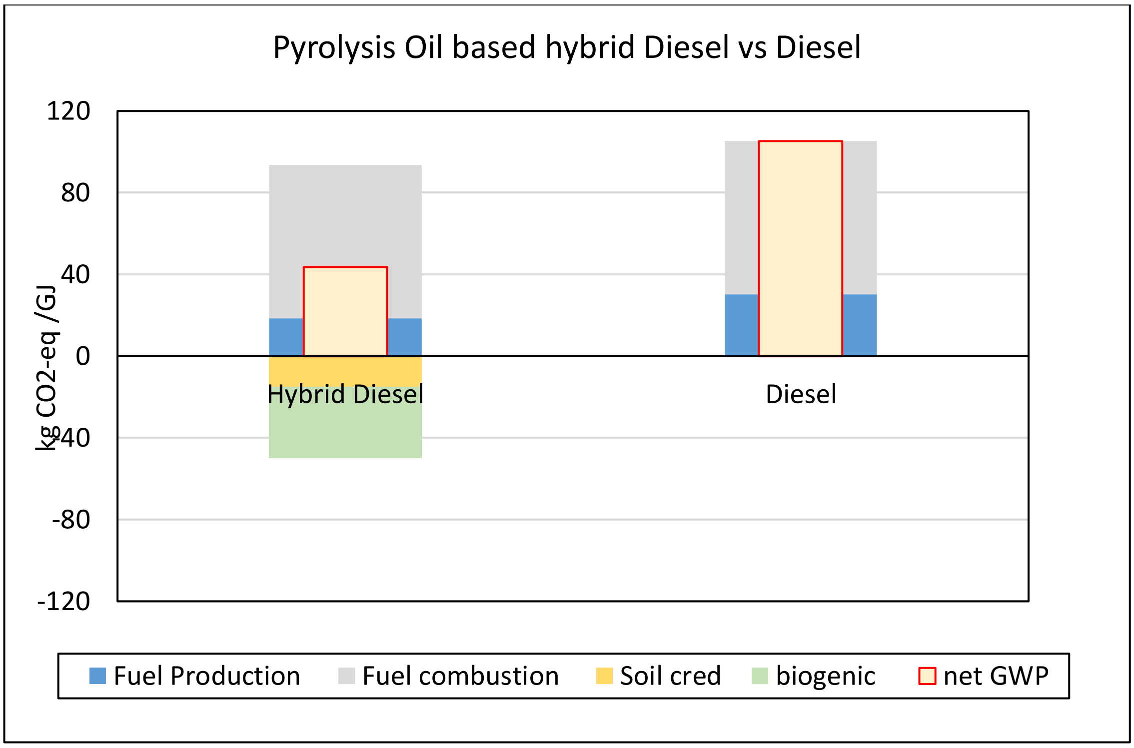

Figure 5.4: Net Global warming potential of bio-CNG and diesel (supply chain 2)

The GWP_{100} of conventional 1 GJ diesel was calculated to be 105 kg CO_2 eq, where fuel production and end use accounted for 28% and 72% of total GWP_{100}, respectively. Net GWP_{100} for supply chain 2 was 43.6 kg CO_2/GJ indicating a GHG savings of 61.4 kg CO_2 (62% GHG reduction potential) for each GJ of conventional diesel replaced. [89] conducted a study to compare the GWP_{100} potential of upgraded bio-oil produced using CaO catalyst with CBO from non-catalytic pyrolysis showed that the catalyst used during pyrolysis was the main contributor (up to 47%) to the positive GWP_{100} of UBO. However, UBO allows greater wt% (up to 20 wt%) to be co-processed, which resulted in a significant decrease of GWP_{100} of the fossil feed at oil refinery [81]. Moreover, [81] also showed co-processing of CBO had net CO_2 emissions (34 kgCO_2/GJ), which is slightly lower than this study (40 kgCO_2/GJ) due to higher emissions from FR transport in the latter. This indicates that the environmental impacts of CBO shown in this study can be lowered by optimization of biorefinery size and therefore the supply chain 2 scenario requires further research.

5.5 Conclusions

The environmental sustainability analysis of two reside to biofuel supply chains showed that net GWP_{100} for supply chains 2 and 3 are 8.4, and 40 kg CO_2-eq/GJ_{fuel} when compared to their fossil counterparts, respectively. Supply chain 1 produced bio-CNG to replace diesel in timber fleets and showed lower net GHG emissions (8.4 kg CO_2-eq/GJ) since transportation, distribution and end use phases were assumed to be emitting biogenic CO_2. Therefore, the main contributor for emissions was the conversion phase due to the use of chemicals and electricity for compression. For this reason, the GHG reduction potential of bio-CNG (92%) was the highest among the supply chains studied. Supply chain 2, which produced crude bio-oil for production of hybrid diesel at an existing oil refinery, had higher GHG emissions (40 kg CO_2-eq/GJ). Supply chain 2 relied heavily on fossil-based resources during whole life cycle of crude bio-oil (fuel production), resulting in the lowest GHG reduction potential (62%). Biochar played a significant role in reducing overall CO_2 emissions as a soil fertilizer.

6 Conclusions

6.1 Chapter overview

This chapter presents a summary of all the significant contributions, findings from previous chapters and future studies. Essential contributions are listed in the contribution section. The overall conclusions are explained in the conclusions sections. Finally, limitations and potential future developments related to this research are provided in the future work section.

6.2 Contributions

Irish energy infrastructure remains heavily dependent on imported fossil fuels, even more so in transport sector than heat or electricity. While there has been considerable development in electrifying light vehicles, little to no advancements have been made in decarbonizing heavy-duty vehicles that are major contributors to overall CO_2 emissions. Throughout the report it was made clear that numerous advancements have been made in utilizing thermochemical technologies to produce advance biofuels for application in hard to abate sector like HDVs. However, most studies displayed lower production cost of advance biofuels due to large economies of scale and lacked documentation on supply and distribution of advanced biofuels especially ones produced from gasification that require additional infrastructure for proper utilization in road transport. For a small country like ROI that has relatively low and widely dispersed forest cover has led to high prices and consequently lower market demand for forest residues. To produce competitive advance biofuels under these conditions it was increasingly important to not only design an optimized supply chain for feedstock but also to identify the size and location of markets that can enhance their decarbonisation potential at a scale possible in Ireland. Therefore, this report utilized existing studies on thermochemical technologies to design optimized supply chains of advance biofuels for decarbonisation of HDVs in the regional context of ROI.

Key contributions of this work include: 1) a supply and distribution chain for forest residues based biorefinery producing bio-CNG or crude bio-oil and biochar 2) optimization techniques to configure optimal location and size of biorefinery based on minimum levelised cost of Bio-CNG production 3) size and locations of biofuel demand (market routes), 4) techno-economic model to analyse annual cash flow in and out, and 5) environmental sustainability analysis framework for three residue to biofuel supply chains supply chains to determine and compare their GHG emissions.

6.3 Conclusions

6.3.1 Chapter 2 Conclusions

Chapter 2 presented and compared potential of state-of-the-art thermochemical technologies for producing advance biofuels using discounted cash flow method. The analysis provided insights on total capital investment, Operating cost and minimum fuel selling price of a biorefinery operating with three different thermochemical technologies namely gasification, pyrolysis and HTL in Ireland using forest residues as feedstock. The competitiveness of advance biofuels was compared with wholesale prices of diesel with carbon tax. The key messages from chapter 2 are listed below.

- Pyrolysis used biochar for upgrading of bio-oil reducing the overall mass yield and energy efficiency. Upgrading bio-oil increased its fuel quality and resulted in higher capital investment for the pyrolysis scenario. Highest operating cost was observed for the pyrolysis scenario, which was mainly associated with catalyst used during H_2 production and Upgrading process. Lower mass and energy yield coupled with additional capital and operating investment due to upgrading process resulted in pyrolysis scenario showing lowest competitiveness with diesel wholesale prices even at higher carbon tax (160 €/tCO_2).
- HTL scenario produced diesel grade biofuel showed higher competitiveness with diesel than pyrolysis scenario due to higher mass yield of biofuel. However, the extreme operating conditions increased the equipment cost resulting in highest TCI for HTL scenario. Green diesel from HTL process did not show competitiveness with diesel even at higher carbon tax rate.
- Gasification produced bio-SNG to replace diesel in HDVs. Gasification scenario showed highest competitiveness for producing diesel grade fuel due to higher chemical and energy efficiency, lower capital and operating cost. However, unlike pyrolysis and HTL scenario proper deployment of bio-SNG requires further investment for its distribution and utilization that will adversely affect its competitiveness with diesel and therefore required further research.

6.3.2 Chapter 3 Conclusions

Chapter 3 evaluates the techno-economic performance of regional-national supply and distribution chains for conversion of forest residues to biomass-derived compressed natural gas

(Bio-CNG) to be used as a transport fuel for forestry trucking fleets. This work combines techno-economic assessment of the bio-CNG production system with geographical information system (GIS) based supply chain optimization. This novel modified location-allocation helps to site and size a forest residue based biorefinery for bio-CNG production. The method also optimizes the amount of residual biomass transported to minimize the levelised cost of bio-CNG ($LCOB_{cng}$), which includes all harvesting, transport, conversion, and fuel dispensing stages. The key messages from chapter 3 are listed below.

- If the biorefinery capacity is unrestricted up to 92 MW bio-CNG production is possible which showed highest profitability (NPV,486 M€), however this adversely affects the competitiveness of bio-CNG with diesel as forest residues get increasingly dispersed from the biorefinery location resulting in higher feedstock transport cost.
- When most expensive feedstock at the outskirts were removed, biorefinery capacity significantly reduced to 75 $MW_{bio\text{-}CNG}$ and a slight increase in bio-CNG competitiveness was observed when $LCOB_{cng}$ was reduced from 1.18 €/LDE to 1.13 €/LDE. However, reducing biorefinery size lowered the NPV to 427 M€;
- Economic results showed that additional components such as bio-CNG compressors, storage unit and filling stations increased the capex by 20% and operational cost by 18% when compared to gasification scenario in Chapter 2.
- At optimized scale, 100% of bio-CNG demand by timber fleets can be practically met by placing 10 filling station at sawmill locations with highest bio-CNG demand and proximity to other demand locations.
- The comparison of $LCOB_{cng}$ with diesel prices showed that at current carbon tax, bio-CNG produced at optimized scale is not yet cost-competitive with incumbent diesel. However, doubling yearly increment rate of carbon tax (from 7.5 to 15 €/tCO_2/a) resulted in $LCOB_{cng}$ reaching parity with diesel in year 2035 and 2037 for 75 $MW_{bio\text{-}CNG}$ and 92 $MW_{bio\text{-}CNG}$ biorefinery size respectively.
- Sensitivity analysis showed that the $LCOB_{cng}$ and NPV are most sensitive to plant capacity and feedstock price. This indicates that increase of forest residue availability near the biorefinery location and lower feedstock prices can enhance the competitiveness and profitability of bio-CNG in future.

6.3.3 Chapter 4 Conclusions

Chapter 4 presented a biorefinery supply and distribution network for co-producing crude bio-oil and biochar or activated carbon from forest residues. With an objective to evaluate Ireland's potential for producing crude bio-oil for co-processing at Whitegate oil refinery, all forestry residues were assumed to be allocated to a single biorefinery location with a maximum capacity of 779 dt/day (8.28% MC). Three pyrolysis scenarios were explored namely Upgraded bio-oil (UBO), Crude bio-oil with biochar (CBO_{BC}) or activated carbon (CBO_{AC}). The key messages from chapter 4 are listed below.

- At maximum capacity, biorefinery can produce 50 kt of bio-oil and 55 kt of biochar or 11 kt of AC. Considering this production volume of crude bio-oil it was determined that 0.8 wt% of VGO used at Whitegate oil refinery for diesel production can be replaced by crude bio-oil.
- Unsurprisingly, CBO_{BC} scenario showed highest competitiveness with its fossil-based counterpart (crude oil/ vacuum gas oil) mainly due to avoiding additional expenditure associated with upgrading by co-processing at oil refinery and co-production of BC.
- Addition of activated carbon plant increased the capital investment by 33% and operating cost by 50% for CBO_{AC}. Additional expenditure associated with AC production from BC lowered the competitiveness of CBO_{AC} scenario. Although AC had higher market value, the NPV (185.2 M€) of CBO_{AC} was lower due to lower yield of AC as compared BC in CBO_{BC} (NPV, 330.9 M€).
- A sensitivity analysis was conducted on the LCOB and NPV of CBO_{BC} scenario by changing significant cost parameter by ± 30%. It was observed that LCOB and NPV were most sensitive to changes in biochar yield, feedstock cost and bio-oil yield.

6.3.4 Chapter 5 Conclusions

Chapter 5 presented an environmental sustainability analysis of the two residue to biofuel supply chains previously introduced to determine their greenhouse gas emissions in units kg CO_2-eq/GJ_{fuel}. The reference system for both supply chains was production and end use of diesel. The key messages from chapter 5 are listed below.

- Supply chain 1 had net GHG emissions of 8.4 kg CO_2 per GJ heat produced from burning bio-CNG in forestry fleets. Bio-CNG was assumed to be used by forestry fleets during, feedstock transportation, product distribution, and end use stages therefore; these life cycle stages of bio-CNG were assumed to be emitting biogenic CO_2. The main source of GHG emissions in fuel production phase was conversion phase due to the chemicals for converting forest residues and electricity use for compression. Supply chain 1 showed higher GHG emissions reduction potential (92%), among the supply chains studied, when compared to its reference system diesel (105.3 kg CO_2/GJ).

- Supply chain 2 had net GHG emissions of 40 kg CO_2 per GJ heat produced from burning hybrid diesel, which is highest among the supply chains studied. Unlike supply chain 1, supply chain 2 was highly dependent on fossil fuel resources for all life cycle stages (fuel production and end use). Although the highest contributor of GHG emissions in fuel production phase was conversion stage (pyrolysis, 81%), the feedstock collection and transportation stage (12.8%) also had significant emissions in contrast to supply chain 1. Co-production of biochar had significant environmental benefits due to direct application to soil (direct carbon sequestration). However, the GHG reduction potential for supply chain 2 was still much lower (62%) than supply chain 1 when compared with its fossil counterpart diesel (105 kg CO_2/GJ).

6.4 Future work

The work presented in this report provided several opportunities for improvement or extensions from what has already built. This section provides suggestions for future work that can enhance or add to findings of this research. Future work can be categorized in to three section thermochemical technologies, design of supply and distribution chain of advance biofuels and environmental sustainability advance biofuel supply chains.

In the case of the thermochemical technologies explored:

- The economic competitiveness of thermochemical pathways explored in this work was mainly based on their chemical and energy efficiency. These efficiencies were insensitive to scale variation due to lack of experimental data on forest residue based advanced biofuel production in ROI. Forest residue can significantly contribute towards increasing renewable liquid biofuels for decarbonisation.
- Bio-CNG from gasification and Upgraded bio-oil have significant potential for reducing emissions from hard to abate transport sector. However, bio-CNG is currently constrained by lack of distribution infrastructure, upgraded bio-oil suffers from high capital and operation investments, and both were negatively affected by high feedstock prices in ROI. Future studies can focus on developing; advance forestry harvesting technique to minimize feedstock price, thermodynamic models for advance biofuels from waste bioresource to identify optimization opportunities, and distribution network to facilitate cost effective utilization of biofuels.

- Crude bio-oil from fast pyrolysis has potential to be competitive with vacuum gas oil and techniques like mild hydrotreatment (HDT) can allow greater percentages of CBO co-processing with crude oil and consequently increase renewable carbon in hybrid diesel without significantly affecting the economic competitiveness of Pyrolysis process.
- Thermochemical technologies can produce other high value products such products such as hydrogen, Fischer-Tropsch liquids, methanol among others from waste biomass depending on the type of downstream techniques applied. Future studies can explore other product supply chains that have higher market demand.

In the case of supply and distribution chains of advance biofuels:

- Bio-CNG filling stations cost in this study was dependent on number of trucks arriving daily for refuelling. However, factors such as refuelling time and frequency can also increase the dispensing cost of bio-CNG. Future studies can focus on exploring new methods or technologies to reduce dispensing cost of bio-CNG.
- Optimization techniques can be applied to reduce feedstock transport cost can enhance the competitiveness of crude bio-oil with vacuum gas oil and thus requires further investigation.

In case of environmental sustainability of advanced biofuel supply chains:

- The environmental sustainability of bio-CNG and crude bio-oil can be integrated with their techno-economic models. This can allow coupling of techno-economic results with environmental impacts to create a spatially explicit tool used to analyse the trade-offs between economic and environmental optima advance biofuel supply chain.

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