Environmental Sustainability Studies of Biohub Archetypes

A report for the IEA Bioenergy Intertask Project on Biohubs

IEA Bioenergy: Tasks 43 and 45

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1 Summary

Biohubs are increasingly seen as essential to the cost-effective deployment of bioenergy at scale for decarbonising hard-to-abate sectors like heavy-duty vehicles and heat. This report presents results of environmental sustainability analysis for three sample biohub archetypes. Biohub-1 converts post-harvest agricultural residues in Croatia to solid fuel pellets for remote domestic heating. Biohub-2 converts forest residue in Ireland to gaseous biofuel to fuel to Irish timber truck fleet. Biohub-3 converts forest residue, also in Ireland, to crude bio-oil for transport to an oil refinery to produce lower-carbon diesel. Global warming impact relative to reference cases for the provision of remote domestic heat (coal), and truck fuel (diesel) was calculated for the biohubs using standard life cycle assessment methods. Greenhouse gas emissions reductions of 62% for biohub-3 and over 90% for biohubs 1 and 2 were calculated. Lower reductions were found for biohub-3 because only a portion of crude oil was displaced by bio-oil due to limitations on the existing oil refinery equipment. Upgrading the refinery infrastructure would enable higher bio-oil fraction and therefore great emissions reduction, but at greater economic cost. Soil carbon credits associated with the use of by-product biochar are responsible for some of the emissions reductions seen in biohub-3. Biohubs 1 and 2 completely displace fossil fuel use and therefore larger emissions reductions were observed. The findings bolster the case for the use of biohubs as part of comprehensive decarbonisation strategies in agricultural and forestry regions.

2 Acknowledgements

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3 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, waste to bioenergy systems have been proven by several studies to be a viable alternative energy source [1]. 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 [2]-[4]. The term biohub refers to an intermediate place where farmers/growers can deliver their by-products such as straw and residues to be processed into products that have higher quality and value along the supply chain [5]. Biohubs are increasingly becoming key enablers for the cost-effective and efficient large-scale mobilization of waste bioresources such as agricultural and forest residues [5]. However, it is important to address critical issues related to climate and sustainability effects of these waste to bioenergy biohub systems.

Life cycle assessment (LCA) is 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 [6],[7]. More recently, LCA studies have started focusing on non-traditional biomass feedstocks such as algae, seaweed, and waste residues from harvesting activities [8],[9]. 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 [10]. On the other hand, expanding the scope of study to include feedback effects of decisions made in the foreground (waste to bioenergy system) and consequences in background systems (substituting fossil fuels) leads to C-LCA [10].

3.1 Motivations and Objectives

As biohubs 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 biohubs optimized for techno-economic performance may not necessarily have optimized environmental impact [11]. It is therefore necessary to integrate methods for the design, sizing, and mapping/siting of biohubs and their 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 biohub archetypes covering diverse bioresource and bioproduct categories. Therefore, in collaboration with the IEA Bioenergy Technology Collaboration Platform ("IEA Bioenergy" for short), this work aims to provide a framework for environmental sustainability analysis of three unique waste to bioenergy supply chains. Supply chains for biomass gasification-derived compressed natural gas (bio-CNG) and crude bio-oil from forest residues in Ireland and agri-pellet production from agricultural residue in Croatia are considered in this work.

Therefore, the objectives of this work are:

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

4 Methodology

The environmental sustainability of three waste to bioenergy production system is assessed through the LCA methodology to analyse and compare their global warming potential fossil-based counterparts. Figure 1 shows an overview of LCA methodology employed in this study. LCA methodology is based on ISO 14040 [12] and 1SO 14044 [13] standards using OpenLCA [14] (open source software) with the Ecoinvent 3.5 database [15]. The impact category used in this work is IPCC2013 GWP 100a.

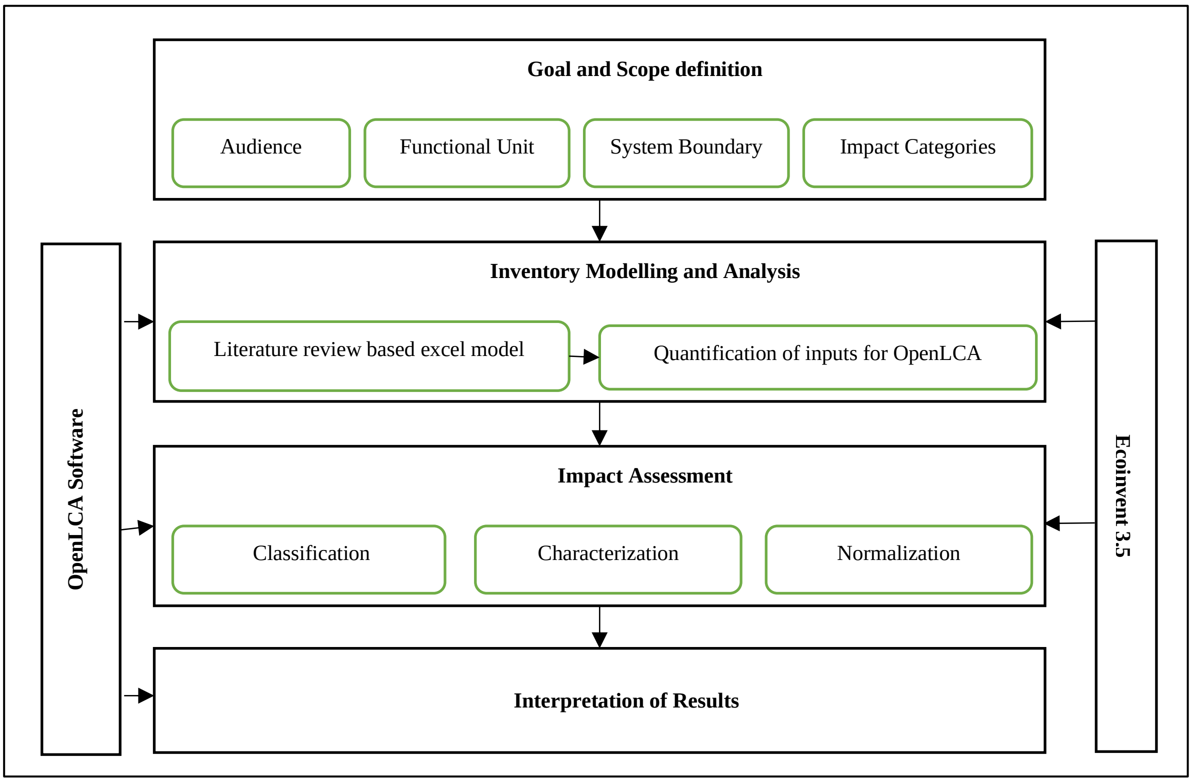

Figure 1: Life cycle assessment methodology description

4.1 Life cycle assessment goal and scope

In this study, the C-LCA approach was applied to evaluate the net greenhouse gas (GHG) impact of three waste to bioenergy biohubs as summarized in Table 1. These biohubs were defined by interviewing members of the IEA Bioenergy Task 43-led biohub project. An initial shortlist of five biohubs was identified, but this was later shortened to three based on the amount of data available from the biohub proposers. The goal of this C-LCA is to assess net GHG impact per unit of energy output. Therefore, the functional unit was set to 1 GJ of agri-pellets or bio-CNG or crude bio-oil.

Table 1: Summary of three waste to bioenergy biohub archetypes

Biohub	**Biohub-1**	**Biohub-2**	**Biohub-3**
Location	Croatia	Ireland	Ireland
Feedstock	Post-harvest agricultural residues, such as cereal straw, soy straw and other plant-based post-harvest residues	Forest residues also classified as unmarketable <7cm in diameter	Forest residues also classified as unmarketable wood tip-7cm in diameter
Conversion pathway	Pelletisation and packaging	Gasification, gas cleaning, methanation and compression	Pyrolysis, biochar separation, co-processing with vacuum gas oil and hybrid diesel production
Final product	Agri-pellets	Biomass-derived compressed natural gas (Bio-CNG)	Pyrolysis Oil based Hybrid diesel
End use	Burned in Boilers for domestic heat application	Liquid transport fuel for forestry fleets	Liquid transport fuel for fleets Biochar as soil fertilizer
Reference system	Coal production and combustion in boilers	Diesel production and combustion in forestry fleets	Gasoline and diesel produced from fossil-based resources (i.e. crude oil) and fuel combustion
Literature	[16]	[11]	[17]

Biohub-1 is located in Croatia and uses plant-based post-harvest agricultural residues such as cereal and soy straw to produces agri-pellets at a sawmill. The agri-pellets are transported to end users for generating heat in boilers. Therefore, the reference system for biohub-1 is the production and end use of coal.

Biohub-2 uses forest residues for producing bio-CNG (biomass-derived compressed natural gas) at a hypothetical biorefinery location in Ireland. The location, shown in Figure 2, was chosen to minimise the distances for getting the forest residue to the hub and for getting the bio-CNG back to sawmills, where the timber fleet is assumed to refuel. 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 biohub-2.

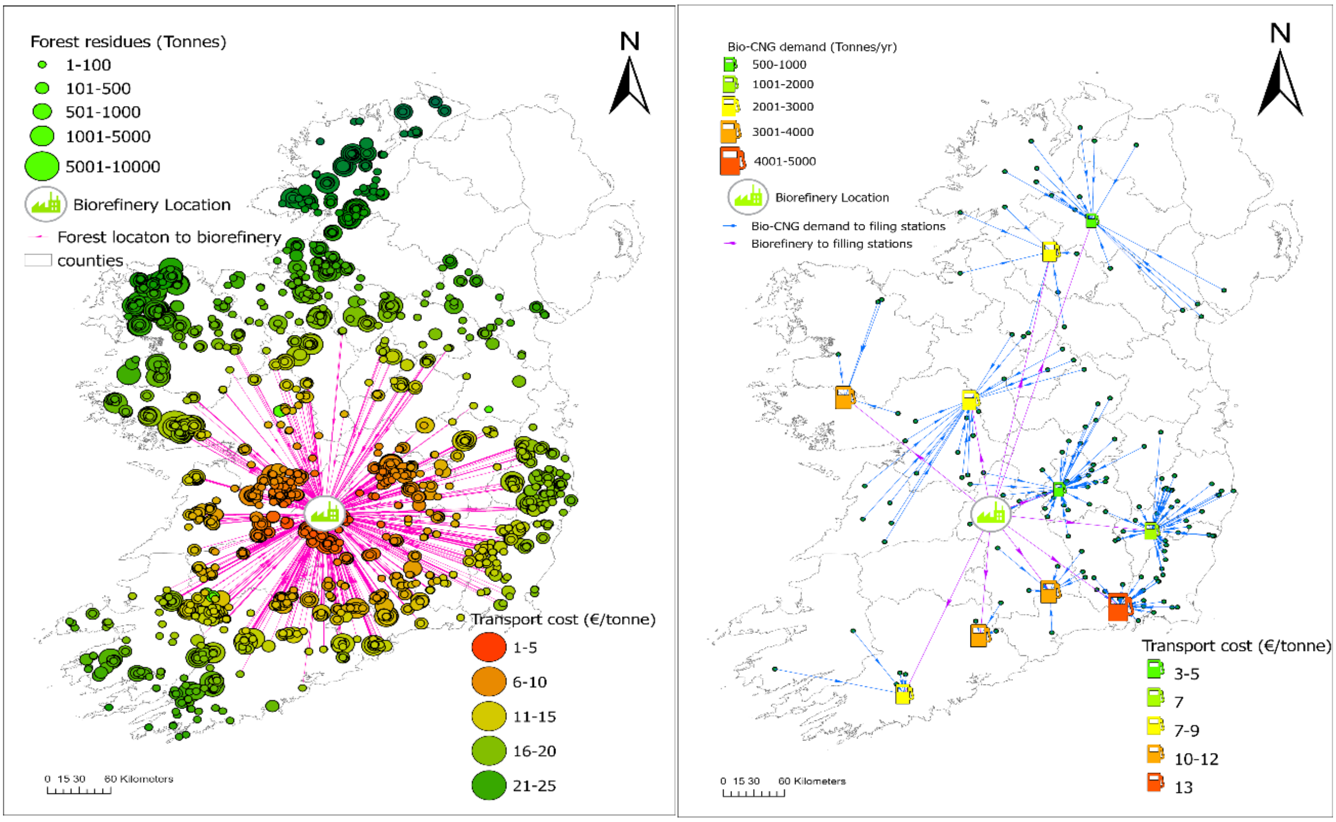

Figure 2: Location of biohub-2 in Ireland

For biohub-3, forest residues are used to produce crude bio-oil (CBO) and biochar (BC) at a hypothetical biorefinery location in Ireland. The location, shown in Figure 3, was chosen to minimise the distances for getting the forest residue to the hub and for getting the CBO to an oil refinery. 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, Ireland. Therefore, production and end use of diesel was selected as reference system for biohub-3.

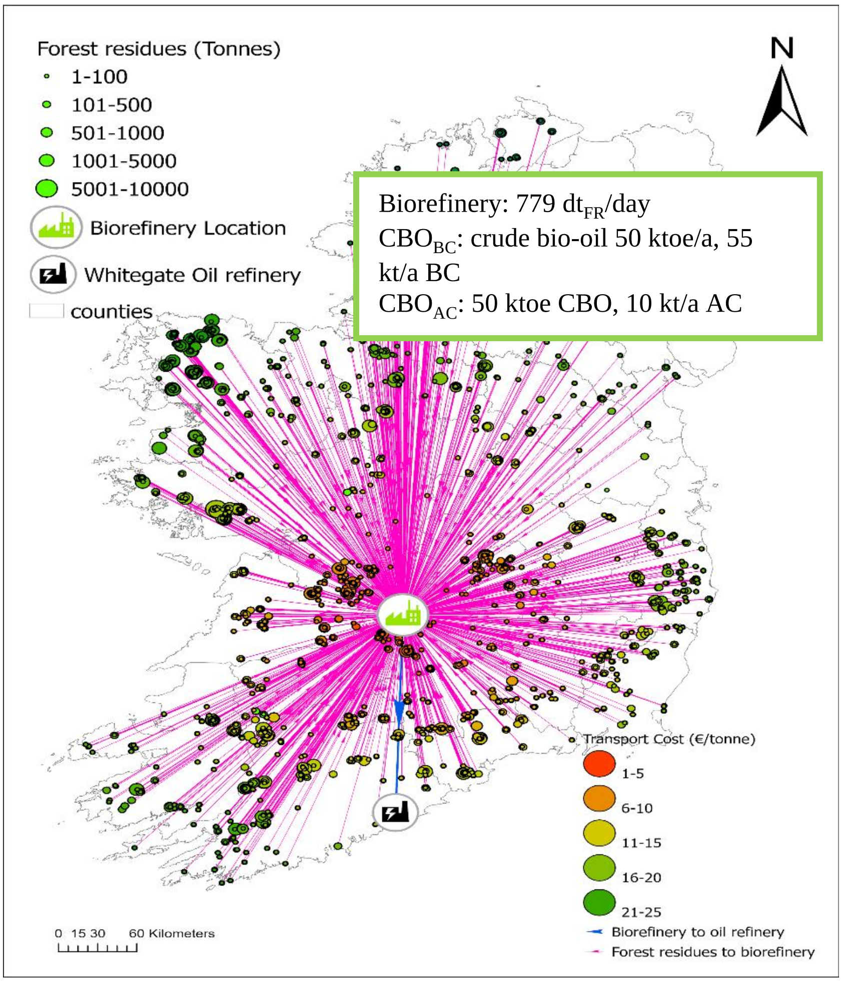

Figure 3: Location of biohub-3 in Ireland

4.2 System boundaries and LCA inventory

Figure 4 and Table 2 provide summaries of all mass and energy inputs used to create a life cycle inventory of all three biohubs.

Biohub-1 involves collection of plant-based residues and transportation to a sawmill where it is dried, ground, pelletizing and packed in 15-kg bags to be transported to the nearest local end users. The end use phase is combustion of agri-pellets in boilers for heat generation [16], as shown in Figure 4.

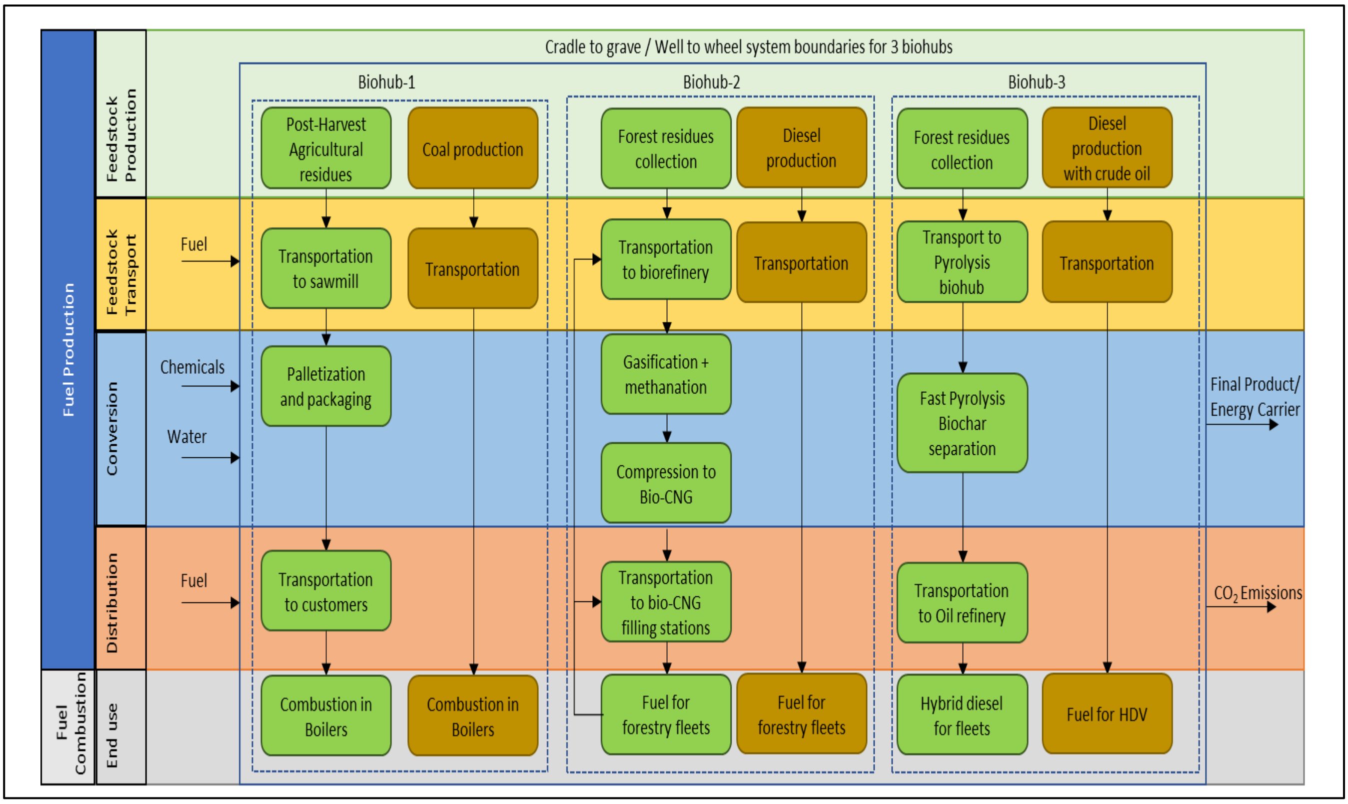

Figure 4: Well to wheel/ cradle to grave system boundaries for three waste to bioenergy scenarios

In Ireland, 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% [18]. Previous work [19] showed that 0.187 GJ per dry tonnes of FR is required during cultivation, harvesting, and bundling of forest residues in Ireland. Bundled FR is then transported to the biohub location using EURO6 6-axle articulated trucks able to transport 32 tonnes of FR with a gross vehicle weight of 46 tonnes [11]. At the biohub, the forest residues are first converted to bio-SNG, which is modelled in a similar manner to [20], 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 [11]. It is important to note that the bio-SNG model presented by [20] considers co-generation of electricity from a 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 the 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 [11]. Bio-CNG is then distributed to filling station locations in high-pressure tankers hauled by EURO6 trucks.

Table 2: Life cycle inventory

		Biohub-1		Biohub-2		Biohub-3	
		LCA process	**Input quantity**	**LCA process**	**Input quantity**	**LCA process**	**Input quantity**
Fuel Production	Feedstock Production	Biomass input: t/a Fertilizer: kg/ha	2500 0	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	Residue site to biohub transportation average distance: km	5	Forest to biohub transportation average distance: km	140	Forest to biohub average transportation distance: km	240
Fuel Production	Conversion	Energy: MJ/dry tonne feedstock Drying Grinding Pelleting Cooling	 324.8 189.5 339.2 8.7	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	Packaging	15 kg bags	Electricity: MJ/ GJ bioCNG	40		
Fuel Production	Distribution	Biohub to customers average distance: km	100	Biohub to bio-CNG filling stations average distance: km	110	Biohub to Oil Refinery average distance: km	120
Fuel	End Use	1 GJ heat from boiler	Agri-pellets	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 biohub-2 and 3. For biohub-3, forest residues are converted to crude bio-oil and biochar (by-product) using non-catalytic fast pyrolysis during the conversion stage. Table 2 shows the material and energy balances for conversion of forest residues to CBO and BC, sourced from [17]. 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 waste to bioenergy system [21],[22] . In the case of biochar it was assumed to be returned to soil as a soil amendment for direct carbon sequestration [17].

5 Results

Table 3 shows the summary of LCA results for all three biohubs. 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 sources of GHG emissions for agri-pellets production (biohub-1) was transportation, conversion, distribution in fuel production stage and end use. The conversion phase had the highest positive emissions, accounting for 85% in fuel production stage caused due to significant reliance on grid electricity for drying, pelleting and cooling process. This led to a net GWP_{100} of 15 kg CO_2/GJ for agri-pellets, which is much lower than GWP_{100} of coal (160 kg CO_2/GJ). This indicated that biohub-1 has a high GHG reduction potential of 90.6% (145 kg CO_2/GHG savings). Figure 5 displays the net GWP_{100} of agri-pellets and compares it with net GWP_{100} coal.

Table 3: Summary of life cycle impact assessment results and GHG reduction potentials of three biohubs

	Biohub-1	**Biohub-2**	**Biohub-3**
Bioenergy product	Agri-pellets	Bio-CNG	Hybrid diesel
Reference energy	Coal	Diesel	Diesel
Biohub net GWP_{100} (kg CO_2-eq/GJ_{fuel})	15.0	8.4	40.0
Reference energy net GWP_{100} (kg CO_2-eq/GJ_{fuel})	160.0	105.3	105.3
GHG savings relative to reference (kg CO_2-eq/GJ_{fuel})	145.0	96.9	65.3
GHG reduction potential (%)	90.6	92.0	62.0

The main source of GHG emissions for bio-CNG production (biohub-2) 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 6 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 biohub-2.

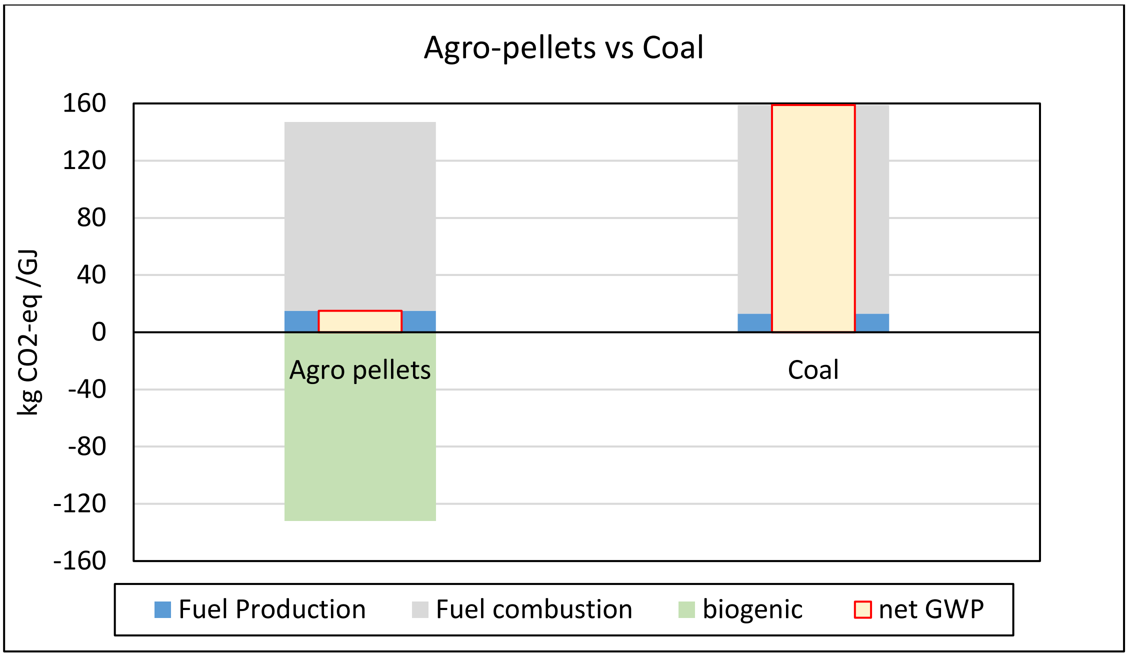

Figure 5: Net Global warming potential of agri-pellets and coal for biohub-1

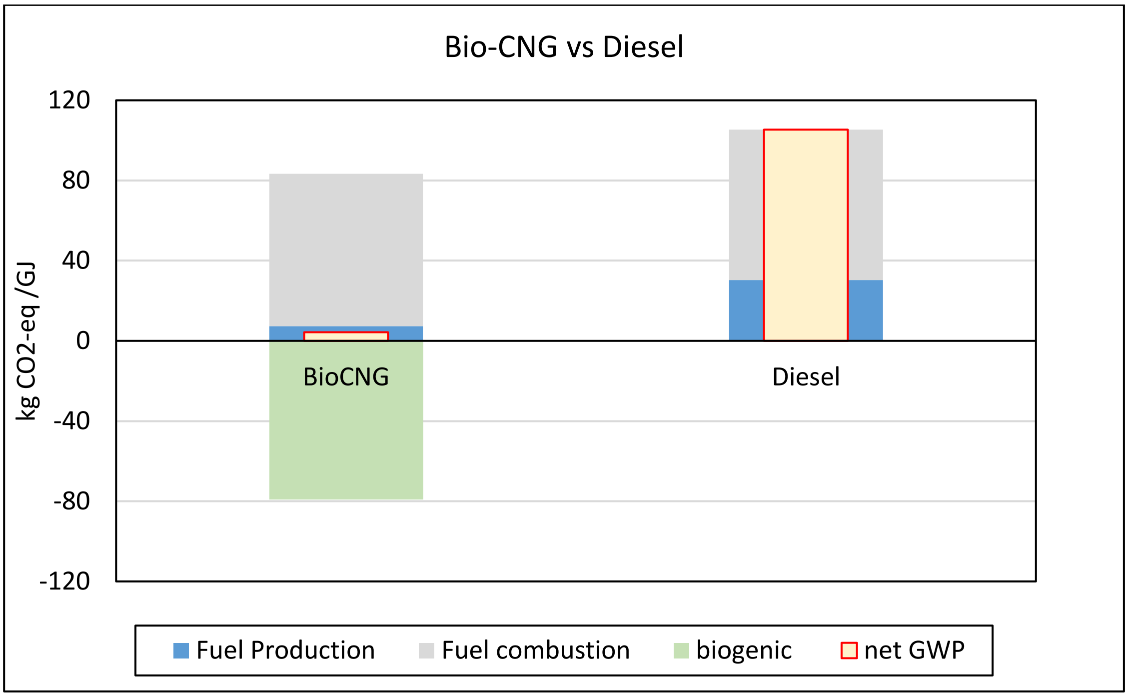

Figure 6: Net Global warming potential of bio-CNG and diesel for biohub-2

The contributions to net GWP_{100} of life cycle stages for production of CBO and end use of hybrid diesel as shown in Figure 7. 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.

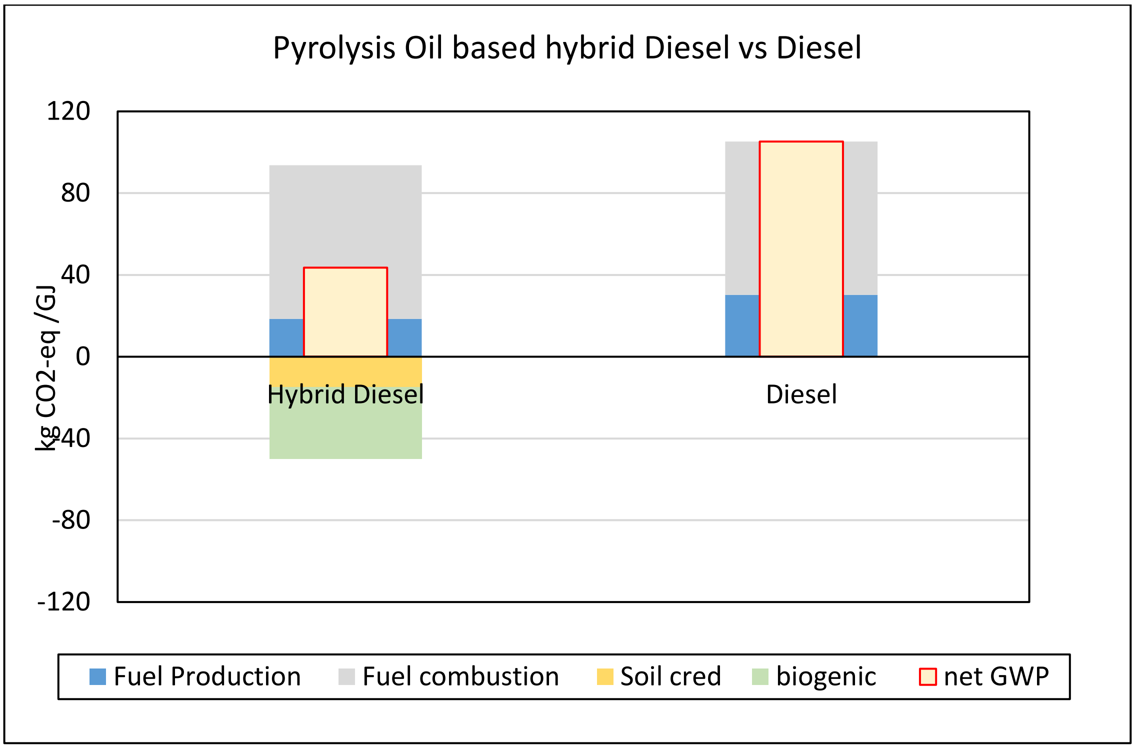

Figure 7: Net Global warming potential of bio-CNG and diesel for biohub-3

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 biohub-3 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. Previous work 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 [17]. 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 [23]. Moreover, that work 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 biohub-3 scenario requires further research.

6 Conclusions

The environmental sustainability analysis of three unique biohub supply showed that net GWP_{100} for biohub-1,2,3 are 15, 8.4, and 40 kg CO_2-eq/GJ_{fuel} when compared to their fossil counterparts respectively. It was observed that the main source of emissions for biohub-1 in the fuel production phase was the conversion stage, due to high reliance on grid electricity. The GHG reduction potential of agri-pellets (90%) was high, mainly due to high emissions intensity of coal, the reference system. Biohub-2 produced bio-CNG to replace diesel in timber fleets and showed the lowest 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 biohubs studied. Biohub-3, which produced crude bio-oil for production of hybrid diesel at an existing oil refinery, had the highest GHG emissions (40 kg CO_2-eq/GJ). Biohub-3 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. However, further research is recommended to identify effects of plant size optimization on net GWP_{100} of CBO_{BC} scenario.

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