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# Determining Suitable Green Biorefinery Locations in Ireland for Irish Agriculture Using Co-design, Economic and Geographical Information Systems

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*Abstract*

The aim of this thesis is to investigate potential locations for a suitable green biorefinery model in Ireland, which would offer an opportunity for sustainable diversification to grassland farmers. A mixed method approach was used to collect data to support the design and analyse a green biorefinery model. A three phased methodology was applied representing the Co-design, Economic and the Geographical Information Systems analysis phase.

Key stakeholders identified in the co-design phase included farmers, cooperatives, market partners as having a direct impact on a biorefinery. This provided insight to the farmers preferred model. Using these findings, an economic assessment was carried out through a capital budget model. A viable economic model would require a capital expenditure of €5.5 million, and an input of 20 tFW/hr of silage feedstock. Scenario analysis determined operating at full capacity to be viable, as the selected biorefinery would have a return on investment of 16.54% and a payback period of 6 years. A sensitivity analysis showed feedstock costs and insulation revenues have a significant impact on the economic feasibility of the model.

Both phases then informed the Geographical Information System analysis. Environmental, socio-economic and infrastructure data was processed through geoprocessing tools. In the case of gas network pipelines and protein market partners, datasets were created. The analysis resulted in 28 suitable locations for deployment.

Overall, a large co-operative led silage based biorefinery supplied by a large group of farmers and producing grass insulation as the main end product was the preferred model. Low farming intensity and income areas such as Louth, Kildare and Donegal would be most suitable, though further geospatial analysis would need to be carried out. The farmers voice should also be forefront in the decision-making process to address socio-economic challenges. Future research will extend the findings to a larger number of stakeholders and analysis of alternative business models.

*Dedication*

Dedicated to my family for all their support and patience.

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# Chapter 1: Introduction

## *1.0 Introduction*

Green biorefineries have been proposed as renewable technologies that could aid in the reduction of carbon dioxide and other greenhouse gas (GHG) emissions while also producing high value products and utilizing waste streams. The agricultural sector in Ireland has become a focus for these technologies due to its contribution to GHG emissions, and the impact climate change has on the sector. Green biorefineries could be used to reduce farmland GHG emissions, while also providing the opportunity for farmers to benefit economically from the products produced. While these technologies have been successfully deployed in Europe, they have yet to be implemented in Ireland. This project aims to locate suitable areas for deployment in Ireland, considering the design of the model and its economic viability.

### *1.1 Research Objectives*

A number of objectives were identified in order to fulfil the aim of this research. First, it would require the determination of a biorefinery model suitable for Irish agriculture. Second, it would require the identification of the key stakeholders involved in implementing a green biorefinery. Third, locations and sectors most suited to the development of green biorefineries would be identified. The fourth objective that would be the economic feasibility of the model selected. Finally, suitable locations for deployment would be determined.

### *1.2 Research Methodology*

To meet these objectives, the research would be divided into three phases that interlink with one another. These three phases were the Co-design, Economic and Geographical Information System (GIS) phases. Within the Co-design phase, the objectives of a suitable model, key stakeholders, and suitable sectors would be met. Data collected from this phase would then be used to inform the economic and GIS phases. The economic feasibility of the selected model would be determined in the Economic phase. Finally, suitable locations would be determined within the GIS phase using the findings from both the Co-design and Economic phase.

### *1.3 Research Limitations*

There would be some limitations to the research, such as the availability of socio-economic literature of a green biorefinery. This included literature based on the farmers outlook of green biorefineries. Other limitations included the availability of economic data of the more commercial biorefinery models, which was expected due to their commercial status. There was also a limit to up-to-date infrastructure and economic spatial data to be used for the GIS analysis. The research itself would also be limited to grassland agriculture, as beef and dairy farmers were the focus of the study. These limitations would be considered throughout the study.

### *1.4 Contribution of the Study*

This study contributes the social aspect of implementing a biorefinery to literature, focusing on the perspectives of the key stakeholders involved in the process. The study demonstrates the importance of including stakeholders within the decision-making stages of designing and implementing a green biorefinery or bioeconomy. The project also contributes a methodology framework of combining co-design, economic and GIS analysis, to literature and further research practice. The framework can be used within other sectors focusing on implementing a biorefinery, such as forestry or aquaculture. Finally, the model selected by the farmers, along with the suitable locations, is submitted as a suitable model for Irish grassland agriculture, with further research needed to extend the findings.

### *1.5 Research Structure*

The research is divided into five chapters, chapter one covering the general introduction to the project, chapter two focusing on the literature review of the Co-design, Economic and GIS phase. Chapter three focuses on the research methodology of each phase, while chapter four looks to the findings of these methodologies. Finally, chapter five carries out the discussion and conclusion of the project.

#### *1.5.1 Chapter Two*

In chapter 2, a literature review is carried out addressing topics in relation to each phase. Section 2.1 will introduce and overview of the bioeconomy, including the European bioeconomy sector, its potential relationship with climate change, and how agriculture and the bioeconomy can have an impact on the environment. The bioeconomy sector in

Ireland is also discussed, along with the innovation opportunities available and how they can be put into practice. Green biorefineries themselves will be the focus of section 2.2, where a critique of the evolution of green biorefineries is provided. The literature review relating to economic aspects will be completed in section 2.3, where agricultural economics will be analysed, along with the role of government funding and the economic challenges faced by farmers. The chapter will then focus on the economics of a biorefinery, including the expenses and revenues involved. The final section of the literature review will focus on GIS (2.4) as they relate to the bioeconomy, including how biomass supply locations can be found using this technology, and the type of data that is involved.

### *1.5.2 Chapter Three*

Chapter 3 will focus on the methodology used to carry out each phase, and how they meet the aims and objectives of the project. Details on the aims and objectives of the project will be provided within this chapter, along with the research design, and a more detailed look at how the methods of each phase intersect with one another. The Co-design methods used in this thesis will be covered in section 3.3.1, with the Economic analysis methodology in 3.3.2, and finally the GIS methods in 3.3.3.

### *1.5.3 Chapter Four*

Chapter 4 focuses on the results of these intersecting methodologies. The Co-design phase results will comprise of a comparison of European green biorefinery models and stakeholder identification and engagement results. The Economic phase results will include a mass balance, capital budget model and sensitivity analysis, while the GIS phase results will focus on suitable locations in Ireland for green biorefineries.

### *1.5.4 Chapter Five*

Finally, chapter 5 will be a discussion of the findings and how they contribute to implementing a green biorefinery in Ireland at suitable locations, along with a perspective on future research needs in this area. The limitations of the research and potential future work to be carried out is discussed in this chapter, along with the final conclusion of the thesis.

*1.6 Summary*

In summary, a mixture of qualitative and quantitative research methods would be used to select potential locations for a suitable green biorefinery model for Irish agriculture using the input of the key stakeholders. The model's economic feasibility would be analysed through scenario and sensitivity analysis. Finally, suitable locations for the model would be determined through a GIS analysis, where environmental, economic and infrastructure data would be analysed.

# Chapter 2: Literature Review of Three Processes of Identifying and Implementing a Green Biorefinery: Opportunity Co-design, Economic and GIS.

*2.0 Introduction*

This section of the literature review presents an introduction to the bioeconomy, green biorefineries as well as the importance of co-design in implementing green biorefineries. In 2.1, the bioeconomy sector in Europe is reviewed, including how the bioeconomy concept has been implemented into government policies and action plans (2.1.1). The manner in which the bioeconomy concept address climate change and sustainability goals is discussed (2.1.2), along with how the bioeconomy and sustainable agriculture address and contribute to climate change challenges and UN sustainability goals. (Chavarria et al., 2020). Limitations surrounding the bioeconomy are also discussed, such as knowledge gaps that are present in implementing the concept. The environmental impacts of agriculture are discussed in 2.1.3, along with the issues the bioeconomy attempts to address (2.1.3.1). An analysis of the broader opportunities for green technologies in Ireland is provided (2.1.4), including renewable energy from wind and solar, along with their potential for implementation in Ireland. Literature associated with innovation and collaborative innovation in the bioeconomy is also reviewed in section 2.1.5 and 2.1.5.1.

Section 2.2 presents a more focused review on green biorefinery technologies as a new opportunity for Ireland. Literature is reviewed to give a critique outlook on the evolution of technology from lab-based research to commercial level production. An overview of the different European biorefinery technologies is provided in 2.2.1, along with the Technological Readiness Level (TRL) classification of these models (2.2.2). The multiple end products produced from these technologies are also reviewed in section 2.2.3.

*2.1. Overview of the Bioeconomy Sector*

*2.1.1 The European Bioeconomy Sector*

The bioeconomy is a concept that sees non-renewable fossil fuels being replaced by renewable, biological resources (Kumar and Verma, 2021). These biological resources can vary from algae, food waste, grass and wood fibres, depending on the target market (McCormick and Kautto, 2013). In 2012, the European Union (EU) defined the bioeconomy concept as a method for converting biological resources, along with their waste streams, into high-value renewable products (Directorate-General for Research and

Innovation, 2012). These high-value products can range from animal feed to bioplastics and biofuels, demonstrating a wide range of target markets that the bioeconomy can reach (Teagasc, 2017; Stern et al., 2018; CSO, 2021; Dillon et al., 2021; O'Brien, 2022).

While the bioeconomy is not an entirely new concept, it has not come to the forefront of European Member State government policies until recent years. The foundations of the concept can be traced back to the 1993 White Paper and Lisbon Agenda in 2000 (McCormick and Kautto, 2013), which referred to it as a more knowledge-based economy and biotechnology, respectively. The development of the European Bioeconomy Strategy in 2012 has helped advancements in integrating the bioeconomy concept into policy making (Directorate-General for Research and Innovation, 2012). The strategy aims to promote a more sustainable economy through knowledge sharing, innovation and utilising natural resources in a sustainable way, with a focus on the fisheries, agriculture and forestry sectors (Anca-Marina, 2021). A study carried out in 2019 (Bezama et al., 2019), showed that there was an 30% increase in the number of policies at a national level that included the bioeconomy in comparison to those found in 2015. One of the reasons contributing to its gaining popularity is aligned with the Member States attempts to address the issue of climate change and the attempt to reduce GHG emissions (Miles, 2018). The issue of climate change and sustainability goals will be discussed further in 2.1.2.

### *2.1.2 Climate Change & Sustainability Goals*

Emissions from the burning of fossil fuels and intensive agricultural practices have contributed to rising global temperatures that in turn have contributed to environmental challenges such as drought and crop damage (D'Amato and Korhonen, 2021). The threat of climate change has led to the European Commission establishing the goal of carbon neutrality by 2050 (The European Comission, 2019). This has prompted governments of the Member States to look at more sustainable strategies and policies to reduce their GHG emissions, such as the European Green Deal (The European Comission, 2019; Vehvilainen et al., 2021). Though governments have set policies to reduce their emissions, the target for 2020 (a 20% reduction of GHG emissions), was not met (Benton, 2021; EPA, 2021), indicating that more needs to be done to reach carbon neutrality goals by 2050. With bioeconomy strategies (such as the circular bioeconomy), being implemented more widely across member states, the role of the bioeconomy in contributing to 2030 emissions targets is now being discussed (Department of the

Taoiseach, 2020; D'Amato and Korhonen, 2021). The circular bioeconomy provides an opportunity for communities to utilise waste streams that would otherwise go unused, hence closing the 'loop', reducing waste and potentially replacing less sustainable products (D'Amato and Korhonen, 2021). This strategy allows for all stakeholders involved in the bioeconomy to benefit.

The European Bioeconomy Strategy itself was recently updated in 2018 in response to new policy priorities, such as those of the Industrial Policy Strategy, the Communication on Accelerating Clean Energy Innovation and the Circular Economy Action Plan (The European Commission, 2019). The updates to the Bioeconomy Strategy have been based on strengthening and scaling up various bio-based sectors, deploying local bioeconomy's across Europe at a faster pace, and ensuring that the bioeconomy operates sustainably and within ecological boundaries. The importance of a bioeconomy which is circular has also been emphasized (The European Commission, 2019).

A sustainable and circular bioeconomy aims to address the Sustainable Development Goals (SDGs) 11 and 12, where sustainable cities and communities are developed and there is responsible production and consumption of products (Chavarria et al., 2020). The promotion of sustainable farming practices through the bioeconomy can also contribute to the SDGs 2 and 13, sustainable food and climate action, respectively. With global food demand set to increase by 2050 (Tilman et al., 2011; Agri-Food Strategy Committee, 2021), methods for transforming agriculture to a more sustainable sector while also meeting the demand are being investigated. For example, the Development of Plant Proteins plan set out by the EU looks at the potential for growing vegetable proteins (primarily soybean) for animal feed domestically, reducing imports (Clark and Lenaghan, 2020). Growing the necessary crops domestically could also help increase the market competitiveness, benefiting local agribusinesses (Patsios et al., 2020; The Newsroom, 2020; Agri-Food Strategy Committee, 2021). Growing crops for protein feed locally would reduce carbon emissions associated with imported feeds, adding another benefit to the economy (Karlsson et al., 2021). Greater integration of renewable technologies could also help the agriculture sector reduce its GHG and carbon emissions while benefiting farmers economically through alternative incomes (Pan et al., 2021). As the agri-food sector is one of the leading causes of climate change resulting from its contribution to GHG emissions (European Environment Agency, 2020), this has prompted more sustainable farming practices and technologies to be investigated.

### *2.1.3. The Environmental Impact of Agriculture*

Agriculture is an important sector in Europe for food production and land use, with around 39 – 41% of land cover being a combination of both cropland and grassland (European Environment Agency, 2020; Eurostat, 2021a, 2021b), with cropland being slightly more abundant in some areas than grassland (Eurostat, 2021b). While crop production is the more dominant agricultural land use in Europe, grassland agriculture in Ireland is by comparison much higher in coverage, with almost 58.4% of the land cover being grasslands (CSO, 2021), while only 9% of land cover was cropland. With a focus on grass production (Teagasc, 2017), agri-food sectors such as livestock production have become more prevalent over practices such as tillage (Dillon et al., 2021). Intensification in farming practices, such as increases in livestock numbers in the dairy industry, have contributed to a significant impact on Ireland's environment, such as the rise in methane gas emissions (Serra, 2021; O'Brien, 2022). For example, in 2019, 35.4% of Ireland's GHG emissions came from agriculture (EPA, 2020). This figure is high when compared to the European average, in which the agricultural sector only contributed to 10% of the GHG emissions (Mielcarek-Bochenska and Rzeznik, 2021). By 2030, it is predicted that agriculture will form 39.7% of Ireland's GHG emissions (EPA, 2021; EPA and SEAI, 2021). If more sustainable alternatives are not found for these farming practices, then this predicted figure will almost certainly be reached (EPA, 2021; EPA and SEAI, 2021). Another prevailing trend in agriculture is the conversion of agricultural land to forestry, a trend that has been growing in recent years across Europe and Ireland (European Environment Agency, 2020; O'Sullivan, 2022). While the conversion to forestry may help to address the issue of emissions seen in agriculture (Ryan, 2021), alternative sustainable farming practices should also be explored for those who do not wish to convert their farming practices.

As previously mentioned, a bioeconomy could also provide an opportunity for agriculture to become more sustainable by reducing the dependency on soybean protein imports for animal feed, which has led to a higher carbon footprint (Cong and Termansen, 2016; Termansen et al., 2016). Currently, protein production for animal feed is low in Europe, but its consumption rate is high (Dei, 2011), leading to a higher import rate (Santamaría-Fernández and Lübeck, 2020). In 2018 alone, Europe imported around 18 million tons of soybean meal for animal feed (Hiel et al., 2020), though under the EU protein plan, strategies are being put into place to help reduce this dependency (Clark and Lenaghan, 2020). Livestock farming in Europe has become dependent on soybean protein imports as they have proven to be a cheaper source of higher quality protein in animal feed (Dei, 2011). Though they may be a cheaper solution to Europe's protein deficiency, the negative impact of deforestation and carbon emissions associated with the imports often outweigh their benefits (Parajuli et al., 2018). For example, countries producing soybean protein, such as Brazil, have been subject to deforestation (Tilman et al., 201; Lathuillière et al., 2017) to convert land to more economically favourable agricultural land. Other environmental issues such as biodiversity loss and an increase in the use of pesticides and fertilizers (Prudêncio da Silva et al., 2010) are also negative impacts caused by the production of soybean proteins. The high import rate of the soybean also leads to costly import rates which can impact on farming communities (Cong and Termansen, 2016; Termansen et al., 2016) as well as impacting the carbon footprint of the consuming country. These negative impacts have led to other alternative protein sources to be developed, as discussed in 2.1.3.1.

#### *2.1.3.1 Alternative Protein Sources*

Along with greener technologies, other solutions that have been developed to reduce the need to import proteins include the use of insect protein, the growing of native beans and using industry by-products such as brewers' grains and dried distillers' grains. The use of insects for animal feed protein is a concept that has been investigated and developed over the last decade (Apri and Komalasari, 2020). The Black Soldier Fly (*Hermetia illucens*), in particular, has been found to have a crude protein content of around 42 – 54% (Kroeckel et al., 2012), similar to that found in soybean protein used in animal feed. Other species have also been investigated, such as crickets (*Grylloidea spp.*) and silkworms. (*Bombyx mori*) (Khan, 2018). Not only do these insect species have a high crude protein content, but they could also contribute to a circular economy (Gasco et al., 2020). By feeding these insect species food waste, the gap in production can be closed by utilising this waste stream, hence contributing to a circular economy. The development of local insect farms would not only reduce the need to import soybean protein but can also help contribute to the economy by creating new jobs in rural communities (Walter et al., 2020). The high turnover rate of species such as the Black Soldier Fly and the smaller land area required for their farming (Stiles, 2017) shows that there is a potential for the innovation to be turned into a successful agribusiness. (Creighton, 2021; Fantom, 2022). In Ireland, an example of this type of protein production is the Hexafly start-up, which converts waste products to feeds, bioplastics and fertilisers through insect farming (Taylor, 2019). Though there are benefits to using insect protein as a method for growing animal feed protein locally, the concept still requires further research. Currently, insects may not be used as animal feed in Europe if they have been fed on waste or manure (Bosch et al., 2019), limiting the potential of this new value chain to contribute to a circular economy.

Another alternative to importing soybean protein is the growing of native bean species. Field beans (*Vicia faba*) can provide high levels of protein similar to that found in soybean imports, helping to reduce the need to import the product (Halleron, 2021). These types of crops also have a lower nitrogen requirement than other cereal species, reducing their impact on the environment (Teagasc, 2020a). This lower fertiliser requirement would be beneficial to agriculture, as nitrous oxide fertilisers in the agri-food sector currently contribute to 35% of Ireland's GHG emissions (Department of Communications, Climate Action & Environment, 2017). In the UK, the faba bean is being used as a locally grown source of protein for cattle feed in place of soybean imports (MacPherson, 2021). While dairy cow feeding trials in the UK and Italy found that milk protein content decreased, other aspects such as yield, fat content and protein yield in the milk were not negatively impacted by the change in feed (Johnston et al., 2019; Tufarelli et al., 2012). While these crops could provide a good opportunity for locally sourced animal feed protein, the farming of such crops are still dependent on local climatic conditions. For example, in Ireland, field bean yields varied as some areas of the country experienced droughts while other areas experienced good growing conditions (Teagasc, 2020b).

Other innovative bioeconomy flagship projects have also investigated other methods of reducing imported protein feed in a sustainable way. Projects such as Plenitude, Farmÿng and ALEHOOP are funded and supported by the Biobased Industries Joint Undertaking programme (now operating under the Circular Bio-based Europe Joint Undertaking programme) to find new ways of creating sustainable protein supplies, with the co-production of additional products and energy. The Plenitude project involves producing food-grade proteins by using an aerobic fermentation process (BBI JU, 2020a). The project looks to reduce $CO_2$ emissions while sustainably using cereal crops as a feedstock to produce biobased packaging, pet food, and meat-free protein food. The Farmÿng project uses mealworms as its feedstock for creating a more sustainable protein source, with pet food and fish feed as their targeted markets for the co-products (BBI JU, 2020b). The project also notes that the use of farming mealworms as an agricultural practice could also help reduce agricultural greenhouse emissions, as the practice does not produce methane emissions. Macroalgal residuals and legume processing by-products are used in the ALEHOOP project as a feedstock to produce protein for the food and feed industry (ALEHOOP, 2021). The project aims to have a positive environmental impact compared to soybean imports as it reduces food waste by utilising waste streams (BBI JU, 2020c). These type of flagship projects are seen across Europe, demonstrating that there is a move towards more innovative and sustainable farming practices, leading to more opportunities for a bioeconomy to be developed in Ireland.

### *2.1.4 Bioeconomy in Ireland & Opportunities*

At a broader level, the move towards a more sustainable bioeconomy can be seen in Ireland through government action plans and strategies. The Climate Action Plan 2021, in particular, looks to encourage sustainable farming practices (Department of the Environment, Climate and Communications, 2021). Objectives of the action plan include reducing the amount of nitrogen fertilizers used in agriculture by 325,000 tonnes/yr. and increasing the amount of land used for organic farming to 350,000 hectares (Department of the Taoiseach, 2020). These objectives of the action plan set out by the Irish government aim to reduce the GHG emissions produced by agriculture by 25-30% by 2030 (Department of the Environment, Climate and Communications, 2023). The Climate Action Plan also targets the publication of a Bioeconomy Action Plan in 2022 until 2025, with a greater focus on how the bioeconomy can be successfully integrated into the Irish economy, along with addressing gaps in education and skills (Department of the Taoiseach, 2020). Other government strategies, such as the National Bioeconomy Policy Statement from 2018 and the Circular Economy Strategy 2021 all work towards integrating bioeconomy objectives into sectors such as agriculture, forestry and fisheries in Ireland (Government of Ireland, 2018; Department of the Environment, Climate and Communications, 2021). The Circular Economy Strategy in particular looks at methods for Ireland to transition to more circular practices in the reduction and management of wastes, production of sustainable products, with an emphasis on improving the use of materials and reducing GHG emissions. To help implement these strategies and objectives, there also needs to be accessible knowledge provided to the general public through research and organisations. Organisations such as the BiOrbic Centre and the Irish Bioeconomy Foundation provide knowledge to the public to help reduce the knowledge gap that is often associated with the bioeconomy concept (Bezama et al., 2019). Research centres such as these also organise events such as the Bioeconomy Ireland Week to help promote public interest in the bioeconomy concept (Chambers, 2021). In addition, research centres and universities also help to support the development of research, and scale-up activities in the bioeconomy sector.

As the bioeconomy concept grows across Ireland, there is an opportunity for greener bio-based technologies to be better developed and implemented to meet the objectives of the concept, such as biorefineries which look to convert biomasses to high-value products (Andersen and Kiel, 2000; Cherubini et al., 2009). Biorefineries can provide a strategy towards reducing GHG emissions in primary production and industrial sectors (Ball, 2018; Andreasen, 2019). For example, biorefineries producing biofuel from wheat straw in Europe saw a change in GHG emissions from -206 to 135g and -221 to -17g $CO_2$ per MJ in the study carried out by Buchspies et al. (2020). Biorefineries can be classified into different colour categories depending on the feedstock used. Yellow biorefineries use cereal straw, brown use waste sludges and blue biorefineries make use of macroalgae (Lange, 2022). Green biorefineries use biomasses such as grass to produces high quality products like biofuels and animal feed, which could potentially replace their non-renewable alternatives (Stern et al., 2018). It has been shown that more sustainable products produced would be favourably received by Irish consumers who look to become more sustainable (Gaffey et al., 2021). In an Irish context, focusing on grass and silage feedstocks, green biorefineries could also provide alternative incomes to farmers (O'Keeffe, 2010). A green biorefinery approach may offer an opportunity to displace unsustainable products and reduce national emissions, by utilising underutilised grass or green waste streams.

Examples of Irish biorefineries include the Glanbia-led AgriChemWhey Project and the Biorescue Project involving Monaghan Mushrooms. The AgriChemWhey project is a biorefinery based concept that utilises the dairy waste streams such as whey permeate and de-lactosed whey permeate to product high-value products such as bio-based fertilisers and lactic acid (European Comission, 2021). The project demonstrates the potential for utilising the otherwise unused waste streams produced by the dairy industry, creating a more circular economy. At farm level, projects such as Farm Zero C work with dairy farmers to reduce their carbon emissions and increase biodiversity and soil health (Hunt, 2021). This is carried out through the integration of clover and multi-species swards grasslands, integration of sustainable technologies, anti-methanogenic feed additives, increased biodiversity spaces and hedgerow growth, and a range of other strategies (UCD, 2021). Other projects in Ireland, such as the Biorescue and FungusChain project, show that there is the potential for the innovative bioeconomy concept to be implemented into Irish economy (BBI JU, 2020d), though as section 2.1.5 will show, there are still challenges in implementing the concept.

### *2.1.5. Bioeconomy Engagement and Implementation*

Though the bioeconomy concept could potentially offer a more sustainable and beneficial economy, there are still difficulties in implementing the concept with stakeholders due to its novelty (Vehvilainen et al., 2021). While governments may support the concept, there are still gaps in public knowledge and understanding of the bioeconomy (Dallendörfer et al., 2022). To close this gap, stakeholders need to be included more a more integrated way, in the decision making for these concepts (BBI JU, 2020).

In the case of green biorefineries, farmers in particular, should be more involved in the decision making as they are the primary producers of the green biomasses required for these systems. The buy-in of farmers may be increased significantly if they were to be consulted in the design of a bioeconomy (Gaffey et al., 2020). While there have been a number of sustainable agriculture demonstration projects across Europe (EIP-Agri, 2021), more long-term infrastructure would encourage the participation of farmers. Literature surrounding green biorefineries was found to be primarily focused on the environmental and economic aspects of sustainability goals, with little focus on their social impacts, with the latter only taking place in recent years (Corona et al., 2018a; Cadena et al., 2019; Jorissen et al., 2020). However, the necessity to consider social aspects of biorefineries will be a key factor in the wider adoption of these technologies. The social life-cycle assessment of green biorefineries carried out by Cadena et al. (2019) highlighted that social aspects of biorefinery models were complex, and would require the application of methodologies from other fields. These fields include those of business and innovation, where the designing of a product, along with testing with consumers, is carried out in the early stages of development (Gaffey et al., 2021). An example of the importance of engaging key stakeholders can be seen in the study carried out by Morone and Imbert (2020), who engaged with stakeholders to determine the social acceptability of the circular bioeconomy and the use of food waste streams for producing bioproducts.

#### *2.1.5.1 Collaborative Innovation*

The use of collaborative workshops have been demonstrated as a useful method in engaging stakeholders in the bioeconomy, as they allow for teams from multiple disciplinaries to work together to design a user focused solution (Minerva Communications UK Ltd, 2021). Workshops that allow for all stakeholders' voices to be considered, provide a useful tool in understanding what the participants are expecting from a bioeconomy. They also allow for expert knowledge from multiple sources to design either prototypes of products or strategies and action plans through a range of different teamwork activities (Geissdoerfer et al., 2016). In some cases, the use of LegoSERIOUS play in these type of stakeholder workshops provides a visual tool for stakeholders to use in demonstrating their understanding of a concept (Grienitz and Schmidt, 2021). Questionnaires may also be used to gauge the level of awareness of the bioeconomy of the stakeholders and for direct consultation with them individually if required through interviews (Gerdes et al., 2018). While this may provide an opportunity to seek information and buy-in from the stakeholders, it does not allow for the same level of engagement and learning afforded through interactive workshops. Design-thinking workshops, along with the use of a visual model, allows for a more detailed approach to determining the strengths and weaknesses of a co-designed bioeconomy (Lokesh et al., 2018). Semi-structured interviews with stakeholders such as policy makers and funding bodies provide an opportunity to directly gain qualitative information (Biodiversa, 2014). Focus groups have also been demonstrated as a useful tool in engaging stakeholders while also allowing for their opinions to be heard (Gerdes et al., 2018). This method of engagement allows for different stakeholders to discuss their perspectives of a bioeconomy with one another, allowing for needs to be addressed and enabling better decision-making for implementing a bioeconomy. All of these will be further discussed in Chapter Three.

## *2.2. A Critique of the Evolution of Green Biorefineries*

Within the last twenty years, green biorefinery technologies have developed from lab-based research to larger commercial scale facilities. Biorefinery research at a lab level initially only looked to produce one or two co-products (Andersen and Kiel, 2000), while more recent demonstration and commercial scale biorefineries now produce multiple high-quality products (Ambye-Jensen, 2020; Mandl, 2010; Wicke et al., 2020). Through a number of research studies carried out over the past two decades, demonstration and pilot plants have been well developed in Germany, Austria, Denmark, the Netherlands and Switzerland (Andersen and Kiel, 2000; Kamm et al., 2010; Ecker et al., 2012). At a demonstration level, these biorefinery plants primarily focus on the use of fresh grass or silage as a feedstock, while this type of feedstock is currently only used in a small number of commercial level biorefineries (Biofabrik, 2021; Gramitherm, 2021). Issues with storing the biomass, costs of production and the difficulty in obtaining grassland for the biomass have all contributed to challenges in developing larger scale biorefineries (Lindorfer et al., 2019) for larger commercial level production. Demonstration plants across Europe have shown that smaller scale green biorefineries can still be successful as there is still a market for the products being produced, and some of these products attract a high value (Mandl, 2010; Gramitherm, 2021). Though a surplus in grasslands is an issue in Europe, the same could not be said for Ireland, as livestock agriculture is the more dominant practice in Irish agriculture (Dillon et al., 2021). While Irish agriculture has a higher abundance of perennial ryegrass (*Lolium perenne*) as a feedstock (O'Keeffe, 2010), agriculture in Europe utilises a wider variety of species, such as red clover (*Trifolium pratense*) and alfalfa (*Medicago sativa*) ( Lamsal et al., 2007; Colas et al., 2013; Ambye-Jensen and Adamsen, 2015). As Europe also has a higher cropland land use than Ireland (Eurostat, 2021), there is a better opportunity for European countries to utilise other feedstocks outside of grass.

### *2.2.1 Summary of Technologies Across European Green Biorefineries*

In green biorefinery models across Europe, technologies used within the first stage of processing are usually similar. A screw press, or another mechanical separation processes, such as an extruder or refiner, is used to separate the green biomass into a liquid and solid form known as the press juice and press cake respectively (Andersen and Kiel, 2000; Kamm et al., 2010; Ecker et al., 2012). It has been found that by using this separation technology, around 40-50% energy can be saved in the later stage of drying the press cake (Kamm et al., 2010). Some models also found that washing the feedstock before separation allowed for impurities to be removed (Aarhus University, 2019; Buckley et al., 2021). In the processing of the press cake, a drying process is commonly used so that the end products of either animal feed, which is further ensiled for storage (Larsen et al., 2019), or biogas fuel can be produced (Kamm et al., 2010; Aarhus University, 2019; Hamoen, 2019). Biorefineries, that focus on producing insulation, such as the model found in Switzerland, usually have an additional drying step and processes to include the binding materials, such as jute fibres, to develop high-quality eco-insulation (Franchi et al., 2020).

Unique technologies are mainly seen in the secondary processes of the models, particularly in the processing of the press juice. To convert the press juice into usable high-quality products, coagulation by heat and separation by decanter-centrifuge is used in some biorefineries such as those found in Germany, Denmark and the Netherlands (Kamm et al., 2010; Mandl, 2010). In the coagulation process, heat treatments can range from 75ºC-85ºC (Ambye-Jensen, 2020) or at 80ºC (Kamm et al., 2010). It was noted by Santamaría-Fernández and Lübeck (2020) that the temperatures for heat coagulation could also range between 60ºC to 95ºC. To carry out coagulation, the biorefineries use the supernatant to preheat the press juice (Kamm et al., 2010) along with steam injection that is superheated and only used for a short time (Santamaría-Fernández and Lübeck, 2020). This allowed for the proteins to coagulate into agglomerates due to the mixture of high temperatures. It was noted by Lamsal (2007) that the produced proteins may have a low solubility after coagulation due to changes in the protein structure. After the proteins are separated further in a decanter-centrifuge, they are dried for use in end products. The process of passing the press juice through nanofiltration, electrodialysis, reverse osmosis is also used in the secondary process to produce higher quality products such as lactic acid and amino acids. This is particularly the case for downstream processing of silage feedstocks. It has been noted by Ecker et al., (2012) that this process would need to be simplified to make it more economically feasible. Other technologies found within biorefinery models include nanofiltration and ultrafiltration. Nanofiltration can be used in this process to filter the brown juice produced after the protein has been separated from the press juice (Aarhus University, 2019; Ecker et al., 2012; Prieler et al., 2019), while ultrafiltration is used to extract fructan sugars (FOS) from deproteinized grass juice (Biorefinery Glas, 2021). The range of technologies found within the secondary processing stage of the press juice allow for multiple co-products to be produced from the green biomass (Mandl, 2010).

### *2.2.2 Technological Readiness Level*

Another consideration when reviewing biorefinery technologies, including green biorefinery technology, is Technological Readiness Level (TRL). The TRL is a classification scale which assesses the maturity range of a technology (Ruyters, 2016). The scale ranges from 1-9, where the lower levels are technologies still in the early stages of development. As classified by Ruyters (2016), biorefineries with a TRL 1-3 would indicate proof of concept, 4-5 would indicate the technologies have been developed into a pilot plant, and 6-7 would indicate a demonstration plant and TRL of 7-8 are either working towards a commercial level or have reached that stage. The models that have reached the final stages of technological readiness and were operating commercially are given a TRL of 8-9 (Humbird, 2018). The TRL level of different European green biorefinery models is later discussed in section 4.2.1.

### *2.2.3 End Products*

The improvement in green biorefinery technologies can also be seen in the variety of end products they produce. For example, in most models seen in Europe the press cake is used as either an animal feed or biogas and biofuels after it had been further dried (Ravindran et al., 2021). In more recent years, the fibre material is not only being used by these products, but is also being converted into materials such as insulation mats, composite, and paper products (Biofabrik, 2021; Gramitherm, 2021). While it is beneficial for biorefineries to produce these products, they must still be able to meet quality specifications and European regulations. For example, insulation produced from grass biorefineries must be able to compete with similar insulation products that are already on the market. When compared to stone wool insulation, grass insulation was shown to have a better environmental impact and was less damaging to human health (Franchi et al., 2020). They also have a better thermal conductivity of 0.040 W/mK (Gramitherm, 2021a). With the EU set to increase the number of buildings that install eco-insulation (Rankin, 2021), it is important that the new eco-insulation materials provide comparable or better thermal conductivity and heat insulation compared with unsustainable materials.

Similar to insulation, the grass biorefinery co-products that look to replace soybean protein, silage and other ingredients in animal diets must also be able to compare with the products currently in use. For example, protein produced from biorefineries must also have a similar or better protein content to be used in animal feed (Kragbæk Damborg et al., 2019; Byrne, 2021). With Europe importing around 18 million tons of soybean protein annually (Karlsson et al., 2021; Serra, 2021), biorefineries should target their grass-based protein at a similar market price or lower in order to entice farmers, many of whom are working on tight margins. While the animal feed market was predicted to grow in 2021 by a CAGR (Compound Annual Growth Rate) of 4.90%, it was impacted negatively by the pandemic (Knowledge Sourcing Intelligence LLP, 2020) due to supply disruptions and delays (Roembke, 2022). The challenge of supply shortage and availability could provide an opportunity for animal feed protein to be grown locally, hence reducing the need to import the products from other countries.

While green biorefineries have shown promise relating to sustainability and environmental impacts, more work is required to determine their economic feasibility. Economic literature will be discussed in the section 2.3.

### *2.3. Economic Analysis*

The economic literature review explores the financial aspects of implementing a green biorefinery. This part of the literature review will provide an overview of the challenges and trends associated with farmer's incomes, as they are both the potential supplier and end user of the green biorefinery and products. The economic analysis will explore existing farming incomes for the different sectors, such as dairy, beef and tillage. Furthermore, a review is undertaken of the government supports that are currently used to help fund farming incomes. The potential future challenges and issues that farming incomes will face is also reviewed under the future proofing section of the literature review. Methods in which government schemes and alternative revenue streams can address these challenges will also be discussed. An introduction into potential green biorefinery revenue streams from products such as building materials, animal feed protein and biogas, will also be provided. The current and potential future market opportunities will also be discussed.

#### *2.3.1 Farming Incomes*

The agri-food sector is a valuable economic sector in Ireland for employment (Department of Agriculture, Food and the Marine, 2021), with a majority of Irish farms within this sector being family run. Incomes are dependent on a combination of government subsidies and market trends such as demand and produce cost (Teagasc, 2021a). In terms of average income, dairy farming is currently the most profitable of the farming practices in Ireland, with the average income for family run dairy farms increasing gradually since 2018 (Dillon et al., 2019, 2021). Increases in food demand and consumption caused by the Covid-19 pandemic in 2020, along with lowered production costs during this time period all played a key role in the increase of farm incomes in 2020

(Teagasc, 2021). An example of this demand is seen in the increase in dairy production in 2020, where there was an increase in products such as cheese, milk and butter sold compared to the previous two years (CSO, 2021). Ireland produced over 8 billion litres of milk in 2021 (Teagasc, 2021), with around 85% being exported worldwide (BordBia, 2023). There was also increases in dairy market prices exports in the EU in 2021, benefiting farmers within this sector (European Commission, 2022a). While there are increases seen in dairy farm incomes, the market for these products has been volatile over the past decade, with milk prices fluctuating during this period (European Commission, 2020a, 2022a; Teagasc, 2021b). In comparison to other European countries, Irish farmers receive lower market prices for their milk products, with prices in 2020 being the lowest in Europe (Roche, 2020). While dairy farmers may receive low market prices for their milk produced, they also benefit from low production costs when compared to tillage farming production costs (Roche, 2020; Teagasc, 2020; O'Brien, 2022). The removal of the milk quota in 2015 by the EU, which limited the annual amount of milk produced by farmers, has also greatly benefited dairy farmers income, as they are no longer limited to the amount of milk they can produce (Donnellan et al., 2015).

While incomes in the dairy sector have benefited from low production costs and increase in demand, the opposite has occurred for tillage farmers' incomes. While family farms in this sector were the second most profitable in 2018, with average incomes reaching €40,650 (Dillon et al., 2019), they have been on the decline since, dropping to €32,100 in 2020 (Dillon et al., 2021). This decline in tillage farming incomes has resulted from a combination of lower production yields of crops such as cereals caused by drought (Kiernan, 2021; CSO, 2022), and changing market prices in Europe for tillage products, such as feed wheat and barley (European Commission, 2020b). In 2020, the beef sector in Ireland also saw changes to average family farm incomes, where beef rearing farming increased from €8,311 in 2018 to €9,043 2020 (Dillon et al., 2019, 2021), but within the same timeframe, other cattle farming incomes fluctuated from €14,560 (2018) to €15,023 (2020) (Dillon et al., 2021, 2019; Donnellan et al., 2020). This fluctuation between the years resulted from issues in 2019 such as a reduction in Irish cattle prices but higher production costs, along with a decrease in demand in European and British markets (Teagasc, 2020a). European beef demand decreased by 0.9%, while demand in the UK fell by 2.1% (BordBia, 2019).

Overall, due to their lower incomes, beef farmers may benefit from alternative incomes from grass production in comparison to dairy farmers, who have much higher incomes (Dillon et al., 2019).

### *2.3.2 Government Supports*

Government subsidies also play a key role in the incomes for farmers in Europe, and Ireland (Teagasc, 2021c). Cattle, sheep and tillage farming are the most reliant on these subsidies as an alternative income in Ireland (Dillon et al., 2021). These payment support schemes are broken down into three overall categories; the Common Agricultural Policy (CAP), Rural Development Schemes and Targeted Agri-Environmental Schemes (IFA, 2021a). The EU's Multiannual Financial Framework (MMF) allocates approximately 30% of its budget towards CAP, which is then further divided into two 'pillars' (European Commission, 2023a). The first pillar is known as the European agricultural guarantee fund (EAGF), which provides direct payments for income schemes such as the basic payment scheme, direct payments for sustainable farming methods and payments to support younger farmers (European Commission, 2023b). The second pillar of CAP consists of the European agricultural fund for rural development (EAFRD), which provides funding to improve competitiveness of the agriculture sector, promote sustainable management in farmlands, and to improve rural communities and development (European Commission, 2023a; European Parliament, 2022). In Ireland, these objectives are met by focusing on six Rural Development priorities (European Commission, 2021). These six objectives include (1) promoting knowledge transfer and innovation in agriculture, forestry and rural areas, (2) improving agricultural competitiveness and viability, (3) promoting animal welfare and risk management, (4) preserving and restoring ecosystems related to agriculture and forestry (5) improving resource efficiency and moving towards a low-carbon economy, and (6) promoting poverty reduction and social inclusion in rural areas (Department of Public Expenditure, NDP Delivery and Reform, 2021; European Commission, 2021).

The CAP funding is provided through a number of agri-environmental schemes. The Basic Payment, which replaced the Single Payment System in 2015, rewards farmers that qualify for the scheme based on the amount of land (by the hectare), that is eligible for agricultural use (DAFM, 2020a; O'Foghlu, 2021). The annual value placed on this type of land varies across Ireland, depending on both funding and the quality of the land (Teagasc, 2021a). In 2020, the highest value of agricultural land was found in counties in the lower regions of Leinster, where values reached over €12,000/ha (Donnellan et al., 2021). In comparison, good quality land found in Connaught only reached values of between €7,000 to €8,225. This scheme allows for farmers to also rent their unused land that still qualifies as agricultural use, earning farmers an additional income (Donnelly, 2021). Payment schemes such as the Green Low Carbon Agri-Environment Scheme (GLAS), organic farming and targeted agri-environment schemes focus more on the environmental aspects of agriculture (IFA, 2021). These schemes fund farmers to create more diversification on their farmland and to enhance the environment (DAFM, 2020b; Teagasc, 2021c). In Europe these subsides form around 38% of the average agricultural income (Matthews, 2019), with farmlands with grazing livestock being the most dependent. In Ireland, it was found that 74% of family farm incomes consisted of government subsides (McDonnell, 2020). While the environmental payment schemes encourage farmers to set land aside for nature, they also result in the farmers income in other subsidies such as the basic payment being reduced as a result (Sargent and McSweeney, 2021). This is primarily seen with the basic payments where payments are based on the amount of land used for agricultural production, and is the most dominant of the payment types to farmers income (Donnellan et al., 2020; Dillon et al., 2021). This type of funding support does not encourage land to be set aside or converted for nature. Issues with these payment schemes have been ongoing for over a decade (Wise, 2004), with poor management of the schemes and cuts in funding (O'Sullivan, 2021; Sargent and McSweeney, 2021) being the main concerns. Therefore, farmers have had to look towards alternative incomes outside of the farmland to sustain a viable income (Dillon et al., 2021; Meredith et al., 2015). A survey in 2021 found that around 54% of farming households were dependant on an off-farm income, as the farmland business was not sufficient to pay the annual minimum wage of a family member of €20,129 (O'Brian, 2022). The challenges associated with on-farm incomes are discussed in the next section.

### *2.3.3 Future Proofing*

Farmers are highly vulnerable, because their incomes are highly dependent not only on government funds, which form almost 74% of family farm incomes (Teagasc, 2020b), but also market prices and demands (IFA, 2021b). Low return on the products produced is an issue for farmers in Ireland, as it leads to lower incomes (Finnerty, 2018), resulting in farmers having to search for employment off-farm. Decreases in demand or changes to the market prices of the products can cause a negative impact to farmer incomes (Donnellan et al., 2021; IFA, 2021b; Kiernan, 2022). For example, a reduction in beef demand to beef supply chains caused cattle prices to significantly decline in 2020 (European Commission, 2020a; Kiernan, 2022), which negatively impacted cattle farmer incomes. The issue of Brexit also poses a threat to farmer incomes, where decreases in exported agri-food goods negatively impacted farmer' incomes, particularly in Ireland by comparison to other European countries (Cheptea et al., 2021). Increases to farmland production such as land and materials is also a cause of concern as it may impact farmer incomes. As low input costs allowed for incomes to rise in 2020 (Teagasc, 2021d), this shows the significant impact production costs have on farmer incomes. Future rising fuel prices and fertiliser costs have been noted as a cause for concern towards future agricultural production costs (Phelan, 2021; Teagasc, 2021e). Increases in fuel prices, specifically natural gas, has seen the cost of fertilisers also rising (Teagasc, 2022). This increase has occurred due to the natural gas supply across Europe and the United States being reduced (Coyle, 2021). This has been further impacted by global events such as the Russian-Ukraine crisis, which has limited European natural gas suppliers stocks, leading to increases in fuel price fluctuations (Mohseni-Cheraghlou, 2022) . As natural gas is used in the production of fertilisers, this has led to an increase in prices in the agricultural market. To reduce high fertiliser costs, farmers have begun to compare retailer prices in order to find cheaper alternatives (Carty, 2022), while also investing in alternative, more sustainable sources. This includes the ongoing practice of recycling the manure produced at a farm level and reusing it as a fertiliser (Ostendorf, 2021).

Changing feed costs are also a cause of concern for farmers production costs, particularly costs associated with imported feed such as soybean protein meal and cereal crops from countries such as Brazil or Argentina. The costs of agricultural animal feed has increased over the last few years, with prices increasing by around 10% across the world (O'Brien, 2020). Low production yields and challenges such as transport have caused these production costs to increase (O'Brien, 2020;Carty, 2021). The sustainability challenge surrounding the production and transport of imported protein feed, such as soybean meal, for livestock production, has led to farmers and retailers to search for more sustainable alternatives (Animal Feed Representitive, 2021; Nutritional Informative, 2022). For example, the UK retailer M&S has removed soya protein from its milk production to address deforestation in its supply chain (Smithers, 2020). Environmental issues such as carbon emissions and deforestation have led to this type of feed supply chain being recognised as unsustainable (Lewis, 2018; Karlsson et al., 2021). These issues associated with this type of feed protein also contribute to volatile market prices. For example, in 2020 soybean protein meals rose from €350/t to around €380/t - €450/t (O'Brien, 2020), then increased further to €550/t due to disruptions to the supply chain (Carty, 2021; Nutritional Informative, 2022). Challenges associated with market prices along with efforts to become carbon neutral has led to governments in the EU proposing strategies to produce local protein and become less dependent on imports (Santamaría-Fernández and Lübeck, 2020; Karlsson et al., 2021). For example, protein derived from a grass-based resource has shown to be a suitable alternative to imported soybean protein (Kragbæk Damborg et al., 2019). In Ireland the government has also proposed to increase tillage production as part of the Protein Aid scheme, which aims to promote the objectives of the CAP 2023 (Walsh, 2021). The local production of animal feed protein can become beneficial to farmers, as the challenge of overseas transport associated with the supply chain would be reduced (Animal Feed Representitive, 2021), further decreasing their production costs. Therefore, alternative protein sources must be found to help reduce feed costs to farmers.

#### *2.3.4 Green Biorefinery Revenues*

The move towards more sustainable products is creating more competitive markets, which could lead to more competitive prices for products generated by green biorefineries (Appolloni et al., 2022). Concepts such as a bioeconomy and sustainability also help promote greener products, as consumers become more aware of environmentally friendly alternatives (Divyapriyadharshini et al., 2019; Guo et al., 2022). Though some sustainable products have the reputation of costing more than similar products at market, it has been demonstrated that certain consumers are more willing to pay the higher cost for the sustainable alternative (Appolloni et al., 2022; Gaffey et al., 2021), particularly in Ireland. This higher cost, known as the green premium, is placed on more sustainable products  in an attempt to address climate change, though the value of this additional cost is dependent on the level of GHG output and if the product has a niche market (Carus et al., 2016; Gates, 2021), for example, greener fuel and agricultural feed. While these additional costs are a challenge associated with greener products, they also promote more research and funding to be made available in an attempt to lower these costs, thus furthering the development of sustainability (Appolloni et al., 2022; Gates, 2021). In terms of the biorefinery itself, the costs associated with the supply chain, along with capital and operational expenditures need to be considered when analysing the cost-benefit of the technologies (Corona et al., 2018; Prieler et al., 2019). Green biorefineries have low capital expenditures in comparison to larger wood and biofuel biorefineries ( Tsagkari et al., 2020; Metsä Fibre, 2022). For example, a model could be from €600,000 to €13 million, depending on scale and the products produced (Ball, 2018). Operational costs, such as feedstock, which can reach up to €150/tdm (tonnes dried matter), and transport also make scaling a challenge (Höltinger et al., 2012; Ambye-Jensen, 2020). The limitations of these costs have resulted in a majority of established biorefineries remaining at demonstration scale (Höltinger et al., 2012; Lan et al., 2021). Due to these challenges, it is vital for a biorefinery to produce multiple products from one bioresource, to increase the amount of revenues to be produced (Corona et al., 2018). A selection of these type of revenue streams will be discussed below.

#### *2.3.4.1 Building Materials*

The move towards more biobased sustainable building materials is being encouraged across countries in Europe in recent years in an attempt to reduce GHG emissions (Cadogan, 2019). As buildings account for almost 40% of European energy consumption (Fedorik et al., 2021), the move towards more sustainable materials to reduce carbon emissions is a key motivation for the construction sector (Zhong et al., 2021). In a building structures lifetime, the total embodied energy, which indicates the overall environmental impact, can reach up to 20% of its total energy use (ISOBIO, 2015). The use of natural biomasses as building materials is not a new concept, where resources such as agricultural waste has been used for buildings in countries such as India (Yadav and Agarwal, 2021). The use of natural resources such as wood or agri-waste has been demonstrated as having a lower energy consumption in the production of building materials in comparison to non-sustainable resources (European Commission, 2019; Yadav and Agarwal, 2021). In an attempt to reduce buildings energy consumption, natural based building materials, such as insulation and plaster, have been developed in Europe from resources such as hemp, lime, sheep's wool and grass (Sheridan et al., 2020; Gramitherm, 2021a). Insulation material produced from grass fibres has shown to have many economic and environmental benefits in comparison to mineral based insulation (Franchi et al., 2020). When grass insulation production was compared to stonewool insulation, it was found that grass insulation caused less environmental damage in the production stage due to its renewable nature (Franchi et al., 2020; Prieler et al., 2019). The high thermal conductivity of grass insulation (0.041W/m.K) can also help reduce the energy consumption of buildings, both at the production and use phase (Deutsches Institut für Bautechnik, 2021; Gramitherm, 2021b).

Other biobased materials have also been used for producing sustainable insulation, in particular the use of hemp fibres and sheep's wool (Page et al., 2017; Florea and Manea, 2019; Sheridan et al., 2020). While biobased resources have been shown to be a viable option for eco-insulation and building materials, it is still a relatively niche market in Europe, with only around 4% of Europe's insulation material being derived from bioresources (Cadogan, 2019). While natural building materials are seen in smaller construction companies, the uptake of the concept by larger construction companies is limited (Bakker, 2017). This reluctancy of larger companies to produce natural building materials has limited its impact on the more mainstream market. Though this does prove to be a significant limitation to development of biobased building materials, there has been an increase in public and government interest in the use of biobased materials for construction (Khoshnava et al., 2020; Gaffey et al., 2021). In Ireland, the government has put forward grants to encourage homeowners to retrofit their households with natural insulation, further promoting the move to natural building materials (McGee, 2022). As part of the Climate Action Plan 2021, the National Retrofit Plan proposes to improve the energy ratings of around 500,000 homes by 2030 to reduce energy consumption and carbon emissions (Department of the Environment, Climate and Communications, 2021). This support by governments can help create a larger market for natural building materials for companies to partake in, which in turn could reduce the high costs that are associated with the materials. Ireland in particular has the potential for producing grass-based insulation (Insulation Expert, 2021). Grass based eco-insulation is still a relatively niche market in comparison to other renewable resources, and there is little data available on how it compares at market. At present, only one company in Switzerland has been identified to both manufacture and supply grass insulation in Europe (Franchi et al., 2020; Gramitherm, 2021a). Due to Ireland having such a high grassland cover and farming output, there is the potential for farmers to grow grass for insulation as part of the bioeconomy (O'Keeffe, 2010). As Irish farmers are familiar with growing grass, there would be less challenges to the supply chain in comparison to the use of hemp fibre in insulation (Insulation Expert, 2021).

In terms of generating revenues for a green biorefinery, studies have indicated that grass insulation can produce a revenue of €0.80/t to €1/t (O'Keeffe, 2010; Höltinger et al., 2014; Prieler et al., 2019), when compared to fibre material such as hemp, depending on the market. Other studies have also produced a cost range of €0.80/kg to €1.20/kg for grass insulation material (O'Keeffe, 2010), showing that depending on the market, there can be a high revenue generated from the production of grass insulation.

#### *2.3.4.2 Animal Feed Protein*

Animal feed protein products are a viable revenue stream for green biorefineries, as there is a potential market available (Mandl., 2016). As stated above, there is an increasing need in Europe to reduce soybean protein imports for agricultural feed (Kamm et al., 2010). This has given the opportunity for homegrown protein to compete at market (Karlsson et al., 2021; Walsh, 2021). Farmers themselves have also noted that there is a need for more sustainable protein sources for animal feed (Walsh, 2021). The move towards more sustainable products, brought on by the Climate Action Plan and other strategies, has promoted research and development in producing lower emission protein (Corona et al., 2018; Department of the Taoiseach, 2020). Protein for monogastric feed produced from grass press juice, and silage alternatives for ruminant feed from press cake fibres have shown to be a viable model for the replacement for soybean protein, as demonstrated in feeding trials (Kragbæk Damborg et al., 2019; Hansen, 2020). These feeding trials demonstrate that there is a potential for locally generated protein as an alternative to soybean imports.

As mentioned earlier, due to disruptions to the supply chain, imported soybean protein feed costs can rise to around €550/t (O'Brien, 2020), where previously they may have only reached €300/t. Changing soybean protein prices caused by fluctuating market trends and challenges such as strikes in the source countries (Lewis, 2018; Carty, 2022). Furthermore, delays and environmental conditions such as drought can further impact the supply demand (Animal Feed Representative, 2021). This issue is seen in Ireland where farmers are dependent on imported protein (Lewis, 2018). By producing local protein feed from sources such as grass, these issues can be reduced, in turn reducing the cost of the feed (Animal Feed Representitive, 2021). For example, the demonstration biorefinery in Germany showed that low production costs allow for protein feed to be sold for competitive prices, such as €290/t compared to soybean protein, which ranges between €300-400/t (Kamm et al., 2010). These market prices are similar to other locally grown protein products such as barley and wheat (European Commission, 2020b; Nutritional Informative, 2022), which provide a good comparison for market trends. The move towards a more carbon neutral economy also provides good market potential for grass-based animal protein, as this type of protein has been shown to reduce carbon emissions both in production and feeding (O'Keeffe, 2010; Corona et al., 2018).

*2.3.4.3 Biogas*

In addition to material or feed products, energy products such as biogas, can also be produced from green biorefinery co-products and residues. Biogas can be produced through the processing of waste streams from the juice (brown juice or whey) and/or the pressed fibre (Kamm et al., 2010; Prieler et al., 2019). The marketable potential for biogas is best demonstrated in Europe, where almost half of global biogas is produced (Scarlat et al., 2018). The need for more renewable energy sources is driven both by the need to reduce global GHG emissions and reduce dependence on finite resource while addressing increasing fuel prices (Chodkowska-Miszczuk et al., 2021). The energy sector in particular has become one of the largest contributors to GHG emissions in Europe, reaching almost 75% (Ravindran et al., 2021). High energy costs in recent years has also contributed the need for more sustainable sources, particulary in natural gas (Burke-Kennedy, 2022). Low supply stock and high demand for natural gas has led to rising fuel costs across Europe in recent years (Coyle, 2021), contributing to high energy costs. In recent times, the Ukraine-Russia conflict has contributed to high energy costs, where Europe looks to reduce its dependancy on Russian natural gas (Mohseni-Cheraghlou, 2022). In comparison to natural gas, biomethane has been shown to be a more cost-effective source of energy, as it can reduce the dependency on natural gas imports (EBA, 2018). Biogas also has a lower production cost when compared to natural gas, which is predicted to reach as low as €57/MWh to €80/MWh, compared to €100/MWh for natural gas by 2050, according to the European Biogas Association (2018). Currently biogas costs are almost 30% less than those of natural gas (Bioenergy Insight, 2022), showing that there is market potential and need for the more sustainable product. These lower costs asscociated with biogas production allows for better market competivness. With biogas production set to increase in Europe further by 2050 in line with climate action goals (Reid et al., 2020), there is also potential future markets for biogas in Europe. Ireland also has the potential for high biogas production due to its high argicultural productivity and feedstock availability, along with the need to meet its energy and climate targets , though the concept is not as advanced as other European countries due to low finacial support (Robb, 2021a). Though this challenge has impacted biogas production and use in Ireland, support from businesses and farmers has shown that there is a market potential and demand in Ireland for this energy source (O'Sullivan, 2017). The goals set by the

Climate Action Plan 2021 also shows that there is government support for the production of biogas, though financal support is still a challenege (Department of the Environment, Climate and Communications, 2021). In Northern Ireland, it has been demonstrated that government support is vital in the development of the biogas sector (Robb, 2021b), though the need for gas grid injection points and policy has shown to be a potential future challenge. These challenges would need to be addressed in order to realise future potential markets.

Overall, green biorefineries can have multiple streams of revenues from the different products they produce, while also providing sustainable alternatives to their less sustainable counterparts already at market.

### *2.3.5 Expenses in Biorefineries*

While holding some economic potential, there are significant investments and expenses associated with biorefineries that must be taken into account. Biorefinery expenses can be divided into three categories; the expenditure, the operational costs, and any other financial expenses that may impact the economic viability of a biorefinery ( Tsagkari et al., 2016; Cristóbal et al., 2018). The capital expenditure of a biorefinery is the initial investment at the beginning of the project (Solarte-Toro et al., 2021), and is categorised as a fixed cost. The capital expenditure of biorefineries vary depending on the scale and type of biorefinery (Ball, 2018). For example, ethanol-producing biorefineries have a larger capital than wood based models, reaching over €300 million in capital investment (Tsagkari et al., 2020). In contrast, grass based biorefinery models can have much lower capital investments, reaching as low as €600,000 (Ball, 2018), once more this figure depends on the level of scale of the biorefinery.

The operational costs that are associated with biorefinery models include the daily operational expenditures of running the technologies (Cristóbal et al., 2018). These expenses can be divided into both direct and indirect costs. Direct costs are those that are subject to change and can directly impact the expenditure of a biorefinery (Lindorfer et al., 2019). These costs can include feedstock prices, transport and energy costs (Prieler et al., 2019). In contrast, indirect operational costs are expenses which are fixed, such as employee wages and insurance (Lindorfer et al., 2019).

Other expenses that are associated with biorefinery models include insurance repayments and depreciation (Cristóbal et al., 2018), which contribute to assessing the economic viability of a biorefinery. Also, the profitability, or losses of the model, along with the return on investment and payback period of the model should be included in the economic assessment. These expenses and calculations are discussed further in section 3.3.2.2.4.

### *2.4. GIS Analysis*

The literature review of how geographical information system (GIS) tools are used within the bioeconomy is outlined in the following sections. Challenges associated with selecting potential biomass supply locations will be discussed in 2.4.1. The section will also examine the type of data that previous studies have used to address these challenges. Within 2.4.2, digital spatial tools are discussed, along with the type of methods used to capture data, such as remote sensing and satellite images. The type of data used within spatial tools are the focus of 2.4.2.1. This section covers the two types of data formats used in GIS, along with their advantages and disadvantages. Finally, how GIS tools are used in scenario analysis is discussed in 2.4.3.

#### *2.4.1 Biomass Supply Locations*

Within bioeconomy studies, locations for feedstock supply sites and transport costs are essential to determine the long-term feasibility of a bioeconomy (Attard et al., 2020). Establishing a secure supply chain by selecting biomass sites allows for studies to determine a number of factors, such as the availability of feedstock and the costs associated with transporting the supply, particularly for biorefineries (Balaman and Selim, 2014; Correll et al., 2014). Evaluating the biomass availability within an area allows for studies to address uncertainties, such as the sustainability of the supply, land use conflicts that may arise and the potential social-economic issues (Mandade and Shastri, 2019; Sharma et al., 2020). In terms of land use conflict, particularly the 'food vs. fuel' argument (Hirschmugl et al., 2021b), underutilised agricultural land such as contaminated or marginal land are presented as more favourable biomass production sites for the bioeconomy (Höltinger et al., 2012; Hirschmugl et al., 2021a) . Marginal land consists of degraded, abandoned, or waste land (Lewandowski, 2015), while contaminated land consists of habitats that have been polluted by heavy metals

(Hirschmugl et al., 2021b). By selecting these type of sites for biomass production, land use issues can be avoided and the production of these crops would have a lower impact on food producing agriculture ( Lee et al., 2019; Hirschmugl et al., 2021a). As detailed in section 2.2*,* the issue of surplus grasslands in Europe presents the opportunity for bioeconomy infrastructues to utilise unused lands (Kamm et al., 2010; Höltinger et al., 2012). As these sites would have previously been used for grazing, there would be little land use change needed for producing the desirable crops for biomass (Orozco et al., 2021). Marginal lands are also beneficial in terms of avoiding land use conflicts, and the conversion to perennial grasses is beneficial to these sites as soil degradation is reduced (Sallustio et al., 2022).

Selecting potential biomass locations is conducted by initially listing specific objectives that the potential locations must meet to be deemed suitable (Franco et al., 2015). These criteria may include factors such as GHG emission levels, crop yields, livestock numbers or transport distances. Both environmental and economic factors can then be further categorised into categories such as required criteria or constraints within a location (Perpiña et al., 2013). This type of data can be evaluated to determine if the potential sites may result in a trade-off between certain criteria or if sites must be eliminated due to conflicting with the objectives (Farahani et al., 2010). For example, a study carried out in Australia determined that any waterbodies that were present at the locations would form a constraint on plant location, while agricultural land use and vegetation cover was a criteria that would need to be met (Jayarathna et al., 2022).

### *2.4.2 Spatial Tools*

Advancements in geospatial tools have contributed to reducing challenges that may be associated with selecting biomass supply locations for the bioeconomy (Valenti et al., 2018). Geospatial technologies are computer based hardware or software tools which can be used to capture and analyse multiple large data sets (Saha and Frøyen, 2021). To capture data for analysis, hardware such as remote sensing and satellite or aerial images are used, while GIS software can be used to process, manage and create data along with many more uses (Farkas, 2017; Angélica et al., 2022) . GIS software includes examples such as ArcGIS or QGIS, which provides tools for analysing captured data for studies to carry out a more in-depth evaluation on locations, particularly in bioeconomy site selection studies (Zheng and Qiu, 2020). Data analysed through GIS tools vary depending on the study being carried out, for example bioeconomy studies focus on environmental, social and infrastructure data (DeFries, 2013; Franco et al., 2015), while climate monitoring studies may focus on changes in environmental data such as GHG emissions (Sapkota et al., 2021).

Through vector GIS, data is organised into discrete objects, where spatial features are represented using coordinates with an affiliated attribute table. These features can then be evaluated through a range of analytic tools, such as queries, georeferencing and distance measurement (Hanna et al., 1998). Queries can be used to determine the relationship between data within a table (Farkas, 2017). For example, a query could be made within a data set to determine which points represent a single crop species location. The georeferencing tool within GIS is used to reference information to a specific geographical location (Hill, 2009), such as latitude and longitude. The use of these analytic tools can be used to produce simple or high definition maps for spatial planning (Valenti et al., 2018; Anejionu et al., 2020). They are used across multiple disciplines for decision-making, such as urban-planning (Barzegar et al., 2021) and biodiversity mapping (du Toit et al., 2009) due to their effectiveness in providing in-depth analysis of data. Depending on the study being carried out, data can be represented through simple or highly detailed maps (Goodchild, 2005). The next section will discuss how these tools are used for site selection and the type of data involved.

#### *2.4.2.1 Raster & Vector Data*

GIS provides a representation of data through two types of layers; raster and vector. Raster layers within GIS software are a combination of cell grid rows that represent information such as temperature, altitude, or precipitation (Pucha-Cofrep et al., 2018). The use of raster layers in particular have become more commonly used for spatial planning studies as it provides a faster analysis in comparison to vector layers (Villacreses et al., 2022). Raster data and satellite images provide the opportunity for studies to evaluate a large area for site selection through a high resolution image (Ahamed et al., 2011). Locations can be analysed from multiple distances through raster data, from a 10m resolution to a wider range of 100m or more, depending on whether locations are to be selected at a local, regional or national level (Zheng and Qiu, 2020).

The use of raster layers to analyse data is still relatively new in comparison to the use of vector data (Mulrooney et al., 2017). Vector layers represent real-world information through data points, lines or polygons (Hoesen et al., 2013), and is more commonly used for GIS analyses. These layers are more favourable due to the availability of a wider range of public data sets, such as land use cover, and census data such as population numbers (Farkas, 2017) due to their ability to encode topological relationships. In comparison to the use of raster layers, vector layers can be seen to provide more accurate representation of geographical data as they make use of coordinate systems, meaning they are often captured at a finer spatial scale (Canales et al., 2022). As vector layers have been more widely used, they have an advantage over raster layers in terms of data accessibility, as a majority of public spatial data is stored as vector layers (Kenny, 2020). Vector layers best support the concept of discreet objects within a map, while raster data layers have a necessary cluster of data applied to them.

### *2.4.3 Scenario Analysis*

To analyse uncertainties such as suitable land for a biorefinery or biomass production, studies adapt an exclusion or inclusion method (Jesus et al., 2021). This method allows for studies to exclude areas such as waterways, protected areas, or food producing land from potential sites (Mulrooney et al., 2017). The use of buffer zones are particularly useful if factors such as unusable protected areas overlap with potential biomass sites (Boruff et al., 2015). Buffer zones allow for a specific distance radius to be created around an area (Harrington, 2009). A buffer zone can be used alongside other analytic tools to remove areas where both factors overlap, hence removing unsuitable areas (Saha and Frøyen, 2021). As seen in section 2.4.1, setting a list of suitability criteria for a site is essential for decision-making planning. When creating scenarios through GIS, this data can be manipulated through analytic tools to give suitable, unsuitable or alternative scenarios for site selection (Lozano-García et al., 2020).

GIS analytical tools can also be used to carry out analysis of location uncertainties when combined with a multi-criteria approach (Feizizadeh et al., 2014). This is particularly useful when analysing land use cover within an area. Due to the ability to read and analyse data within a single platform, GIS is particularly useful for analysing current and future trends that may occur within a geographical area for scenario analysis (Jeong and Ramírez-Gómez, 2017). This is vital for bioeconomy studies, as they can then estimate trends such as the long-term biomass availability and future transport costs. Determining these type of trends is particularly important for bioeconomy infrastructures such as biorefineries (Jesus et al., 2021). By combining spatial analytic tools and the multi-criteria approach, scenarios addressing uncertainties can be formed, such as economic trends within the area or potential market partner locations for the products produced (Ma et al., 2005; Ahamed et al., 2011). Assessing the potential challenges that may arise through GIS allows for studies to determine potential locations that would be suitable for both biomass production and infrastructure implementation (Feizizadeh et al., 2014; Valenti et al., 2018).

### *2.5 Conclusion*

In conclusion, while the bioeconomy and biorefineries provide an opportunity for economic and environmental benefit to the agricultural sector, there is still much work to be done to fully implement the concept in Ireland. Though a novel concept, there are still opportunities for the bioeconomy in Ireland, as presented in the literature review. Economically, they could provide an alternative farming income, which could help reduce farmers dependency on government supports, while also future proofing their business. The potential end products highlighted in the literature review show that there are opportunities to locally produce sustainable products. Along with the multiple potential revenue streams that a biorefinery could present, the expenses should also be considered. Furthermore, the GIS literature review demonstrated the potential for this type of technology to be used in assessing biorefinery deployment areas and supply chains.

Knowledge gaps were also found within the literature. As previously mentioned, the novel concept of the bioeconomy in Ireland has led to limited literature surrounding the impacts of implementing a biorefinery in Ireland. These include the social and economic impact on Irish grassland agriculture. This thesis looks to address this knowledge gap through stakeholder engagement and economic analysis. The literature review also shows that studies carried out on biorefineries only focus on one or two aspects of the model, such as the environmental impacts or the model's economic viability. This study looks to address this gap in the literature by analysing the social, economic and geographical aspects of a biorefinery model to better understand the impact it may have on grassland agriculture.

# Chapter 3:  Research Methodology

*3.0 Introduction*

This chapter will present the methodologies used to conduct the empirical research for this study. Section 3.1 will outline the aims and objectives of the study. Section 3.2 will describe the research design and how the overall framework of a three-phase methodology will be carried out. A mixed methods approach was used to meet the aim and objectives of this study, and the methodologies used have been divided into three phases. Phase 1 addresses the use of the co-design method to design a biorefinery approach with all of the key stakeholders (3.3.1). This informed phase 2 which provides the economic analysis of the selected biorefinery model (3.3.2). Finally, the outputs of both phase 1 and phase 2 informed phase 3 which provides a description of the process used to conduct a spatial analysis of the biorefinery using GIS (3.3.3). The method of data collection and analysis will be presented and discussed under each phase. The process used to identify the key stakeholders for engagement in the co-design phase and in the semi-structured interviews will be provided.

*3.1 Aim and Objectives of Research*

The aim of this thesis was to investigate potential locations for a viable green biorefinery model in Ireland that may offer sustainable diversification opportunities for Irish agriculture through the use of GIS and scenario modelling. Green biorefineries have been proposed as a renewable method for reducing carbon dioxide and other greenhouse gas (GHG) emissions in agriculture, while also creating diversification opportunities and ensuring feed independence. While these technologies have been successfully developed in European countries, they have not yet been commercially deployed in Ireland. This project aimed to co-design a green biorefinery model for Irish agriculture and assess its economic viability and potential locations for deployment.

To achieve this, the project has a number of key questions that need to be answered:

1. Which green biorefinery models are most suitable for Irish agriculture?
2. Which stakeholders need to be involved to implement the model?
3. Which locations and sectors in Ireland are most suited to the development of green biorefineries?
4. Is the green biorefinery model economically feasible in Ireland?

5. Which locations in Ireland are most suitable for green biorefinery models to be implemented?

To answer these questions, the research methodology is divided into three interrelated phases. Phase 1 will answer question 1 and 2 through a triangulation of mixed qualitative research methods. Following on from this, phase 2 will answer question 3 and 4 through an economic analysis of the identified green biorefinery model. The final phase of the study will answer question 5 using GIS to undertake a spatial analysis of potential locations for green biorefineries.

### *3.2 Research Design*

The overall research design steps are presented in Figure 1, which used a mix of both qualitative and quantitative methods as discussed below:

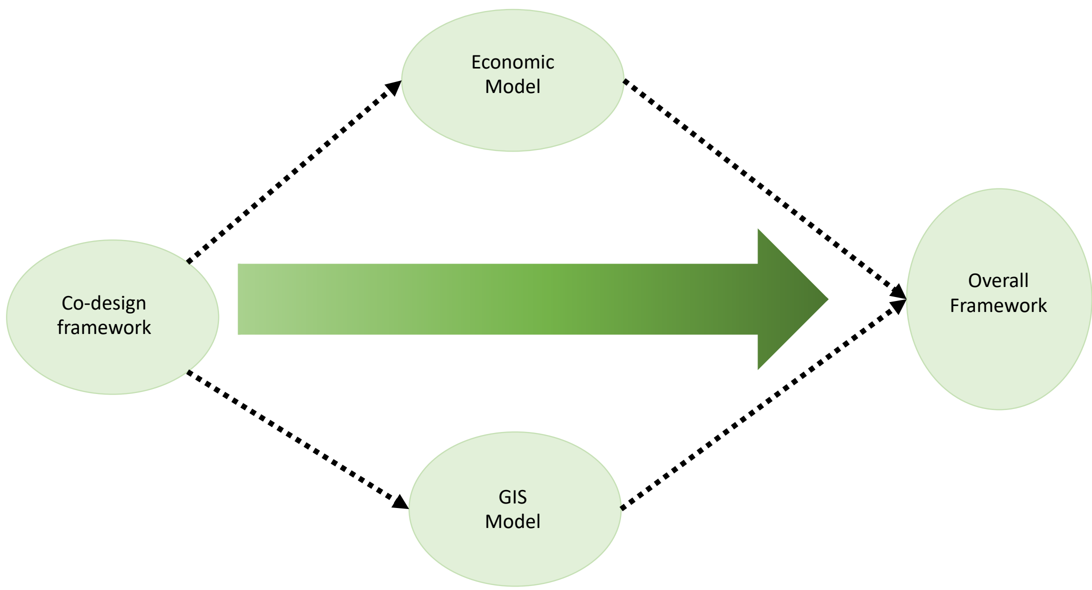



*Figure 1. Process model of the different phases of the research design of the project.*

A co-designed framework of the key stakeholders was conducted to support determining which biorefinery models are best suited to Irish agriculture and who should be the key stakeholders in such a model. The co-designed framework is formed by a review of the current literature which conducted a comparative analysis of successful biorefineries in

Europe. The overall findings from the co-design stage were then used to develop the economic analysis and the GIS model. Methods used in the economic analysis determined if the model chosen in the co-design stage was economically feasible in an Irish context. The GIS stage of the research design also considered the findings of the co-design stage to determine suitable locations for the chosen green biorefinery model. The combination of the findings from each of these stages of the research design informed the overall framework of the thesis which will be presented in chapter 5.

Figure 2. provides a more in depth look of the research methodology. Within the co-design stage of the research, a literature review was first carried out to identify and compare different green biorefineries found in Europe and their technologies. Following this, a triangulation of mixed qualitative methods was applied. This involved firstly carrying out design-thinking workshops to identify key stakeholders and the type of data to be collected from them. Secondly, these workshops determined target stakeholders for an extended focus group, and how the focus groups would be used to engage these key stakeholders. Thirdly, several semi-structured interviews were conducted to seek more detail from key stakeholders as identified from the focus group. The integration of the analysis of the findings of each of these qualitative methods were then used to inform the economic and GIS inputs of a suitable green biorefinery model for Irish agriculture.

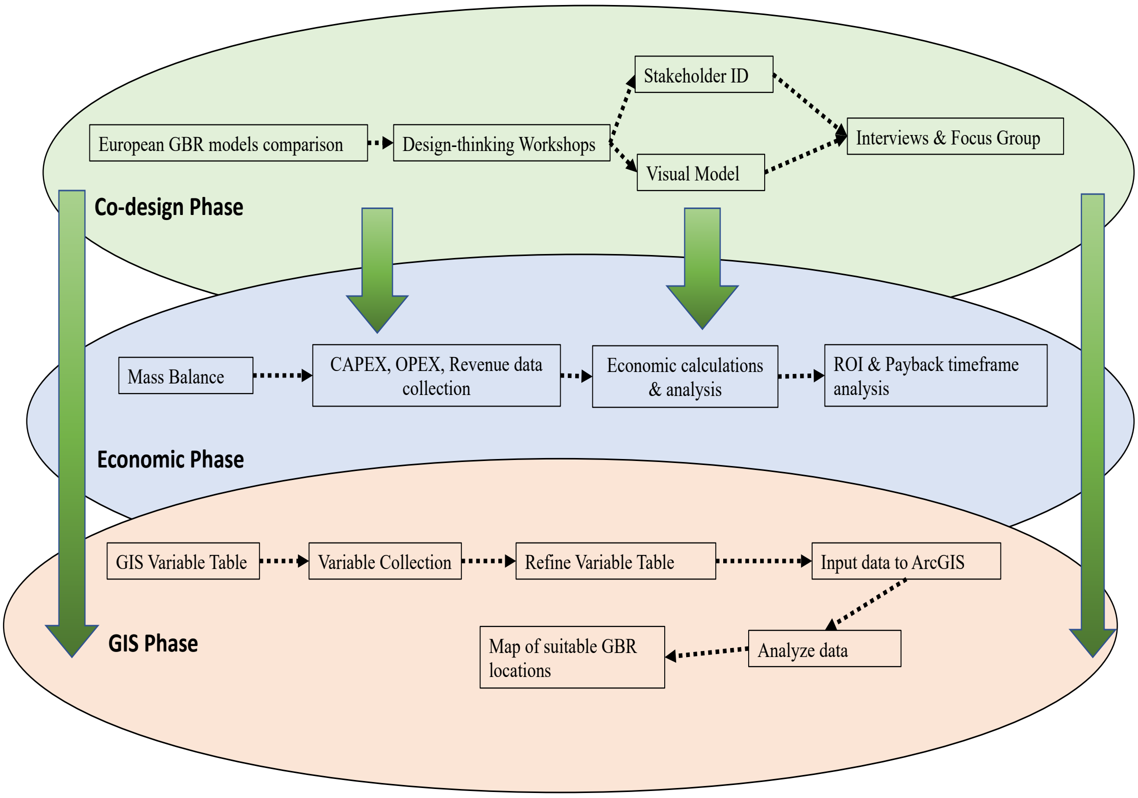



*Figure 2. A more detailed look of the research design of the project. All of the phases involved will form the overall framework of the research, with results from the co-design phase informing both the economic and GIS analysis.*

The economic analysis was carried out using the results of the co-design stage. Firstly, a Mass Balance and Process Flow Diagram was designed to analyze the energy, heat and biomass inputs and outputs of the chosen model. This method will be further described in section 3.3.2.1. Following this, an economic analysis was carried out, with the costs and revenues being informed by a synthesis of both the extant literature and interviews with experts. This analysis was carried out to determine the economic feasibility of the selected model from phase 1.

The GIS stage of the project determined suitable locations for the selected green biorefinery model. Data collected from the mixed qualitative co-design stage and literature was used to inform the key variables that need to be collected for use within the GIS model. These variables were then inputted into ArcGIS to analyze suitable locations in Ireland for the chosen model.

### *3.3 Research Method*

The methodology for this project is divided into three phases, the co-design phase, the economic assessment and the GIS assessment phases. The process followed in each phase is presented below.

### *3.3.1 Co-design Phase Methodologies*

A co-design methodology involves a number of steps and stakeholders to ensure wide consultation and buy-in for the identification of suitable biorefineries in Ireland. These steps included a comparison of European green biorefinery models; (section 3.3.2), collaborative design process to identify the model potentially best suited to Ireland; (section 3.3.3) and finally consultation with a number of key stakeholders to provide further input on the findings of the co-designed workshop as presented in sections 3.3.4 – 3.3.6. Results from the data collected from each of these methodologies were then brought forward as the basis for the economic and GIS models, thus creating the overall framework of the project.

#### *3.3.1.1 Comparison of Green Biorefineries*

The first objective to be met was defining which green biorefinery model is most suitable for deployment in Irish agriculture. To meet this objective, a selection of models from across Europe were identified and evaluated through a literature review supported by input from relevant stakeholders. By carrying out a literature review, insights can be gained into the necessary criteria that the model should meet, along with the current state-of-the-art technologies that are available (Kamm et al., 2010; Höltinger et al., 2012; Prieler et al., 2019). The literature review considered an overview of models as given by both Mandl (2010) and Ball (2018). This allowed the researcher to select state-of-the-art models for consideration in this study based on the following criteria for a more accurate comparison:

- Feedstock type (i.e. what type of feedstock is currently being used at the plant?)
- The size and capacity of the plant (i.e. what is the current or most recent feedstock input amount that the plant is able to process?)
- Types of processes involved (i.e. what are the types of technologies involved that make this plant unique/successful?)

- Any economic information of the model and its feasibility
- The TRL of the model (i.e. how close is the technology to commercialisation?)
- End products produced by the model (i.e. what are the type of products produced and the targeted market?)
- Does the model meet environmental goals? (i.e. sustainability goals, government goals and policy)
- Any limitations found within the literature (i.e. if the plant was a demonstration plant, are there any identified barriers to commercialisation?)

These guideline criteria allowed for the shortlisting of models that may be suitable for adoption in Irish agriculture by comparing the models in the literature that focused on green biorefinery.

Previous studies on the implementation of biorefinery models in Europe have shown that a literature review should be carried out to identify current state-of the-art technologies that are available at the time of study (Kamm et al., 2010; Prieler et al., 2019). This method is best conducted in the first stages of designing the model as it allows for a more in-depth understanding of the processes involved and the motivations and context for implementing the different biorefinery models. Based on previous literature surrounding green biorefinery models, there has been little comparative research conducted on green biorefinery models found in Europe, with only a brief overview of the status of each model found (Mandl, 2010). A review of the available literature of the European models [as of 2021] allows for a consideration of the differences in the technologies applied in the models. For example, the Dutch mobile model had been updated to a more fixed unit with a high capacity, in comparison to the model used in the previous year (Buckley et al., 2021). The findings of this review will be provided in chapter four.

#### *3.3.1.2 Collaborative Planning*

The next objective of this study required the identification of key stakeholders that would be involved in selecting a green biorefinery model. As stated in section 2.1.6, stakeholders need to be included more in the decision-making aspects of the bioeconomy and biorefineries due to gaps in the knowledge surrounding the concept and the complex supply chains associated with biorefineries (Geissdoerfer et al., 2016; Dallendörfer et al., 2022). Though European models are to be discussed, compared and shortlisted as mentioned in section 3.3.1.1, the social aspect of implementing one of these models is not documented within the literature. By being able to identify the key stakeholders of a green biorefinery, it can be determined who will be impacted by its implementation. This is a key step in selecting a suitable model for economic and GIS analysis, as it would better determine a model that would be suitable in an Irish agriculture context, and which model is more likely to get buy-in from key stakeholders.

A mixed method approach as presented in Figure 3 below was used to screen a shortened list of European biorefinery models and the identification of key stakeholders to include in the ultimate selection of one shared preferred model.

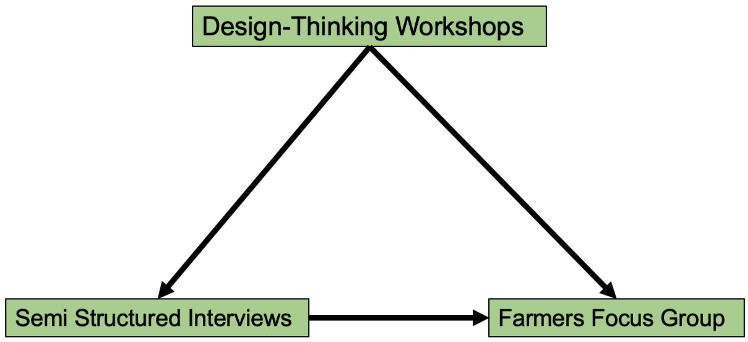



*Figure 3. Overview of the methods used in the co-design phase. There will be a flow of information between the three stages; where the workshops will inform the interviews and focus group. In turn, the interviews will shape the focus group.*

Workshops were first carried out to identify the stakeholders and to design the data collection methods. These workshops were designed based on a similar approach used by Geissdoerfer et al. (2016) and recommendations by Risdon and Quattlebaum (2018). The goals of the study were clearly defined at the beginning of the workshop, along with how these would be met. Key stakeholders were identified through several exercises, including value mapping tools, which allow for multiple stakeholder views of value to be mapped for visual representation (Appendix 1), journey analysis and the building of a visual model of a preferred green biorefinery in Ireland using LegoSERIOUS Play. An outline of the workshops is further described in Appendix 1.

#### *3.3.1.3 Design-Thinking Workshops: Identifying Stakeholders*

As stated in section 2.1.6 of the literature review, biorefineries are an innovative aspect of the bioeconomy, impacting stakeholders from a diverse group of disciplines ( Van Lancker et al., 2016; Gerdes et al., 2018). Design-thinking workshops supported with LegoSERIOUS play were carried out with these multi-disciplinary stakeholder groups (Risdon and Quattlebaum, 2018). These workshops allowed the research to observe the issues and opportunities of setting up a grass biorefinery from a number of perspectives including the consumer, the farmer, the R&D provider, retailer, end user and others in the end to end supply chain of such a refinery (De Goey et al., 2018).

The collaborative design-thinking workshops were carried out over a 2-day time period. These workshops involved 6 experts with different backgrounds; environmental, socio-economic, business and research. These experts were asked to represent the voices of the farmer, consumer and industry personas that would be developed through the workshops exercises. To identify the key stakeholders involved in the green biorefinery process, several practical exercises were used throughout the workshops. These included stakeholder insight mapping, stakeholder value mapping, stakeholder persona development, journey analysis, action plan design, and LegoSERIOUS Play visual model (Appendix 1). These type of collaborative workshop exercises were based on previous studies by Geissdoerfer et al. (2016) and guidelines set out by Risdon and Quattlebaum (2018) and Plattner et al. (2011).

*3.3.1.4 LegoSERIOUS Play Model*

Having identified the key stakeholders (personas) through the design-thinking process and the customer journey map involved in setting up a grass biorefinery, day two of the workshop focused on building a visual model of the end-to-end process involved in implementing a green biorefinery model. This model provided the opportunity to evaluate any gaps in the design through a LegoSERIOUS Play model. Lego has become a more widely used method in qualitative methods and innovation as it allows for participants to address complex problems through collaboration and visual representation ( Kristiansen and Rasmussen, 2014; Dann, 2018; Deloitte, 2021). It allows for prototypes to be built, engagement of feedback from multiple stakeholders, and a collaborative buy-in to the agreed solution at a relatively inexpensive level.

Participants were first introduced to LegoSERIOUS Play and how it could be used to build visual representations. Once participants were familiar with the product and process, they then built individual models of a green biorefinery based on their interpretation of what the ideal model would be. Participants were also asked to include the goals of the project as stated at the beginning of the workshop, within their models.

Once each participant had completed their individual model, each model was presented and discussed. Any gaps present in the designing of these models was then addressed by the different participants. Once this step had been carried out, participants worked together to collectively design a green biorefinery model, while using pieces from their own individual models to complete this task. Once the collaborative model was completed, it was then discussed amongst the participants to identify and address any gaps in the design process. This model was then further refined to identify which stakeholders would be engaged for data collection, and how best to undertake this process of engagement.

#### *3.3.1.5. Stakeholder Data Collection*

It was decided that semi-structured interviews and a focus group would be used for stakeholder data collection. This data collection method was chosen as it provided the opportunity for one-to-one engagement with stakeholders (Houston, 2022). The use of semi-structured interviews also provides the opportunity to present open-ended questions to gain more detailed data for the study (Busetto et al., 2020). Other data collection methods that were considered included surveys and structured interviews. These methods were not used as they would limit the amount of information and detail that could be gathered from stakeholders (Mashuri et al., 2022).

Ethical approval was applied for and gained from Munster Technological University (MTU) Ethics Committee to interview the stakeholders as will be discussed in Section 3.5. These stakeholders were divided into two categories: primary and secondary stakeholders. Primary stakeholders were identified as farmers due to their position as both the feedstock producer and potential end users of a green biorefinery. All other stakeholder categories fell under the secondary stakeholders, as they would have an indirect impact or supporting role on the development and implementation of the green biorefinery. Target candidates for each stakeholder category were recruited through the Circular Bioeconomy Research Group (CircBio), Munster Technological University, network and invited to participate (Appendix 2). Insights from those who fell under the secondary stakeholder category were collected through semi-structured interviews.

##### *3.3.1.5.1 Semi-structured Interviews*

The workshops carried out in section 3.3.1.3, identified a number of key stakeholders as having an indirect impact on a green biorefinery model. These interviews were carried out with a purposeful sample of experts who could provide a good representation for the following stakeholder categories: Dairy sector, Beef sector, Agricultural Cooperatives, Finance sector, Policy Makers, Eco-Insulation Market Partners and Animal Protein Feed Market Partners. Semi-structured interviews were conducted with a representative of each of these key stakeholder groups. Each interviewee was contacted by email seeking request and consent to participate in a thirty-minute video interview. A copy of the consent form can be found in Appendix 2. Each interview was recorded and subsequently analysed following permission from each interviewee.

A selection of both general and focused questions were put forward in order to gain the experts knowledge and opinion related to the benefits and challenges of implementing a green biorefinery in Irish agriculture (Appendix 3). Interviews were conducted between (June-August 2021), with findings used to inform and structure the focus group later carried out with the primary stakeholders. The knowledge and viewpoints gained from the interviews were used to help structure the topic guide for the focus group. These included input from the farmers on topic such as future proofing opportunities, finance, investment and supports, type of green biorefinery model, operational scales, as well as barriers to implementation. Each interview was later transcribed to a written format so that the findings could be analysed in section 4.2.3.

*3.3.1.5.2 Focus Group*

Following on from the interviews and the workshops, a 2 hour focus group was carried out amongst a selected range of grassland farmers on 23rd August 2021 using a topic guide and format suitable to a focus group discussion (Krueger, 2002; Morgan, 1993). The sample was a representation of tillage, dairy and beef farmers. They were identified through the network of the Circular Bioeconomy Research Group (CircBio) at the Munster Technological University. The purpose of the focus group was to understand which green biorefinery models were of interest to primary stakeholders and what conditions would encourage farmers to diversify some of their operations to a grass biorefinery. Topics discussed within the focus group included are presented in Table 1 below:

*Table 1. Topics covered in the farmers focus group.*

| ***Preferred Model*** | ***Knowledge Gaps Based Around the Circular Bioeconomy & Green Biorefineries*** |
|---|---|
| Type of business model | Future Proofing  Methods Available to Farmers |
| Scale & Supply Chain | European Green Biorefinery Models |
| Location | Models for Selection (shortlist of 6) |
| End products Market Size | Overviews of Each Model for Selection |

A PowerPoint presentation covering each of these topics was presented to the farmers to ensure common understanding of each topic.  Time was then allocated for discussion with the farmers on each topic. Participants discussed preferred green biorefinery models, feedstocks, scale and product types. Data gathered from both the interviews and the focus group were then used to inform the economic and GIS models of the project.

### *3.3.2  Economic Model Methodologies*

Once a biorefinery model had been selected from the Co-Design Phase, it was necessary to identify the economic feasibility of that model. This economic assessment is a vital step in determining the potential success in implementing bio-based value chains, including green biorefineries. It provides a mechanism for evaluation of the processes, the level of investment needed, and the type of revenues that can be obtained from the end products (Lindorfer et al., 2019). As seen from previous biorefinery studies (Zetterholm et al., 2020; Kumar et al., 2021; Lan et al., 2021), techno-economic assessments are a key step in assessing the level of scale that is viable for a green biorefinery, and determining if the possible end products produced are viable in creating a high enough return on investment (Höltinger et al., 2013; Prieler et al., 2019).  Taking this into account, the economic phase of this thesis will develop a process mass balance, economic model including capital, operational expenditures and returns, and conduct market research to assess the viability of the chosen model and its end products through desk-based research and interviews with industry members. A scenario analysis will be carried out on two capacity levels, along with a sensitivity analysis on feedstock and insulation price ranges.

### *3.3.2.1 Designing a Mass Balance*

The first objective of the economic phase was to develop a mass balance to determine the material and energy inputs and outputs of the chosen model. Once the mass balance has been established, different scale scenarios can then be analysed to determine the type of costs and revenues involved (Prieler et al., 2019). This method of analysis has been included within other biorefinery studies, including green biorefineries (Corona et al., 2018a) and bioethanol biorefineries (Ko et al., 2013). The mass and energy balance, may be highly detailed or simplified, depending on the type and scale of assessment carried out, and is a very important data set for system analysis such as environmental analysis and economic analysis (Höltinger et al., 2013; Corona et al., 2018a). When creating a mass balance, a base unit is used that can be scaled up further. The base unit can vary depending on the study (Höltinger et al., 2013; Corona et al., 2018a; Prieler et al., 2019). The unit can be feedstock based or product based depending on suitability of the study, for example Prieler et al. (2019) utilised 1kg of product within their analysis while Höltinger et al. (2013) used 1 ton dry matter (tDM) of feedstock.

The mass and energy balance were then represented through a Process Flow Diagram (PFD). The PFD shows each detailed step of the biorefinery process, while also taking into account the material and energy inputs and outputs of each step (Lindorfer et al., 2019; Prieler et al., 2019).

#### *3.3.2.1.1 Mass Balance*

The design of the mass balance for this thesis consulted with studies by O'Keeffe et al. (2011), Corona et al. (2018), Höltinger et al (2013) and Prieler et al. (2019) due to their similar feedstock choices and end-products. To determine the economies of scale, the study from O'Keeffe et al. (2011) and expert interviews (Amby-Jensen, 2021) were consulted. These economies of scale ranged from 0.2tDM for smaller scaled biorefineries such as mobile units, intermediate scales of 5t DM, (O'Keeffe et al., 2011) and higher scales of 10t/DM for a fixed large biorefinery (Amby-Jensen, 2021).

The mass balance template by Höltinger et al. (2013) was chosen for its simplicity (Figure 4), and production of products similar to the model chosen by the farmers in section 4.2.3.9 (fibre, animal feed protein and biogas). For this study, the scale of the mass balance was increased to 4.6 tDM/hr (20t fresh weight/hr) for a medium to large scale biorefinery, following recommendations by literature and expert interviews (Amby-Jensen, 2021; Ball, 2018).

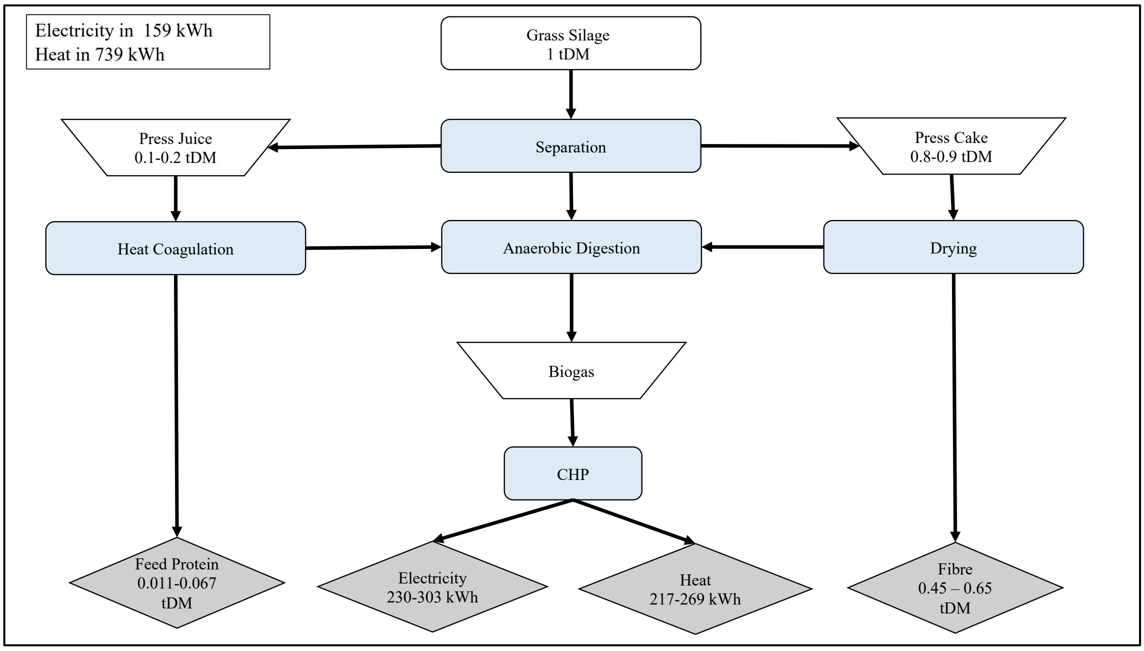



*Figure 4. Process flow diagram of the mass balance template by Höltinger et al (2013) used to determine the inputs and outputs of the chosen biorefinery model.*

Using the figures from the mass balance template, the hourly inputs and outputs were first calculated. The mass/energy balance was designed based on the mass balance by Höltinger et al. (2013), who had an insulation based biorefinery model, supplemented with information from Prieler et al. (2019). The 20t fresh weight (FW) input was converted to dry matter by multiplying by the DM percentage (23%) (O'Keeffe, 2010; Stack, 2022). From this figure, the hourly electricity input (159 kWh x silage tDM) and heat input were calculated (739 kWh x silage tDM). To calculate the fibre insulation output, the fibre value of 0.45t was used (0.45t x silage tDM). The animal feed protein output was calculated using the 0.067t value (0.067t x silage tDM). Electricity and heat outputs were calculated using the CHP (combined heat and power) electricity and heat values of 303 kWh (303kWh x silage tDM) and 269 kWh (269 kWh x silage tDM) respectively. The energy balance was then calculated for the electricity and heat used within the biorefinery. The electricity output was subtracted from the electricity input to determine the energy balance of the model. This calculation was also carried out for the heat energy balance.

The annual values of the mass and energy balance were then calculated by multiplying the figures by the daily hours the biorefinery would operate (10 hours a day) and the number of days in the year (280 days), which were estimated from previous models. Using the calculated annual values, a process flow diagram was then designed, following the template design from Höltinger et al. (2013) .

*3.3.2.2.1 Capital Budget Model*

From the mass balance of the selected model, the economic analysis was carried out through a capital budget model. The capital budget model provides an economic feasibility assessment of a biorefinery by assessing the investment and operational costs, along with the type of revenues that may be expected (Tsagkari et al., 2020). The model is assessed in four sections; the capital expenditure, both direct and indirect operational costs, revenues, additional costs, and the profit/loss calculations. The capital expenditure figure is the sum of the initial investment into the biorefinery, such as land securement and machinery costs and management (Lindorfer et al., 2019). In other techno-economic assessments of biorefineries, the capital investment is primarily based on previous models, depending on the TRL and level of scale up (section 2.2.2) (Usmani et al., 2021). From this method, and from consulting with an expert, a capital expenditure of €5,000,000 was estimated for a 20tFW/hr biorefinery (Amby-Jensen, 2021).

*3.3.2.2.2 Operational Costs*

The operational expenditures of a biorefinery include the type of costs that are associated with the daily operating of the facility. Specifying each cost associated with the operations of a biorefinery is a key step in determining the economic feasibility of a model (Lindorfer et al., 2019). These costs may include purchasing the raw material, transport costs associated with the raw material, the labour involved in operating the machinery, and other costs such as electricity or heat (Zetterholm et al., 2020). To determine the operational expenditures of the model, both direct and indirect expenses associated with the daily operations of the biorefinery were categorized and calculated. Operational expenses that were subject to change were listed under direct costs, such as feedstock costs, binding materials that are used for the fibre insulation products, cleaning solutions, energy inputs, waste disposal, conditioning and distribution costs (Table 2), (Cristóbal et al., 2018; Prieler et al., 2019). Operational costs that had a fixed rate were listed under the indirect costs. These expenses included repairs and maintenance costs, insurance, labour and overheads costs (Lindorfer et al., 2019). To calculate the total direct costs of the model, literature was consulted to give benchmark costs to each item listed, as seen in Table 2.

*Table 2. List of the cost benchmarks used for the direct, indirect and revenue streams of the capital budget model. Assumptions are also made where no benchmark could be found.*

| ***Operational Expenditure*** | ***Cost (€/UNIT)*** | ***Assumption*** | ***Reference*** |
|---|---|---|---|
| *Direct Expenses* | | | |
| Grass Silage | 150.00 | The cost of the feedstock at the biorefinery, including transport from the farm and harvest costs. | (Höltinger et al., 2013; Ambye-Jensen, 2020;) |
| Binding Materials | 1.00 | Assumed at €1/unit due to previous studies including the material in the overall fibre costs. | (Franchi et al., 2020; Annibaldi et al., 2021; UK Green Building Council, 2021) |
| Cleaning Solutions | 26.00 | Overall cost of NaOH, HCL and $H_2O$ cleaning solutions listed by the mass balance carried out by Prieler et al (2019). | (Prieler et al., 2019; ReAgent, 2022) |
| Heat Energy | 0.12 | Rates assumed to be similar to those of natural gas in Ireland and potential renewable energy costs at the time of this study. | (Stanley, 2018; Biogas Expert, 2022; SEAI, 2022;) |
| Waste Disposal | 0.18 | Adapted from a previous biorefinery model and literature. | (Lindorfer et al. (2019) |
| Conditioning & Distribution | 193,750.00 | Figure adapted from previous biorefinery model. | |
| *Indirect Expenses* | | | |
| Repairs & Maintenance | 5% | Assumed to be 5% of capital expenditure. | |
| Insurance | 50,000 | Adapted from previous biorefinery model. | |
| Labour | 44,000 per Worker | Estimated to be the annual salary for two workers | |

| | | | |
|---|---|---|---|
| Overheads | 10% | Assumed to be 10% of the labour costs. Includes costs such as administration and telephone. | |

These costs were then multiplied by the annual quantity of each item. For the indirect costs, the repairs and maintenance were assumed to be 5% of the capital expenditure, the insurance costs were adapted from a previous biorefinery model and the overheads, which included costs such as telephones and administration, were assumed to be 10% of the labour costs. To calculate the labour costs, the annual salary for two workers was assumed (Lan et al., 2021). Once the direct and indirect costs were calculated, they were combined to get the overall operational expenditure cost of the model.

*3.3.2.2.3 Revenues*

The types of revenue streams produced from a biorefinery model can be used to analyse the feasibility of the unit. As seen in section 2.3.4, a variety of end products can be produced from a biorefinery, creating multiple revenue pathways. An economic assessment of these pathways can determine which end products would be most beneficial for the biorefinery to produce (Corona et al., 2018a; Prieler et al., 2019). To determine the type of market prices that may be expected for these products, benchmarks were used in reference, as shown by studies by Prieler et al. (2019) and Höltinger et al. (2013). Benchmark prices allow for a set baseline to be formed for comparing the end products to those already at market by creating a reference system for the end products (Prieler et al., 2019). This is an important step in helping to understand the market prices of the products, as well as market trends and fluctuations (Höltinger et al., 2013; Cristóbal et al., 2018). The study by Prieler et al. (2019) best describes how benchmarking can be used to attribute values for green biorefinery protein products. Some examples of the benchmarks used for this study are soybean isolates, skimmed milk powder, whey protein and protein hydrolysate from lupine grass (Prieler et al., 2019).

*Table 3. Benchmarks given to the multiple end products produced from the biorefinery model.*

| ***Revenue*** | ***Cost (€) per unit*** | ***Source*** |
|---|---|---|
| Insulation Material | 850/T | (CSO, 2022a; Höltinger et al., 2013)<br>(Höltinger et al., values adjusted according to the inflation figures of December 2021) |
| Animal Feed Protein | 300/T | (European Comission, 2020; Nutritional Informative, 2022) |
| Biogas energy | 0.12/ kWh | (Biogas Expert, 2022; SEAI, 2022; Stanley, 2018) |

Based on findings from the co-design phase and the mass balance, market research was carried out to ascertain market prices for insulation material, animal feed protein and biogas, as products from the selected biorefinery. A purposeful sample of experts with backgrounds on each product were consulted to determine the current and possible future costs of each product, along with a literature review. Insulation material values were estimated at €850/t from the study by Höltinger et al (2013) and adjusting the figures from the study to account for inflation (CSO, 2022a). The benchmark price of €300/t for grass-based animal protein was estimated to be competitive with that of barley or soybean protein currently used in agricultural animal feed (Nutritional Informative, 2022). The benchmark price of 0.12c/kWh was given to the biogas output after consulting with literature and a biogas expert (Stanley, 2018; Biogas Expert, 2022). Once the estimated benchmark prices were found, they were multiplied by the annual outputs of the model (based on the mass balance) and combined to give the overall revenue of the model.

*3.3.2.2.4 Other Costs*

The final section of the economic model was the other costs that did not fall under the previous categories listed. These included the depreciation, loan repayment, profit or loss (before tax), return on investment and the payback period of the biorefinery model (Cristóbal et al., 2018).

The depreciation of the model is the degraded value of the biorefinery over a lifetime, as value is lost over time (Warnes, 2022). Loan repayment is included in other costs as this expense is paid over a period of time different than that of the projects lifetime (Babusiaux and Pierru, 2000). The profitability or loss of a biorefinery determines if the end products will be successful economically (Cristóbal et al., 2018). The return on investment (ROI) is the percentage ratio of how much profit is gained from the initial investment, taking into consideration depreciation (Cristóbal et al., 2018; Kumar et al., 2021). This calculation gives an insight into the feasibility of a biorefinery, by understanding if there is sufficient revenue generated compared to the initial investment cost (Albarelli et al., 2016). Finally, the payback period determines the length of time it will take the biorefinery to pay back the initial spending cost with the revenues produced.

*Table 4. Assumptions used to calculate the depreciation and loan costs of the biorefinery.*

| | ***ASSUMPTIONS*** |
|---|---|
| *Depreciation* | Cost of item assumed at 60% of CAPEX |
| | Biorefinery lifetime assumed at 20 years<br>Salvage value assumed at 10% of Cost price |
| | Machinery not taken into account |
| *Loan* | Loan amount assumed at 80% of CAPEX<br>Interest rate 5%<br>Loan term 10 years<br>Assume interest rate is fixed |

For this project, once the capital cost, operational costs and revenue streams had been calculated, the depreciation was calculated. This was carried out using the assumptions in Table 4, and equation 1. The loan repayment was then calculated, also using the assumptions found in Table 4 and equation 2.

$$\text{Depreciation} = \text{SLN} \; \frac{(\text{asset cost} - \text{salvage value})}{\text{useful life}}$$

*Equation 1. The straight-line formula for calculating the depreciation of a biorefinery (Warnes, 2022).*

Loan repayment = PMT (rate, nper, pv, [fv], [type] )

*Rate* – interest rate

*Nper* – total number of loan payments

*Pv* – current value of all loan repayments

*Fv* – (optional) the cash balance after the loans has been paid. Default used is 0.

*Type* – when the payments are due, default used is 0.

*Equation 2. Excel Payment formula for calculating the loan repayment of a biorefinery (Cheusheva, 2021).*

The profitability of the biorefinery was then calculated using equation 3, where the costs of the model were subtracted from the revenues produced.

Profit/Loss = Total rev. – total opex – deprec. – loan

*Total rev.* – total revenues

*Total opex* – total operational expenditures

*Deprec* – depreciation

*Loan* – loan repayment

*Equation 3. Profitability equation.*

The ROI was calculated from the annual net profit and total capital investment and expressed as a percentage as shown in Equation 4. The payback period for the green biorefinery was calculated following Equation 5, which considers the interest and lifespan of the project.

$$\text{ROI (\%)} = \frac{\text{annual net profit}}{\text{total capital investment}}$$

*Equation 4. Return on investment (Albarelli et al.,2016; Cristóbal et al., 2018).*

Payback time (years) = total capital investment annual net profit

*Equation 5. Payback timeframe (Cristóbal et al., 2018).*

### *3.3.2.4 Scenario & Sensitivity Analysis*

While a biorefinery operating at full capacity is an ideal model, this is not always possible in reality. Alternative scenarios are explored in studies to determine the best possible outcome for the model (Höltinger et al., 2012; Corona et al., 2018b). These types of scenarios may include changes in the biomass availability, as this may change depending on environmental conditions, and changes in costs due to market trends. Along with determining alternative type of scenarios, economic models can also carry out sensitivity analysis, where uncertainties can be analysed (Feizizadeh et al., 2014).

For this study, two different capacity scenarios were carried out for the mass balance and capital budget model. Scenario A was a biorefinery model operating at full capacity, and scenario B was the same model operating at a 90% capacity. A sensitivity analysis was also carried out on feedstock costs and insulation selling prices, as these were subject to change with market trends. For the feedstock costs, a parameter of 15% was given, where the costs would fall by -€5/t, -€10/t and - €15/t from the original €150/t cost. The parameters were used for an increasing price range from €150/t, to + €5/t, + €10/t and + €15/t. From these parameters, the profitability, return on investment and payback period were calculated and presented in a graph.

For the insulation price sensitivity analysis, the parameters of €10/t were applied, beginning at the initial cost of €850/t, the price was reduced by €10/t intervals until €820/t was reached. The price was also increased in the same manner until €880/t was reached. The profitability, return on investment and payback period were also calculated from these parameters and presented in a graph.

### *3.3.3. GIS Analysis*

To determine potential locations for biorefinery implementation, spatial analysis was carried out. Data which represented the economic, environmental and infrastructure variables identified from the Co-design phase (4.2.3), were collected following the methodology described in section 3.3.3.1.1. This data was collected in the form of both existing vector layer shapefiles from geoportals and newly generated spatial data. Spatial data was created in the case of variables that did not have corresponding public data sets using the methods in 3.3.3.1.2. The pre-processing of spatial data for use in ArcMap was also described within this section of the methodology. Justifications for data included in the spatial analysis are provided following the methods in 3.3.3.1.3, along with justification for exclusion of certain datasets in the analysis. Map preparation for data input, such as setting the coordinate system, is described within 3.3.3.2.1. Data input into ArcMap, along with processes that were carried out to extract data from attribute tables is described in 3.3.3.2.2. Similar methods were also used to extract data layers from the vector shapefiles (3.3.3.2.4). Once data had been input into the ArcMap application, geoprocessing tools were used to analyse the data (3.3.3.2.4). The final stage of the spatial analysis process included creating maps of the potential biorefinery sites within several buffer zones (3.3.3.3). These maps were then used to visually analyse the findings for suitable biorefinery locations, with the use of farming income data and average county cattle numbers for both dairy and beef farming sectors.

##### *3.3.3.1.1 Variable Collection*

To carry out a spatial analysis, data was first selected following similar methods used by Valenti et al. (2018), who utilized surveys and techno-economic analysis for data collection. Within this study, the findings from the co-design phase stakeholder engagement (4.2.3) and literature review (2.4.1) were used as potential variables. To categorise these variables, the study by Jayarathna et al. (2022) was used as a template. This study categorised collected data into main criteria, such as economic, environmental and infrastructure, and further divided these into sub-criteria (Table 5). This method allowed for the necessary data to be collected to represent the findings of the co-design phase.

*Table 5. Variables collected from the stakeholder engagement of the co-design phase.*

| ***Theme*** | ***Sub-theme*** |
|---|---|
| Environmental | Feedstock sites |
| | Habitats & species to avoid |
| | Land use |
| Economic | Farming Incomes |
| | Farming Intensity |
| Infrastructure | Distance to market |
| | Protein Feed Market |
| | Insulation Market |
| | Biogas Market |
| | End Users |

Using these sub-themed headings, variables were collected from public data sources such as the EPA (Environmental Protection Agency), CSO (Central Statistics Office) and other government data sites. Public data sources were used following methods by Sallustio et al (2022), as they provided high-value open data from government sources (Kenny, 2022a). As public datasets are primarily provided in the form of vector shapefiles, it was decided that analysis would be carried out using vector layers. Following methods used in multi-criteria analysis (Bell et al., 2007; Perpiña et al., 2013) the variables were listed under their sub-theme headings, along with the justification of their use, source, and description of the type of variable (Table 6-8). This was carried out to determine which variables would be included in the spatial analysis.

*Table 6. Environmental variables and their justification, description and source.*

| ***Sub-theme*** | ***Variable*** | ***Justification for Use*** | ***Description*** | ***Source*** |
|---|---|---|---|---|
| *Unsuitable Land* | Soils | Potential areas for agriculture & environmental damage. | Vector layer of soil groups polygons across Ireland classified into Great Soil Groups, Soil Sub-Groups, Soil Series and Soil Associations. Sensitive soil types include gley soils, such as the great soil group surface water gley and groundwater gley. These soils can become waterlogged due to seasonal precipitation (EPA, 2022a). Other sensitive soils include peat soils such as the great soil group podzol, which have a high carbon content and can be found in peatbogs and risen bogs (EPA, 2022). | Teagasc (Teagasc, 2022a) |
| | Birds Directive | Protected areas that should be taken into consideration when selecting sites. | Known best estimate of distribution (either 10 km or 50 km grids) of breeding birds nesting sites that are protected or listed under the Birds Directive. Vector layer of polygon shapefile. | NPWS (NPWS, 2019a) |
| | Habitats Directive | | Known or best estimate of distribution (either 10 km or 50 km grids) of habitats and species that are protected or listed under the Habitats Directive. Vector layer of polygon shapefiles. | NPWS (NPWS, 2019b) |

| ***Sub-theme*** | ***Variable*** | ***Justification for Use*** | ***Description*** | ***Source*** |
| --- | --- | --- | --- | --- |
| | SAC & SPA | | SAC and SPA datasets contain a mixture of legacy Irish Grid/1:10,560 and modern ITM/1:5000 data. Sites with version numbers of 1.x represent boundary amendments to legacy Irish Grid/1:10,560 data. Contain site codes and names of Special Area of Conservation and Special Protected Areas. Vector layer of polygon shapefiles | EPA (EPA, 2022b) |
| | Rivers, Lakes | Areas of land that should be avoided for biorefinery infrastructure | Water Framework Directive river and lake vector layers showing all river networks and lakes in Ireland. Polygon and line shapefiles. | EPA (EPA, 2022b) |
| *Feedstock Selection Sites* | Pastures | To determine potential areas for feedstock production | 'Pasture' vector layer in the Corine Land Cover 2018 dataset. This dataset shows all habitats found in Ireland as of 2018. Polygon shapefile. | EPA (EPA, 2022b) |

*Table 7. Infrastructure variables and their justification, description and source.*

| ***Sub-theme*** | ***Variable*** | ***Justification for Use*** | ***Description*** | ***Source*** |
|---|---|---|---|---|
| *Biogas Product* | Gas Network Ireland Pipelines | Areas connected to gas injection points would provide good market potential. | Coordinates of gas pipeline injection points across Ireland entered into a excel spreadsheet table, including names of the locations. | Gas Network Ireland, Irish Grid Reference (Gas Network Ireland, 2022; Irish Grid Reference, 2022) |
| *Insulation Products* | Population density (ED) | Potential market for insulation material. Areas with higher population densities provide higher potential for market | Excel data table of total population density estimate of ED from 2016. | CSO (CSO, 2008) |
| | Settlements | | 2015 vector layer of polygon shapefiles of settlement boundaries where a town is defined as a cluster with a minimum of 50 occupied dwellings, with a maximum distance between any dwelling and the building closest to it of 100 metres, and where there was evidence of an urban centre (shop, school etc). The proximity criteria include all occupied dwellings within 100 metres of an existing building. Generalised to 20m. | OSI (OSI, 2022a) |
| | Townlands | | Vector layer of polygon shapefiles of townlands (2015) varying in size from ~ 1 acre to 7000 acres. Generalised to 20 metres. | OSI (OSI, 2022a) |

| ***Sub-theme*** | ***Variable*** | ***Justification for Use*** | ***Description*** | ***Source*** |
|---|---|---|---|---|
| | Built-up areas | | Vector layer of polygon shapefiles containing a concentration of buildings and other structures. | OSI<br>(OSI, 2022a) |
| *Protein Feed Products* | Feed suppliers Locations | Agricultural feed suppliers which could provide a market for the protein feed produced. | Excel spreadsheet table of agri feed suppliers in connection with BordBia Ireland along with their lat. long. coordinates from Irish Grid Reference (BordBia, 2022). | BordBia, Irish Grid Reference (BordBia, 2022; Irish Grid Reference, 2022) |
| *Distance to Market* | Roads | Transport to and from the biorefinery. | Vector layer of line shapefiles of the primary, secondary roads and motorways in Ireland. All roads connecting built-up areas. Inside built-up areas only main roads. | OSI<br>(OSI, 2022a) |

*Table 8. Economic variables and their justification, description and source.*

| ***Sub-theme*** | ***Variable*** | ***Justification for Use*** | ***Description*** | ***Source*** |
|---|---|---|---|---|
| *Farming intensity* | Beef_Dairy_Report_2020 | Farmlands with higher livestock numbers may be less inclined to give up land for grass production. | Excel spreadsheet table of 2020 data of the average number of livestock (Cattle/dairy) numbers on farms by ED. Contains number of herds, average number of beef or dairy cows per farm. | Department of Agriculture, Food and the Marine (DAFM, 2022) |
| | Crops_and_Livestock_Survery_June_Final_Results_2021 | | Excel data table of the average dairy and beef cow numbers per county in Ireland from the June 2021 survey carried out by the CSO, who obtained estimated cattle data from the Department of Agriculture, Food and the Marine, and the Irish Cattle Breeding Federation (ICBF). | CSO (CSO, 2022b) |
| *Farming Income* | General Median Income | Farms with lower incomes may be inclined to look to alternative incomes for their grass/silage | Excel data table of median incomes of farms across Ireland by county (2016). Extracted from an overall median income of Ireland. | Department of Agriculture, Food and the Marine (CSO, 2020) |

Other data variables that were collected include the vector layers ‘Counties’ and ‘Electoral Division’ polygon shapefiles to act as a base map for the data to be inputted on.

*3.3.3.1.2 Data Creation and Formatting*

Where readily available data could not be found, particularly in the case of the compound feed industry and biogas injection point locations, spatial data was created. To carry out this step, a list of potential market partners for each variable was first obtained from the public Gas Network Ireland pipeline map and the feed supplier members list provided by BordBia (BordBia, 2022; Gas Network Ireland, 2022). This list of market partners and gas pipelines was then entered into separate Excel spreadsheet tables.

*Table 9. Template of the category headings used to create the animal protein feed market partners data table.*

| Object_ID | Company | Town | County | Focus | Lat. | Long. | X | Y |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |

As shown in Table 9, for the feed market partners, this table included a unique identification number, the name of the company, the town and county they were located within, along with the focus of their business. This was carried out following the guidelines provided by the Environmental Systems Research Institute (ESRI) (ESRI, 2022a).

*Table 10. Template of the category headings used to create the gas network pipelines data table.*

| Object_ID | County | Gas_grid_point | Description | Pipeline | Lat. | Long. | X | Y |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |

For the gas network pipelines, a unique object identification number was also given, along with the county, gas grid point, description of the pipeline and type of pipeline (Table 10).

Using Irish Grid Reference Finder, longitude and latitude coordinates were found for each market partner, and gas grid injection point along with the Irish Transverse Mercator coordinates (represented as X and Y). This data source was used as it provides geographical grid references for gathering coordinates in Ireland (Irish Grid Reference, 2022). The Irish Transverse Mercator projection system was used as it is utilised in Irish mapping datasets (Kenny, 2022b).

As the 'Beef_Dairy_Report_2020' Excel dataset did not include coordinates, the table was formatted so that it could be joined to the existing electoral division boundary spatial layer within ArcMap. Firstly, the data was sorted by Electoral Division. The corresponding Object_ID and Electoral_Division tabs from this file was then added to the 'Beef_Dairy_Report_2020' table. This step was carried out to allow for the data to be visually plotted within ArcMap. The additional Electoral Division column was then removed, as the data table was joined with the original 'Electoral Division' within ArcMap.

As Excel spatial data may not always be utilised by the ArcMap application, the files were converted to a *.csv format before being inputted to the application following the ESRI guidelines for open data (ESRI, 2021a).

#### *3.3.3.1.3 Inclusion/ Exclusion of data*

Once the data variables had been collected, they were further categorised into data that would best meet the criteria of the analysis. This method followed the multi-criteria methods used in studies carried out by Bell et al. (2007) and Perpiña et al. (2013). It was determined that the variables that closely matched the sub-themes listed in Table 1 would be included in the analysis.

*Table 11. Variables that were included in the spatial analysis and their justification.*

| ***Included Variable Layers*** | ***Justification*** |
|---|---|
| Pastures | To determine potential feedstock sites, as dairy and beef farming use pastures for grazing. |
| Water_Framework_Directive_River_Network<br>Water_Framework_Directive_Lakes | Areas to avoid. Biorefinery infrastructure cannot be built on a waterway. |
| Peat_Bogs layer from Corine_Land_Cover_2018 | Unsuitable land for a biorefinery infrastructure to be built on. Some sites are included within the SAC shapefile. |
| All Forestry data layers from Corine_Land_Cover_2018 | Unsuitable locations for grass production as this study is focused on utilising farming grasslands. |
| SPA & SAC | Areas to avoid as they are protected or contain protected species. |
| OSI_Road_Network | To determine if transport infrastructure is available, or closely available to the biorefinery. |
| Gas Network Pipelines | To locate the possible market points for biogas products. |
| Protein Feed Partners | To location the potential market partners for the protein feed product produced. |
| Settlements (generalised to 20m) | To  determine if a national market is available for the insulation product produced. |
| Crops_and_Livestock_Survery<br>_June_Final_Results_2021 | To determine the level of farming intensity within the selected sites at a county level. Areas with high herd numbers would not be suitable as this will indicate that there would be little grass available to be used as a feedstock. |

| | |
|---|---|
| General_Median_Income | To estimate the level of income available to farmers within the selected sites. Farmers with low incomes may be more included to take part in a biorefinery to gain an additional income. The farming income layer was extracted from this dataset. |
| Counties | Used to create a base-map in which the variables can be layered on. |

Vector layers that were not included in the analysis include the Habitats and Birds Directives, Soils, all other layers from the Corine Land Cover 2018, Townlands, Built up areas, the 2020 beef and dairy report and Population Density. The Habitats and Birds Directive layers were not included as the data was already available within the SPA and SAC layers. The Soils vector layer was not included as areas that would be impacted by environmental damage were included within the SAC , SPA, Water Courses and Bodies, Peat Bogs and Forestry layers. All layers from the Corine Land Cover 2018 vector layer were not included as the necessary shapefiles would be extracted (all Forestry layers, Pasture and Peat Bogs). The Townlands, Built up areas and Population Density layers were not included as the data was similar to that of the Settlements layer. While the Beef and Dairy Report 2020 provided a more detailed look at average cattle numbers at an electoral division level, the Crops and Livestock survey 2021 provided a more up to date look at this data, though at county level.

*3.3.3.2.1 ArcMap Formatting*

To carry out a spatial analysis, ArcMap 10.8.1 was used. Before the data was inputted into ArcMap, the data frame properties of the map were set using the guidelines provided by the ESRI (ESRI, 2021b). Within the Data View window, the data frame properties were selected (Figure 5).

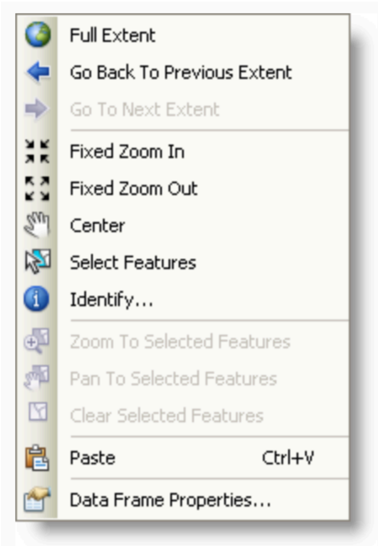



*Figure 5. The data frame properties is used to set the coordinate system in ArcMap (ERSI, 2021b).*

From this setting, the Coordinate Systems tab was selected (Figure 6) and the coordinates were converted to the projection Irish Transverse Mercator. Once this step had been carried out, the variables were added through the 'folder connections' in the Catalog tab to be analysed.

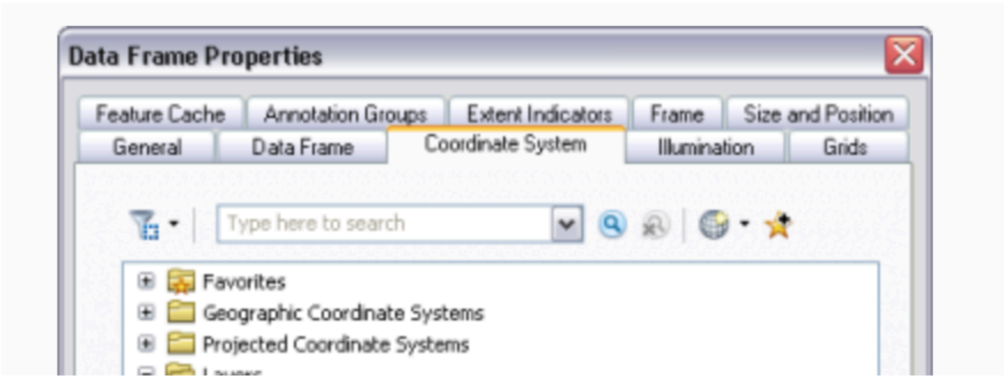



*Figure 6. The coordinate system tab is used to alter the coordinates of the map and all layers added.*

*3.3.3.2.2 Data Table Formatting*

Due to some of the data tables collected containing data that was not relevant to the study, the necessary data was extracted from them. This included the data tables 'Genereral_Median_Income' and 'Crops_and_Livestock_Survery_June_Final_Results_2021'. As these data tables did not contain coordinate systems which would allow the data to be visually represented on a map, they were first joined to the relevant feature layer 'Counties'. Using the ESRI guidelines for joining tables (ESRI, 2021c), both data tables were joined to the 'Counties' feature layer through the manually created Object_ID field for the 'General_Median_Income' and the Name_Tag field for the 'Crops_and_Livestock_Survey_June_Final_Report_2021'. Once these joins had been carried out, the data layers were exported as the feature layers ‘Median_Income’ and ‘Cattle’. Within ArcMap, the ‘Median_Income’ feature layer was used to create a map displaying farming incomes within each county. The ‘Cattle’ feature layer was used to create maps displaying average dairy cow and beef cow numbers within each county.

The ‘Gas_Network’ and ‘Feed_Partners’ tables were then added. To display these data tables as location points, the ‘Display XY Data’ function was used to display the layers as point layers. From the ‘Corine_Land_Cover_2018’ shapefile, using the ‘Selection by Attributes’ tool, the datasets for each ‘Forestry’ layer along with the ‘Peat_Bogs’ layer were extracted and exported. These feature layers were then joined together with the ‘SAC’ and “SPA’ feature layers through the Object_ID field to gain the feature layer ‘Unsuitable_Land’. This layer was used to determine areas that would not be suitable for a biorefinery to be implemented, or for feedstock to be grown. Also from the ‘Corine_Land_Cover_2018’ attribute table, the ‘Pastures’ layer was extracted and exported to determine areas in which feedstock could be supplied from.

*3.3.3.2.4 Geoprocessing Tools*

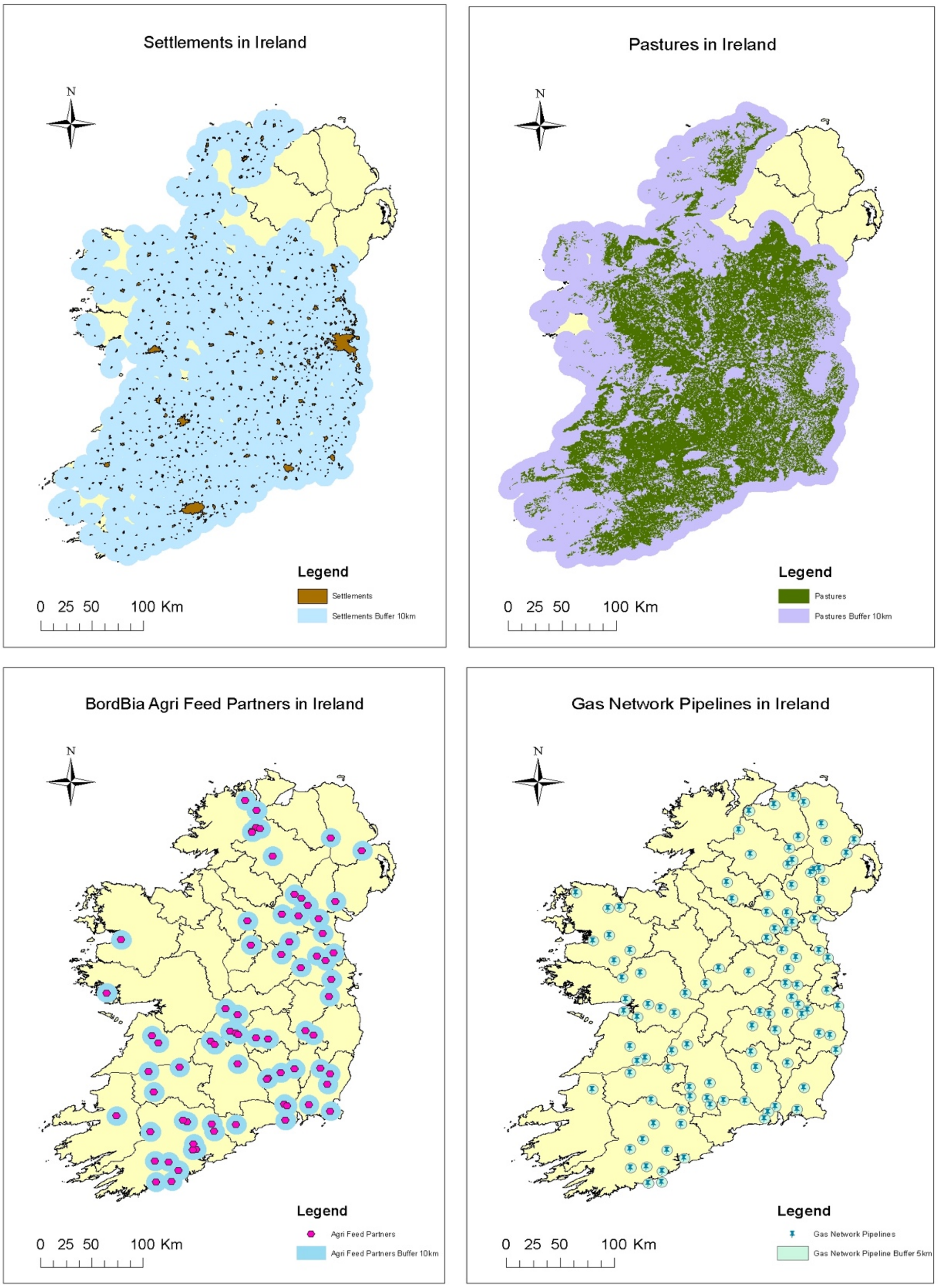
Once the necessary data layers had been added to ArcMap, they were then processed using tools from the ‘Geoprocessing’ tab. Features such as rivers and protected areas require a safety area to ensure that pollution or disturbance does not occur (Perpiña et al., 2013; Jayarathna et al., 2022). To create safety areas surround each feature layer, the ‘Buffer’ geoprocessing tool was used.

Buffer zones are used within GIS to show an area of a certain distance around the selected feature (Flater, 2011). This selected area can be used as a ‘safety area’, where construction or certain features cannot be present, or certain features must be excluded from. For example, Perpiña et al (2013) used a 100m buffer zone around roads due to roads requiring a safety area for drivers safety. Buffer zones may also be used to restrict the feedstock supply chain radius, or product end markets to within a certain distance of the biorefinery.

*Table 12. Buffer zone distances given to each feature layer, along with their criteria.*

| ***Variable*** | ***Buffer zone*** | ***Criteria*** |
|---|---|---|
| Rivers | 200m | A buffer zone of this distance is recommended for rivers where pollution may occur.  (Teagasc, 2022b) |
| Lakes | 20m | Recommended distance for infrastructure or agriculture to take place from lake shorelines (EPA, 2017) |
| Unsuitable land | 1km | Building cannot take place within areas that would disturb protected areas (Perpiña et al., 2013) |
| Roads | 2km | Safety area surrounding roads to ensure that the infrastructure has access to them, increased to 2km from the study by  Perpiña et al (2013). |
| Pastures | 10km | Recommended distance from a centralised biorefinery, the dried insulation product can also be transported at long distances ( Höltinger et al., 2012; Ambye-Jensen and Adamsen, 2015; Beef Farming Representitive, 2021). While this distance was the minimum recommend, it can be increased to 15km, 20km or even 40km ( Kamm et al., 2010; Höltinger et al., 2012; Beef Farming Representitive, 2021). |
| Settlements | | |
| Gas Network Pipelines | 5km | Biogas market partners should be located close or within a short distance from biorefineries producing the product as biogas has a shorter transport distance than natural gas (Kamm et al., 2010; Hengeveld et al., 2016) . |
| Agri Feed Partners | 10km | Dry matter can be transported at longer distances (Kamm et al., 2010; Ambye-Jensen and Adamsen, 2015). |

Using distances recommended from literature (Höltinger et al., 2012; Perpiña et al., 2013; Jayarathna et al., 2022), and from stakeholder interviews (Beef Farming Representitive, 2021), buffer zone distances were given to each feature layer as shown in Table 12 and Figure 7.



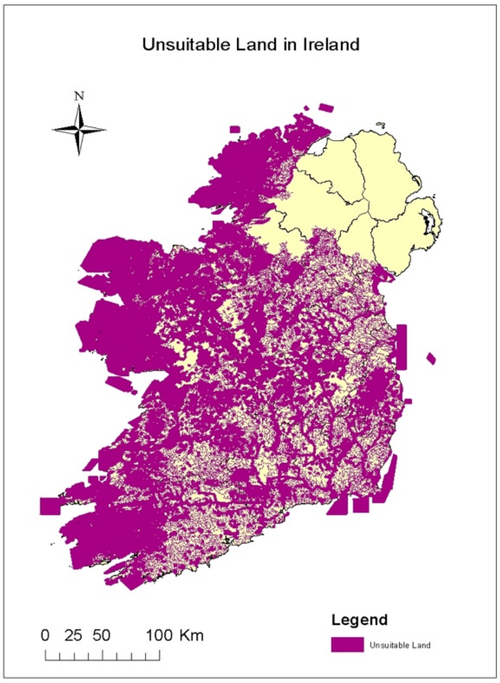



*Figure 7. Buffer distances given to (a) settlements, (b) pastures, (c) BordBia agricultural feed partners, (d) Gas Network Ireland pipelines, and (e ) unioned unsuitable land, used to determine suitable and unsuitable areas for biorefineries in Ireland.*

The 'Union' geoprocessing tool was used to combine all the buffered unsuitable land layers (Figure 7e). This geoprocessing tool combines multiple polygon feature layers to form one single layer (ESRI, 2022b). This new union layer was used to determine areas which would be excluded from the analysis of suitable locations. The 'Intersect' tool was used to determine where the buffered suitable land layers (Figure 7a -d), overlapped with one another (ESRI, 2022c). The buffered vector layers of 2km Roads, 10km Settlements, 10km Pastures, 5km Gas Network Pipelines and 10km Agri Feed Partners were all intersected with one another to determine areas where all of the layers overlapped (Figure 8).

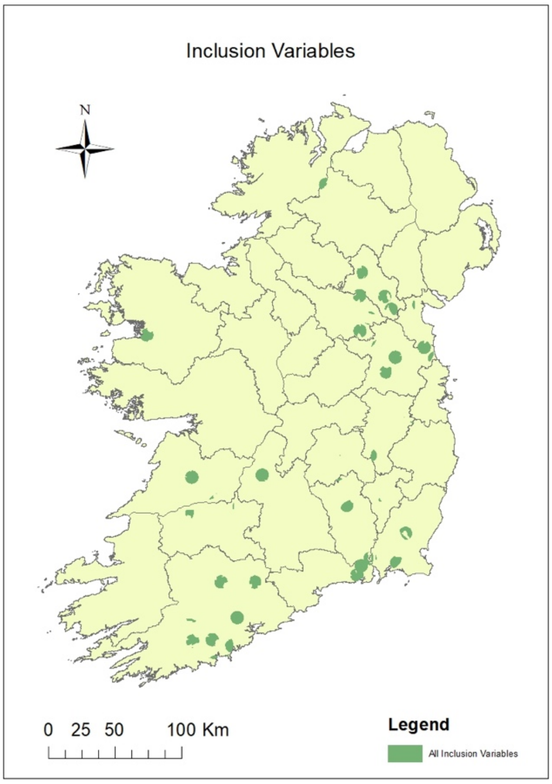



*Figure 8. Map displaying all of the overlapping inclusion variables before the 'erase' tool was used to remove areas found within unsuitable land sites.*

The ‘Erase’ tool was then used to remove suitable land areas which fell within unsuitable land. The ‘Erase’ tool allows for a new feature layer to be created by removing unwanted feature layers from the final analysis (ESRI, 2022d). The suitable areas feature layer was added to the input column of the tool, while the unsuitable areas feature layer was added to the erase feature column.

### *3.4 Conclusion*

A mixed method approach of co-design, economic analysis and GIS analysis provided a more in-depth analysis of a suitable model and locations for deployment. By using the co-design phase to inform the economic analysis, and both in turn informing the GIS model, the chosen green biorefinery can be observed from multiple angles.

# Chapter 4: Findings

### *4.1 Introduction*

Chapter 4 will look at the findings from the three phases outlined in section 3.2 and Figure 2. Beginning with the Co-design phase, the green biorefinery models from across Europe are identified and compared in 4.2.1. The comparison will include the models technological readiness level (TRL), feedstock used, capacity, end products and technologies used. The key stakeholders are then identified in 4.2.2, along with the type of impact they will have on the biorefinery model. The data collected from these stakeholders are outlined in 4.2.3, beginning with the semi-structured interviews, then carrying on into the farmers focus group. From these stakeholder engagement findings, a green biorefinery model upon which to conduct the economic and spatial analysis is selected. The findings from the economic phase will be covered in 4.3, beginning with the mass balance and process flow diagram in 4.3.1. Using these visual models displaying the level of scale of the inputs and outputs of the model, the capital budget model is analysed in 4.3.2. Calculations for the annual profit, return on investment and payback time period are carried out in 4.3.3. Once the economic model is complete, the variables from the stakeholder engagement and literature review are determined in 4.4.1, which are then inputted into ArcGIS for spatial analysis. This technology allows for the variables collected from the outputs of the co-design phase to be analysed.

#### *4.2.1 Comparison of European Green Biorefineries*

Based on the criteria listed in 3.3.1.1, ten green biorefinery models were selected from Austria, the Netherlands, Denmark, Germany, Switzerland, and Ireland as shown in Table 13. To provide a balance on feedstock options, five of the selected models used fresh grass as a feedstock while the other five used silage. It was found that the models operating commercially used silage as their feedstock, as it can be stored for longer periods in comparison to fresh grass. Fresh grass as a feedstock has also only been fully realised in recent years in comparison to the use of silage. Nine of the ten models were a fixed unit, with the Irish model being the only mobile unit.

In terms of TRL, the ten models are divided into three categories. Those with technologies in the early stage of development fell under the TRL 6, which included both the Austrian and the (1a) Netherlands model. Five of the European models were categorised under the TRL 7, where the technologies were operating at demonstration scale, but still working towards a commercial level. The Germany (3b), Netherlands (3a) and Switzerland models all fell under the higher TRL of 8-9, as they were operating commercially (Table 13), with the Netherlands (3a) model collaborating with other commercial partners.

Focusing on the processing capacity of each model, the literature was found to provide data on either the hourly, daily or annual input of the biorefineries. The Switzerland model was the only model which did not provide the input capacity as they received their feedstock from the Netherlands (3a) model as part of their involvement with the GrasGoed. Comparing those with an hourly input, the Irish unit had the lowest, operating with a 2 t/hr capacity, while the (2a) Netherlands model had a capacity of 4 t/hr. This difference in capacity was due to (2a) Netherlands model using an upgraded version of the Ireland model. The models that provided the daily capacity were the Austria and (1b) Germany model. Both of these models used silage as a feedstock, though as it was operating commercially, the (1b) Germany model had a higher daily capacity of 20t when compared to the 10t of the Austria model. The remaining five models annual capacity ranged between 8,000 t/yr to 50,000 t/yr. Of these five models, the (3b) Germany and (3a) Netherlands models had the lowest capacity of 8,000 t/yr and 10,000 t/yr respectively, though they were both operating commercially and had a TRL of 9. The (1a) Netherlands model had the highest capacity, with the model expected to reach 50,000 t/yr at full capacity. This model was also in the beginning stages at TRL 6 at the time of the literature review, therefore it is unknown whether this capacity will be met. The remaining Denmark and (2b) Germany model had an annual capacity of 20,000 t/yr, with both models operating at a TRL of 7 and using fresh grass.

*Table 13. Comparison of European Green Biorefinery models that use either a silage or fresh grass feedstock. The comparison includes the TRL, capacity and end products produced by each model.*

| ***Biorefinery Model*** | ***TRL*** | ***Capacity (tonnes of dry matter (tDM)/tonnes of fresh weight (tFW)*** | ***Biomass*** | ***End Product*** | ***Source*** |
|---|---|---|---|---|---|
| **Austrian Pilot Plant** | 6 | 10 tDM/day | Silage | Lactic Acid, Amino Acids, Biogas | (Ecker et al., 2012; Prieler et al., 2019) |
| **(1a) GrasGoed, Netherlands** | 6 | 50,000 tFW/yr | Fresh Grass | Paper, Packaging materials, Fertilizer, Animal Feed, Insulation Mats | (van Calker and Thiewes, 2018; Embo, 2019) |
| **Aarhus University, Denmark** | 7 | 20,000 tFW/yr | Fresh Grass | Animal Feed, Biogas, Fertilizer | (Aarhus University, 2019; Ambye-Jensen, 2020) |
| **(1b) BioFabrik, Germany** | 7 | 20 tDM/day | Silage | Degradable Plastic, Fertilizer, Animal Feed, Sugar, Lactic Acids, Minerals | (Ball, 2018; Biofabrik, 2021) |
| **BiorefineryGlas, Ireland** | 6 | 2 tFW/hr | Fresh Grass | Fertilizer, Bioenergy, Animal Feed, FOS | (Biorefinery Glas, 2021; Buckley et al., 2021) |
| **(2a) Grassa!, Netherlands** | 7 | 4 tFW/hr | Fresh Grass | Protein, Prebiotic Fibre, Fertiliser | ( Grassa Bioraffinage, 2017; Buckley et al., 2021) |
| **(2b) Havelland Pilot Plant, Germany** | 7 | 20,000 tDM/yr | Fresh Grass | Lactic Acid, Animal Feed, Biogas, Fibre | (Kamm et al., 2010) |
| **Gramitherm, Switzerland** | 8 | n/a | Silage | Insulation Boards, Feed, Biogas | (Franchi et al., 2020; Gramitherm, 2021b) |
| **(3b) Biowert, Germany** | 9 | 8,000 tDM/yr | Silage | AgriCell (insulation material), AgriPlast (plastic) , AgriFer (fertiliser), AgriPro (protein), Biogas | (IEA Bioenergy, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| **(3a) NewFoss, Netherlands** | 9 | 10,000 tDM/yr | Silage | Energy, Fibres for Paper, Insulation Material, Fertilizer, Biogas, NFF-pulp (cardboard) | (Ball, 2018; Hamoen, 2019) |

The end products produced by each green biorefinery model varied depending on the targeted market. From the press cake fibres, products such as animal feed for ruminants, insulation material, paper and packaging material were produced. The Switzerland, (3a) Netherlands, (3b) Germany and (1a) Netherlands all produced insulation material as a product from the fibre fraction. As the (1a) Netherlands model was part of the (3a) Netherlands model project, similar additional products were produced from the fibre material in addition to the insulation material. This included paper and cardboard (NFF-pulp). The (3b) Germany model also produced additional fibre products to the insulation material, this included biodegradable plastic. The Switzerland, (3b) Germany, (3a) Netherlands and (1b) Germany models all produced these products commercially, with the (3a) Netherlands model collaborating with other businesses to sell their products.

The other models did not produce insulation material or biodegradable plastic from their fibre material, mainly using the material as a ruminant feed instead (in the case of fresh grass feedstock models), or using it for biogas production as seen in the Austrian model. These models place an emphasis on valorising the press juice that was separated from the fibre. These products included protein feed, fertiliser, lactic acid and amino acids, along with fructan sugars. With the exception of the (2a) Netherlands model, all of the models produced biogas or energy as an end product.

*Table 14.Comparison of the technologies involved in the primary and secondary processes of each European Green Biorefinery model.*

| ***Biorefinery Model*** | ***Secondary Process – Press Juice*** | ***Source*** |
|---|---|---|
| **Austrian Pilot Plant** | Sedimentation<br>Softening – cation exchange<br>Ultrafiltration<br>Two-stage nanofiltration – Membrane filtration<br>Reverse Osmosis<br>Electrodialysis<br>Ion Exchange | (Ecker et al., 2012; Prieler et al., 2019) |
| **(1a) GrasGoed, Netherlands** | This model's processes were based on the NewFoss model. | (van Calker and Thiewes, 2018; Embo, 2019) |
| **Aarhus University, Denmark** | Filtration through Bow screen<br>Protein Precipitation by fermentation/ heat treatment 80C<br>Separated into solid & liquid through decanter centrifuge | (Aarhus University, 2019; Ambye-Jensen, 2020) |
| **(1b) BioFabrik, Germany** | Filtration<br>Separation<br>Membrane technology | (Ball, 2018; Biofabrik, 2021) |
| **BiorefineryGlas, Ireland** | Based on Netherlands 2(a) model process | (Biorefinery Glas, 2021; Buckley et al., 2021) |
| **(2a) Grassa!, Netherlands** | Coagulation<br>Decanter centrifuge<br>Drying<br>Nanofiltration<br>Reverse Osmosis | (Grassa Bioraffinage, 2017; Buckley et al., 2021) |
| **(2b) Havelland Pilot Plant, Germany** | Press juice is preheated in a counter flow by a supernatant.<br>Heated to 75-85ºC by a short time direct superheated steam injection, leading to protein coagulation.<br>Separated in a decanter centrifuge.<br>Part of dried product is blended in with wet protein coagulates & thermally dried by hot water/air heat exchanger at max temperature of 50ºC. | (Kamm et al., 2010) |

| | | |
|---|---|---|
| **Gramitherm, Switzerland** | Press Juice used as a biogas energy booster to dry and work on the fibre<br>Press Cake dried and processed with additives to produce insulation panels | (Franchi et al., 2020; Gramitherm, 2021b) |
| **(3b) Biowert, Germany** | Press juice is used for biogas<br>Heat and electricity derived from the biogas plant is used as energy in the biorefinery<br>Fibres blended with recycled plastics to produce composite materials | (IEA Bioenergy, 2019) |
| **(3a) NewFoss, Netherlands** | Nanofiltration<br>Reverse Osmosis<br>Water from this is purified & reused | (Ball, 2018; Hamoen, 2019) |

The comparison of the technologies used in each model found that almost all of the models used a screw press to separate the feedstock into a liquid and a solid material, (the press juice and press cake) during the primary processing steps. The one exception is Newfoss who used a mild microbial water-based extraction technology to open the grass cells for further valorisation (Ball, 2018). For the processing of the press cake fibres, only an additional drying step was used, with binding additives being added when the material was used for insulation material. Both the Switzerland model and the (3b) Germany model appeared to use similar approach focused on further processing press cake fibre and with press juice being used for biogas and/or fertiliser production. Differences and similarities are also seen within the secondary processing technologies for the remaining models. As the (1a) Netherlands model had similar processes as the (3a) Netherlands model, they were grouped together for the technology comparison. Similarly, the Ireland and (2a) Netherlands models were also clustered together on this basis. The Austrian model was found to be the only biorefinery model which used ion exchange to produce the amino acids from the press juice of silage, while the fresh grass-based models used a form of heat coagulation and decanter centrifuge to separate a protein concentrate. The Austrian model also had additional technologies for processing the press juice when compared to the other models, including sedimentation and softening processes. The bio-based chemical lactic acid was additional output from this downstream processing, which is concentrated and isolated using a combination of advance membrane separation and electrodialysis. Both the Demark and Ireland model used similar technologies for processing the press juice. Both models used membrane filtration processes, heat coagulation and separation through a decanter centrifuge to gain multiple end products from the press juice. The (2b) Germany model also used similar heat and separation methods, though this model did not use membrane filtration in its processes. The (1b) Germany model was the only model found not to use heat coagulation in the secondary process, though the model did use membrane filtration and separation by decanter centrifuge processes similar to the Denmark model. As some models were shown to use similar technologies and processes, for the purpose of the stakeholder engagement the most unique models were clustered together. The Austrian model and Germany (1b) were clustered together, while the Ireland, Netherlands (2a) and Denmark models were grouped together. The Switzerland, Germany (3b) and Netherlands (3a) were not clustered with other biorefinery models but were still presented.

Overall, the comparison between green biorefinery models showed that European models were still able to operate commercially at a TRL of 7 and above. The end products were also dictated by the feedstock used and the target market, though a majority of models produced animal feed and fertilizer, showing that agriculture is the target market. The technologies used in the secondary process of the biorefineries would provide unique examples to present to stakeholders to determine a suitable model for Irish agriculture.

#### *4.2.2 Identified Stakeholders*

From the exercises carried out in the collaborative workshops in section 3.3.1.3, the key stakeholders associated with a green biorefinery were identified. Eight stakeholders were identified to have an impact on the biorefinery, or to be impacted by the model. These stakeholders were identified as farmers, market partners, policy makers, cooperatives, consumers, funding bodies, academia & research, and the local community (Figure 9). Based on the stakeholder mapping and analysis exercise and the Lego model (Appendix 1), the farmers, cooperatives, academia and market partners were deemed to be directly impacted or have an impact on the biorefinery model. The remaining stakeholders were found to have an indirect impact on the model.


*Figure 9. Key Stakeholders that were identified within the collaborative workshops.*

As the model focused on utilising fresh grass or silage as a feedstock in Ireland, livestock farmers that use grassland for grazing and silage, mainly for beef and dairy production, were considered as the main category of farmers impacted by the biorefinery. As tillage farmers could also be impact by the model, both in terms of feedstock supply, but also in their role as current feed supplier they were also considered as primary farmer stakeholders. Based on review of literature and previous models, the main market partners impacted include companies who specialise in agricultural animal feed (ruminants and monogastric) and those who would potentially utilise sustainable fibre, such as sustainable building producers and suppliers. Stakeholders within the cooperatives category would include established agricultural cooperatives and cooperative associations in Ireland. The funding bodies or finance category included national or international funding bodies, such as banks, government schemes or the European Investment Bank. While the farmers were identified as a stakeholder that could supply the biorefinery, it was also noted that they could potentially become consumers of the products produced. Therefore, farmers could also be classified under the consumers category, which also includes others who would potentially use the end products.

### *4.2.3 Stakeholder Engagement*

From the stakeholders identified in 4.2.2, a representative from the dairy, beef, protein (ruminant and monogastric) market, eco-insulation market, policy, finance and cooperative category were interviewed. The template for the interview questions can be found in Appendix 3. The interviews were analysed using a thematic analysis.

The main themes that were discussed during the analysis of the semi-structured interviews with the stakeholder representatives were:

- Knowledge of the bioeconomy/green biorefineries
- Farming Diversification
- Collaboration
- Biorefinery Implementation
- Supports available
- Market potential
- Challenges
- Transport

The findings of these themes are outlined in section 4.2.3.1 to 4.2.3.8.

The broad range of potential consumers was found to be difficult to assess within the space of this study, therefore market partners from the various industries were used to gain some perspectives on the type of consumers available for the products. Along with the semi-structured interviews of these stakeholders, a focus group was carried out with dairy, beef and one tillage farmer, with the results discussed in section 4.2.3.9. As the findings from the interviews were used to shape the focus group, some similar themes were identified in both settings.

#### *4.2.3.1 Knowledge of the Bioeconomy/Green Biorefineries*

Representatives of a purposeful sample of the dairy and beef industry, cooperatives, policy and finance all identified that there were gaps in the knowledge and education of the bioeconomy amongst the farming community at ground or farm level. They agreed that the concept of the bioeconomy itself, and in turn a green biorefinery, was a broad subject, and that if farmers were to be encouraged to take part, they would need to be informed on how they could be involved. Both the dairy and beef representatives noted that farmers should also be informed on the type of products that a biorefinery could produce, and be aware of the options available to them. It was also indicated that peer-to-peer education may be beneficial in informing the farmers on the bioeconomy. This would involve farmers and other stakeholders who previously took part in such projects, or were familiar with the bioeconomy, to speak to other farmers and showcase the concepts. The finance stakeholder also noted that there would be a requirement for education of other stakeholders on the bioeconomy concept, such as bankers or other funding bodies that would not be familiar with the subject.

#### *4.2.3.2 Farm Diversification*

Stakeholders interviewed from the farming categories all agreed that farmland diversification is rapidly changing in Ireland when compared to previous years, particularly among more progressive farmers and cooperatives. For example, farmers partaking in agri-environmental projects, tourism, renewable energy projects and converting areas to forestry. Though there is a rapid change, it was noted in the interviews that there are still concerns regarding risk and uncertainty among farmers. This was cited as being due to farmers having a more traditional farming background, unfamiliarity with newer technologies. The stakeholders interviewed did note that these farmers may be more open to newer technologies if there was little to no disruption to their current farming methods, or if technologies could integrate well within existing operations. There were also concerns regarding financial protection for the farmers. These concerns included uncertainties regarding the way in which farmers' incomes may be impacted by changing to these new practices. A need for transparency between the farmers and the other stakeholders involved in the value chain would help address these concerns. The farmers would also need to be informed of the long-term viability of the biorefinery, including farmer investment requirements and remuneration models for participation.

#### *4.2.3.3 Collaboration*

In order for farmers from different agricultural backgrounds to collaborate on a biorefinery project, the stakeholders remarked on the importance of how the concept is framed and presented. According to the dairy and beef stakeholders, the concept must be made clear to the farmers from the beginning. All of the stakeholder representatives noted that a collaborative model would be suitable for Ireland, as it would give the farmers and stakeholders involved ownership of the model, particularly if a cooperative mode is to be adopted. The cooperative representatives agreed that if a cooperative was involved as a stakeholder, there would be benefits to the farmers in the form of a wider network of market partners and supports. Through a collaborative model, there would be a sharing of the risk amongst the stakeholders, in contrast with an individual farmer taking all the risk. This sharing of risk could also help to increase the economy of scale and result in the sharing of the benefits.

#### *4.2.3.4 Green Biorefinery Implementation*

For green biorefineries to be implemented in Ireland, the Cooperative, dairy and beef stakeholders interviewed commented that the farmers would need support from trusted stakeholders, such as the cooperatives and farming organisations. From these interviews it was found that not all farmers would have a surplus of grasslands available, therefore they may be less willing to set aside a portion for the biorefinery. It was noted by the beef representative that farmers who fell under this category, such as dairy farmers, may be willing to provide a proportion of grass as long as the majority of their grass remained as a forage source. In terms of the infrastructure of the biorefinery, the cooperative stakeholders agreed that co-ops could provide support and capital investment in the development of the model. These stakeholders noted that the model would need to be economically viable for them to take part, and that there must be a good collaboration between both farmers and industry participants.

#### *4.2.3.5 Supports*

From the interviews, it was found that to gain support from the farmers, the biorefinery would need to be presented through the correct narrative, demonstrating the potential for sustainability and multiple revenue streams. For the farmers themselves to take part, government supports such as funding would be critical, along with the participation of trusted partners such as research centres, universities and Cooperatives. For the biorefinery and the farmers to gain financial support and investment, a viable business model would need to be presented. The finance representative did remark that funding bodies are eager to fund projects promoting or benefiting the environment, but a strong business model is key. For the farmers, there are funding supports through the CAP, GLAS schemes, EIP-Agri projects, Leader funding and private companies. The cooperative representatives remarked that there is already an established trust between the cooperatives and funding bodies, which could be beneficial to their farming members looking to become part of a biorefinery model.

#### *4.2.3.6 Market Potential*

The protein market partner stated that there is an increasing pressure on farmers to become more sustainable, particularly regarding imported protein feed. There is also pressure on government to reduce Ireland's overall level of imported protein and find more sustainable sources. The stakeholder did agree that there was significant potential for grass to be used as a sustainable protein for monogastric and ruminant feed. They highlighted that local production of this feed should be able to compete on costs and performance with the feed protein already at market. The market partners expressed a concern regarding security of supply of protein which currently exists. Issues such as disruptions to the supply chain and geopolitical issues have become more frequent in soybean protein supply countries. They also noted that there is a possibility of supply shock. In this regard, locally produced grass protein could provide a solution. As the biorefinery model would be based in Ireland, the cooperatives could provide a good network of market partners to the biorefinery and farmers, as they would have an established trust and network among these partners. Both the cooperative and the insulation market partner representatives noted that the building sector has strong market potential for the fibre products produced. It was noted throughout the interviews that market partners in Ireland have the expertise and knowledge to determine how these type of products would perform at the Irish market, particularly those who specialise in agricultural animal feed and building insulation. The transport and tourism sectors were also noted as being a potential market partner for a biogas product, as the sectors look to become more sustainable, though it was also noted by the cooperative stakeholders that their organisations could provide the opportunity for farmers to sell the energy back to the national grid.

While there is a potential market for grass insulation in Ireland, it was noted by the insulation market representative that the eco-insulation industry was still a niche market in Ireland. They also commented that eco-insulation companies still import their materials, and a majority of the insulation installers in Ireland do not supply a natural insulation option. Though it is still a niche market, it was also noted that there is a growing interest from consumers in natural insulation, arising from an increase in awareness of carbon emissions and sustainability aspects of buildings. The market stakeholder noted that when compared to less sustainable insulation products currently at market, natural insulation was perceived to be a premium product. They stated that consumers presume that there is a premium cost associated with natural insulation.

Though this is still a factor that should be considered, they re-emphasized the trend that consumer interest and awareness of environmentally friendly products is increasing in recent years.

#### *4.2.3.7 Challenges*

Throughout the interviews, a number of challenges associated with implementing a biorefinery model were highlighted. These challenges difficulty with funding, as well as overcoming the mindsets of the farmers and local communities in regards to using the grass as a biorefinery feedstock. Strong engagement with the local community, emphasizing the sustainability benefits of the model were suggested to help overcome these barriers. In terms of preparing the products for the market, consistency of supply was indicated to be a challenge by the market partner stakeholders. Both stakeholders observed that for the products to be supplied to market partners, there must be a constant or regular supply from the biorefinery. Other stakeholders interviewed noted that regulations, including regarding fertiliser use, already exist and may impact on grass productivity of farmers, that may wish to supply a biorefinery.

Regarding the insulation material, as grass is a natural product, it was indicated that the regulatory barriers would be similar to that of other natural insulation, such as wood fibre. These type of regulatory barriers may relate to the quality of the product, as there may be variables associated with raw materials, such as inconsistency with multiple grass species being used. For the manufacturing of the product, it was noted that this process would have to be supervised by a 3$^{rd}$ party, to ensure the product is ISO 9001 approved. The insulation stakeholder also stated that there must be quality controls on the product and that environmental accreditations must be met. In terms of national and international market potential, the product would have to comply with British Standards. For the European market, the classifications for the fire safety conductivity would have to be conformed with to gain market acceptance. There would also be a need for a declaration of performance for the material from an architectural point of view due to the products novelty. The product would also have a unique selling point as an environmental product to appeal to consumers and compete with products already at market.

#### *4.2.3.8 Transport*

Both the dairy and beef representatives agreed that a 10-15km could be a potential distance for the feedstock to be transported, as farmers currently transport silage at distances of up to 30-40 miles (48-64km). Should the biorefinery model be economically viable, then distance would not be a significant issue for the farmers, according to the stakeholders. The stakeholders noted that the gross energy output for the transport could be compensated by the overall biogas energy output, and other emissions savings from the biorefinery. They agreed that the distance travelled by the farmers to supply the biorefinery would also depend on the model being a mobile or fixed unit. Taking this into account, the stakeholders did note that a fixed model would be a more effective model for Ireland, as the scale could be increased, and more advanced technologies could be incorporated within the model.

#### *4.2.3.9 Focus Group Outcomes*

From the farmers' focus group, a number of specific concerns and risks were brought forward. Land expansion for producing the grass was highlighted in terms of farmers producing the feedstock. Currently, farmlands are competing with other enterprises such as forestry or the energy industry regarding land expansion. Due to this issue, farmers indicated that the incentive should come from the government, in which land would be set aside for the biorefinery. This aligns with the findings from the stakeholders interviews, who had similar concerns regarding farmers willingness to part with their land for a biorefinery. During the focus group it was indicated that tillage farmers could possibly be the solution for this issue, should there be strong economic support for them to grow grass for biorefineries instead of crops. On this topic, all of the farmers agreed that unless a strong financial argument could be made in favour of the biorefinery, then the farming community would not be willing to part with their grass. Dairy farmers in particular, were noted to be less inclined to part with the feedstock as they would not have a surplus of grasslands. The farmers also highlighted that in similar previous projects, there was difficulty in utilising the end products, particularly those produced from an anaerobic digestor. These concerns aligned with responses from the cooperative stakeholders, who had previously stated that there would be concerns of risk amongst farmers.

Regarding the topic of feedstock selection and harvesting locations, the farmers highlighted that the west of Ireland could be proposed as a viable area for producing the biomass. This was due to sheep farming being a more dominant industry than dairy and beef farming in the area. The farmers also highlighted that a majority of Irish farms are family run, and as such, there may be a concern associated finding extra labour required to implement new projects while managing traditional farm activities. Similar to the findings from the stakeholder interviews, it was highlighted that it would be difficult to change farmers mindsets from traditional farming methods to newer bioeconomy models. Geographical issues were also addressed. The farmers stated that as Ireland was diverse in terms of landscape and farming methods, it would be difficult to design a 'blanket rule' for bioeconomy or diversity projects for the entire country. Other issues that were identified were market volatility, economic challenges for the farmer, the labour requirements for the farmer and the issue of trust from the farmers within these new models.

The farmers were then presented with six of the ten models from Table 14 (generic models clustered together as outlined in section 4.2.1), and asked to choose one or two models they deemed would be suitable for Irish agriculture. From these six models, the mobile fresh grass unit was considered to be unsuitable for Irish agriculture. The model was noted to be labour intensive for the farmers, and of insufficient scale. The participants were most favourable towards the silage model which produced insulation, stating that the product could provide the opportunity for exportation, increasing its market potential. Similar to the stakeholder interviews, the farmers agreed that a fixed unit would be suitable for Ireland. The farmers also agreed that the business model should ideally be led by a cooperative, and that a large group of farmers taking part would be more favourable. This type of structure would reduce the risk to an individual farmer, and would address the issue the farmers previously had with parting with a majority of their grass. Similar to the cooperative representatives, the farmers stated that a strong business case would need to be presented to the cooperatives for them to take part in such a project. The farmers also agreed that a clear market for the products would have to be established to support the economic viability of the project. Other issues that would need to be taken into account for the biorefinery would be the end of life, the level of scale the model would need to be, the level of farmer investment required, and the types of market involved. It was indicated that the revenues produced from the biorefinery would dictate the decision for the farmers to be involved. Finally, it was highlighted that the voice of the farmer is critical in any decision–making moving forward, and that there would be a need for transparency between all parties involved in the biorefinery. This would address the farmers concern of risk and trust.

Overall the feedback from the co-design phase indicated that a large scale fixed biorefinery model, preferably cooperative owned and supplied by a large group of farmers was the preferred model. Silage was indicated as the preferred feedstock, with grass insulation as the main product output. The criteria from the co-design process are further developed into a model through the next sections and the economic viability and potential site locations are analysed.

The next section looks to analyse the economic viability of the selected model from the co-design phase through a mass balance, capital budget model, scenario and sensitivity analysis.

### *4.3.1 Mass Balance & Process Flow Diagram*

Operating at full capacity, the mass balance of the selected green biorefinery model resulted in an annual input of 12,880t of grass silage (Table 15). From the 12,880t DM grass silage input, 10,304tDM was separated into the press cake fibre, while 2,576tDM was separated into press juice. To convert the press cake to fibre insulation material, a further drying stage is used (Figure 10), resulting in an output of 5,796tDM insulation product. The press juice was further processed using a heat coagulation stage to separate the proteins, resulting in 862.96tDM of animal feed protein.

*Table 15. Mass balance for a biorefinery model operating at full capacity.*

| ***Input/Output*** | ***Tonnes DM/hr*** | ***Annual Input/Output*** |
|---|---|---|
| 20t fresh grass feedstock (23% DM) | 4.6 | 12,880 |
| Electricity Input | 731.4 | 2,047,920 |
| Heat Input | 3399.4 | 9,518,320 |
| Fibre Output | 2.07 | 5,796 |
| Protein Output | 0.3082 | 862.96 |
| Electricity Output | 1393.8 | 3,902,640 |
| Heat Output | 1237.4 | 3,464,720 |

| Energy Balance | | |
|---|---|---|
| Electricity Out (From Biogas CHP)-Minus-Electricity In | 662.4 | 1,854,720 |
| Heat Out (From Biogas CHP) -Minus - Heat In | -2162 | -6,053,600 |

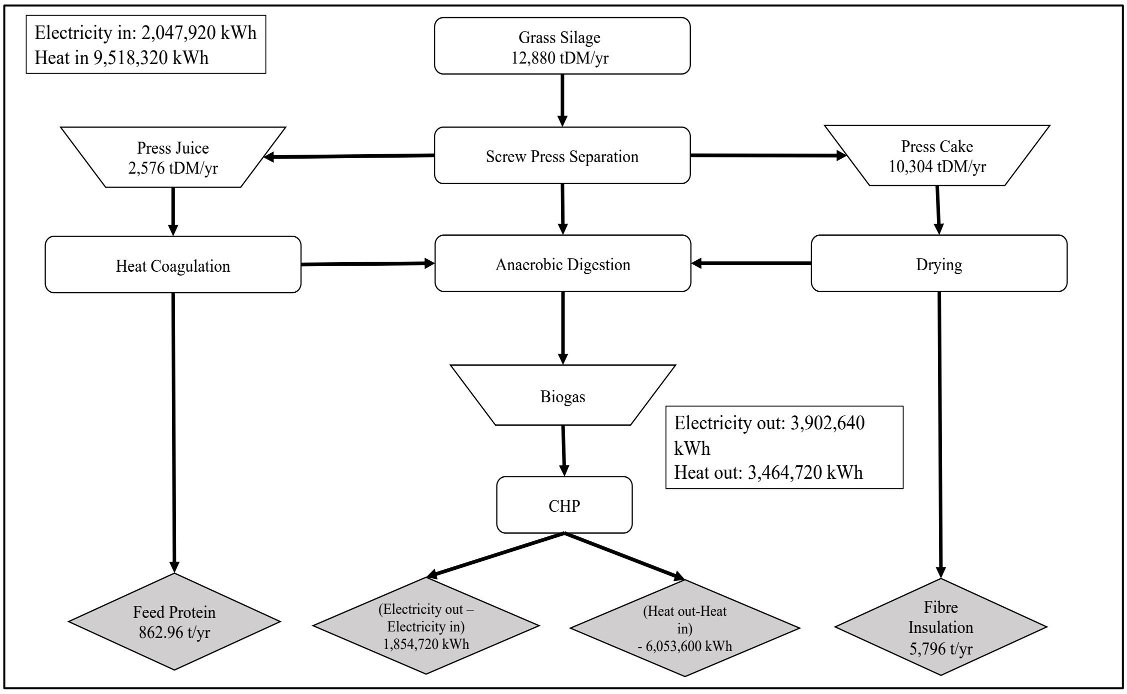



*Figure 10. Process flow diagram of a biorefinery model operating at full capacity.*

From both the heat coagulation stage and the drying stage, the residues are utilised in the anaerobic digestor, producing biogas, which can be used in a CHP (combined heat and power) stage. The mass balance showed that there was a high heat input requirement of 9,518,320 kWh and electricity input requirement of 2,047,920 kWh. In comparison to this, there was a lower heat and energy output from the biogas and CHP unit (Table 15), but with higher electricity output, resulting in the heat and electricity energy being recycled back into the biorefinery model to help meet its energy needs. While the electricity requirements of the biorefinery could be met using electricity from the biogas CHP unit, additional heat energy needed to be sourced. This was visually represented in Figure 10.

*Table 16. Mass balance for a biorefinery operating at a 90% capacity.*

| ***Input/Output*** | ***Tonnes DM/Hr*** | ***Annual Input/Output*** |
|---|---|---|
| 18t Fresh Grass Feedstock (23% DM) | 4.14 | 11,592.00 |
| Electricity Input | 658.26 | 1,843,128.00 |
| Heat Input | 3059.46 | 8,566,488.00 |
| Fibre Output | 1.863 | 5,216.40 |
| Protein Output | 0.27738 | 776.66 |
| Electricity Output | 1254.42 | 3,512,376.00 |
| Heat Output | 1,113.66 | 3,118,248.00 |
| Energy Balance | | |
| Electricity Out (From Biogas CHP)-Minus- Electricity In | 596.16 | 1,669,248.00 |
| Heat Out (From Biogas CHP) - Minus - Heat In | (1,945.80) | (5,448,240.00) |

In comparison, a biorefinery model operating at 90% capacity resulted in much lower input and output quantities (Table 16) The annual silage feedstock input was reduced to 11,592 tDM, resulting in a decrease in the press juice and press cake quantitates (Figure 11). There was a decrease in the end products as a result of this low feedstock input. There was also a decrease seen in the protein and biogas products as a result of the lower feedstock input.

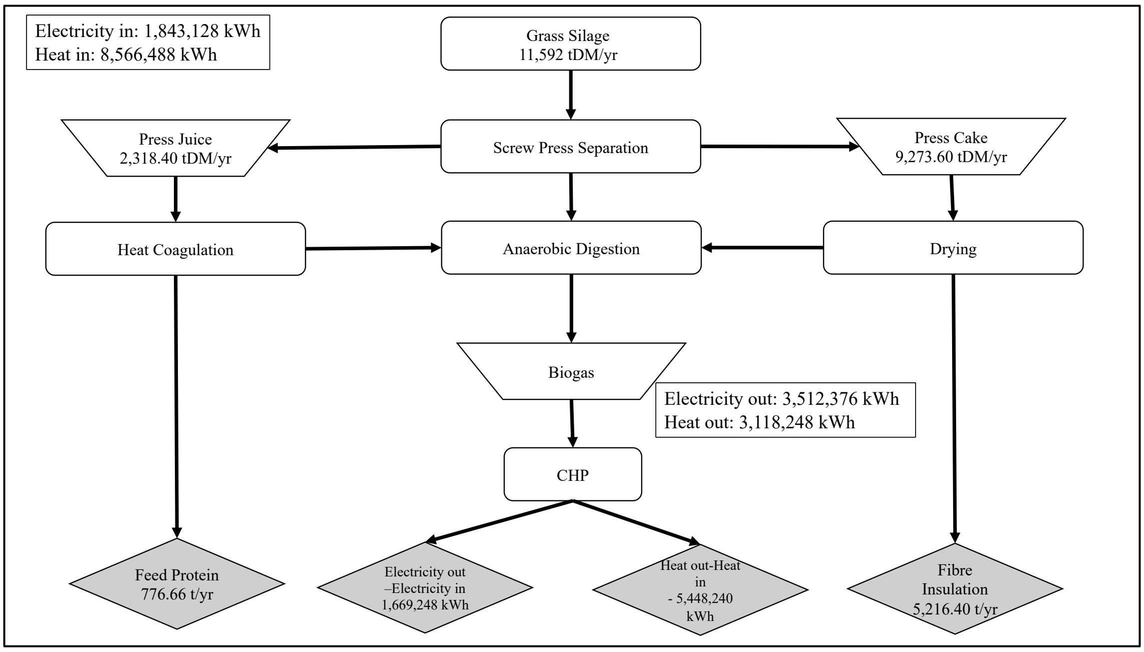



Figure 11. Process flow diagram of a biorefinery operating at 90% capacity.

The reduction in end products produced from a biorefinery operating at 90% capacity would result in a lower revenue stream available to the biorefinery, which is shown in the capital budget model in section 4.3.2.

### *4.3.2 Capital Budget Model*

For the capital budget model, the given capital expenditure remained the same for both scenario A (100% capacity) and scenario B (90% capacity). Following the calculations in section 3.3.2.2.2, the direct and indirect operational costs were calculated. The grass silage feedstock was found to have the highest operational cost for both scenarios, with a full capacity production of 12,880t at €150/t reaching €1,932,000, in comparison to a lower capacity output of 11,592t in scenario B. This variable also had the biggest difference between scenarios, €193,200. The second highest direct expenditure was found to be the heat energy, which had a high productivity of 6,053,600 kWh in scenario A and 5,448,240 kWh in scenario B. This high volume of heat energy required within the direct costs has shown to be the most impactful when analysing the economic feasibility of the model. The third highest direct cost was the cleaning solutions, which resulted in a €63,310.46 difference between the two scenarios. Electrical energy was not considered within the capital budget model as the energy was sufficient to meet the biorefinery electrical requirements and was recycled back into the biorefinery. The lowest direct cost for both scenarios was found to be the binding material, which is more commonly included in the overall insulation product cost.

*Table 17. Capital budget model for scenario A (full capacity) and scenario B (90% capacity).*

| ***Input/Output*** | ***Total Annual €*** | ***Total Annual €*** |
|---|---|---|
| | **Scenario A (100% Capacity)** | **Scenario B (90% Capacity )** |
| **Capital Expenditure** | | |
| Total Capital Expenditure | 5,500,000.00 | 5,500,000.00 |
| **Operational Expenditure** | | |
| Direct Expenses | | |
| Grass Silage | 1,932,000.00 | 1,738,800.00 |
| Binding Materials | 8,144.82 | 7,330.34 |
| Cleaning Solutions | 633,104.64 | 569,794.18 |
| Heat Energy | 726,432.00 | 653,788.80 |
| Waste Disposal | 13,200.00 | 11,880.00 |
| Conditioning & Distribution | 193,750.00 | 174,375.00 |
| Total Direct Expenses | **3,506,631.46** | **3,155,968.31** |
| Indirect Expenses | | |
| Repairs & Maintenance | 275,000.00 | 275,000.00 |
| Insurance | 50,000.00 | 50,000.00 |
| Labour | 88,000.00 | 88,000.00 |
| Overheads | 8,800.00 | 8,800.00 |
| Total Indirect Expenses | 421,800.00 | 421,800.00 |
| Total Operational Expenditure | **3,928,431.46** | **3,577,768.31** |
| **Revenue** | | |
| Insulation Material | 4,926,600.00 | 4,433,940.00 |
| Protein | 258,888.00 | 232,999.20 |
| Surplus Electrical Energy (Biogas) | 222,566.40 | 200,309.76 |
| Total Revenues | **5,408,054.40** | **4,867,228.96** |
| Total Operation Expenditure | 3,912,931.46 | 3,581,643.31 |
| Depreciation | 148,500.00 | 148,500.00 |
| Interest + Loan Repayment | 569,820.13 | 569,820.13 |
| Profit /Loss Before Tax | **761,302.81** | **571,160.52** |
| Return On Investment | **16.54%** | **13.08%** |
| Payback Period | **6** | **8** |

Within both scenarios, the indirect costs remained the same as they were not subject to change. The total repairs and maintenance costs were the highest indirect costs, reaching €275,000. The second highest indirect cost were the labour costs, which reached €88,000 for two people. The total indirect costs for both scenarios were found to be €421,800. When combined, the direct and indirect operational expenditures for scenario A reached €3,928,431.46, while at a lower capacity, the total for scenario B reached €3,577,768.31.

Overall, the direct operational costs were found to be the most impactful costs for each scenario, as they were subject to change. The feedstock costs in particular were found to be the highest cost to the biorefinery, while the binding materials were found to be the lowest direct cost.

#### *4.3.2.1 Revenues*

The insulation material was found to have the highest revenue output from the model for both scenarios. For a full capacity scenario (A), an annual output of 5,796 t resulted in a revenue of €5,408,054.40 at a rate of €850/t. At a lower capacity (scenario B), the insulation material still produced the highest income, with a total of €4,867,228.96 for an output of 5,216t. A difference of €492,660 shows that the selling price of the insulation material output plays a major role in the profitability of the biorefinery model. While the biogas output quantity was the highest in both scenarios, 1,854,720 kWh in scenario A and 1,669,248 kWh in scenario B, the product had the lowest revenue. At a rate of 0.12/kWh, biogas in scenario A had a revenue of €22,566.40, while in scenario B, the product had a revenue of €200,309.76, the lowest revenue difference of €22,256.64 between the two scenarios. The total revenues for both scenarios were € 5,408,054.40 (A) and €4,867,248.96 (B).

Overall, the profitability of a biorefinery operating at full capacity (A) was found to be more favourable than a model operating at 90% capacity (B). The insulation revenue in particular was found to be the most influential in the profitability of the model when compared to the other products produced.

#### *4.3.2.2 Additional Costs & Profitability*

Following the calculations from section 3.3.2.2.4, the depreciation and loan repayment costs remained the same between the two scenarios. The depreciation of the biorefinery was found to be €148,500, while the loan repayment reached a value of €569,820.13. There was a difference in the profit/loss before tax for both scenarios as a result of the lower inputs and outputs in scenario B. Scenario A was found to be more profitable, with a profit of €761,302.81 in comparison to scenario B, with a profit of €571,160.52. At a full capacity, scenario A was found to be the more favourable scenario in comparison to a model operating at 90% capacity. This was seen in the higher ROI in scenario A, 16.54%, compared to the 13.08% return rate in scenario B. When the figures were brought to the nearest round figure, scenario A was found to have the shorter payback period, 6 years. In comparison, scenario B had a payback period of 8 years, which would not be as favourable to stakeholders.

Overall, scenario A was found to be more favourable that scenario B, where the biorefinery would be operating at a lower capacity of 90%. While a model operating at full capacity had higher operational costs, the high revenues generated by the end products, have shown a more favourable profitable outcome than running at a lower capacity.

#### *4.3.2.3 Sensitivity Analysis*

The results of the sensitivity analysis show that changes in the insulation selling price does have an impact on the profitability and return rate of both scenario A and B of the biorefinery model. The linear increase in insulation price from €850/t to €880/t results in a positive increase in the profitability and return on investment. Table 18 shows that the profitability of scenario A increased from €761,302.81 to €935,182.81 when the insulation price was increased to €880/t. The return rate of scenario A also increased from 16.54% to 19.70%, demonstrating that should the selling price for insulation increase, the biorefinery model would be more favourable. The increase in price was also found to be favourable in scenario B, where the profitability of the model increased from €571,160.52 to €727,652.52. The return rate of scenario B also increased from 13.08% to 15.93%.

*Table 18. Sensitivity analysis for an increase and decrease in insulation selling price.*

| ***Insulation Sell Price (€)*** | ***Profit/Loss (€) - Scenario A*** | ***Profit/Loss (€) - Scenario B*** | ***ROI (%) – Scenario A*** | ***ROI (%) – Scenario B*** |
|---|---|---|---|---|
| 820 | 587,422.81 | 414,669.52 | 13.38% | 10.24% |
| 830 | 645,382.81 | 466,832.52 | 14.43% | 11.19% |
| 840 | 703,342.81 | 518,996.52 | 15.49% | 12.14% |
| 850 | 761,302.81 | 571,160.52 | 16.54% | 13.08% |
| 860 | 819,262.81 | 623,324.52 | 17.60% | 14.03% |
| 870 | 877,222.81 | 675,488.52 | 18.65% | 14.98% |
| 880 | 935,182.81 | 727,652.52 | 19.70% | 15.93% |

The decrease in the insulation price, from €850/t to €820/t had a negative impact on the profitability and return on investment of the model in both scenarios. Table 18 shows that the profitability of scenario A decreased from €761,302.81 to €587,422.81, while scenario B decreased from €571,160.52 to €414,669.52. The return rate of both scenarios also decreased, with scenario A decreasing from 16.54% to 13.38%, and scenario decreasing from 13.08% to 10.24%.

*Table 19. Sensitivity analysis of the deceases and increases in feedstock cost prices.*

| ***Feedstock Cost (€)*** | ***Profit/Loss (€) - Scenario A*** | ***Profit/Loss (€) - Scenario B*** | ***ROI (%) – Scenario A*** | ***ROI (%) – Scenario B*** |
|---|---|---|---|---|
| 135 | 954,502.81 | 745,040.52 | 20.05% | 16.25% |
| 140 | 890,102.81 | 687,080.52 | 18.88% | 15.19% |
| 145 | 825,702.81 | 629,120.52 | 17.71% | 14.14% |
| 150 | 761,302.81 | 571,160.52 | 16.54% | 13.08% |
| 155 | 696,902.81 | 513,200.52 | 15.37% | 12.03% |
| 160 | 632,502.81 | 455,240.52 | 14.20% | 10.98% |
| 165 | 568,102.81 | 397,280.52 | 13.03% | 9.92% |

Increases in the feedstock price from €150/t resulted in a negative impact on the profitability and return on investment of the model (Table 19). The profitability of the model decreased from €761,302.81 to €568,102.81 with the increasing feedstock price in scenario A. The return on investment also decreased from 16.54% to 13.03%. The profitability of scenario B also decreased with higher feedstock costs, where profitability decreased from €571,160.52 to €397,280.52, while the return rate decreased from 13.08%

to 9.92%. Lower feedstock costs resulted in a more positive impact on the economic feasibility of each scenario. The profitability of scenario A increased from €761,302.81 to €954,502.81, while the return rate increased from 16.54% to 20.05%. The profitability of scenario B also increased from €571,160.52 to €745,040.52, while the return rate increased from 13.08% to 16.25%.

*Table 20. Payback period for insulation selling price changes sensitivity analysis for scenario A and B.*

| ***Insulation Sell Price (€)*** | ***Payback Period (yrs) - Scenario A*** | ***Payback Period (yrs) – Scenario B*** |
|---|---|---|
| 820 | 7 | 10 |
| 830 | 7 | 9 |
| 840 | 6 | 8 |
| 850 | 6 | 8 |
| 860 | 6 | 7 |
| 870 | 5 | 7 |
| 880 | 5 | 6 |

Increases to the insulation selling price was found to have a more significant impact on scenario B, where the payback period decreased from 8 years to 6 years. In comparison, the payback period for scenario A only decreased by a year (Table 20). Similar changes to the payback period were seen in both scenarios when the insulation selling price was decreased. The payback period for scenario A increased to 7 years, while the payback period for scenario B increased to 10 years.

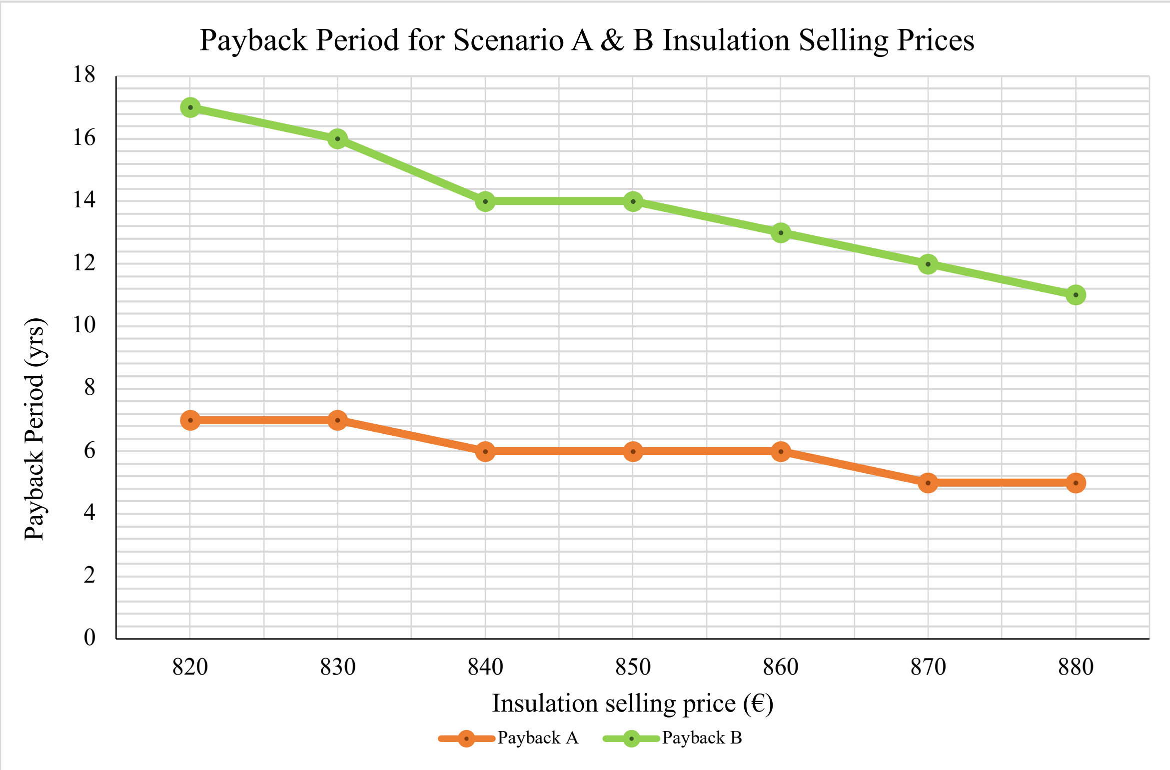



*Figure 12. Graphical representation of the sensitivity analysis of the payback period with changes in insulation selling prices.*

Figure 12 shows that with the increasing insulation selling price, the payback period for scenario A remained level at 6 years when the selling price was increased from €840/t to €860/t. Figure 12 also shows that for scenario B, the payback period only remained level at 8 years when the selling price was increased from €840/t to €850/t. The graph in Figure 12 also shows that scenario B had a more gradual decrease in the payback period when the selling price was increased from €850/t to €880/t.

*Table 21. Payback period for feedstock cost changes sensitivity analysis for scenario A and B.*

| ***Feedstock Cost (€)*** | ***Payback Period (yrs) Scenario A*** | ***Payback Period (yrs) Scenario B*** |
|---|---|---|
| 135 | 5 | 6 |
| 140 | 5 | 7 |
| 145 | 6 | 7 |
| 150 | 6 | 8 |
| 155 | 7 | 8 |
| 160 | 7 | 9 |
| 165 | 8 | 10 |

Increases to the feedstock costs were shown to have a negative impact on the payback period of both scenario A and B. Table 21 shows that when the feedstock cost was increased from €150/t to €165/t, the payback period for scenario A increased from 6 years to 8 years. Similarly, the payback period for scenario B also rose by two years, increasing from 8 years to 10 years. Figure 13 shows that there was a gradual increase in the payback period for scenario B as the feedstock increased, while the payback period for scenario A had a more staggered increase as the feedstock cost rose.

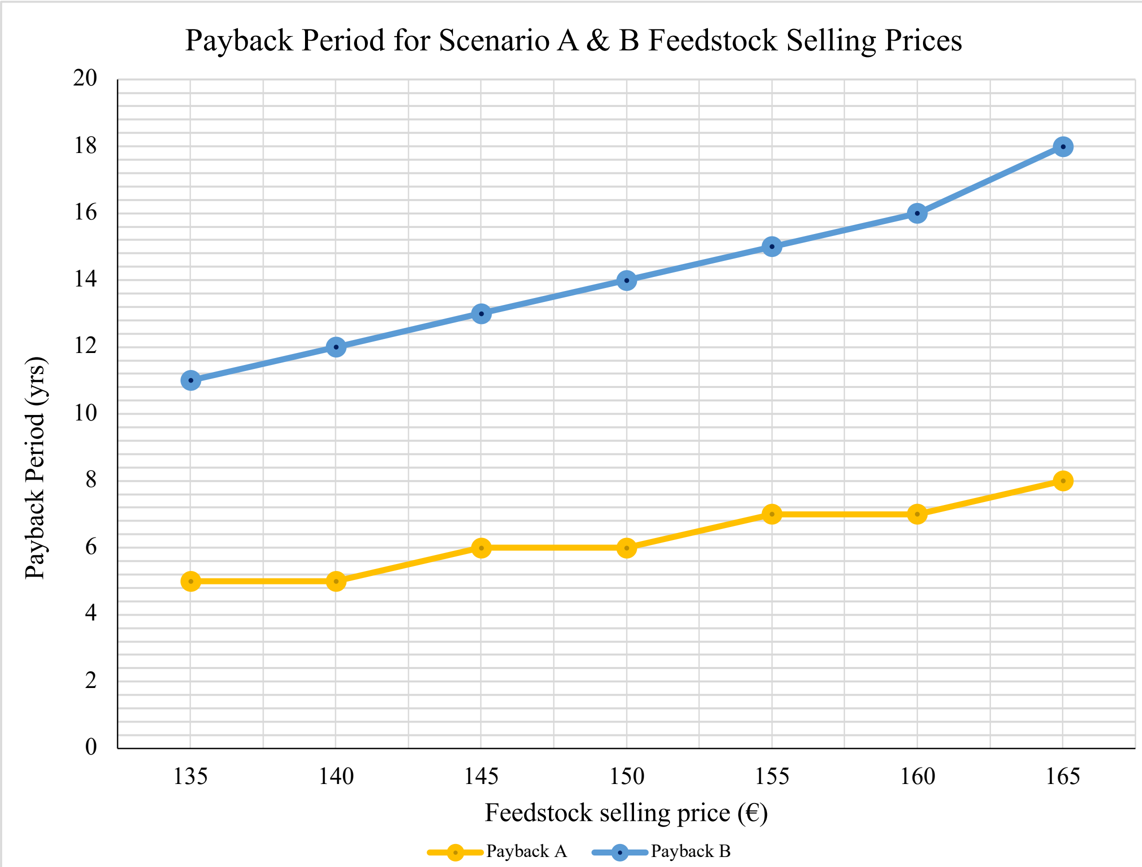



*Figure 13. Graphical representation of the sensitivity analysis of the payback period with changes in feedstock cost price.*

Overall the sensitivity analysis found that higher insulation selling prices and lower feedstock costs would result in higher profitability and return rate, along with lower payback periods for both scenarios. The sensitivity analysis also showed that scenario B would become more favourable with these changes, particularly the payback period.

Building on from the co-design and economic analysis findings, suitable locations for biorefinery deployment were analysed through a GIS analysis.

#### *4.4.1 GIS Results*

##### *4.4.1.1 Suitable Locations*

Once the unsuitable land had been erased from the suitable land layer, 28 suitable location sites were found (Figure 15). These sites were located in the counties Monaghan, Cavan, Meath, Louth, Kildare, Kilkenny, Wexford, Waterford, Tipperary, Cork, Limerick, Clare, Mayo and Donegal. While the overall area of each site differed due to the removal of areas which overlapped with unsuitable land, sites with a 10km radius were identified as a single site. The location of each site was limited to the availability of roads and distance to market partners (Table 12). In particular, the availability of agricultural protein feed market partners was limited, as most were located in the east and south of Ireland, as presented earlier in Figure 7c & d. The distance to settlements for an insulation product market was not deemed as a limiting factor due to the large coverage available at a 10km distance (Figure 7a). The distance to pastures was also shown to not be a limiting factor, as there is a wide coverage of available biomass sites across Ireland (Figure 7b). Figure 7a shows that there is a market available for the insulation product produced from the biorefinery in Ireland, while Figure 7b demonstrates that there is a wide availability of feedstock available in Ireland for a biorefinery.

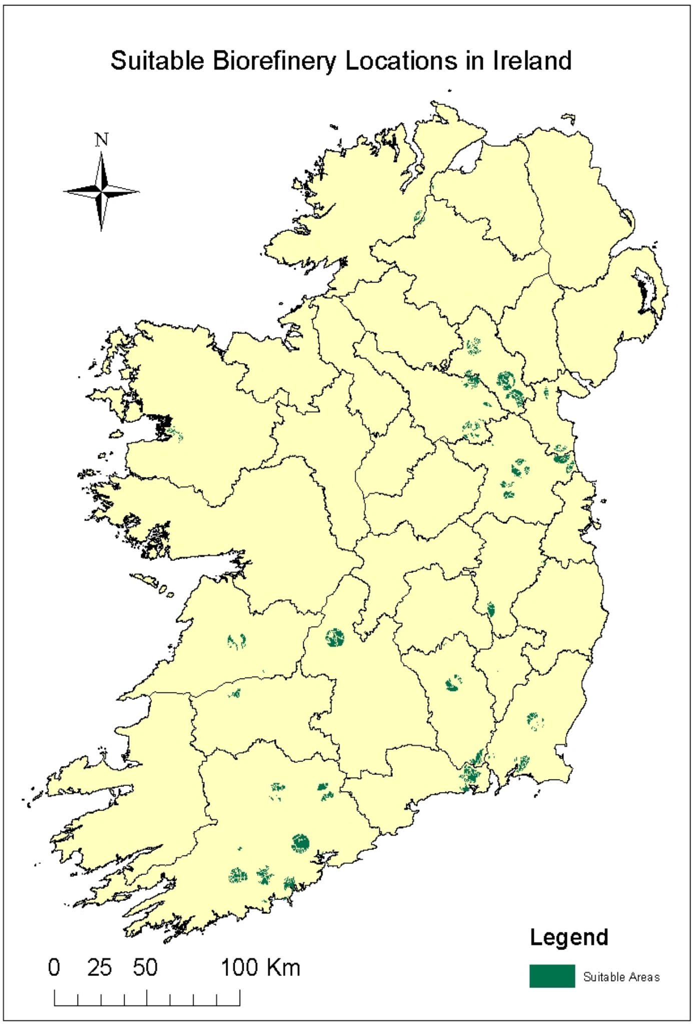



*Figure 14. Suitable locations found in Ireland for biorefinery implementation.*

As shown in Figure 15, six of the suitable sites were found in counties Cork and four in Monaghan, largely due to the availability of protein feed market partners and gas network pipelines. County Meath had the third highest amount of suitable sites, with three found within the county (Figure 15). Two sites were located within the counties Kilkenny, Wexford and Cavan, while the remaining counties only contained one suitable site. From Figure 8, counties in the North-East, such as Monaghan, Cavan, Louth and Meath, along with counties in the South, such as Cork, Waterford and Wexford were found to be the most suitable areas for green biorefineries to be implemented in Ireland.

The low number of sites available in the remaining counties was largely due to the high density of unsuitable land as shown in Figure 7e, and the location of gas pipelines and protein feed market partners. Mayo, Kerry and Donegal in particular had a high density of unsuitable land and low number of feed market partners (Figure 7c).

*4.4.1.2 Farming Income in Suitable Sites*

Following the findings from 4.4.1.1, the median income of farmers was analysed to determine if suitable sites for biorefineries would be beneficial to farmers with low income. While limitations were present with the farmers median income dataset, as the data was from 2016 and did not specify the type of farming practice, it did nonetheless provide a baseline of farmers income in each county (Figure 16). As shown in Figure 10, annual farming income was found to be below €20,000 primarily in the West of Ireland, with counties Leitrim, Donegal and Mayo having the lowest incomes of €11,130, €11,655 and €12,100 respectively. Counties in the East and South of Ireland were found to have higher incomes, with county Waterford having the highest at €30,567 (Figure 16). When compared to the National Farming Survey results of 2016 (Dillon et al., 2016), it was determined that these incomes were lower than the average annual dairy farming income of €52,155 and above cattle farming incomes of €16,853. The 2021 survey shows that these incomes increased primarily in dairy farming, where the average incomes was €97,400 (Dillon et al., 2022). Annual cattle farming incomes had decreased to €16,400 in comparison to the 2016 results.

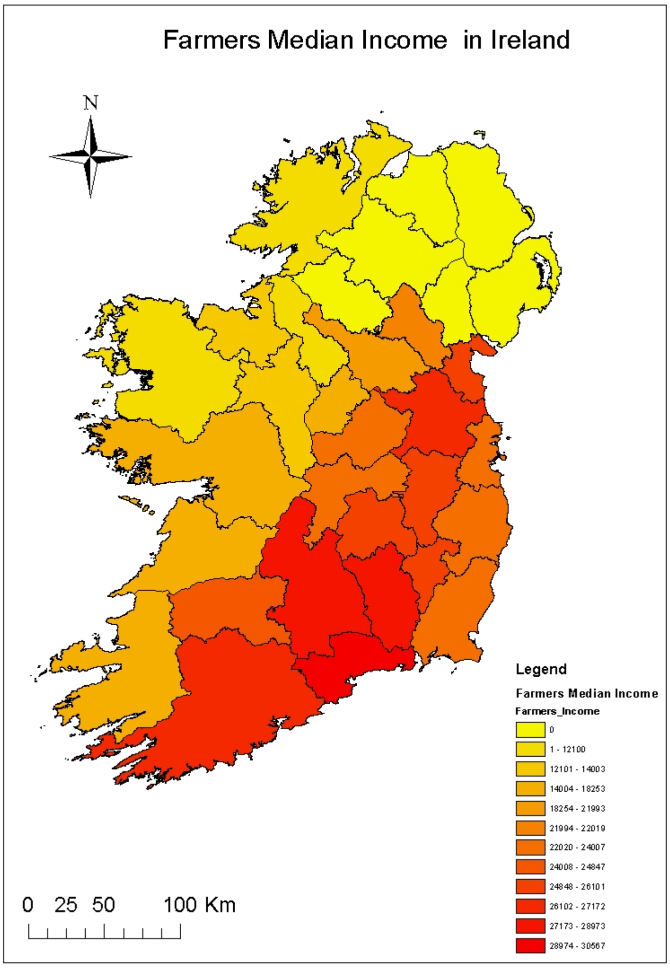
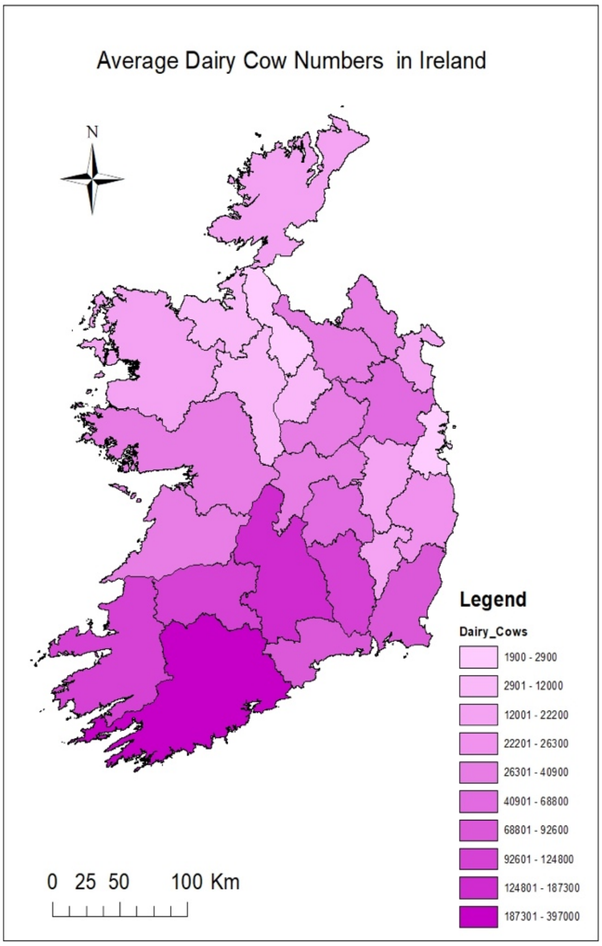



*Figure 15. Farming incomes within suitable site locations.*

Following the findings from 4.4.1, only two suitable biorefinery sites were identified in low farming income areas, counties Donegal (€11,655), and Clare (€17,144), as shown in Figure 15 and Figure 16. While Cork had the highest availability of suitable sites, average farming income within the area was found to be €27, 172, which was higher than the overall average farming income of €23, 848 (Dillon et al., 2016). Farming income within Monaghan, which contained four suitable sites, was found to be below the farming income average, reaching €22, 019 (Figure 16). Other suitable sites were found to be within areas where farmers' incomes ranged between €23, 180 to €30,567 (Figure 16).

*4.4.1.3 Farming Intensity*

The farming intensity present within areas containing suitable sites was determined by analysing average dairy and beef cattle numbers as shown in Figure 17 a and b. While county Cork was identified as having the highest availability of suitable sites, the county also had the highest average of dairy cow numbers, reaching 397,000 (Figure 17a). Even though beef herd numbers within Cork were not as high as dairy cow numbers, they did reach 69,100 (Figure 17b). With the second highest availability of suitable sites, county Monaghan, had an average dairy cow number of 39,300 and average beef cow numbers of 29,800. County Meath, which also contained a number of suitable biorefinery sites, also had a high number of dairy cow numbers of 68,900 and a lower average of beef cow, reaching 33,300 (Figure 17a & b).



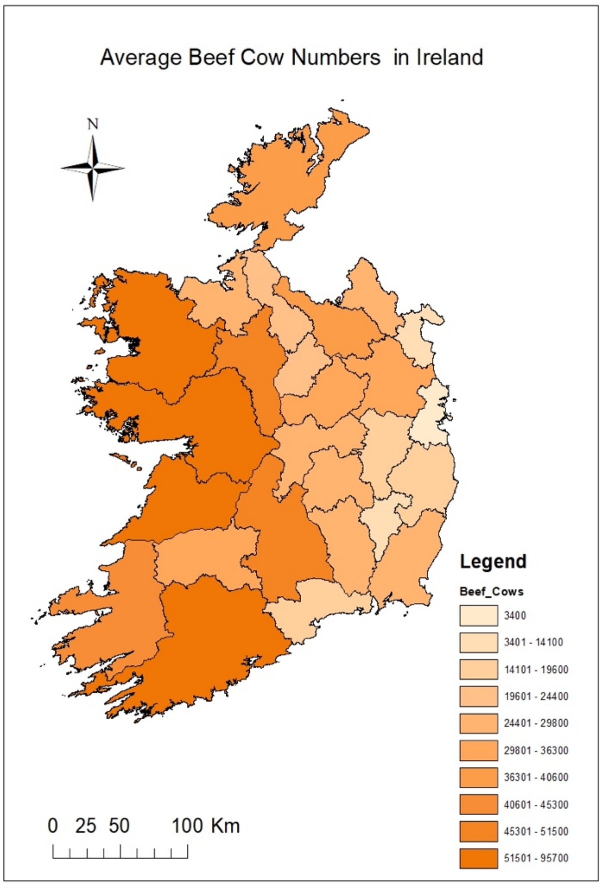




*Figure 16. Average (a) dairy cow numbers and (b) beef cow numbers within each county in June 2021.*

The counties containing two suitable sites, county Kilkenny, Wexford and Cavan, were also found to have a high number of dairy cow numbers, with Kilkenny containing the highest average of 103,100 dairy cows (Figure 17a). County Cavan had the lowest average dairy cow numbers of the three counties, reaching only 40,000, while county Wexford had an average of 87,100. Average beef cow numbers within county Wexford and Kilkenny were much lower than dairy numbers, only reaching 27,500 and 28,600 respectively (Figure 17b). Beef cow numbers in county Cavan were found to be higher than dairy numbers, reaching 40,600.

Of the counties that contained only one suitable site, county Louth, Kildare, Waterford, Tipperary, Limerick, Clare, Mayo and Donegal, it was determined that county Limerick and Tipperary had the highest average of dairy cow numbers. County Limerick was found to have an average of 124,800 dairy cows, while Tipperary was found to have an average of 187,300 dairy cows (Figure 17a). In comparison to this, the counties Clare, Donegal, Kildare, Louth and Mayo were found to have much lower average dairy cow numbers, ranging from 19,200 to 35,000. In terms of beef cow numbers of areas with a single suitable site, counties Mayo and Clare were found to have the highest average, reaching 71,900 and 70,000 respectively (Figure 17b). In comparison county Louth had the lowest beef cow numbers, with an average of 10,700 as shown in Figure 11b.

#### *4.4.1.4 Conclusion*

Based on the environmental and infrastructure variables used in the GIS analysis, counties Cork and Monaghan had the highest availability of suitable sites for green biorefinery deployment. However, when the analysis focused on the socio-economic variables such as farming intensity and income, these sites were less desirable due to the high farming intensity and incomes. When all of these factors were taken into account, it was found that counties Louth, Kildare and Donegal were more favourable for green biorefinery deployment as they had a lower farming intensity and incomes. These sites also met the environmental and infrastructure requirements of the study.

# Chapter 5: Discussion & Conclusions

## *5.1 Introduction*

This chapter discusses the overall findings of the project. Section 5.2 discusses how the multi-actor approach was used to address knowledge gaps by involving stakeholders in the decision-making stages of implementing a green biorefinery. The role of the farmer in the decision-making stages of a green biorefinery are also discussed in 5.2.1, as they play an important role in implementing a biorefinery. Section 5.3 discusses the type of economic concerns that need to be addressed to implement a green biorefinery. The type of factors that could impact the implementation of a green biorefinery are also discussed in 5.3.1. Next, section 5.4 discusses how farmers can help to determine suitable sites for a green biorefinery in Ireland, along with how the concept should be presented to farmers to include them in the process (5.4.1). Section 5.5 discusses the limitations to the research, while 5.6 discusses the type of future work that needs to be carried out to further develop the project. Finally, the conclusion of the project is discussed in 5.7.

## *5.2 Collaborating with Multiple Stakeholders*

The overall findings from the co-design phase demonstrated that while literature can provide a list of potential biorefinery models (3.3.1.1) for Irish agriculture, the selection of the most suitable biorefinery requires expert knowledge from multiple stakeholders. Involving stakeholders in this decision-making stage of a biorefinery through a multi-actor approach has been shown to both address knowledge gaps (Dallendörfer et al., 2022) and encourage potential stakeholders to become involved in a biorefinery project (Cronin et al., 2022). While the current literature of successful biorefineries provided information on the economic, technological and environmental aspects of the models, gaps were still found with regard to knowledge on the social aspects of the models. This issue was also highlighted in section 2.1.6.1, where there were still difficulties in implementing biorefineries with stakeholders due to biorefinery's novelty factor. The co-design phase of this project showed that while a literature study can present green biorefinery models suitable for Irish agriculture (4.2.1), it does not address challenges such as farmers willingness to commit to a biorefinery, the level of funding support, or the level of scale suitable for Irish farmers.

Section 4.2.3 showed that by using the multi-actor approach, knowledge gained from stakeholder engagement created the opportunity for these issues to be identified and addressed in the early stages of model design. The multi-actor approach allowed for the transfer of both scientific and practical knowledge between stakeholders. This has been shown to be a useful tool in encouraging stakeholders to participate in bioeconomy projects (Cronin et al., 2022), as they become more involved in the decision-making process. A model can be analysed from multiple viewpoints by using knowledge gained from multiple expert stakeholders, those who both directly and indirectly impact a biorefinery (Gerdes et al., 2018; Hoes et al., 2021). The knowledge of the farmers, market partners and cooperatives in particular were shown to be useful in addressing the challenges of knowledge gaps and issues of risk (section 4.2.3.1, 4.2.3.6, 4.2.3.9). This was not highlighted in the literature review of the potential models. For example, while the literature contained little information regarding the current market potential of the products that could be produced, the interviews with the market partners filled this gap in the knowledge (section 4.2.3.6). By addressing this challenge in the early stages of model design selection, the potential products could be finalised and an economic assessment could be carried out to determine the type of revenues they could produce, informed by the multiple stakeholders.

### *5.2.1 Bringing Farmers into the Decision-making Process*

Uncertainty and risk were highlighted to be a major challenge in encouraging farmers to take part in a green biorefinery model (4.2.3.3). Collaboration with farmers in the decision-making stages of a biorefinery development can address issues of trust and uncertainty, highlighted by the farmers themselves (4.2.3.9), as the voice of the farmer is acknowledged from the beginning of the biorefinery development process. The farmer plays an important role in a biorefinery process, as they can both supply the feedstock and benefit from the purchase of the products produced (Savonen et al., 2020). Farmers can also provide ground level knowledge of how farmlands are operated as shown in the focus group findings (4.2.3.9). This tacit knowledge is particularly useful in selecting a biorefinery model, as they can help determine suitable areas for feedstock, logistical issues that may arise and the level of commitment farmers can provide to supplying the biomass. Acknowledging farmers inputs and concerns throughout a biorefinery development can also help to develop a suitable business model to present to other stakeholders and funding bodies. Creating a strong business model, while also utilizing the knowledge provided by the farmers and other expert stakeholders, would help address the concerns of financial risk highlighted by the farmers (4.2.3.2, 4.2.3.3, 4.2.3.4).

### *5.3 Addressing Economic Concerns*

The economic assessment demonstrated the need to carry out an economic analysis that addresses stakeholders concerns in regard to financial risk when investing in a green biorefinery, while also considering any potential changes that may occur. Assessing possible future scenarios and accounting for changing costs and revenues can reduce the risk of economic uncertainty (Zetterholm et al  2020). Therefore, a capital budget model along with scenario and sensitivity analysis (3.3.2) would help to form a baseline economic model that could be presented to stakeholders while also demonstrating potential economic scenarios. The capital budget model used in section 4.3.2 allowed for all of the expected costs and revenues to be considered, along with any other costs that would impact the economic feasibility of the model, such as loan repayments (4.3.2.2). The scenario analysis demonstrated the expected economic viability for different capacity levels, with a model operating at full capacity being more favourable than one at 90% due to the shorter payback period of 6 years (4.3.2). A sensitivity analysis allowed for any future impacts to be accounted for in each scenario, with the model operating at full capacity still being more favourable (4.3.2.3). These future impacts could also include environmental or socio-economic issues that may arise during or after the biorefinery is implemented. For example, as highlighted in section 2.3.3, the shortage of natural gas in Europe has led to rising costs (Mohseni-Cheraghlou, 2022), which could impact future heat energy costs for the biorefinery model.

#### *5.3.1 Impacting Factors to Consider*

*Feedstock costs* were found to be the most expensive operational cost in a green biorefinery model (4.3.2) therefore any potential variances of this cost should be considered for future green biorefinery models. Section 4.3.2.3 demonstrated that even minor potential feedstock cost changes can considerably impact the profit, investment return and payback period of the biorefinery (Table 19).  These cost changes could be impacted by economic challenges such as fodder shortages, or the current fuel crisis in Ireland. Increasing fuel costs could increase the transport of biomass and the resulting delivered cost of biomass (Phelan, 2021; Burke-Kennedy, 2022). Other environmental factors such as drought, could lead to slower grass growth rates and less feedstock available to a biorefinery (McDonnell, 2022).

*Inflation* should also be considered when carrying out an economic analysis. While literature provided an expected price for products ( O'Keeffe et al., 2011; Höltinger et al., 2013), inflation may have caused these prices to increase over the years. Due to grass insulation being the main output product of the chosen model, any changes to the market price can impact the payback period and the profitability of the biorefinery (4.3.2.1). While eco-insulation is considered a niche market in Ireland (Insulation Expert, 2021), future impacts such as the move to retrofit housing with sustainable insulation products (McGee, 2022) would cause an increase in demand, and possibly change market prices of the product. Though higher revenue prices would be beneficial to a biorefinery, consumers' willingness to pay a higher price should also be taken into account (Gaffey et al., 2021; Insulation Expert, 2021). Therefore, market research should be used to update the capital budget model throughout the biorefineries lifetime to account for these impacts (Zetterholm et al., 2020).

Accounting for the *payback period and return on investment* are also important factors that should be included within an economic assessment (Cristóbal et al., 2018). Stakeholders would need to know the length of time it may take for the biorefinery to become profitable, along with the type of investment return they could expect. Stakeholders, particularly the farmers and co-operatives, may be less inclined to invest in a project that would not become profitable for a long period of time. Therefore, the capital budget model, along with any potential impacts to the economic feasibility of the model, and the length of time expected for any investment return are important factors to present to investing stakeholders. Presenting these factors to investing stakeholders, particularly farmers and co-operatives, can help to address any financial concerns that may have been present.

Another impact that should be considered is the *difference of opinion between stakeholders* that can occur in collaborative design projects. Studies have shown that while multiple stakeholders are important in co-creation, stakeholders may be focused on how the model can benefit their sector, rather than the overall benefit of the model (Dieken et al., 2021). The level of impact that the stakeholders have on the biorefinery model should also be considered, as it can help to manage how their perspectives impact the model (Feo et al., 2022). While this conflict of interest may occur between stakeholders, this issue could be addressed though revisiting the model's design stage (Geissdoerfer et al., 2016).

## *5.4 Determining Suitable Sites Using Farmers Input*

It was found that combining a GIS analysis with the findings from the farmers focus group was the most useful method for selecting sites, when determining suitable locations for the chosen green biorefinery model. While the findings from the farmer focus group had suggested that the west of Ireland would be the most suitable locations for green biorefineries (4.2.3.9), the GIS data maps show that counties in the east and south of Ireland provide more suitable sites (4.4.1.1). Though it should be considered that the suitable sites were limited to the location of the gas network pipelines, agri-feed providers and the high coverage of unsuitable land were also found in the west of Ireland (3.3.3.2.4, Figure 7 a-e). There was also a limitation to the available number of roads  found within the road network data set, as this data set only contained major road networks and those found within built up areas (OSI, 2022b). Therefore, the data set would not include smaller country roads. The counties containing the highest number of suitable sites also contradicted the comments by the farmers focus group, as the counties Cork, Monaghan and Meath were found to have high farming incomes (in regards to the 2016 survey), and high dairy and beef livestock numbers (ICBF, 2021a, 2021b).

While the spatial analysis did contradict the farmers suggestions on location, it did highlight the point made by the farmers that a 'blanket rule' would not be able to be applied to Ireland when implementing a biorefinery (4.2.3.9). Taking this into account, the buffer distance within areas of lower income and livestock numbers should be increased. Diversification in farming methods would be needed more within these areas, particularly for beef farming, due to the lower incomes (Meredith et al., 2015). Larger buffer distances in these areas would also be able to address the limitation of country road coverage found in the road network dataset. The counties Louth, Kildare and Donegal in particular have been noted as being suitable biorefinery locations, that also have lower farming incomes and livestock numbers. Implementing a green biorefinery within these locations would also provide the opportunity for exporting the insulation product, as suggested by the farmers focus group (4.2.3.9), as the counties are located near airports and the Northern Ireland boarder. Though it should also be noted that this may impact the economic feasibility of the biorefinery model as transport costs and factors such as Brexit may increase operational costs (Cheptea et al., 2021).

### *5.4.1 Presenting the Findings to Farmers*

Taking these factors into account, when presenting suitable locations to the farmers, they should be made aware of the type of limitations present to implementing a green biorefinery, such as the short transport distance of biogas (Hengeveld et al., 2016), and the high coverage of unsuitable land (3.3.3.2.4, Figure 7e). Due to the larger transport distance available for feedstock locations and the dried protein and insulation products (3.3.3.2.4, Table 12), farmers may be inclined to be more favourable towards producing these products as opposed to biogas which is restricted by access to grid injection points. Though biogas is a sustainable product, the combination of the products novelty, low levels of government support and only one renewable gas injection point (Gas Network Ireland, 2022; Robb, 2021), may lead farmers to becoming less inclined to produce biogas. Therefore, farmers should be presented with different scenario analysis, for example, the map produced in section 4.4.1.1 (Figure 15) provides alternative scenarios, where the buffer distances within low income and livestock numbers is increased (including all product market partners), and where only the dried products markets are accounted for (agri-feed providers and settlements). Presenting these scenarios to farmers may also address the issue of trust highlighted in section 4.2.3.9, as the farmers inputs are being consulted to determine suitable biorefinery locations.

## *5.5 Limitations of the Research*

While the project was able to determine a suitable model through a co-design phase, economic analysis and GIS analysis, there were still limitations to the project. Within the literature study, there were limitations to the availability of literature surrounding the social aspect of a green biorefinery. This challenge was due to the socio-economic aspect of biorefineries only being brought forward in research in recent years (Cadena et al., 2019; Eversberg and Fritz, 2022). There was also a limitation to the availability of economic data surrounding the green biorefinery models compared in 4.2.1. This was expected due to some of the models operating at a commercial level. The economic model itself was also limited to the time of the study, particularly energy costs, though it could still be used to provide a baseline of expected economic costs and revenues of the biorefinery. Limitations to data was also present within the GIS analysis, particularly economic and infrastructure data. While there was an availability of updated environmental datasets, this was not the case for farming income data, gas network pipelines or protein market partner locations. To address this limitation, a dataset was created for the gas network pipelines and protein market partners (3.3.3.1.2), while national farm surveys were referred when determining farming income changes (4.4.1.2).

## *5.6 Future Work*

Though the project did address some knowledge gaps that were found in regards to implementing a green biorefinery in Ireland, gaps still remain in areas such as the socio-economic aspect. In this regard, more work should be undertaken to understand quantitatively the local impacts of implementing a green biorefinery, such as the impact on local job creation, the potential impact on average farm incomes in a specific region, and the possibility to support generation challenges, such as farm succession, associated with agriculture in Ireland.

The economic model would need to be further elaborated to account for any economic impact that may occur after the project, such as increases to energy costs and inflation to the revenue streams (5.2.1). The GIS findings have also shown that data would need to be updated, particularly the farmers income data (2016 data), road network data and buffer zone distances, to account for logistics, socio-economic impacts and farmers inputs (4.4.1). The farmers focus group showed that at a small scale, a mixture of participants who are both familiar and unfamiliar with biorefineries is required to provide valuable insights to selecting a biorefinery model and site locations. Therefore, should the method be repeated, a much larger group should be used to gain valuable insights to farmers mindsets towards partaking in a biorefinery project. The farmers focus group should also be revisited with the economic and GIS findings to determine if their views towards partaking in a biorefinery supply chain has altered with the new information.

While the combination of social, economic and technological methods used within this project were used for a biorefinery focusing on grassland agriculture, the methods could also be applied for biorefineries in other sectors. For example, in place of grasslands, forestry could provide a wood based feedstock (Nitzsche et al., 2016) to a biorefinery, or an algae feedstock could be used for a marine based biorefinery (Boruff et al., 2015). Therefore, while the findings of the project could be seen as a baseline for a grass based biorefinery implementation in Ireland, the blueprint provided using the mixed methods could be applied to different sectors.

*5.6 Conclusion*

Determining a suitable green biorefinery model for implementation within Ireland's grassland agriculture sector has been a complex process which requires a combination of social, economic and technical methods. Knowledge from multiple stakeholders was required to ensure the model was analysed from multiple angles, with insights provided by farmers being highly valuable in addressing challenges and selecting sites. Farmers can provide valuable ground level knowledge in the decision-making stages, which can on one hand build trust with potential farm participants, while also helping to determine a model that is suitable for Irish agriculture. Collaboration with a broader set of stakeholders to gain other expert inputs is also key, and can help to build relationships between actors in the future value chain. Transparency within this approach is essential to ensure issues of trust and risk do not pose a challenge to such projects. The green biorefinery model was seen to hold potential for deployment, with several suitable sites identified. However, farmers, government support and incentives are still required to motivate farmers to part with their grassland for this new opportunity.

A suitable business model should be developed to support the involvement of farmers, and the project must also be economically feasible, in order to enable a successful green biorefinery model within Ireland's agriculture. Furthermore, the above factors should be considered if this silage-based green biorefinery model selected by the farmers focus group is to be implemented in Ireland. Future work would be needed to account for any limitations to the data, particularly within the economic and spatial analysis. The study highlighted the value of GIS in determining suitable locations for green biorefineries in Ireland, as multiple scenarios can be easily analysed through the software. While the stakeholder engagement provided a general outlook of suitable locations, combining these findings with GIS analysis allowed for a more in-depth look of green biorefinery deployment locations.

In conclusion, the aim of this thesis was met. Suitable locations were found for a suitable green biorefinery model in Ireland. The objectives of the thesis were also met. A suitable model for Irish agriculture was chosen, the key stakeholders were identified, along with locations and sectors that would be most suited to develop the model. The economic feasibility of the biorefinery was assessed and suitable deployment sites were located.

The overall conclusion of the thesis suggests that a mixed method approach of both quantitative and qualitative data collection from multiple stakeholders, which in turn can be used to inform the economic model. Together this data can inform the GIS model and collectively lead to a more informed decision of more suitable green biorefinery locations and models. While each approach could be used individually to assist the determination of suitable locations for green biorefineries in Ireland, the mixed method approach of engaging multiple stakeholders did challenge the single perspective approach more commonly seen in biorefinery location studies.

Further research would be needed to extend the findings of the research to a larger number of stakeholders and further analysis of alternative business models including the perspective of a larger number of end consumers. Social knowledge gaps at farm level would need to be further analysed, which could be carried out through a social life-cycle assessment. Further research would also need to be carried out on the economic viability of a biorefinery model, as literature did not provide up-to-date economic values of end products such as grass insulation, nor various production costs. This could be addressed in future research by consulting with stakeholders who engaged in the economic aspects of biorefinery implementation. The selection of suitable sites through GIS could also be expanded through further scenario analysis, depending on the type of end market being targeted.

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# Appendices

## Appendix 1 – Design-Thinking Workshop Outline, Exercises & Templates

*Table 22. Co-design Workshop outline.*

| *Exercise* | *Purpose* |
|---|---|
| *Day 1.* | |
| Introduction | Introduction to the activities and purpose of the workshops. |
| Concept tool | To determine the overall goals of the workshop and project to be taken into consideration throughout the workshop. |
| Stakeholder mapping | To collaboratively identify the type of stakeholders involved in a biorefinery. Also, to determine their level of impact on or by the project, either directly or indirectly. |
| Stakeholder value mapping | To determine stakeholders values associated with a biorefinery by looking at the project from their point of view and taking on a stakeholder persona. |
| Persona development | To further develop the personas of the three key stakeholders, looking at the project from their perspective. |
| *Day 2.* | |
| Review | A brief summary of the excises and findings from the previous workshop |
| Presentation | Presentation of the biorefinery models researched, reducing this number down to the unique models. |
| Persona development | Further development of the stakeholder personas in further detail. |
| Journey Analysis | Description of the journey undertaken by a stakeholder to take part or leave the project |
| Action Plan | Development of the action plan to be carried out to design a strategy for data collection from the identified stakeholders |

| | |
|---|---|
| Lego Serious Play Introduction | Introduction to the Lego material and how it can be used for collaborative workshops. |
| Individual Lego models | Participants individually design their version of the ideal biorefinery for the project to understand their perspectives of the project. |
| Collaborative Lego Model | Using pieces from the individual models, participants collaboratively design a biorefinery model and discuss. |
| *Day 3.* | |
| Review of Lego model | Participants review the designed Lego model and identify any design gaps, while also identifying the key stakeholders that are directly impacted by the model |

**DATE**
**CONCEPT TOOL**

| **COMPLETE DESCRIPTION OF THE CONCEPT** | |
|---|---|
| TITLE | |
| TAGLINE | |
| ACCEPTED CONSUMER BELIEF | |
| INTRODUCTING<br>What it is | |
| REASONS TO BELIEVE | |

*Figure 17. Concept tool used in the design-thinking workshops to gain insight to the goals of the project.*

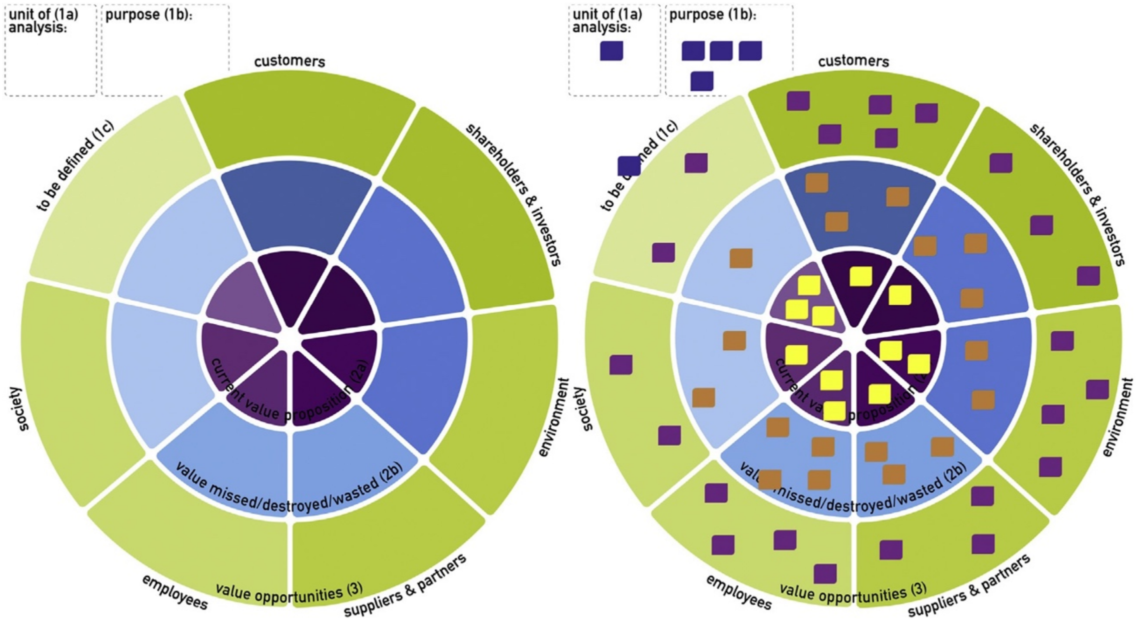


*Figure 18. Value Mapping tool, which can be used in design-thinking workshops to identify stakeholder's values in regards to a project. (Short et al., 2013).*

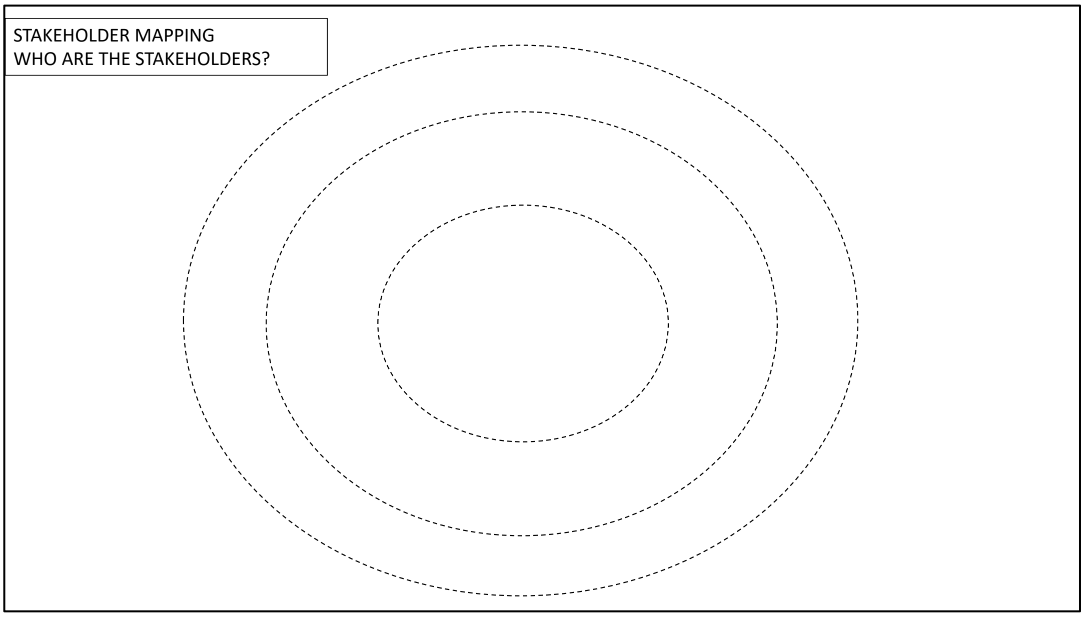


*Figure 19. Stakeholder mapping exercise to identify key stakeholders by their level of impact.*

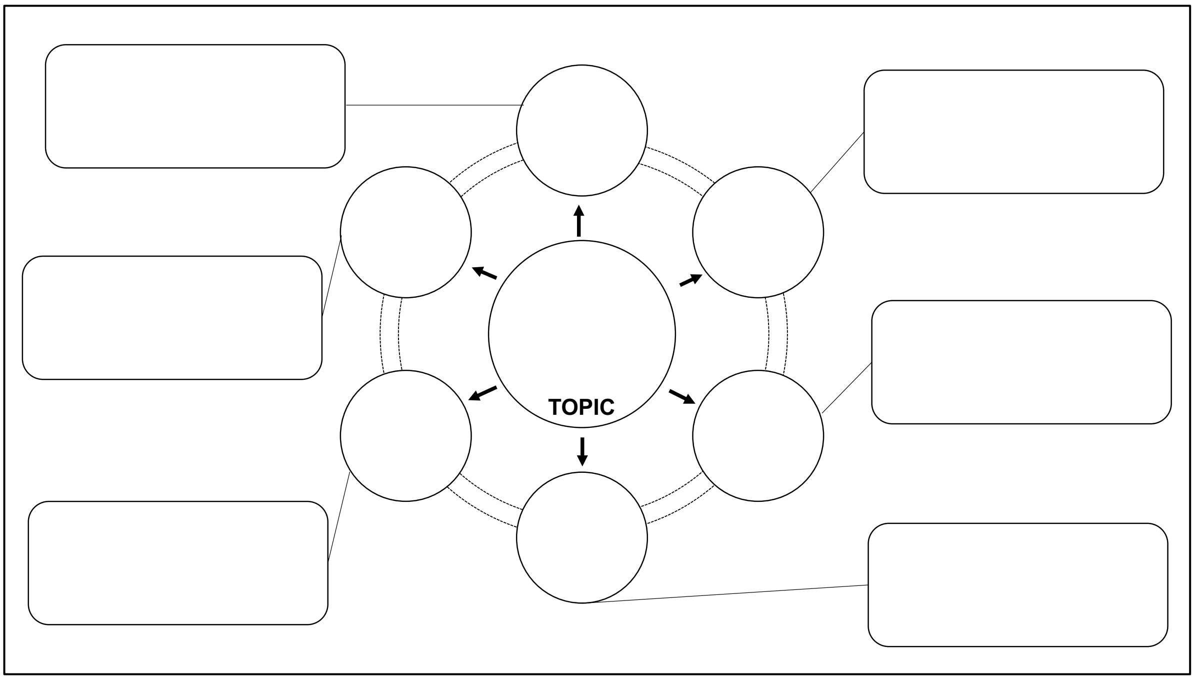


*Figure 20. Stakeholder Value Network Map used to identify the key stakeholders and their values.*

| | | |
|---|---|---|
| **PERSONA** | **PERSONA** | **PERSONA** |
| **NAME** | **NAME** | **NAME** |
| **QUOTES** | **QUOTES** | **QUOTES** |
| **MOTIVATION** | **MOTIVATION** | **MOTIVATION** |
| **BARRIERS** | **BARRIERS** | **BARRIERS** |

*Figure 21. Persona Development exercises, used to address the goals of the biorefinery from the stakeholder's perspective.*


*Figure 22. Journey Analysis tool used to map the stakeholders journey from beginning to either participating or leaving the project.*

| PEOPLE | OBJECTIVES | STRATEGIES | TRANSFORMATIONS |
|---|---|---|---|
| | | | |

*Figure 23. Action Plan Development exercise to develop a strategy for data collection from the stakeholders identified.*

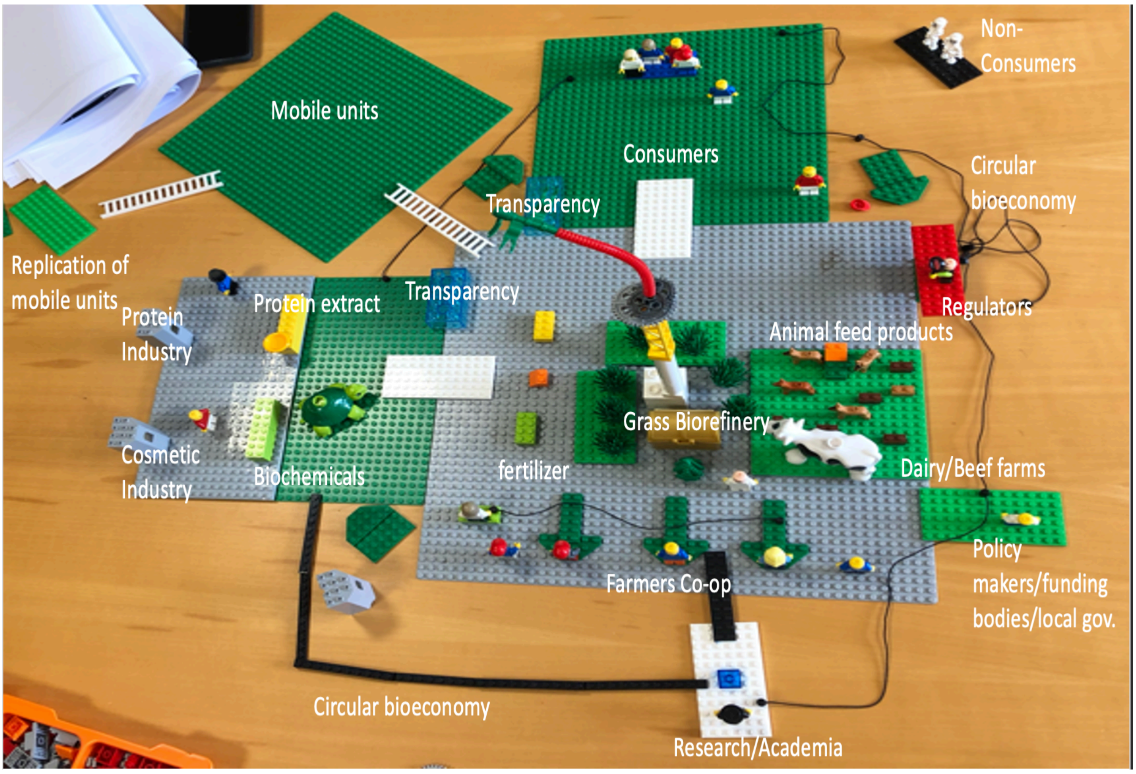


*Figure 24. Co-design Lego Serious Play model that involved all the identified stakeholders within the model.*

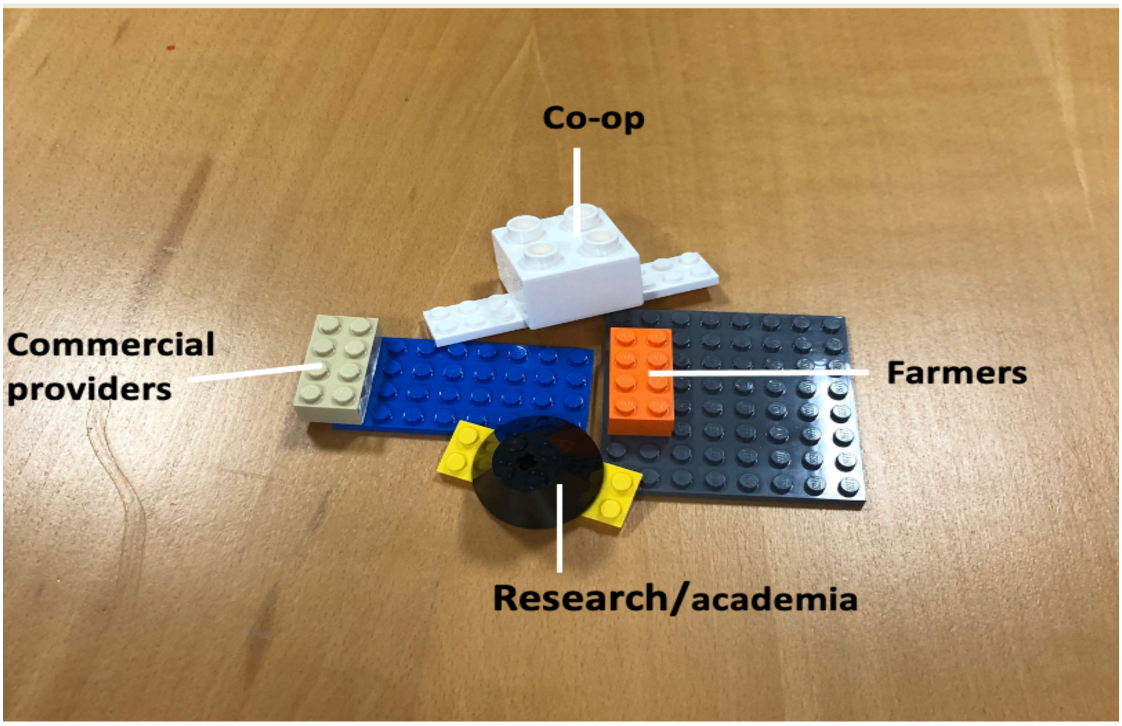


*Figure 25. A further refined Lego model that attempted to address the design gaps of the previous co-designed model.*

Appendix 2 – Stakeholder Engagement Ethical & Consent Forms

| | |
|---|---|
| **RE12.1.3 ETHICS SCREENING/MINIMAL RISK APPICATION FORM**<br>**INSTITUE OF TECHNOLOGY TRALEE** | |

**Prior to completing this form: Refer to Institute's *Research Ethics Policy* and associated guidance available on *Research Ethics Support* portal on blackboard.**

## PART A - APPLICATION

### SECTION 1: THE APPLICANT AND RESEARCH OVERVIEW

| |
|---|
| **Applicant**[1] **Alice Hand** |
| **Contact Details: (Address, Phone number, e-mail)**<br><br>**Postgrad Student Office**<br><br>**D Block,**<br><br>**South Campus**<br><br>**Clash Road**<br><br>**Tralee**<br><br>**Co. Kerry.**<br><br>**Phone:** [redacted]<br><br>[redacted] |
| **Current Role**<br><br>**MSc by Research Student** |
| **Co-investigators involved in this project (May include student as applicable)** |

[1] Main point of contact for this application

| |
|---|
| **Breda O'Dwyer, Helena McMahon, Abhay Menon, Emily Marsh** |
| **Principal Investigator/Lead Supervisor** (As relevant) **James Gaffey** |
| ****Applicants Signature:** I confirm that; (a) I have read the Institute's Research Ethics Policy and undertake to carry out the work outlined here in accordance with this policy and other relevant ethical and regulatory requirements, (b) the details contained in this document are, to the best of my knowledge, correct. [redacted] |
| ****Signature of Principal Investigator /Head of Department/ Research Centre Manager Signature:** I confirm that I am familiar with the research project outlined in this application and support the proposal as outlined: [redacted] |

****Applications submitted without appropriate signatures will <u>not</u> be accepted. Electronic signatures or scanned signed copies are required for all electronic submissions in order to process applications.**

**<u>Submission:</u>** If an UG or Taught Masters student, adhere to submission guidelines provided by your Department. For all other research, please submit this form and attached documentation to: Chairperson of the Institute Research Ethics Committee, c/o Office of the Vice President of Academic Affairs and Registrar. Alternatively, electronic applications are accepted and can be e-mailed to the Chair at irec@ittralee.ie or in the case of animal research to sap@ittralee.ie. Ethics Screening/Minimal Risk Applications are accepted throughout the academic year. Queries to be directed to **irec@ittralee.ie**

### Research Type – Please tick all that apply

| |
|---|
| UG Degree Programme Research Project ☐<br>Taught Masters Postgraduate Programme Research Project ☐<br>Research Degree Programme ☐ Yes<br>Professional Research ☐<br>Other /External Research ☐ Please Specify ______________________<br><br>Health Research ☐ Compliance with the Health Research Regulations (2018) |

| |
|---|
| is required. |

**Responsibility**

| | |
|---|---|
| School | MTU Kerry |
| Department | Biological and Pharmaceutical Sciences |
| Research Centre | Shannon ABC |
| Other | |

**Course/Module Details (As applicable)**

| | |
|---|---|
| Programme | / |
| Year/Semester | / |
| Module | / |

**Project Duration**

| | | | |
|---|---|---|---|
| **Proposed Duration (in Months)** | | | |
| **Start Date:** | **01.01.2021** | **End Date:** | **30.06.2022** |

**If the project require approval by an external research ethics committee – please detail**[2]

| |
|---|
| **n/a** |

| |
|---|
| **SECTION 2: RESEARCH PROPOSAL SUMMARY** |

**Title of the Project:**

[2] Researchers are required to submit a copy of external ethical to IREC on receipt of same

Using GIS and scenario modelling to determine the potential for green biorefineries to become a sustainable diversification opportunity for Irish Agriculture

**Plain Language Statement**

(A <u>brief</u> summary of the entire research proposal. Max 200 words.
The content should be comprehensible to non-experts.)

The project will identify using a co-design approach, key opportunities for green biorefinery deployment in Ireland. Green biorefineries are processing plants which separate grass into new novel products such ruminant protein, prebiotics and insulation materials.
The student will work with farmers and input from experts to choose 2 scenarios which will be evaluated from an economic perspective and the modelling of supply chains for these facilities will be undertaken by GIS.

**Aim and Objectives of the project**

(State the overall aim and objectives of the study. The aim should be clear and feasible. Objectives emphasise how the aim is to be accomplished.)

Aim: To understand potential of green biorefineries in Ireland
Objectives – Identify suitable green biorefinery models with input from stakeholders

- Assess the economic viability of the models
- Identify supply chains and potential locations suitable for technology deployment

**Recruitment Strategies and Consent Process**

(Briefly summarise how any human/animal subjects will be recruited. Note how consent will be obtained for human participants. What steps are taken to ensure that consent is freely given, specific, informed and unambiguous (GDPR 2018))[3]

Human subjects will be recruited for interviews and a focus group. A structured interview will be conducted with key relevant commercial stakeholders to obtain information for use in a focus group. Farmers will be recruited to participate in a focus group and provide perspective on green biorefinery opportunities with the most promising potential for Ireland.

An information sheet highlighting the purpose of the work and a consent form will be supplied to all participants.

Participates for the interviews and the focus groups will be recruited through the Circular Bioeconomy Research Group network. The Circular Bioeconomy Research Group actively participate in multiple projects and will be able to provide a direct link with commercial stakeholders and farmers in Ireland. Their projects, such as BiorefineryGLAS, AgriForValor and COOPID, will provide linkage to farmers across Ireland in multiple sectors, including beef and dairy farming. The Circular Bioeconomy Group actively engage extensively with farmers on bioeconomy activities in Ireland and this relationship will support the recruitment of participants and farmers for the focus group and interviews. Participants will be invited via emails containing an outline of the project, when the interviews and focus group will take place, the format (online), and the right to withdraw from the project at any given time if they wish to do so.

[3] Information Leaflet and Consent form guidance and template are available at *Research Ethics Support* Portal on Blackboard.

| |
|---|
| I have accessed the Institute's Consent Form Guidance and Template<br>and will comply<br>with same when acquiring consent : YES ☐ NO ☐<br>If no please indicate alternative arrangements and why.<br><br>I have accessed the Institute's Information Leaflet Guidance and Template<br>and will comply<br>with same in communication to prospective participants: YES ☐ NO ☐<br>If no please indicate alternative arrangements and why. |

**Methodology**

| |
|---|
| (Provide a summary of the methods to be used in the research; it is very important that this section is clear and to the point, procedures/protocols should be explained including data collection methods and data analysis methods).<br>Structured interviews will be conduct via online platform (teams or zoom), recorded and documented in a written summary, the key points will be anonymously summarized for presentation within the focus group and within the final thesis.<br>Focus group will be designed using a mixture of presentations and open forum discussions to capture ideas for the most promising approaches for green biorefining among farmers.<br>A description of focus group outputs will anonymously be summarized in a s report and within the student thesis, forming the basis for further economic analysis. |

**Data Protection**

| |
|---|
| (Provide details relating to treatment of Participant Data including Sources, Collection Methods, Storage & Retention (Refer to Data Protection Act 2018). |

| |
|---|
| The Institute recommends retaining research data for a period of five years):[4]<br><br>The interview and focus group reports will be stored by MTU on the staff One Drive accounts provided by MTU for no longer than 5 years.<br><br>Have you completed a Data Protection Risk Assessment Form (mandatory)? YES x☐ NO ☐<br>**Please attach with your application** |

**Consultancy Research**[5]

| |
|---|
| Where applicable have you adhered to the Institutes Research Consultancy Policy and Procedures?<br><br>**YES** ☐ **NO** ☐ **N/A** x☐ |

**Funding**

| |
|---|
| Has any funding been received or applied for in respect of this project? **YES** ☐ **NO** ☐ x **N/A** ☐<br><br>If Yes, please give details and note if any conflict of interest or restrictions apply. |

| |
|---|
| **SECTION 3: ETHICS SCREENING/MINIMAL RISK CHECKLISTS** |

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4 Data Protection guidance, including DP Risk Assessment Form, is available at *Research Ethics Support* Portal on Blackboard. The Institute recommends researchers access the EC document, *Ethics and Data Protection* (2018), For special categories of data, a Data Protection Impact Assessment may be required. https://ec.europa.eu/research/participants/data/ref/h2020/grants_manual/hi/ethics/h2020_hi_ethics-data-protection_en.pdf . Specific queries should be raised with the Data Protection Officer at dataprotection@ittralee.ie

5 Staff are advised to refer to the Institute's 'Research and Consultancy Policies and Procedures' for the definition of research consultancy and the policies and procedures associated therein. The document is available to download here: X:\lab\Research Office\Research and Consultancy Procedures

The following checklists are designed to alert you to the major types of ethical issues that may arise with your research. It is envisaged that most applicants will be completing Checklist A only; however, dependent on the specific study type other checklists may also be relevant. **PLEASE DELETE ANY CHECKLISTS NOT RELEVANT TO YOU.**

**Checklist A – Research Involving Human Participants**

**Checklist B – Research Involving Business Impacts on Society**

**Checklist C – Research Involving Animals**

**Checklist D – Research Involving Impacts on the Environment**

***Note 1:*** *Research that raises concerns that are over and above what is determined to be Minimal Risk will need Full Ethical Approval before it can proceed. Table 1 below illustrate the approach required for ethical evaluation of projects that are **NOT** approved at the level of Minimal Risk Review.*

***Note 2:*** *At UG/Taught Masters Postgraduate level Project Supervisor(s) have the primary responsibility to ensure that students/researchers do not take on research that could expose them and participants to significant risk.*[6]

**Table 1: Competent Body for Full Ethical Approval beyond Minimal Risk**

| **Type of Research** | **Competent Body for Full Ethical Approval beyond Minimal Risk** |
|---|---|
| **Checklist A** – Research involving Human Participants or Impacts on Individuals or General Public | Institute Research Ethic Committee (IREC)<br><br>*(In accordance with Scope of IREC)* |

[6] In exceptional circumstances, a Taught Masters Postgraduate research project deemed beyond minimal risk level may be referred to IREC. However, researchers and supervisors are reminded that the life cycle of a taught masters postgraduate programme may preclude engagement with more ethically challenging research.

| | |
|---|---|
| **Checklist B** – Research Involving Business Impacts on Society | Institute Research Ethic Committee (IREC) |
| **Checklist C** – Research Involving Animals | IREC Animal Ethics Sub-Committee |
| **Checklist D –** Research Involving Impacts on the Environment | External Environmental Ethics Review Committee * |

*The Institute does not have such a committee and such research will require referral to a competent external body if approval is not provided at the level of Minimal Risk. It is the responsibility of the Proposer/Researcher to arrange such referral in association with VPAAR.

### Checklist A – Research involving Human Participants

**Delete this section if not applicable**

| **Does the research involve:** | |
|---|---|
| 1. A vulnerable person/groups? *(Vulnerable groups include children and any adult whose personal circumstances or social context restrict his or her "capacity to guard himself / herself against harm or exploitation or to report such harm or exploitation" (HSE 2014 p.5).* | **YES** ☐ **NOx** ☐ |
| 2. Participants who may not have the authority (children) or capacity to give informed consent? *(This could include children or individuals with impaired cognitive ability. Individuals may be able to give their own consent with appropriate support in accordance with Assisted Decision-Making (Capacity) Act 2015).* | **YES** ☐ **NOx** ☐ |
| 3. Research undertaken outside the state where legislation/requirements etc. may vary? *(Researchers may need to justify why research is not undertaken within the state)* | **YES** ☐ **NOx** ☐ |
| 4. Participants who are in a dependent situation, e.g. students, residents of a long-term care facility? *(This is important as it alludes to possible power relationships that will need to be acknowledged and managed ethically)* | **YES** ☐ **NOx** ☐ |
| 5. Deception of the participants including concealment and covert observation? | **YES** ☐ **NOx** ☐ |
| 6. Subjection to physical pain, beyond mild discomfort? | **YES** ☐ **NOx** ☐ |
| 7. The use of a medical device or medical preparation? | **no** |
| 8. Any novel procedure/intervention in the therapy/management of participants in a care setting? | **YES** ☐ **NOx** ☐ |
| 9. The administration of any form of drug, medicine or placebo? | **YES** ☐ **NO** x☐ |

| | |
|---|---|
| 10. Potential inducement of psychological stress or anxiety beyond the risks encountered in normal life? (This relates to the subject matter of the study – what are participants being asked about/being asked to do.) | YES ☐ NO x☐ |
| 11. Any physically invasive procedure such as body fluid/tissues collection (e.g. blood, urine, semen), exercise regimens or physical examination, which is not part of existing clinical management? | YES ☐ NO x☐ |
| 12. Obtaining and storage of blood, body fluid or tissue samples from the participants? | YES ☐ NO x☐ |
| 13. Processing of sensitive data in accordance with GDPR (2018)? | YES ☐ NOx ☐ |
| 14. Sharing of Data Outside the EU? | YES ☐ NO **x** ☐ |
| 15. Any intention to use the data from this study in further studies? (If this is the case explicit consent is required from participants) | YES ☐ NOx ☐ |
| 16. The disclosure of personal information to third parties? (Appropriate consent is required) | YES ☐ NO x☐ |
| 17. Acquisition of personal information on individuals through any form of database, online forum or social media? (Appropriate consent is required) | YES ☐ NOx ☐ |
| 18. Use of questionnaires or interviews which may be linked either directly (e.g., through recording of names) or indirectly (e.g. through a cross-linked code) to the individual/ participant/researcher at any stage of the research? (This would require justification in light of the methodology and participants would need to be informed) | YES ☐ NOx ☐ |
| 19. The potential disclosure of personal information about participants or others with associated professional or legal responsibilities (e.g., Mandatory Reporting Regulations in terms of child protection) (Participants would need some information about this in the consent process if disclosure could arise in an interview setting) | YES ☐ NOx ☐ |

| | |
|---|---|
| 20. The disclosure of information which could place the participants at risk of criminal prosecution or civil liability or be damaging to their financial standing, employability, professional or personal relationships? | **YES** ☐ **NOx** ☐ |
| 21. Payments or inducements to participate that could reasonably be viewed as exerting undue influence over the particantant? (Out-of pocket expenses is generally acceptable) | **YES** ☐ **NOx** ☐ |
| 22. Access to vulnerable groups that merits Garda clearance? | **YES** ☐ **NOx** ☐ |
| 23. The permission of a 'gatekeeper' from an external site to access participants? (This is an important consideration to manage at the outset of a project) | **YES** ☐ **NOx** ☐ |
| 24. Any requirement for Ethical Approval of the proposed research from another body involved in any way with the research project? (This may include a clinical or other external organization committee) | **YES** ☐ **NOx** ☐ |
| 25. Any methodology that is novel, unconventional or lacks a theoretical basis? | **YES** ☐ **NO** x ☐ |
| 26. Risks to the researcher that are beyond those experienced in everyday life? (Consider physical, psychological and professional risks) | **YES** ☐ **NOx** ☐ |
| 27. The use of physical agents or processes that the Institute is licensed to use and for which there are Standard Operating Procedures in place? | **YES** ☐ **NOx** ☐ |
| 28. The use of chemical agents or processes that the Institute is licensed to use and for which there are Standard Operating Procedures in place? | **YES** ☐ **NOx** ☐ |
| 29. The use of biological materials or processes that the Institute is licensed to use and for which the Institute has Standard Operating Procedures in place? | **YES** ☐ **NO** x☐ |

| | |
|---|---|
| 30. The use of agents or processes requiring any special license or permission from an external agency and which the Institute does not currently hold a licensed/permit or for which Standard Operating Procedures are not in place? | **YES** ☐ **NOx** ☐ |
| 31. Any other ethical issues that have not been addressed in this Checklist? | **YES** ☐ **NO** x ☐ |

| **Provide clarification on points to which you have answered YES** | |
|---|---|
| **Number** | **Clarification** |
| | |
| | |
| | |
| | |
| | |
| | |

## Checklist B – Research Involving Business Impacts on Society

**If the study involves human participants complete Checklist A also**

**Delete this section if not applicable**

| **Does your research involve:** | **(Please tick)** |
|---|---|
| 1. Work on an Individual's or Organization's Planning, Management or Operations in a Business environment that are not under the control of the Institute? | **YES** ☐ NOx ☐ |
| 2. Funding, either partially, or wholly, from an external source? | **YES** ☐ NOx ☐ |
| 3. Any aspect of an Individual's or Organization's Business Practices that does not comply with Irish and EU law? | **YES** ☐ NO x☐ |
| 4. Business Research Methodologies that are not fully in accordance with recognized ethically approved standards nationally or internationally? | **YES** ☐ NOx ☐ |
| 5. Methodologies that are novel, unconventional or lack a theoretical basis? | **YES** ☐ NOx ☐ |
| 6. Risks to the researcher that are beyond those experienced in everyday life? (Consider physical, psychological and professional risks) | **YES** ☐ NO x☐ |
| 7. Any other ethical issues that have not been addressed in this Checklist? | **YES** ☐ **NO x**☐ |

| **Provide clarification on points to which you have answered YES** | |
|---|---|
| **Number** | **Clarification** |
| | |
| | |
| | |
| | |

## PART B – ETHICS SCREENING/MINIMAL RISK REVIEW/OUTCOME

| **RESEARCH AS PER QA 12.2 - UG AND TAUGHT MASTERS POSTGRADUATE RESEARCH**<br><br>***To be completed by Chair of Department Minimal Risk Review Panel*** | |
|---|---|
| **a)** Research Proposal Approved | ☐ |
| **b)** Research Proposal Approved subject to Recommendations (attached)<br>Ethical concerns are identified, and some additional measures will manage risk effectively | ☐ |
| **c)** Research Proposal Not Approved<br>Project Review Required – Ethical issues are beyond Minimal Risk level. The Chair of the review panel will arrange a meeting with the supervisor and student to discuss how ethical issues can be minimized, so that the project progresses at a Minimal Risk level | ☐ |
| **d)** Research Proposal Rejected on the grounds:<br>a. that the Institute is not licensed of otherwise authorized to approve such research<br>b. that the project presents major ethical concerns | ☐ |

**Chair of Department Minimal Risk Review Panel (or nominee)**

*(BLOCK LETTERS)* ______________________________

Signature**:** ______________________________________

Date: __________

***In respect of c) above where projects require revision***

| | |
|---|---|
| **a)** Project proposal revised and is now approved at Minimal Risk level | ☐ |
| **b)** Project proposal remains beyond Minimal Risk level and is not approved | ☐ |
| **c)** Taught Masters Project referred to IREC for full ethical review as an exceptional circumstance | ☐ |

**Chair of Department Minimal Risk Review Panel (or nominee)**

*(BLOCK LETTERS)* ______________________________

Signature**:** ______________________________________

Date: __________________________________________

| **RESEARCH AS PER QA 12.3/12.4 - POSTGRADUATE RESEARCH DEGREE PROGRAMMES, PROFESSIONAL AND EXTERNAL RESEARCH**<br><br>**To be completed by the Chair (or nominee) of Institute Research Ethics Committee (IREC) another IREC member** | |
|---|---|
| **a)** Research Proposal Approved | ☐ |
| **b)** Research Proposal Approved subject to Recommendations and/or conditions (attached)<br>Ethical concerns are identified, and some additional measures will manage risk effectively | ☐ |
| **c)** Research Proposal Not Approved<br>Ethical issues are beyond Minimal Risk level. Project is referred to IREC (or authorized/competent ethics committee) for Full Ethics Review | ☐ |
| **d)** Research Proposal Rejected on the grounds:<br>a. that the Institute is not licensed of otherwise authorized to approve such research<br>b. that the project presents major ethical concerns | ☐ |

| **ETHICS SCREENING Project not suitable for ethical approval at this point or is beyond the authorisation of IT, Tralee REC. Outcome of Ethics Screening:** |
|---|
| |

**Chair Institute Research Ethics Committee (or nominee)**

*(BLOCK LETTERS)* ______________________________

Signature: ______________________________________Date: ______________________

**IREC member**

(BLOCK LETTERS) ______________________________

Signature**:** ______________________________________Date: ______________________

*Figure 26. Example of the MTU ethical approval form used, which must be submitted before engaging with stakeholders.*

Research M.Sc. dissertation by Alice Hand

Research Project: Using GIS and Spatial Modelling to determine suitable locations for Green Biorefineries for Irish Agriculture.

Purpose: The purpose of the interview is to gain expert knowledge and opinions of green biorefineries and their products to help inform a focus group of farmers. The purpose of the focus group will be to collect data on the farmers perspective of which type of biorefinery model could possibly suite Irish agriculture. Collected data from both interviews and focus group will be pseudonymous. Expert quotes may be used in the farmers focus group, but source will remain anonymous.

## Consent to take part in research

- I [interviewee name] ........................................................................ voluntarily agree to participate in this research study.

- I understand that even if I agree to participate now, I have the right to withdraw at any time or refuse to answer any question without any consequences of any kind.

- I understand that I can withdraw permission to use data from my interview within two weeks after the interview, in which case the material will be deleted.

- I have had the purpose and nature of the study explained to me in writing and I have had the opportunity to ask questions about the study.

- I understand that participation involves answering questions in my area of expertise as they relate to the exploratory study being undertaken
- I understand that I will not benefit directly from participating in this research.

- I agree to my interview being audio-recorded.

- I understand that all information I provide for this study will be treated confidentially.

- I understand that in any report on the results of this research my identity will remain anonymous, **if I so choose**. This will be done by changing my name and disguising any details of my interview which may reveal my identity or the identity of people I speak about.

- I understand that disguised extracts from my interview may be quoted in a dissertation for MTU by Alice Hand.

- I understand that if I inform the researcher that myself or someone else is at risk of harm, they may have to report this to the relevant authorities -they will discuss this with me first but may be required to report with or without my permission.

- I understand that signed consent forms and original audio recordings will be retained in at the home of Alice Hand at address. The data will be stored on a password-protected laptop with adequate virus protection, with backup on an external hard drive. Access to this data will be restricted to Alice Hand and data will be stored the exam board confirms the results of the dissertation.

- I understand that a transcript of my interview in which all identifying information has been removed will be retained for two years from the date of the exam board.

- I understand that under freedom of information legalisation I am entitled to access the information I have provided at any time while it is in storage as specified above.

- I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

| Name | Affiliation | Contact details |
|---|---|---|
| James Gaffey | Circular Bioeconomy Research Group, MTU<br><br>Academic supervisor | [redacted] |
| Alice Hand | Research M.Sc student, MTU | [redacted] |

Signature of research participant

------------------------------------------ -----------------

Signature of participant Date

Signature of researcher

I believe the participant is giving informed consent to participate in this study

Signature of researcher Date 01/08/2021

*Figure 27. Example of the consent form sent to each participant of both the stakeholder interviews and focus group to ensure ethical approval was gained before data collection was carried out.*

# Appendix 3 – Semi-Structured Interview Questions

*Table 23. List of questions presented to each expert representing the stakeholder categories identified in the co-design workshops.*

*Beef Stakeholder Expert Interview*

| | |
|---|---|
| 1 | What would be the type of skill gaps in farmers education on grass biorefineries? |
| 2 | How willing are beef farmers to diversify their farming methods and take part in green biorefinery projects? |
| 3 | What would be the concerns they would have in regards to diversifying their farming methods? |
| 4 | How comfortable would beef farmers and dairy farmers be working together on a biorefinery process? |
| 5 | What would be needed for green biorefineries to work with biogas plants? (i.e. grass quality, distance, etc) |
| 6 | [Are there any other type of collaboration barriers to biorefineries working with biogas plants? ] (if not already answered in previous comments) |
| 7 | What would the benefits be to the farmers in relation using silage and slurry biogas? |
| 8 | What would be the challenges be to farmers in relation to using silage and slurry biogas? |
| 9 | What type of regulatory barriers would present themselves for green biorefineries to be implemented in Ireland? |

*Co-op Expert Stakeholder Interview*

| | |
|---|---|
| 1 | What would be needed to get farmers involved in a bioeconomy in Ireland? |
| 2 | What might be the challenges for famers to be involved in a bioeconomy? |
| 3 | What would be the potential role of Co-ops in a farmer led biorefinery/bioeconomy? |
| 4 | What would be the challenges involved for farmers wanting to form their own co-op? |

| | |
|---|---|
| 5 | [Would factors such as distance or location be an issue on their implementation?] |
| 6 | Are there any benefits/advantages to farmers being part of a co-op if they wish to be involved in a bioeconomy? |
| 7 | What is the advantage to co-ops being involved in a bioeconomy or bioenergy sector internationally? |
| 8 | In terms of the bioeconomy, how do newly formed co-ops and established co-ops perform in comparison to each other? [e.g. market partners more willing to interact with known co-ops, interacting with funding bodies, etc]. |

*Finance Expert Stakeholder Interview*

| | |
|---|---|
| 1 | How would a farmer gain financial support to take part in a bioeconomy? |
| 2 | What would be the best method for farmers to present a business case to banks to gain financial support to take part in a bioeconomy? |
| 3 | How do banks engage with co-ops and individual farmers, in comparison to one another, who wish to be part of a bioeconomy? |
| 4 | What are the type of supports/funding available at a European level to farmers and biorefineries? |
| 5 | What would be the potential challenges for farmers to qualify for these supports? |
| 6 | What type of safeguards are in place for the farmers for potential market changes/challenges? |
| 7 | What would make a green biorefinery model/concept feasible for funding in Ireland? |
| 8 | How would you see agricultural payments being influenced by sustainability based policies in the next 10 years/future? |
| 9 | In regards to the European committee setting a target for carbon neutrality by 2050, would there be an increase in funding for farmers looking to change to more sustainable farming options? |
| 10 | What would be the typical scale of biorefinery projects being funded in Europe? |

*Dairy expert stakeholder interview*

| | |
|---|---|
| 1 | What would be the type of skill gaps in farmers education on grass biorefineries? |
| 2 | How willing are farmers to diversify their farming methods and take part in green biorefinery projects? |
| 3 | What would be the concerns they would have in regards to diversifying? |
| 4 | How comfortable would dairy and beef farmers be working together on a biorefinery process? |
| 5 | What is needed for green biorefineries to be successful in Ireland? |
| 6 | What are the types of market partners available in Ireland for possible end products? |
| 7 | What type of bioeconomy business model would be ideal for Irish grassland agriculture? |
| 8 | What type of regulatory barriers would present themselves for green biorefineries to be implemented in Ireland? |

*Policy Expert Stakeholder Interview*

| | |
|---|---|
| 1 | What would be needed for green biorefineries to be successful in Ireland? |
| 2 | What would be the challenges be in implementing them with farmers? |
| 3 | What are the type of policies that might be involved? |
| 4 | Would there be other initiatives that could support/influence green biorefineries in Ireland? |
| 5 | What are the type of supports available to farmers wanting to take part in a bioeconomy? |
| 6 | Are there non-policy supports that could be introduced? |
| 7 | What type of regulatory barriers would present themselves for green biorefinery implementation in Ireland? |
| 8 | How would you see agricultural payments being influenced by sustainability based policies in the next 10 years/future if famers change to more sustainable options? |
| 9 | What would be the European strategies and policies, that have worked well for the bioeconomy in Europe, that could be used in Ireland? |

| | |
|---|---|
| 10 | Are there any European examples of best practice with biorefineries that Ireland could learn from? |

*Beef/Dairy Expert Stakeholder Interview*

| | |
|---|---|
| 1 | What would be the type of skill gaps in farmers education on green biorefineries? |
| 2 | How willing are farmers to diversify their farming practices and take part in green biorefineries? |
| 3 | What would be the concerns they would have? |
| 4 | In your opinion, what do you think is needed for grass biorefineries to be successful in Ireland? |
| 5 | Who would be the type of market partners available in Ireland for possible end products? |
| 6 | What type of regulatory barriers would present themselves for green biorefineries to be implemented in Ireland? |
| 7 | What would be the benefits to farmers using these sustainable end products, such as fertilisers and feed products? |
| 8 | How would dairy and beef farmers be encouraged to work together on a grass biorefinery process? |

*Protein Market Partner Stakeholder Interview*

| | |
|---|---|
| 1 | What would be the type of concerns amongst protein feed industry partners in regard to issues with imported protein? |
| 2 | What are the market opportunities for grass-based protein feed? |
| 3 | What is needed for these products to be feasible at market? |
| 4 | What would be the challenges in bringing sustainable feed products to the poultry and pig feed market? |
| 5 | What would be the benefits? |
| 6 | How would locally produced green animal feed compare to soybean imports at market? |
| 7 | How feasible would it be for farmers to change to a more sustainable feed source? |

| | |
|---|---|
| 8 | What would be the benefits for farmers wanting to change to a more sustainable feed source? |
| 9 | What would be the challenges? |
| 10 | What type of regulatory barriers would you envision for getting these green products to market? |

*Insulation Market Partner Stakeholder Interview*

| | |
|---|---|
| 1 | What is the level of reception of biorefinery products amongst eco-insulation suppliers? |
| 2 | What type of market opportunities are present in Ireland for eco-friendly products? (market size) |
| 3 | What is needed for these products to be feasible at market? |
| 4 | How do they compare to non-eco-friendly products? |
| 5 | What would be the benefits to using eco-insulation over regular? |
| 6 | What kind of potential is there for using grass based eco-insulation? |
| 7 | What kind of potential is there for companies to work with farmers to produce grass based products? |
| 8 | What would be the challenges in producing grass based eco-insulation in Ireland? |
| 9 | What would be the benefits? |
| 10 | What type of regulatory barriers would you envision for getting these green products to the market? |

## Appendix 4 – Farmers Focus Group

*Table 24. Green biorefinery models that had unique technologies, along with the feedstocks used and end products produced. These biorefineries were presented to the farmers focus group.*

| **Model** | **Biomass** | **End Product** |
|---|---|---|
| Austrian Pilot Plant & BioFabrik | Silage | Lactic Acid, Amino Acids, Biogas |
| BiorefineryGlas, Grassa, Aarhus University | Fresh Grass | Ruminant Feed, Protein concentrate pig/poultry feed, bioenergy/fertiliser, added co-products |
| Gramitherm | Silage | Insulation Boards, Feed, biogas |
| Biowert | Silage | Fibre composites, fertiliser, biogas |
| NewFoss | Silage (roadside) | Fibres for Paper and packaging, Fertilizer, Biogas, |

# Appendix 5 – Capital Budget Model

*Table 25. Capital Budget Model for both scenario A and scenario B.*

| | | ***Scenario A (100% Capacity)*** | ***Scenario B 90% Capacity*** | | ***Scenario A 100% Total Annual*** | ***Scenario B 90% Capacity Total Annual*** |
|---|---|---|---|---|---|---|
| | *Unit* | *Quantity t/year (100%)* | *Quantity t/year (80%)* | *Price/ Unit* | *Total (Euros)* | *Total (Euros)* |
| **Capital Expenditure** | | | | | | |
| **Total capital expenditure** | | | | | 5,500,000 | 5,500,000 |
| **Operational Expenditure** | | | | | | |
| *Direct Expenses* | | | | | | |
| Grass silage | t/DM | 12,880 | 11,592 | 150 | 1,932,000.00 | 1,738,800.00 |
| Binding materials | kg | 8,145 | 7,330 | 1 | 8,144.82 | 7,330.34 |
| Cleaning solutions | litres | 24,192 | 21,773 | 26 | 633,104.64 | 569,794.18 |
| Heat Energy | kW/ hr | 6,053,600 | 5,448,240 | 0.12 | 726,432.00 | 653,788.80 |
| Electrical Energy | kW/ hr | 0 | 0 | 0.00 | 0.00 | 0.00 |
| Waste disposal | kg | 74,901 | 67,411 | 0.18 | 13,200.00 | 11,880.00 |
| conditioning and distribution | | 193,750.00 | 174,375.00 | 0 | 193,750.00 | 174,375.00 |
| **Total Direct Expenses** | | | | | 3,506,631.46 | 3,155,968.31 |
| *Indirect Expenses* | | | | | | |
| Repairs and maintenance | € | 5 | 5 | 5,500,000 | 275,000 | 275,000 |
| Insurance | € | 50,000 | 50,000 | 0 | 50,000 | 50,000 |
| Labour | € | 2 | 2 | 44,000 | 88,000 | 88,000 |
| Overheads | € | 0.1 | 0.1 | 0 | 8,800 | 8,800 |
| **Total Indirect Expenses** | | | | | 421,800 | 421,800 |
| **Total Operational expenditure** | | | | | 3,928,431.46 | 3,577,768.31 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Revenues** | | | | | | |
| Insulation material | tDM | 5,796.00 | 5,216.40 | 850.00 | 4,926,600.00 | 4,433,940.00 |
| Protein | tDM | 862.96 | 776.66 | 300.00 | 258,888.00 | 232,999.20 |
| Surplus electrical energy | kWh | 1,854,720 | 1,669,248 | 0.12 | 222,566.40 | 200,309.76 |
| **Total Revenues** | | | | | 5,408,054.40 | 4,867,248.96 |
| **Total Operation Expenditure** | | | | | 3,928,431.46 | 3,577,768.31 |
| Depreciation | | 101,000.00 | | | 148,500.00 | 148,500.00 |
| Interest + loan repayment | | 569,820.13 | | | 569,820.13 | 569,820.13 |
| Profit /Loss Before Tax | | | | | 761,302.81 | 571,160.52 |
| Return on Investment | | | | | 16.54% | 13.08% |
| Payback period | | | | | 6 | 8 |

# Appendix 6 – GIS Maps

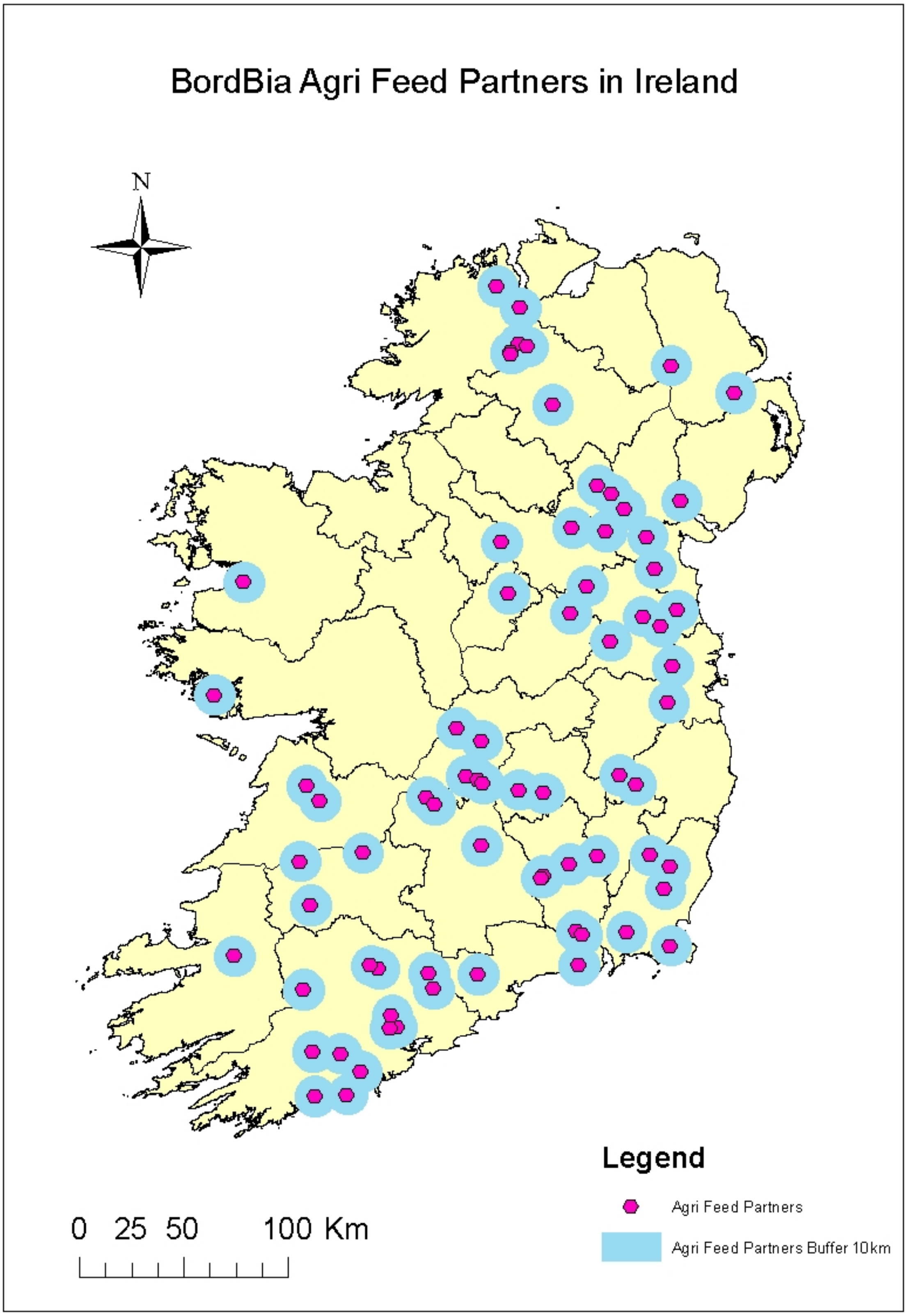


*Figure 28. Spatial map of Bordbia Agri-feed partners and the buffer distance assigned to the variable.*

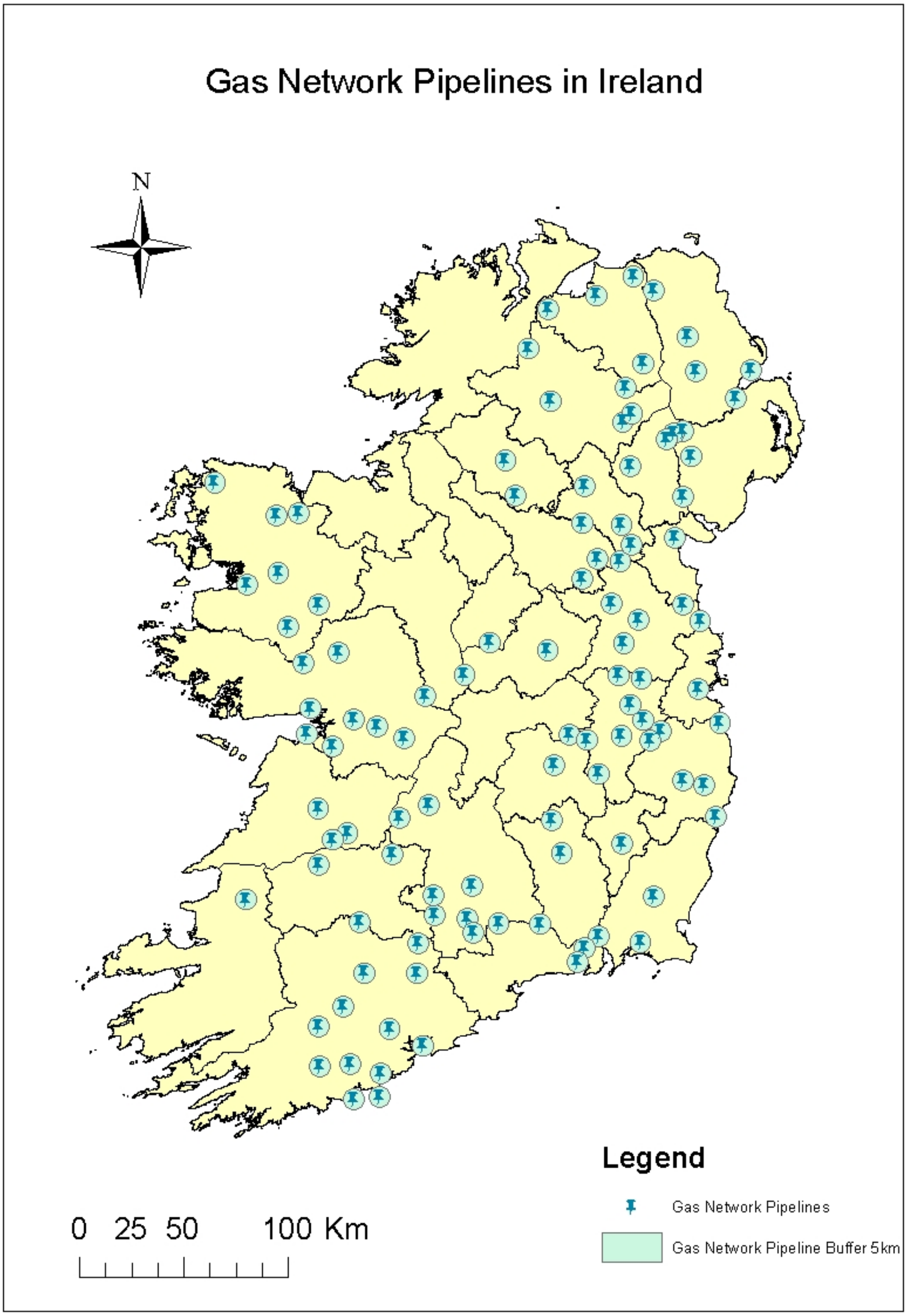


*Figure 29. Map of the Gas Network Pipelines in Ireland and Northern Ireland, along with the buffer distance assigned to the variable.*

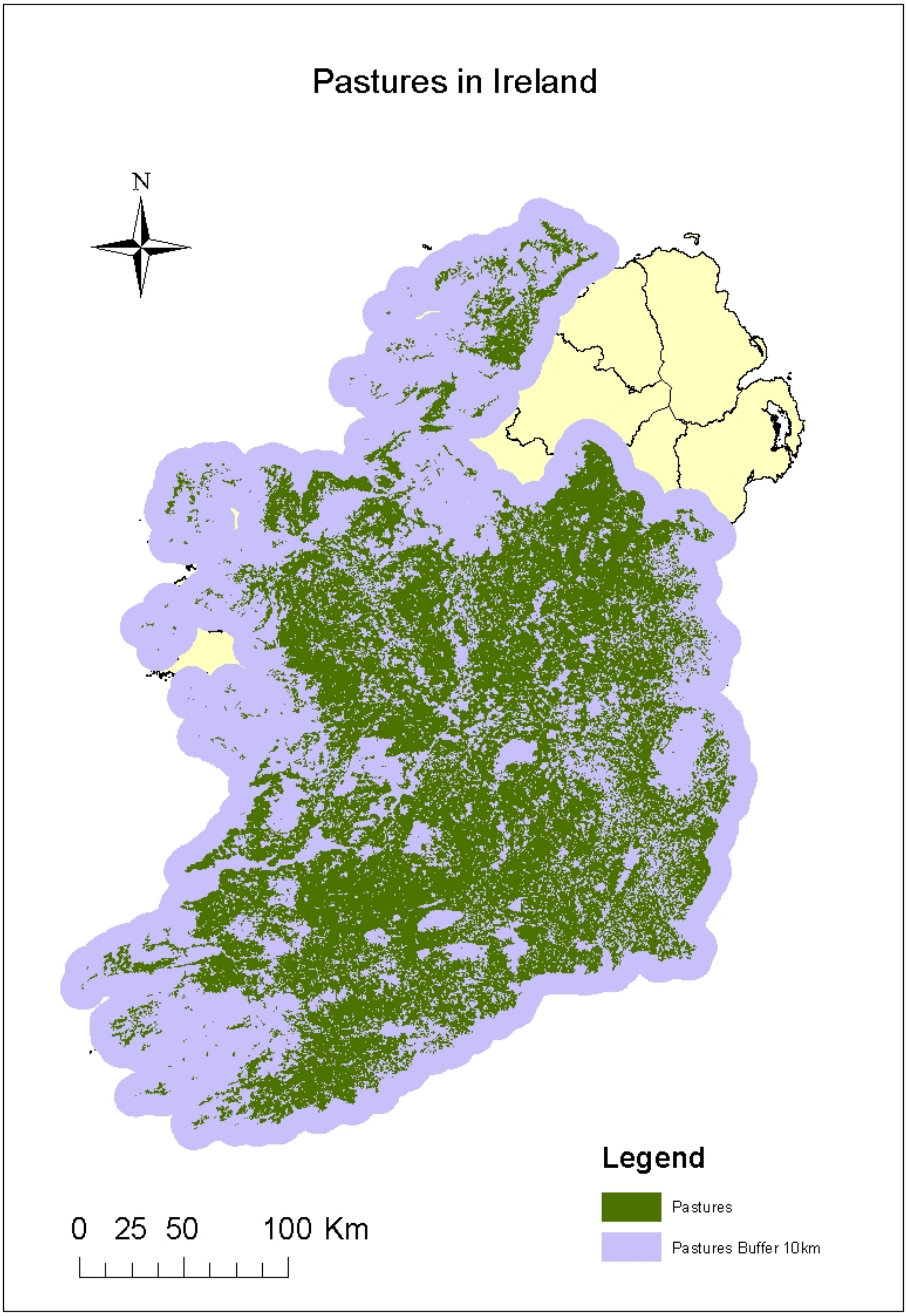


*Figure 30. Map of pastures across Ireland along with the buffer distance assigned to the variable.*

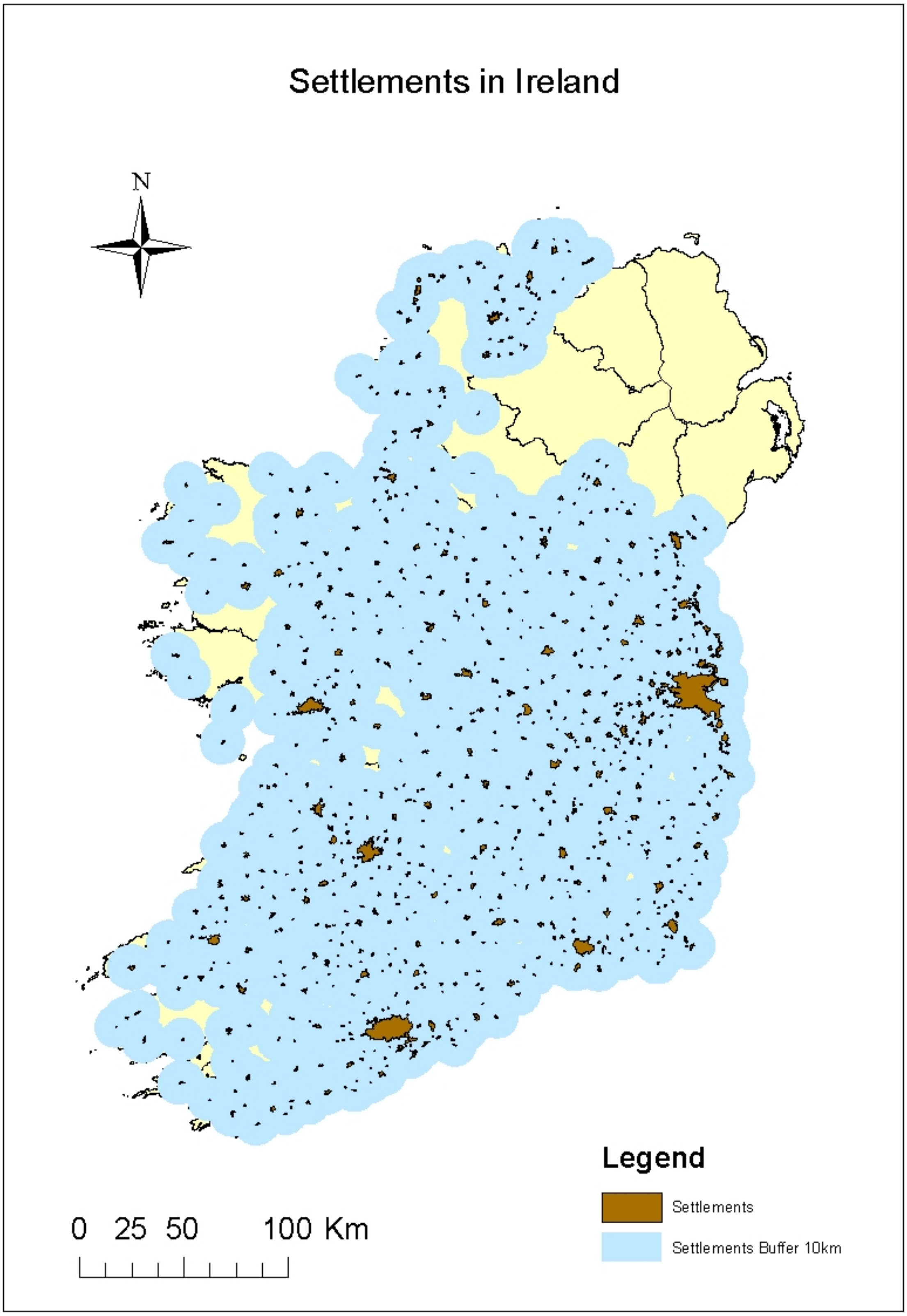


*Figure 31. Map of the settlements across Ireland along with the buffer distance assigned to the variable.*

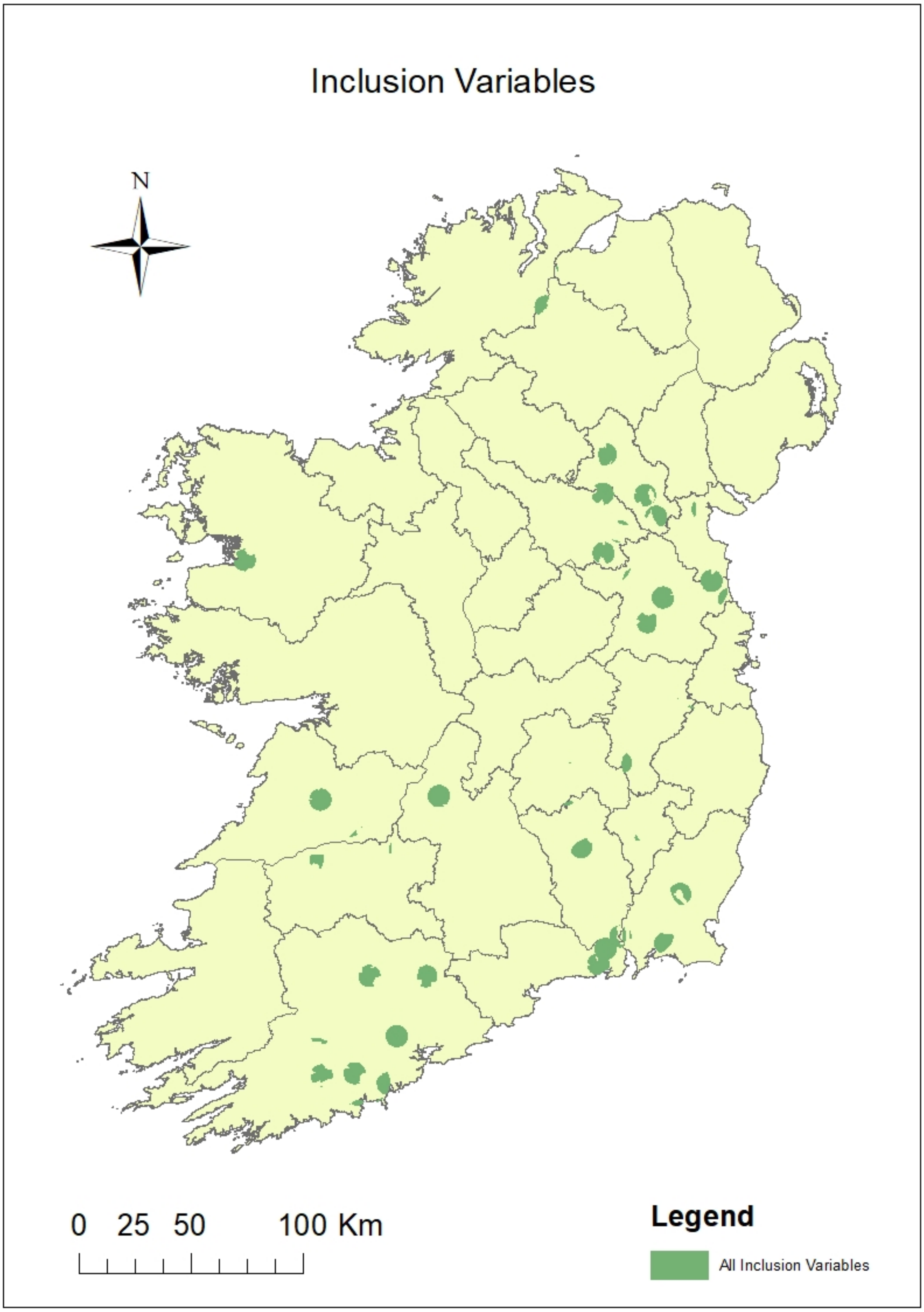


*Figure 32. GIS map of all intersected suitable land variables.*

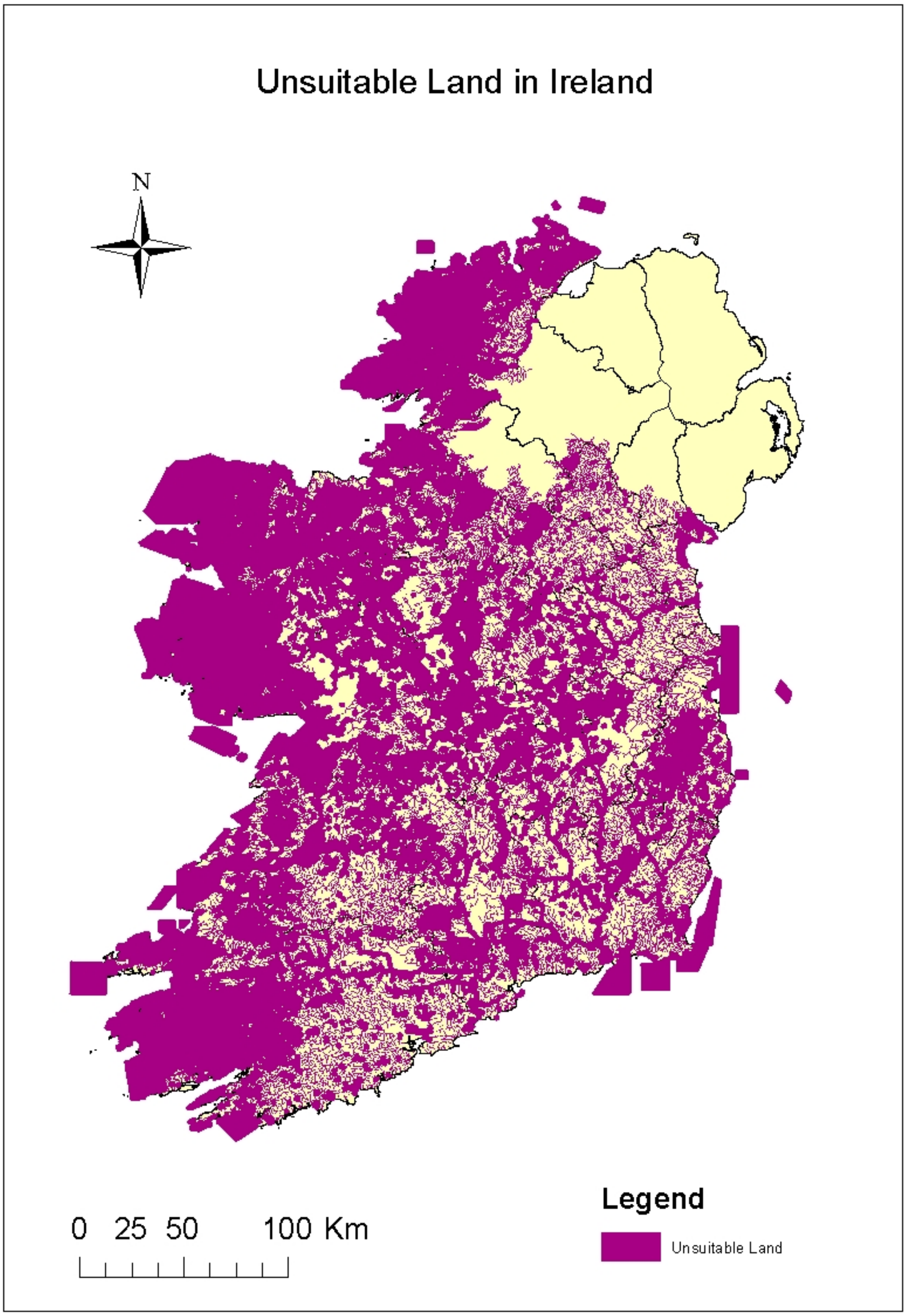


*Figure 33. Map of all unsuitable land variables and their buffer distances. This layer included forestry, protected areas (SAC & SPA) areas and bog habitats.*

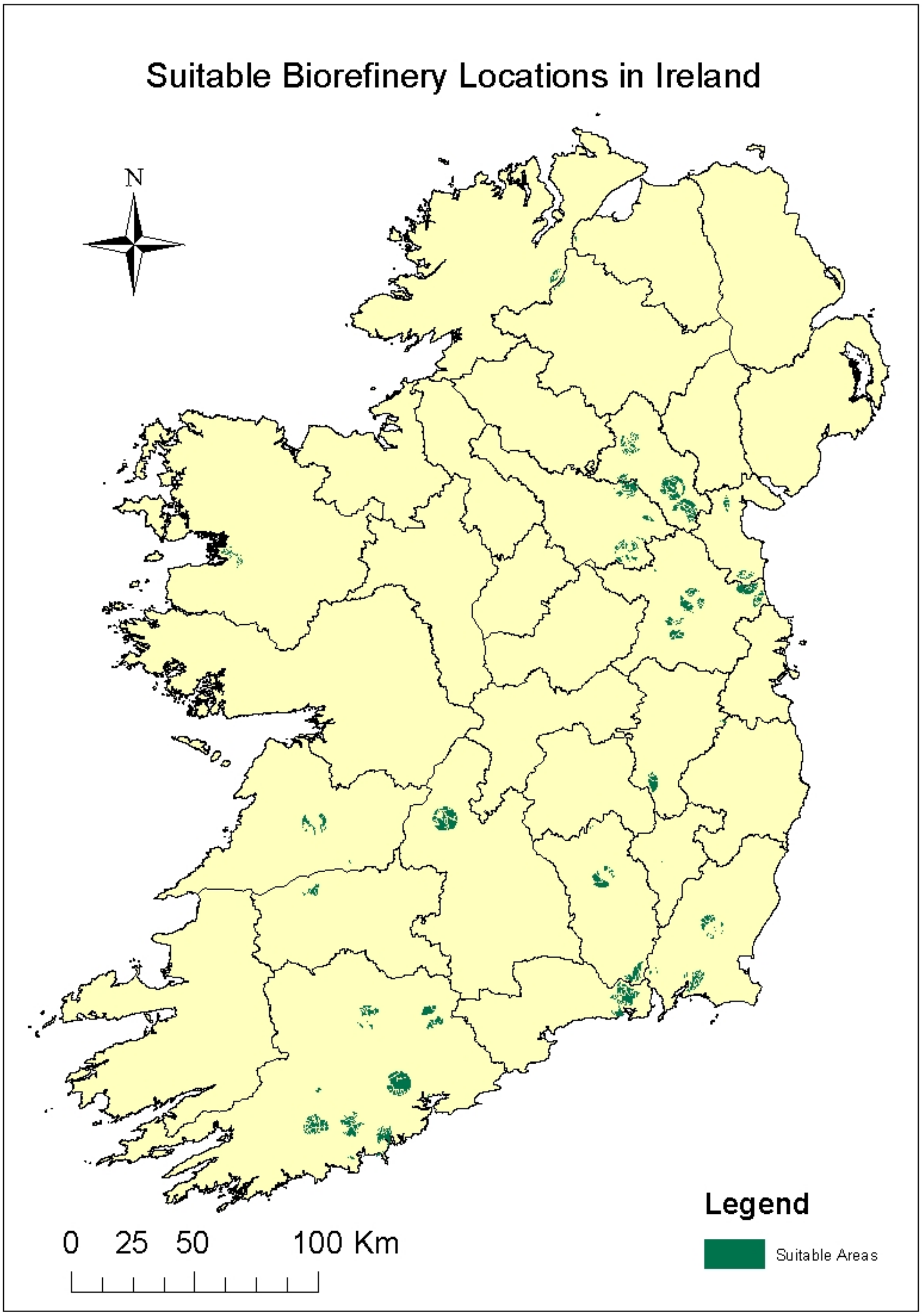


*Figure 34. Map of the suitable sites for biorefineries in Ireland. Areas of suitable land which overlapped with the unsuitable land variable have been removed through the 'erase' tool.*