REPORT

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ACTION: Circularity assessment of PHA production potential for one NWE region

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SUBJECT: D1.3 Report on circularity measurement and assessment of PHA recovery and reuse from wastewater

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Executive Summary

A regional circularity measurement and assessment (CMA) has been undertaken to quantify the economic, environmental, and social impacts of PHA recovery from primary sludge. This CMA process applied a new ISO standard, with the regional of Scotland, in NWE, being considered for this exercise. This builds upon previous technical, economic and spatial analysis reports previously undertaken and stored in past WOW! deliverable reports. As PHA reflects one of several pathways for this by-product from primary sludge, thus a comparison with biogas and incineration as alternative pathways will be accounted for. The CMA findings informs key decision-makers of the economic, environment and social credentials of PHA production.

The CMA framework is presented as having three key stages, namely (i) setting the regional boundary conditions; (ii) undertaking a circularity measurement and data acquisition exercise; and (iii) evaluating results through a circularity assessment and reporting. Four two million p.e. scenario were investigated for Scotland, representing a decentralised, centralised or stand-alone system. Life cycle assessment (LCA) and sustainable development goal (SDG) mapping were applied as complementary methods to produce additional valuable outputs to inform decision-making.

Seven indicators were selected for the evaluation of PHA, with one core indicator (lifetime of product relative to industry average) and six additional indicators (energy, economic and social factors). The comparison of resource flows between PHA and other plastics presented a wide-ranging set of results when compared to a fossil-derived plastic e.g. polyethylene. PHA derived plastics were also identified as not yet being economic for all centralised or decentralised scenarios.

The LCA model applied, and the indicators selected, reflect resource, energy, and water flows, as well as economic and social metrics. The evaluation of embodied, transport and operational burdens demonstrated that despite high impact attributed to tanks, the operational impacts represent the dominant burden across all three endpoint areas of protection over the 25-year period. The net impacts PHA as compared to biogas and incineration pathways represented the need for improvements in its production to ensure environmental impacts are minimised as compared its counterparts.

A set of specific and relevant SDGs (#7, 8#, #9, #10 & #12) were selected as complementary outputs for the CMA of PHA, addressing technical, economic, social, environmental, and social factors. This is considered to inform stakeholder pathways to PHA production, providing information that can improve the performance of these systems.

The final CMA findings was also mapped against stakeholder priorities, with PHA producing companies, local water authority / waterboards and policy-makers representing those who can benefit from or are the gatekeepers to success for PHA in the commercial market. These priorities included: (i) it can help determine the appropriateness of PHA production as opposed to alternative resource pathways (biogas or incineration), (ii) it provides a benchmark to support improvements in PHA production through implementing renewable energy sources, and (iii) identifying where incentivisation is required to accelerate PHA production as a circular resource on the market.

PHA has the potential to join the regional and European market, but its success relies on a complex mix of technical and non-technical resources, and possible incentivisation until it is scaled to a level that more cost effective operational burdens can be achieved.

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1 Introduction

1.1 Background

Globally, there is a large capacity for bioplastic production, with an estimated potential of 1,400 tonnes of bioplastics per year (Plastics Europe, 2013). The production of polyhydroxyalkanoates (PHAs) from wastewater streams present a novel circular pathway; however, this may compete with other valuable resources currently extracted from sewage, such as biogas through anaerobic digestion. PHA is a renewable resource which can be produced by a range of different processes, such as bacterial fermentation. It has the benefits of being bio-based, water insoluble, biocompatible (Rodrigues et al., 2022, Serafim et al., 2008, Moshood et al., 2022), and it has similar physical properties as traditional polymers which are based on fossil oil (Rodrigues et al., 2022). The importance of replacing traditional polymers with PHA products is based on its biodegradable characteristics, making this biobased product a more circular resource in comparison to petroleum-derived plastics.

Making PHA by means of bacterial fermentation requires steps of enrichment, accumulation, and extraction from a biomass (Persiani & Raingue, 2022). This process is currently more expensive (€ 1.18–6.12 per kilogram) than traditional polymer (€ <1 per kilogram) (Rodrigues et al., 2022, Gholmai et al., 2016), which has limited market penetration. Due to these high cost, operating PHA plants in Europe hasn't fully matured, despite strong research on this topic in Europe (M.N. et al., 2021).

1.2 Circular Resources

The traditional perspective on the value of wastewater is to solely consider it as a waste, but Circular Economy (CE) principles suggests we look beyond the linear end-of-life to identify products from effluent (Roibas-Rozas et al., 2020). PHA represents a product that can be extracted as a resource from a by-product of human and industrial processes. CE promotes this type of value chain to be sustainable, thus promoting renewable sources and resources. It is clear that the linear economy has focused on profitability (Roibas-Rozas et al., 2020), therefore new business models must be identified to support circular resources that allow recycling, retaining, or adding value.

CE standards are currently in development, the ISO 59000 family of standards. These standards will provide a means of quantifying the circular potential and sustainability of PHA as compared to traditional polymers. It will also support organisations with guidance to implement a circular business model and apply circular measurement and assessment to their value chain. This can be complemented by other recognized and complementary methods such as life cycle assessment (LCA), life cycle costing (LCC) or cost-benefit analysis (CBA) to inform strategies that will provide the best value and prioritize them. (European Commission, 2014, Lovrenčić Butković et al., 2021).

1.3 Circular PHA Production – Opportunities and Challenges

PHA can replace petroleum-derived plastics since it has a lot of attractive advantages being biobased and potentially represents a more circular product. PHA decomposes into resources like water, $CO_{2,}$ and inorganic chemicals. PHA has the potential to be used in different industries and sectors. Producing PHA from sewage can reduce waste, reduce carbon emission. So, using PHA can mitigate the worldwide plastic problem we are facing now. However, it has disadvantages like fragility, hydrophily, and high cost (Acharjee et al., 2023). Moreover, as compared to biogas or incineration, producing PHA consumes energy. Table 1.1 lists some considerations relating to opportunities and challenges of PHA production summarised as technical, economic, and environmental aspects.

PHA is a biodegradable product that has the potential to be produced from a waste resource and can become a biobased waste at the end of its life, and therefore it reflects a circular product. However, the CE aims to maximise its potential and minimise the associated environmental impacts of its production e.g., by maximising the use of renewable energy to support in the steps of processing PHA. As a circular resource, PHA as an end product can be recycled and removes the need for virgin materials as an input (Acharjee et al., 2023).

Table 1.1. Opportunities & Challenges of PHA Production.

Aspect	Opportunities	Challenges
Technical	Technology readiness level (TRL) and commercial opportunities arising from stakeholder engagement with WOW! and WOW! Capitalisation project.	The efficiency of producing PHA is low and existing PHA production is mostly at pilot scale.
Economic	It is an attractive alternative to heat & power generation for sewage treatment, and it has the potential to create more job opportunities (Perez et al., 2020).	The price of PHA is higher than traditional polymers due to need for added infrastructure, energy and resources requirements (Gholmai et al., 2016).
Social	Create new circular economy jobs and develop new skills to support production of PHA value chain	Uncertain as to clear pathways in which PHA will be used in marketplace based on consumer concerns of using bioplastic.
Environment	PHA is biobased and biodegradable and can help reduce biowaste from sources like cheese whey etc (Asunis et al., 2021).	If waste is regarded as a resource for PHA production, people may produce more waste.

1.4 Goal of this Study

This study will apply new CE ISO standard principle to evaluate the circular performance of PHA production and evaluate the appropriateness of these standards for value generation from a by-product from wastewater effluent. This expands the previous work undertaken in the WOW! and WOW! Capitalisation project to quantify the potential of PHA production in different regions, accounting for a value chain of relevant stakeholders.

LCA is applied as a complementary method to help determine the environmental impacts of PHA production and provide a basis for benchmarking circular performance for impacts such as embodied carbon, contribution of energy from renewable versus fossil-fuel sources, and the resource footprint of this product. The use of PHAs to help achieve SDGs are also briefly addressed within the report. PHA can represent a more appropriate circular resource that traditional polymers and evidence supporting this can support its accelerated uptake in the marketplace.

2 Circularity Assessment of Regional PHA Production Potential

2.1 Key Findings of Regional Assessment Study

The findings from the WOW! Capitalisation Activities 1.1 & 1.2 report focuses on the technical feasibility for economically viable scenarios for PHA production in three different regions in North-West Europe (NWE). This is informed by data produced using the site selection GIS tool in the project, which provides a mechanism to calculate important logistical information and to compare different scenarios to identify the most viable location(s) for PHA production.

This approach considered the capital investment (CAPEX) costs and operational (OPEX) costs required to produce PHA from primary sludge (P.S.), accounting for centralised, decentralised, or stand-alone infrastructure expenditure, fuel for transportation of the PHA-rich biomass, and a range of electrical and fossil-fuel based sources of energy for operating PHA infrastructure, and staff resources related to installation and operation of the equipment.

2.2 Circular Measurement and Assessment of PHA production

The CMA methodology has been defined in WOW! Capitalisation Activities D3.4 and is based on the new ISO 59000 family of standards for the Circular Economy (CE), which is summarised in Chapter 3. The procedure applied in this study is summarised in Chapter 4 and applied in detail in Chapter 5 of this report. This report evaluates the different PHA production scenarios in Scotland by comparing circularity performance, accounting for resource flows, as well as economic, environmental, and social impacts in the form of different core and additional circularity indicators.

To undertake the CMA for each scenario, the following steps are defined in Chapter 4:

- Setting an overarching context of application for CMA within a strategic framework.
- Defining clear boundaries for the system in focus, i.e. PHA production, to ensure a sustainability-driven outcome is effectively captured.
- Measuring circularity for defined indicators based on specified primary and secondary data requirements.
- Assessing the circular performance and reporting on the economic, social, and environmental aspects of the system in focus (PHA production), considering comparative pathways for P.S.

2.2.1 Case Study Region - Scotland

Based on an evaluation of the three NWE regions evaluated in the WOW! Capitalisation Activities 1.1 & 1.2 report – Saarland in Germany, Ireland, and Scotland – Scotland was identified as the most appropriate region for the circularity measurement and assessment (CMA). Specifically, the case study region will focus on Glasgow which was identified as the most viable location due to its higher population density, a few medium-sized (>50,000 P.E.) wastewater treatment plants (WWTPs) within a maximum of 70 km from a centralised location.

The technical feasibility presented costs of between 5,548 and 6,739 €/t PHA for different PHA production scenarios. In all cases, OPEX costs (excluding transport) represented 55.7-66.1% of the total costs, with CAPEX costs, transport, and labour and maintenance, representing the other higher costs for PHA production depending on the scenario being evaluated.

Four scenarios are proposed for the CMA activity, with each scenario reflecting a centralised, decentralised, or stand-alone setting, with different levels of drying of sludge in cases where transport is a requirement to make a site viable.

2.2.2 Comparing Circular Pathways for Primary Sludge

This study recognises that PHA production is not the sole pathway for P.S. to act as a resource. Incineration and anaerobic digestion presents alternative pathways for P.S. and can be valorised to produce energy in this manner, thus extracting value from a WWTP by-product. The scope of this report will therefore aim to provide a comparison of pathways for P.S. such as PHA production.

In addition, whether P.S. is sent for incineration, or produces a bioplastic, it will offset alternative resources and represents a circular resource. Lastly, considering that PHA would provide a feedstock to produce a bioplastic and replace conventional petroleum-derived plastics e.g. polyethylene (PE) will also be considered in the assessment process.

The CMA will aim to compare the PHA, and other P.S. resources pathways by quantifying its social, environmental, and economic impacts, as well as how it contributes to sustainable development.

3 Circular Economy ISO Standards

3.1 Overview of Standards

In 2020, expert representatives from national bodies around the world were brought together to begin the task of producing a set of Circular Economy (CE) standards to provide a harmonised approach and a universally agreed set of terminology and principles to support the transition to and measurement of circular systems.

As shown in Figure 3.1, three primary standards within the ISO 59000 family were initially defined: ISO 59004 focusing on terminology, principles and guidance for implementing circular principles; ISO 59010 providing guidance on implementing circular business models and creating value chains or networks; and ISO 59020 presenting a consistent approach to measuring and assessing circular performance of systems. Several additional complementary standards are in earlier stages of development and will provide supporting guidance for organisations to align environmental management responsibilities, tracing of material flows, and appropriate methods for organisations to implement circular business models.

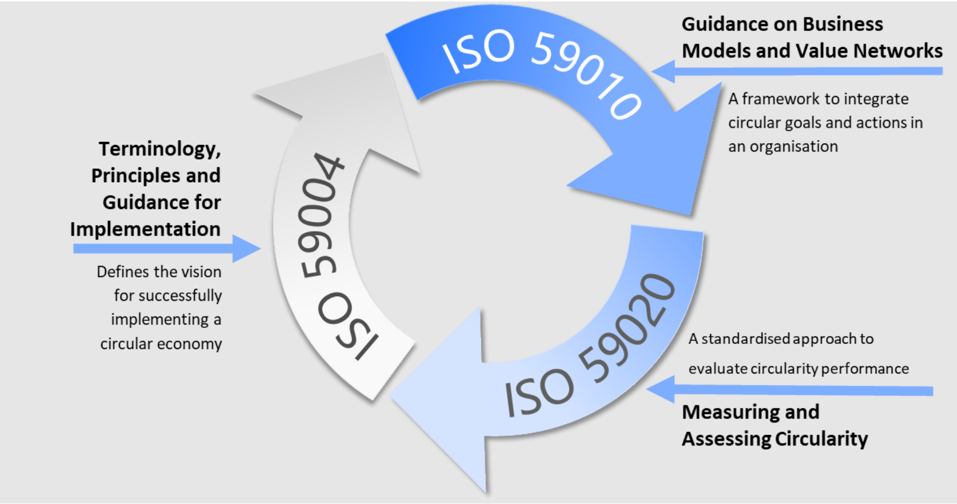

Figure 3.1. Current structure and connectivity of ISO 59000 family of standards.

The standards will be published in 2023. These standards will provide an organisation with the appropriate guidance to transform linear supply chain activities into circular value chains that enables organisations to contribute to sustainable development.

3.2 Relevant Circularity Economy Standards

In this report, ISO 59020 Measuring and Assessing Circularity will represent the primary standard to follow for this study, with ISO 14040 and ISO 14044 acting as complementary methods for life cycle assessment (LCA) to quantify the environmental sustainability of the PHA production as the system in focus. However, the overarching guidance that is provided in ISO 59004 and the relevant indicators that are outlined in ISO 59010 will inform the measurement and assessment of PHA production.

ISO 59004 – Terminology, Principles and Guidance for Implementation

This standard provides the conceptual framework governing the concept of CE and this family of standards. This includes all the relevant terms and definitions, a rationale for CE and its fundamental principles, and guidance for organisations to implement circular values in practice.

ISO 59010 – Guidance on Business Models and Value Networks

This standard provides guidance to support an organisation prepare its vision for transitioning its existing linear business model and supply chain to a circular business model. This can be achieved by mapping the interdependencies within the value chain or value network, which can help define actions and determine strategies for implementing circularity within an organisation.

ISO 59020 – Measuring and Assessing Circularity

This standard provides a methodological process for circularity measurement and assessment (CMA) for a given system in focus. This system in focus may represent a product, service, or process, and sits within an economic system, and is connected to external social and environmental systems. By considering circular goals and actions in this framework, the outputs support broader sustainable development goals.

Complementary Methods – ISO 14044 & 14044 for Life Cycle Assessment

These LCA standards act as a complementary means to evaluate the environmental burdens attributed to the system in focus, providing a means of enhancing the circularity assessment process. Complementing CMA with LCA can avoid uninformed negative impacts attributed to the system in focus to strengthen its sustainable performance.

4 Framework for Circularity Measuring and Assessing Circularity

4.1 Introduction

The methodology for undertaking a circularity measurement and assessment (CMA) requires the application of specific principles that are relevant to the system in focus and is conducted within a specified timeframe. In this case, Figure 4.1 provides an illustration of the CMA framework for the system in focus in this study, specifically the valorisation of PHA production from P.S. with a 3-5% dry matter (DM) content over a 1-year period.

A comparison to an alternative valorisation method of P.S. will also be evaluated, as energy from incinerating the P.S., to determine the appropriateness of PHA production in all scenarios.

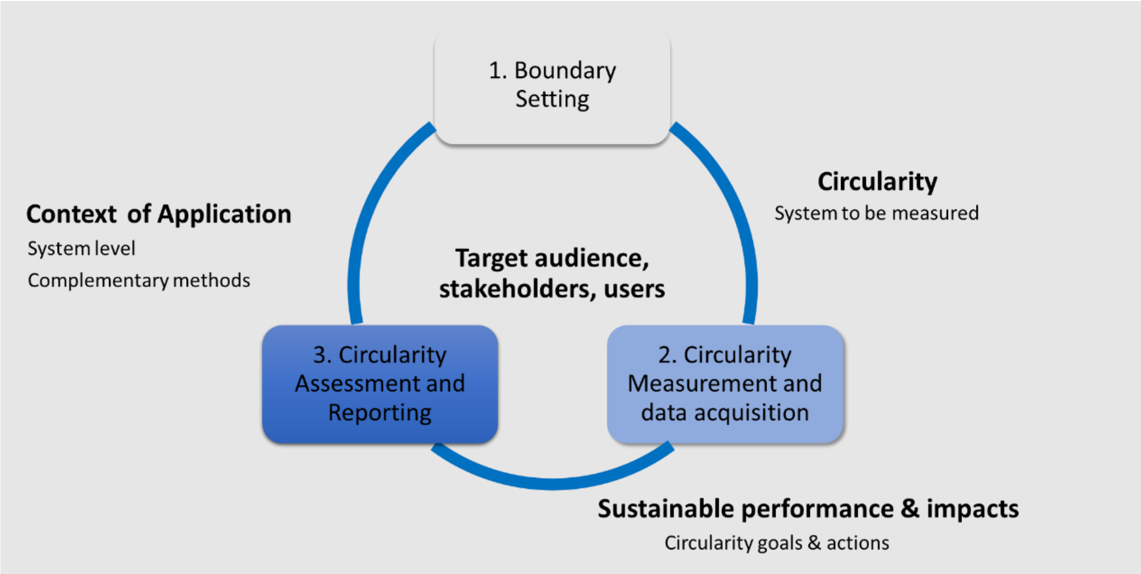

Figure 4.1. Circularity measurement and assessment framework to be applied to PHA production from P.S. (3-5% DM).

As described, the CMA framework proposed three steps for determining the valorisation potential of PHA production; (i) set boundary conditions; (ii) undertake a circularity measurement and data acquisition exercise; and (iii) evaluate results through a circularity assessment and reporting. A brief overview is provided within Section 4.2, with more detailed information and guidance in relation to the PHA production system in focus in Chapter 5.

4.2 Context of Application

4.2.1 Purpose and Intended Use of CMA Results

The primary purpose of this activity is to apply the CMA methodology to compare the potential of PHA production in Scotland. The results of this study will inform the appropriate approach to valorising this resource from P.S. and provide a benchmark for the circular performance of PHA production.

This report represents one of the first studies to apply new circular economy principles from the forthcoming ISO 59000 family. It will provide unique insights into the potential for PHA, going beyond complementary methods of assessment such as LCA. The study will also critically evaluate the appropriateness of the CMA methodology on its suitability for application for resource recovered from wastewater streams, as the current guidance considers anaerobic digestion as the primary method of valorisation of sludge from WWTPs. To achieve this goal, the results will reflect a range of economic, environmental, and social indicators, collectively addressing sustainability, with the findings providing insights and value to different stakeholders representing the target audience of the study.

4.2.2 Applicable System Level(s)

The different scenarios evaluated in this CMA Activity for the region of Scotland will consider local extraction of PHA as a resource from P.S. Each scenario requires a unique approach to be considered, and this defines the need for clear regional or national considerations to be considered depending on the management structures of WWTPs in a specific country. Waterboards and water authorities can represent either public or private organisations, and the consideration that contractors may take some responsibilities in the management, PHA production processing or P.S. transport activities, there is scope for both inter-organisational and organisational impacts in the value chain. Similarly, the CMA results can provide an insight into the circular and life cycle credentials of the final product itself i.e., PHA cake.

4.2.3 Circular Goals, Aspects and Actions

The circular goal aims to position the capacity of the system in focus in support a circular economy, i.e., PHA production as a resource from P.S., whilst also addressing economic, social, and environmental objectives using complementary methods. The circular aspect in this study focused on resource recovered from P.S. The primary action to be derived from the CMA results will inform stakeholders of PHAs valorisation potential and position their respective role within the value chain. To obtain these results, P.S. resource flows are only considered economically viable for a 2 million P.E. (Nazeer Khan et al., 2020), thus several centralised, decentralised and stand-alone scenarios are evaluated to ensure a 500,000 tons per year of processed P.S. is processed to produce 5,000 tons of PHA per year.

A range of core circularity indicators, and additional social, economic, and environmental indicators will be defined in the PHA production CMA, with LCA impact data and SDG target data providing complementary information to support the sustainability impact measurement and assessment of the system in focus. This will help meet the requirements of the circularity framework and support more informed decision-making for stakeholders on the most appropriate pathway for P.S.

Typically, all 14 core indicators are only required when applicable, otherwise are consider as zero. In this report, only two core indicators may produce values other than zero, one of which shall be a formal requirement (Outflow: *Average lifetime of product or material relative to industry average*) and one that should be a requirement (Energy: *Average % of consumed energy from renewable source*). Further details in relation to these indicators and how they are calculated are provided in Section 5.2.2.

Additional LCA impact categories and Sustainable Development Goals (SDG) targets and indicators assessed in this study act as complementary methods for the CMA activity. A life cycle assessment (LCA) of the PHA production process will quantify its environmental performance as a circular product.

4.2.4 Relevant stakeholders in the value chain

The target audience will include a range of stakeholders within the value chain including PHA producing companies, local water authorities / waterboards, and policy makers. Each stakeholder plays a different role or has a unique impact on the value chain, with this project focusing on producing PHA from P.S. (3-5% DM) and producing a PHA cake. For PHA producing companies, the CMA will support current and future decision-making with regards to pursing a centralised or decentralised system based on resource flows and a range of sustainability (economic, environmental, and social) indicators. It will also evaluate the quality of PHA cake prior to transforming it into a pellet form for production lines, providing a benchmark on the inputs required, and associated hotspots, for PHA production.

Waterboards or water authorities will be able to determine the optimal valorisation method of P.S. as a resource, depending on the size and spread of their WWTPs. For these water bodies, their boundary condition represents the provision of the P.S. feedstock to PHA cake production, depending on what infrastructural investment is implemented at WWTP sites for centralised or decentralised systems. It also allows for informed decision making on whether to support the production of PHA as opposed to incineration. Lastly, policy makers play an important role in driving standards or setting requirements for wastewater effluent treatment and end-of-life pathways for P.S. Quantifying the circular performance of PHA production will provide evidence with regards this option for using P.S. and inform decisions for its improvement in the future through benchmarking.

5 Circularity Measurement and Assessment Process

5.1 Step 1: Setting Boundary Conditions

5.1.1 System to be measured

The system in focus in this study is a regional CMA of PHA production from P.S. as a form of resource recovery. Scotland represent the region in focus, with three primary scenarios defined in the Glasgow region as this specific area of Scotland was shown to have the population density to process over 2 million P.E. of sewage.

Scotland produces an estimated 120,000 tons of plastic packaging each year (BBC, 2018), thus PHA has the potential to replace 4% of the total demand based on producing PHA from all wastewater plants, which reflects an optimising scale due to many plants having a small population in the area. It can also help introduce a new pathway for plastics as currently all plastics are non-organically recycled, increasing jobs to support the circular economy.

5.1.2 Goal and Scope

The circular goal is to produce PHA from P.S. and provide a benchmark for production in the case study region of Scotland. A comparison to an alternative pathway for P.S. through the incineration of P.S. is also undertaken in the assessment. In addition, appraising the impacts of PHA as a replacement to support reducing plastic production e.g. polyethylene (PE) will be examined. The circular aspect to be considered of importance in achieving this circular goal is to capture potential recovered losses from P.S. through PHA production, as compared with energy production from incineration.

The actions that can be derived by the results of the CMA study of PHA production from P.S. and its potential for valorisation will inform the range stakeholders (section 4.2.4.) on their options and clarify their role within the value chain. This will be based on the different scenario outcomes with regards the PHA resource potential of the system in focus, and the associated economic, social, and environmental impacts as compared to different existing pathways or offsetting alternative sources of plastic.

The resource flows to be assessed will consider economically viable scenarios with a 2 million P.E., which can be made up of a single centralised WWTP or multiple WWTPs as different decentralised scenarios (Nazeer Khan et al., 2020). The associated reference flow for each of these 2 million P.E. scenarios represent 25,550 tons per year of dry matter P.S. per year. From this, the functional unit for assessment of PHA production will represent 1 ton of P.S. (DM). These results with provide a benchmark of circularity performance for annual PHA production in each Scenario.

This quantity of P.S. will produce PHA and can be compared to an existing potential pathway of producing energy from P.S. incineration. Also, it will be a comparator to the impacts of producing petroleum-derived plastic i.e. PE.

5.1.3 Boundaries of the system in focus

Four scenarios are examined in this CMA study in the Glasgow region in Scotland to compare the performance of centralised, decentralised, or stand-alone options for PHA production. Infrastructural requirements, transport logistics and energy demands were accounted for in the study to produce the same quantity of PHA (5,000 tons) in each scenario over a 1-year period. Each scenario has a common 2 million P.E. and can be described as follows:

- Scenario 1: Centralised; 3%/5% DM from >50,000 P.E. plants
- Scenario 2.1: Centralised 3%/5% DM from >300,000 P.E. plants
- Scenario 2.2: Decentralised 3%/90% DM from >300,000 P.E. plants
- Scenario 3: Stand-alone 3% DM from a ~2,000,000 P.E. plant

Data for these scenarios originate from the previous WOW! project reports, including an expanded analysis of previously considered scenarios to produce a common P.E. for fair comparison. These results will be valuable to wastewater treatment companies who can evaluate the circular potential of effluent through producing PHA as an alternative by-product from sludge, as compared to energy production from incineration of P.S. from the same availability of sludge over a 1-year period. The assessment scenarios consider that the TRL for all technologies are advanced to full-scale (TRL 7-9 i.e., full-scale demonstration to commercial product).

5.1.4 Resource Flows of the system in focus

Scenario 1: Centralised >50,000 P.E. plants

Scenario 1 is based on variant 1.1 from previous reports, as illustrated in Figure 5.1. An algorithm in GIS was used to select WWTPs with a total sum of 2 million P.E., with a cut-off distance of 45 km and only selecting plants >50,000 P.E. Despite having slightly less capacity than Dalmuir, Shieldhall was selected as the central plant location for Scenario 1, as the software calculated it to be the most efficient due to location optimization, resulting in a sum of 2,009,231 P.E. This marginally exceeded the 2 million P.E. capacity and to balance the capacity, the difference was deducted from the WWTP located furthest away to minimize the total distance. In Scenario 1, this was Allers S.T.W., where the original data is highlighted by a red rectangle. The deducted data displayed directly above the highlighted data will be used for the continuation of this research. However, the deducted data is below the original cut-off value of 50,000 P.E., which will be an exemption to the rule.

Scenario 2.1 & 2.2: Centralised or Decentralised plants with >300,000 P.E.

The same GIS method for location selection that is used for Scenario 1 was used for Scenarios 2.1 and 2.2 (Figure 5.2). This means a cut-off distance of 45 km was used while only selecting plants >300,000 P.E. This resulted in a P.E. 2,028,071. The surplus amount exceeding 2 million P.E. was deducted from the WWTP located furthest away to minimize the total distance. In Scenarios 2.1 and 2.2, this was Meadowhead W.W.T., where the original data is highlighted by a red rectangle. The deducted data displayed directly above the highlighted data will be used for the continuation of this research. Nevertheless, Dalmarnock S.T.W. is below the original cut-off value of 300,000 P.E., which will also be an exemption to the rule.

Scenario 3: Stand-alone ~2 million P.E. plant

Scenario 3 is a fictional scenario, based on a large 2,000,000 P.E. central plant. No sludge transport is required. However, the sludge has a 3% DM content, as no sludge needs to be thickened for transport.

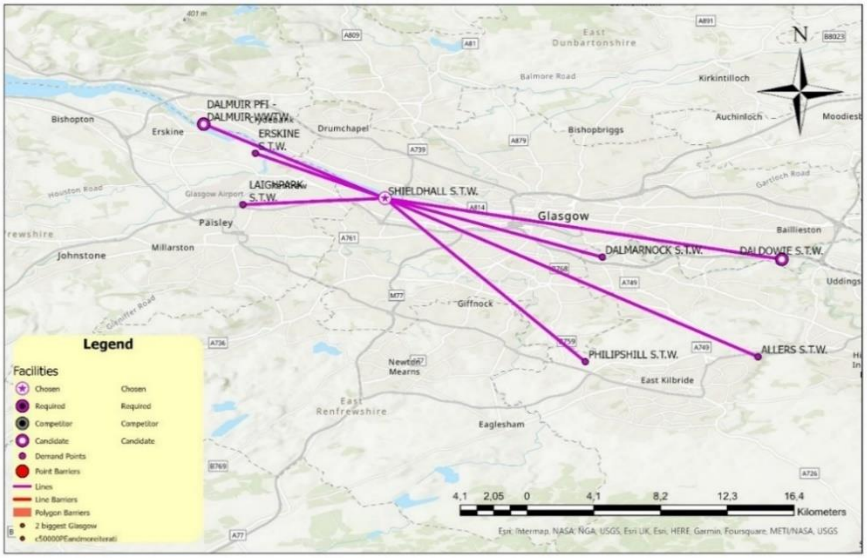

Figure 5.1. Chosen locations from GIS for Scenario 1.

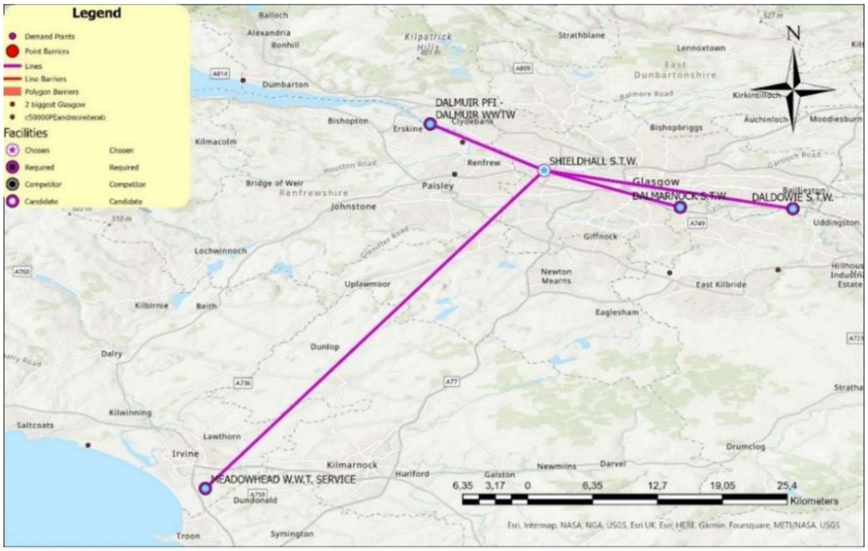

Figure 5.2. Chosen locations from GIS for Scenario 2.1 and 2.2.

5.1.5 Temporal boundary setting

The production of 5,000 tons of PHA were considered in each scenario for a 1-year period, as this reflected technological constraints for PHA production in a region. It also represents a scale that would produce PHA in the most economical manner. This can provide an adequate temporal boundary for effective benchmarking of PHA production over time for circular assessments. In these scenarios, all infrastructure would be expected to be functioning beyond this 1-year period (as defined in WOW! Capitalisation Report 1.1 & 1.2).

5.1.6 System perspective at different levels

PHA production could encompass a range of different levels, depending on the governance structure for wastewater treatment, the specific location of focus, and scale of production in question. Table 5.1 provides an overview specific to this assessment, providing commentary of variable factors in terms of their relevance to different levels for the system in focus.

Table 5.1. Levels of relevance for PHA production for the system in focus.

Level	Relevance	Outside of boundary
Regional	Focuses on part of Scotland as a region for PHA production (5,000 t/yr).	Omits many WWTPs and does not consider sources from across the land boundary of England.
Inter-organisational	n/a	To produce a finished bioplastic or even PHA pellets for bioplastic production would extend the boundaries of assessment to consider interactions between organisations in the value chain who produce pellets and/or the bioplastic product from the P.S. or PHA cake.
Organisational	The water company is the only stakeholder involved in the production of PHA cake as they own and operate the WWTPs. The transport of sludge between plants may require another organisation (contractor), but it is assumed they are staff of the water companies in this study.	This could include independent operators of WWTPs based on different governance structures of a water utility within a region.
Product	The data required to measure and assess the circularity of producing PHA cake from P.S. (3-5% D.M.), or undertake an LCA, can be obtained from a single organisation i.e. the water company as they represent the entire value network.	Incorporating the impacts attributed to the production of the equipment (components) itself that are used to produce the PHA cake, not just the energy they require over time.

5.2 Step 2: Circularity measurement and data acquisition

5.2.1 Circularity measurement taxonomy

The production of PHA from P.S. (3/5% D.M.) aims to add value to the pathway for wastewater sludge, offering an alternative pathway to recognised management and disposal. Given the role of PHA is to replace polymers as a more sustainable product, a set of relevant circularity indicators will be defined, and LCA will be applied to quantify the performance of PHA.

5.2.2 Choice of indicators for circularity measurement

The following seven indicators were selected to be applied in the CMA, as presented in Table 5.2Table 5.2, and this includes two core indicators and five additional indicators.

Table 5.2. Core and additional circularity indicators from ISO 59020 and other supporting documentation to assess PHA resource recovery from P.S. (3%/5% DM) from the wastewater stream.

Type	Category	Indicator Description
Core (Shall)	Outflow	Average lifetime of product or material relative to industry average
Core (Should)	Energy	Average % of consumed energy from renewable source
Additional	Energy	% recovered energy from residual, non-renewable resource outflows
	Economic	Value per mass
		Investment costs
		Production costs
	Social	Labour

The data requirements for this assessment includes transport between WWTP, and different forms of energy for producing the PHA reflecting operational costs (OPEX).

From the seven indicators, one core indicator and one additional were deemed relevant to enable a sustainability impact measurement and assessment, specifically the percentage energy from renewable energy sources and the percentage energy recovered from residual, non-renewable resource flows, respectively.

Life cycle assessment indicators to complement circularity measurement

Complementary to this, a LCA was also undertaken which provides a range of relevant indicators to support an in-depth assessment of the broader range of impacts that may be associated with PHA production. The ReCiPe impact assessment method will be applied in line with ISO 14040 and 14044 standards, specifically evaluating all midpoint and endpoint impacts using the 2016 v1.03, (H - hierarchist) dataset.

Contributing towards sustainable development

To provide a link between the production of PHA and its role in contributing towards sustainable development, an evaluation of the sustainable development goals, and their related targets and indicators, was undertaken. Table 5.3 provides an overview of relevant SDG targets and indicators that relate to the PHA focus of this study and aligns with the core and how this aligns with circularity indicators considered in this report. The SDG indicators encompass social, environmental, and economic dimensions that a region could improve upon where organisations implemented PHA production to produce a circular resource.

Table 5.3. Relevant SDG targets and indicators as defined in 59020 that are relevant to the core and additional circularity indicators for PHA production from P.S. (3%/5% DM).

SDG	Target	Indicator
#7	Affordable and clean energy	7.2.1 Renewable energy share in the total final energy consumption
#8	Decent work and economic growth	8.4.2 Domestic material consumption (DMC), DMC capita, and DMC per GDP
#9	Industry, innovation, and infrastructure	9.2.1 Manufacturing value added as a proportion of GDP and per capita
#10	Reduce inequalities	10.4.1 Labour share of GDP
#12	Responsible consumption and production	12.2.1 Domestic material footprint, material footprint per capita, and material footprint per GDP
		12.5.1 National recycling rate, tons of material recycled

5.2.3 Data acquisition

The data required for the CMA was extracted from previous WOW! reports which captured the resource flows, infrastructure, energy, and transport requirements to produce PHA, as presented in Figure 5.3.

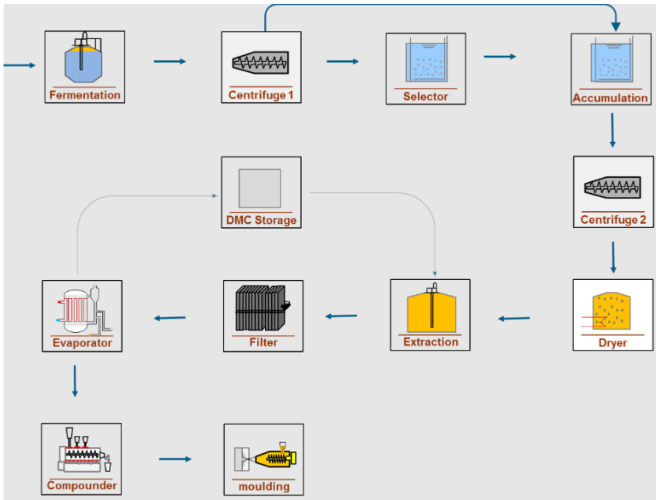

Figure 5.3. Flow Diagram of PHA Production (Nazeer Khan et al., 2020).

For each Scenario, a S.T.W will have some, or all, of the following infrastructure to support the production of PHA in a region.

Energy

Three distinct forms of energy were required for PHA production, specifically electricity, heat, and steam. Electricity representative of Scotland's energy mix was used in the PHA production process was deemed to be a mix of different sources, including 40% natural gas, 21% nuclear, 21% renewables (wind, solar and hydro), 11% from bio/waste sources, and 7% from coal and oil derivatives (Ecoinvent, 2023). Heat was produced from electricity, and steam was produced from the combustion of natural gas. Details relating to the total electricity, heat and power requirements for all Scenario were assumed to be the same, with a summary of these demands provided in Table 5.4.

Table 5.4. Electricity, heat, and steam consumption for each Scenario to produce 5,000 tons of PHA per year (present as per functional unit of 1 ton of P.S. (dry matter)).

	Electricity (kWh/ ton P.S.)	Heat (kWh/ ton P.S.)	Steam (ton/ ton P.S.)	Steam (kWh/ ton P.S.)*	Total (kWh/ ton P.S.)
All Scenarios	192.55	92.57	0.05	33.31	317.43

* Based on estimated energy demand for 1 ton of steam from ASME Steam Tables (ASME, 2006).

Transport

For transport distance calculations, the WOW! Capitalisation report proposed the use of a 25-ton truck. In this report, to align with available LCA modelling data, a 24.7-ton truck was used. As such, the 'Distance' data column in Table 5.5 to Table 5.8 represents Error! Reference source not found.the revised one-way distance in kilometres between the supply plant and the central plant for Scenarios 1-3.

Table 5.5. WWTPs included in Scenario 1 (from Figure 5.1).

Name	Weight (PE)	Distance (km)	PS (3%) (ton/y)	PS (5%) (ton/y)	Frequency (trips/y)	Ton kilometer (ton*km)
DALMUIR PFI - DALMUIR WWTW - SHIELDHALL S.T.W.	581,220	11.32	-	148,502	6,012	1,680,500
SHIELDHALL S.T.W. - SHIELDHALL S.T.W.	563,713	-	240,048	-	-	-
DALDOWIE S.T.W. - SHIELDHALL S.T.W.	317,927	16.98	-	81,230	3,289	1,378,974
DALMARNOCK S.T.W. - SHIELDHALL S.T.W.	232,840	9.87	-	59,491	2,409	587,080
LAIGHPARK S.T.W. - SHIELDHALL S.T.W.	126,440	7.01	-	32,305	1,308	226,317
ERSKINE S.T.W. - SHIELDHALL S.T.W.	83,015	6.82	-	21,210	859	144,562
PHILIPSHILL S.T.W. - SHIELDHALL S.T.W.	54,258	15.97	-	13,863	561	221,374
ALLERS S.T.W. - SHIELDHALL S.T.W.*	40,587	19.90	-	10,370	420	206,324
TOTAL	2,000,000	87.85	240,048	374,173	14,857	4,445,130

* Denotes that only 81.47% of the total available P.S. was taken from this S.T.W. to precisely total 2,000,000 P.E.

The column denoted as ‘PS’ represents the total quantity of P.S., in tons per year, that must be transported to the central plant. The column marked as ‘PS DM’ specifies the amount of dry matter, in tons per year (ton/y), present in the P.S. The ‘Frequency’ column indicates the number of journeys taken per year between the supply plants and the central plant. The last column in each Tables 5.6-5.8 illustrate the total distance, in kilometres (km), that must be covered for sludge transportation to the central plant. Both Scenarios 2.1 and 2.2 were applied to variant 2.2. However, the tables are different as Scenario 2.2 is using dried sewage sludge (90% DM) instead of conventional wet sewage sludge (5% DM).

Table 5.6. WWTPs included in Scenario 2.1 (from Figure 5.2).

Name	Weight	Distance	PS (3%)	PS (5%)	Frequency	Ton kilometer (ton*km)
	(PE)	(km)	(ton/y)	(ton/y)	(trips/y)	
DALMUIR PFI - DALMUIR WWTW - SHIELDHALL S.T.W.	581,220	11.32	-	148,502	6,012	1,680,500
SHIELDHALL S.T.W. - SHIELDHALL S.T.W.	563,713	-	240,048	-	-	-
DALDOWIE S.T.W. - SHIELDHALL S.T.W.	317,927	16.98	-	81,230	3,289	1,378,974
DALMARNOCK S.T.W. - SHIELDHALL S.T.W.	232,840	9.87	-	59,491	2,409	587,080
MEADOWHEAD W.W.T. SERVICE - SHIELDHALL S.T.W.*	304,300	42.09	-	77,749	3,148	3,272,272
TOTAL	**2,000,000**	**80.25**	**240,048**	**366,971**	**14,857**	**6,918,826**

* Denotes that only 91.55% of the total available P.S. was taken from this S.T.W. to precisely total 2,000,000 P.E.

Table 5.7. WWTPs included in Scenario 2.2 (from Figure 5.2).

Name	Weight	Distance	PS (3%)	PS DM (90%)	Frequency	Ton kilometer (ton*km)
	(PE)	(km)	(ton/y)	(ton/y)	(trips/y)	
DALMUIR PFI - DALMUIR WWTW - SHIELDHALL S.T.W.	581,220	11.32	-	8,250	334	93,361
SHIELDHALL S.T.W. - SHIELDHALL S.T.W.	563,713	-	240,048		-	-
DALDOWIE S.T.W. - SHIELDHALL S.T.W.	317,927	16.98		4,513	183	76,610
DALMARNOCK S.T.W. - SHIELDHALL S.T.W.	232,840	9.87		3,305	134	32,616
MEADOWHEAD W.W.T. SERVICE - SHIELDHALL S.T.W.*	304,300	42.09		4,319	175	181,793
TOTAL	**2,000,000**	**80.25**	**260,435**	**20,387**	**825**	**384,379**

* Denotes that only 91.55% of the total available P.S. was taken from this S.T.W. to precisely total 2,000,000 P.E.

Table 5.8. WWTPs included in Scenario 3.

Name	Weight	Distance	PS (3%)	PS DM (90%)	Frequency	Ton kilometer (ton*km)
	(PE)	(km)	(ton/y)	(ton/y)	(trips/y)	
DALMUIR PFI - DALMUIR WWTW - SHIELDHALL S.T.W.	2,000,000	-	851,667	25,550	-	-
TOTAL	**2,000,000**	**-**	**851,677**	**25,550**	**-**	**-**

Additional information on resources and operational requirements

In addition to energy and transport, technical and economic data were taken from previous project reports. This includes the PHA plant equipment, and capital or operational costs, and any assumptions made in relation to resource requirements and treatment efficiencies. In cases where this data could be refined for the specific case region of Scotland, Table 5.9 provides revised details for the CMA, LCA and SDG evaluation.

Table 5.9. Details of modified costs specific to case region of Scotland.

Item	Cost	Unit	Details
Electricity	57.5	€/MWh	Average £50 per MWh in 2022 (1.15 £ to € exchange rate)
Natural gas	15.0	€/MWh	Average £13 per MWh in 2022 (1.15 £ to € exchange rate)
Steam	10.2	€/t	Proportionate to change in natural gas costs in UK for 2022
Labour	11.98	€/hr	Scotland real Living Wage of £10.42 (<23 years old, April 2023)

5.2.4 Calculation of circularity indicators and complementary methods

Resource Outflows

To provide evidence that the production of PHA as opposed to alternative pathways helps retain resource value, this core circular indicators requires the calculation of the average lifetime of PHA as a product relative to the industry average, which in this case is PE (Eqn. 5.1).

$$LR_M = LS_{PHA} / LS_{PE} \qquad \text{Eqn. 5.1}$$

Where:

LR_M	*is the lifespan ratio of the PHA (bioplastic) versus PE*
LS_{PHA}	*is the lifespan of the PHA (years)*
LS_{PE}	*is the industry average lifespan of PE (years)*

The link between resource outflows with LCA and SDG indicators is outlined in Table 5.10.

Table 5.10. Relationship between resource outflows as a CMA indicator with complementary LCA and SDG indicators.

Indicator type	Specific indicator	Relationship to resource outflow indicator
LCA	All ReCiPe midpoint and 3 endpoint impact categories.	The production of PHA will inevitably impact all ReCiPe impact categories.
SDG	SDG 7.2.1 Renewable energy share in the total final energy consumption.	If PHA production diverts primary sludge away from other resource pathways, then this will reduce the share of renewable energy in the total final energy consumption at a global level.

Energy

Two circular indicators focus upon energy, one quantifying the proportion of renewable energy consumed in production (Eqn. 5.2), and the other focusing on the non-renewable resource outflows to support the life cycle of the product (Eqn. 5.3) i.e. residuals.

$$RE_{\%} = ((I_{RE} - O_{RE}) / (I_{TE} - O_{TE}))*100 \qquad \text{Eqn. 5.2}$$

Where:

$RE_{\%}$ *is the average percentage of renewable energy required to process one unit of P.S. (%)*
I_{RE} *is the inflow of renewable energy to process one unit of P.S. (kWh/ton P.S.)*
O_{RE} *is the outflow of renewable energy to process one unit of P.S. (kWh/ton P.S.))*
I_{TE} *is the total energy inflow to process one unit of P.S. (kWh/ton P.S.))*
O_{TE} *is the total energy outflow to process one unit of P.S. (kWh/ton P.S.))*

$$REC\text{-}E_{\%} = (I_{RES} / I_{TE})*100 \qquad \text{Eqn. 5.3}$$

Where:

$REC\text{-}E_{\%}$ *is the percentage of recovered energy from non-renewable flows in P.S. processing*
I_{RES} *is the inflow energy to process one unit of P.S. using residual, non-renewable sources (kWh/ton P.S.)*
I_{TE} *is the total inflow energy to process one unit of P.S. (kWh/ton P.S.)*

The quantities, forms and sources of forms energy has an impact on the following CMA, LCA & SDG as outlined in Table 5.11.

Table 5.11. Relationship between renewable energy and non-renewable resource as CMA indicators with complementary LCA and SDG indicators.

Indicator type	Specific indicator	Relationship between energy and indicator
LCA	Climate change, incl. biogenic carbon (kg CO_2 eq.)	Reflects the climate change impact associated with the energy required to produce PHA.
	Fossil fuel depletion (kg oil eq.)	Accounts for the non-renewable component of the total energy mix required in PHA production.
SDG	7.2.1 Renewable energy share in the total final energy consumption	If PHA production diverts primary sludge away from other resource pathways, then this will reduce the share of RE in the total final energy consumption at a global level.

Economic

Three economic circularity indicators were considered in this assessment and related to the value per mass of producing PHA (Eqn. 5.4). This can provide an estimation of resource use efficiency and validate the production of PHA as a valued resource for the region. In addition, the associated investment costs (i.e. capital expenditure or CAPEX costs) and production costs (i.e. operational expenditure or OPEX costs) as per the previous WOW! Capitalisation report and revisions are provided in Eqns. 5.5 and 5.6, respectively.

$$C_{PS} = C_T + O_T \qquad \text{Eqn. 5.4}$$

Where:

C_{PS} *is the cost per unit mass of P.S. processing (€/ton P.S.)*
C_T *is the total investment costs (€/ton P.S.)*
O_T *is the total operational costs to process one unit of P.S. (€/ton P.S.)*

$$C_T = C_E + C_c \qquad \text{Eqn. 5.5}$$

Where:

C_T *is the total investment costs (€/ton P.S.)*
C_E *is the total equipment costs including piping and instrumentation (€/ton P.S.)*
C_C *is the total civil engineering installation works (€/ton P.S.)*

$$O_T = O_E + O_T + O_R + O_c \qquad \text{Eqn. 5.6}$$

Where:

O_T *is the total operational costs to process one unit of P.S. (€/ton P.S.)*
O_E *is the total energy costs to process one unit of P.S. (€/ton P.S.)*
O_T *is the total transport costs to process one unit of P.S. (€/ton P.S.)*
O_R *is the total resources costs to process one unit of P.S. (€/ton P.S.)*
O_P *is the total personnel costs to process one unit of P.S. (€/ton P.S.)*

The economic implications of producing PHA were also evaluated to align with relevant SDGs as outlined in Table 5.12.

Table 5.12. Relationship between economic CMA indicators with complementary SDG indicators.

Specific indicator	Relationship between economics and indicator
8.4.2 Domestic material consumption (DMC), DMC per capita, and DPM per GDP	The proportion of PHA to be produced that can offset regional consumption of fossil-derived plastics, thus reducing DMC.
9.2.1 Manufacturing value added as a proportion of GDP and per capita	Creation of new value chain and jobs for PHA production to impact GDP.
12.2.1 Domestic material footprint, domestic material footprint per capita, and domestic material footprint per GDP	PHA can reduce the domestic material footprint by replacing a fossil-derived plastic with PHA as a bioproduct for the region.
12.5.1 National recycling rate, tons of material recycled	Reduce the overall quantity or tons of materials recycled and increase the volume of material being composted in the region.

Social

One social indicator was proposed to account for fair labours costs in the production of PHA, thus ensuring a Real Living Wage was applied rather than current National Living Wage which was considered in the initial CMA. This impact of providing a Real Living Wage within the cost of PHA production is evaluated, thus the percentage impact on overall production costs was considered in Eqn. 5.7.

$$LW_{\%} = ((R_{LW} - N_{LW}) / N_{LW}) * 100 \qquad \text{Eqn. 5.7}$$

Where:

$LW_{\%}$ *is the percentage difference between the real living wage and the national living wage (%)*
R_{LW} *is the real living wage in the UK in 2023 (€ or £)*
N_{LW} *is the national living wage in the UK in 2023 (€ or £)*

The social implications of producing PHA were also evaluated to align with relevant SDG as outlined in Table 5.13.

Table 5.13. Relationship between labour as a CMA indicator with a complementary SDG indicator.

Specific indicator	Relationship between labour and indicator
10.4.1 Labour share of GDP	Increasing the labour costs to align with Living Wage requirements would increase the labour share of GPD in the region.

5.2.5 Comparative Resources Pathways

Two alternative pathways were considered within the CMA based on (i) a comparison between PHA and incineration as both compete for P.S. as a resource, and (ii) a comparison between PHA and fossil-derived plastic as PHA can offset PE demands. Table 5.14 provides an overview of these alternative resource pathways with respect to their impact on relevant circularity indicator results.

The LCA will produce comparative midpoint and endpoint results of PHA production from P.S. with the incineration of P.S. and the subsequent production of energy, and PHA offsetting PE production as a fossil-derived plastics. The life cycle inventory collated from previous WOW! reports and adapted and to the specific Scenarios evaluated in this report. Midpoint and endpoint indicators (2016 v1.3 H (hierarchist)) will be presented using the ReCiPe impact assessment method to represent the direct and final impacts of PHA production and its comparative pathways for P.S.

The relevant SDGs relate to the energy impacts of each alternative to PHA production, with the differences outlined in Table 5.14 provides an overview of these alternative resource pathways with respect to their impact on relevant circularity indicator results.

Table 5.14. Impact of alternative circularity pathways to produce energy (incineration) or polyethylene (PE) on circularity indicators used to assess PHA resource recovery from P.S. (3%/5% DM).

Indicator Description	Alternative Pathway (Incineration)	Offset Fossil-derived Plastic (Polyethylene)
Average lifetime of product or material relative to industry average	n/a	PHA offers a shorter lifespan than PE (industry average).
Average % of consumed energy from renewable source	Incineration consumes no energy, with PHA production requiring different forms of energy.	PHA would consumes more energy in its production than PE, with both having a similar percentage consumption.
% recovered energy from residual, non-renewable resource outflows	Incineration recovers energy from this resource outflow.	n/a
Value per mass	n/a	PHA and PE unit costs

Table 5.15. Impact of alternative circularity pathways to produce energy (incineration) or offset polyethylene (PE) on SDG indicators used to assess PHA resource recovery from P.S. (3%/5% DM).

SDG Indicator	Alternative Pathway (Incineration)	Offset Fossil-derived Plastic (Polyethylene)
7.2.1 Renewable energy share in the total final energy consumption	n/a	Increasing the renewable energy share can occur by leaving the fossil resources used for PE in the ground.
8.4.2 Domestic material consumption (DMC), DMC capita, and DMC per GDP	PHA produces a product for the economy, incineration presents an end-of-life for the resource.	Requires a transition in consumption from PE to PHA.
9.2.1 Manufacturing value added as a proportion of GDP and per capita	Increased regional manufacturing to support PHA production, thus increasing manufacturing added value as a proportion of GDP as compared to other P.S. resources pathways.	
10.4.1 Labour share of GDP	More jobs required to support PHA production, thus increasing labour share of GDP as compared to other P.S. resource pathways.	
12.2.1 Domestic material footprint, material footprint per capita, and material footprint per GDP	n/a	Reduce material footprint by replacing PE with PHA.
12.5.1 National recycling rate, tons of material recycled	n/a	Replacing PE with PHA would remove some plastic from these statistics and reduce the tons of material recycled.

5.3 Step 3: Circularity assessment and reporting

5.3.1 Circularity performance

Resource Outflow

Literature suggests a wide range of expected lifespans for both PHA and PE (Acharjee et al., 2023). Polyethylene (PE) has a design life, (LS_{PE}) of 50-100 years for many products, but its potential to last up to a 1,000 years has been considered feasible (Moshood et al., 2022), representing a significant risk as microplastic pollution. PHA is a more challenging lifespan to quantify (LS_{PHA}), as it's biodegradability is attributed to the conditions in which it is exposed. PHA can last as long as fossil-derived plastics, but in the natural environment and exposure to water it can biodegrade in much less than one year, i.e. several weeks. As such, the $LR_{\%}$ may range from <1% to 100%, depending on the use conditions of the PHA.

The LR_M range for PHA of <1% to 100% represents an uncertainty around the circularity performance of PHA. However, this represents a positive outcome as PHA has the possibility of producing a result that is lower than the industry average lifespan of fossil-derived plastics like PE. For a typical material resource, a value of or near 1 would be deemed a strong result; however, in the case of bioplastics, reduced environmental burdens and an improved sustainability performance presents a case for a low value representing a strong result.

As the life cycle assessment (LCA) results may support the decision-making process in relation to the value of PHA as a replacement for PE, the comparison of both materials is presented in Section 5.3.3. The impact of the shift from fossil fuel based, to renewable electricity on PHA production is also considered in Section 6.3.4.

Energy

To quantify the percentage or proportion of renewable energy ($RE_{\%}$) consumed in PHA production, data relating to the energy inflows (both RE and non-RE) were required. The RE inflow (I_{RE}) and outflow (O_{RE}) equated to the proportion of RE consumed and produced from the PHA production process, respectively. In this case, the I_{RE} was determined as 21% (Section 5.2.3) of the 317.43 kWh/ton P.S. (Table 5.4) equating to 66.66 kWh/ton P.S. processed to produce PHA. This process did not produce RE, therefore the O_{RE} was deemed as 0 kWh/ton P.S. For the total energy inflows (I_{TE}) and outflows (O_{TE}), values of 317.32 kWh/ton P.S. (Table 5.4) and 0 kWh/ton P.S. leading to the production of PHA. The resultant $RE_{\%}$ equates as 21%, representing the percentage inflow of RE (I_{RE}) as no energy was produced from outflows of this process.

In this case the percentage of recovered energy from non-renewable flows, $REC\text{-}E_{\%}$, is 0 as no energy (RE or non-RE) was recovered in the PHA production process. This assumes that no excess sludge is produced and goes to anaerobic digestion or incineration, although it is recognised that the remaining biomass could be incinerated after PHA extraction.

The LCA results in Section 5.3.3. will address the climate change and fossil fuel demands of PHA production. Furthermore, the impact of an increased share of RE produced if an alternative pathway of incineration is considered will be addressed in Section 5.3.3.

Economic

The cost per unis mass (ton) of PHA (C_{PHA}) firstly requires the total investment costs (C_T) and the total operational costs (O_T), taking a 25-year operational period as part of the lifespan of operations.

The total investment costs (C_T), or CAPEX, to process P.S. equalled a total of €6.99 (£6.08) / ton P.S. or €709 (£616) / ton PHA were used for all Scenarios.

The operational costs (O_T) or OPEX, each Scenario has different totals, due to differences in transport costs (O_T), however similar energy (O_E), resource (O_R) and personnel (O_P) costs. Table 5.16 provides a breakdown and total of the operational costs associated with PHA production.

Based on this data, the cost per unit mass in processing P.S. or producing PHA (C_{PS}) can be determined as the combined investment and operational costs to represent the revenue value of one unit of P.S. processed (V_{PS}). This equates to a cost per unit equated to between €29.37-35.76 (£25.44-31.10) / ton P.S. or €2,972-3,619 (£2,584-3,174) / ton PHA.

The results show that annual resource costs (dimethyl carbonate (DMC), cooling and process water, and raw material) represented the greatest proportion of the total costs, ranging from 34.9-41.6%, followed by energy costs (25.6-30.2%) and the embodied or infrastructure costs (16.4-19.3%). Staff costs represented the smallest percentage in most Scenarios at between 7.7-9.0% of the total costs. Lastly, transport varied significantly from 0% in the stand-alone Scenario or as little as 0.8% for the decentralised scenario (Scenario 2.2), and up to 15.4% in the centralised scenario of Scenario 2.1.

Table 5.16. Breakdown and total operational costs for different regional Scenarios (as €/ton P.S. and €/ton PHA).

Item	Energy	Transport	Resources	Personnel	Total
Processing 1 ton of P.S.					
Scenario 1: Centralised; >50k P.E.	€10.97	€4.22	€14.95	€3.28	€33.42
Scenario 2.1: Centralised 300k P.E.		€6.57			€35.76
Scenario 2.2: Decentralised >300k P.E.		€0.28			€29.48
Scenario 3: Stand-alone 2m P.E.		-			€29.37
Processing 1 ton of PHA cake					
Scenario 1: Centralised; >50k P.E.	€1,110	€426	€1,530	€332	€3,381
Scenario 2.1: Centralised 300k P.E.		€664			€3,619
Scenario 2.2: Decentralised >300k P.E.		€28			€2,982
Scenario 3: Stand-alone 2m P.E.		-			€2,972

Considering that the cost of virgin PE is approximately €920 (£800), this means that offsetting fossil-derived plastic requires further cost reductions of up to 79%. Recycled plastic costs approximate €1,700 (£1,480) which makes it 85% more expensive than virgin PE. It should be noted that PHA production represents a new process and opportunities to optimise the costs of the associated processes can reduce these costs in the future. As such, PHA can become more competitive as its potential is realised.

The economic implications of producing PHA are dependent on the capacity to identify cost reductions or financial incentives to allow PHA to impact these SDG indicators. PHA production in Scotland can clearly create jobs in the region, and enhance its value chain, and in doing so impact domestic material consumption and footprints. This can impact the value chain by reducing the overall recycling rate of plastic by reducing the quantity of recyclable plastic in the economy.

Social

In the UK in 2023, the Real Living Wage is estimated at €12.54 (£10.90) as opposed to €11.98 (£10.42) for the National Living Wage. The percentage deficit between the current national living wage and real living wage is 4.6%.

This increase would present a further increase in the unit cost of P.S. processing or PHA production of €0.15-0.46 (£0.13-0.40) / ton P.S. or €15-46 (£13-40) / ton PHA. This cost would not make a significant impact on the total costs of P.S. processing or PHA production, equating as an approximate increase in the per unit costs of 0.5% to ensure the real living wage is met.

5.3.2 Complementary Methods

Environmental - Life Cycle Assessment

A summary of the LCA results, either as midpoint (Appendices) and/or endpoint results, are presented to provide an overview of the environmental impacts of PHA production as embodied and operational impacts (including transport as a distinct consideration for each scenario.

Embodied (Infrastructure) Burdens

The embodied burdens that arise from the PHA plant infrastructure were also quantified. Plant equipment includes the seven acidogenic fermentation reactors, the enrichment Sequential Batch Reactor (SBR), the accumulation vessel and the extraction vessel. Additional processing support equipment includes three centrifuges, a sludge dryer, evaporators for DMC recovery, a PHA compounder, pumps, and plant pipework. A small structure was also included to house the downstream processing equipment. The environmental burdens were based on the material requirements of the plant equipment. The reaction vessels were sized based on the volumetric flow that entered the vessel each cycle. The vessels were assumed to be made of 1% steel reinforced concrete with a thickness of 300mm, along with 100 mm of polyethylene insulation. The extraction reactor, downstream processing equipment, pumps, and pipework are all assumed to be stainless steel. The quantity of steel required for the downstream equipment is based off the weight of appropriately sized units found online. The pipework was quantified based on a basic plant layout. Civil works include excavations, foundations, and the downstream equipment housing structure. The foundation requirements for each vessel and housing structure were calculated based on the weight of materials and the mass of process materials contained within the equipment. The soil bearing capacity of clay was used as this is a conservative estimate of the footing area requirements.

The embodied impacts of infrastructure were calculated for the three areas of protection: damages to terrestrial ecosystem quality (EQ), human health (HH) and natural resources availability (NR). The embodied impact per tonne of primary sludge were $1.1\text{x}10^{-2}$ USD 2013 for Natural Resource availability, $6.55\text{x}10^{-10}$ species.yr for EQ and $6.91\text{x}10^{-7}$ DALY for HH. A further breakdown of the embodied impacts for each piece of infrastructure across the 25 impact categories that contribute to the three areas of protection can be found in Appendix A.

As shown in Figure 5.4, the tanks dominated overall and contributed to between 46-61% to these three endpoint areas of protection, reflected by the large amounts of reinforced concrete and stainless steel they required. Considering the process steps, the acidogenic fermentation step has the greatest impact from an embodied perspective. The fermentation vessels are the largest contributor to the overall EQ (75%), HH (63%) and NR (76%) burdens arising from the vessels or 44%, 29% and 46% of overall EQ, HH and NR impacts. The large daily inflow of sludge, combined with the seven-day retention time required for acidogenic fermentation means that this step requires the greatest volumetric capacity in the PHA production process; thus, a considerable quantity of concrete and reinforcing steel is required for these vessels.

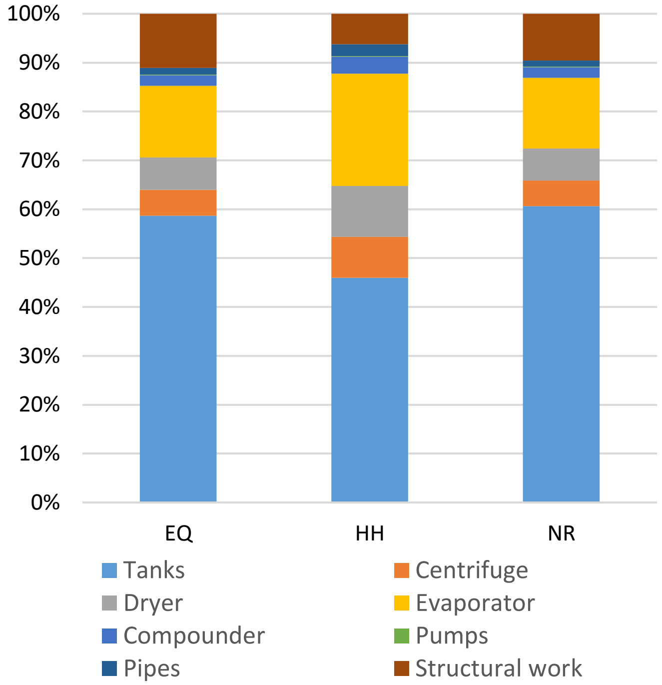

Figure 5.4. Percentage breakdown of the contributions from each infrastructure item to the three protecton areas relating to damange to terrestrial ecosystem quality (EQ), human health (HH) and natural resources availaiblity (NR).

The evaporators were the second largest contributor to all three areas of protection at 15% of EQ, 23% of HH and 14% of NR burdens. The significant burdens on the environment and HH this comes from the considerable quantity of steel included in the evaporator equipment, but also the marked impact that comes from stainless steel production, which is orders of magnitude higher than concrete production. Structural Work was the third largest contributor in the EQ and NR areas of protection, accounting for 11% and 10 % of the overall burdens respectively but was lower than either the dryer or centrifuge in the HH category. This is due to the relatively small HTPc impact arising from the structural work in comparison to the dryer and centrifuges (See Appendix A for breakdown). The centrifuges and sludge dryer presented comparable burdens across all impact categories, ranging from between 5% to 10%. The compounder and pipework represented a maximum of 3% of any impact on the areas of protection, with the pumps considered negligible across all impact categories.

Transport Considerations

The plots shown in **Figure 5.5** represent the endpoint areas of protection for transport impacts. These are derived from the details provided in Appendix B that represents the breakdown of impacts across a broader range of impact categories.

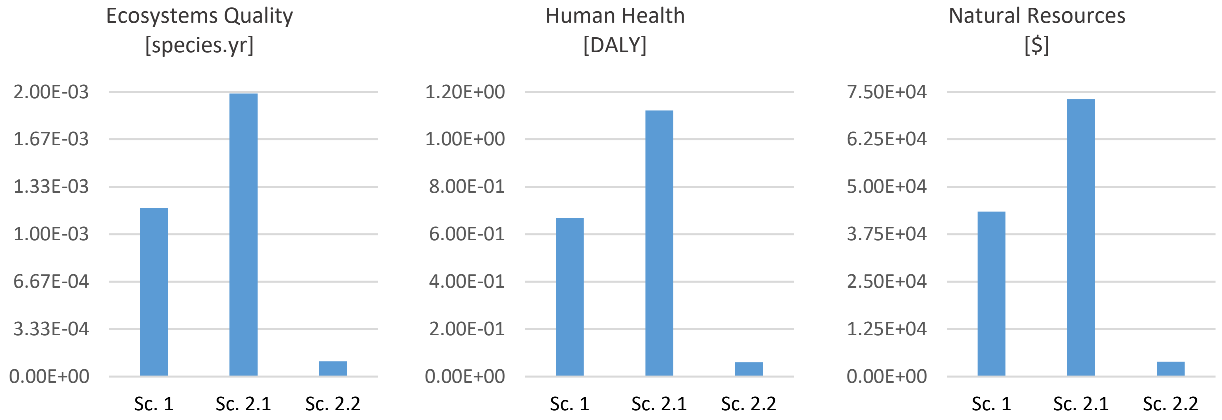

Figure 5.5. Comparative impact assessment for the different transport scenarios based on damage to terrestrial ecosystems quality (EQ), human health (HH) and natural resources availability (NR).

The Damage to EQ and HH consider emissions that are harmful to freshwater species, terrestrial and marine species, such as acidification of land and eutrophication of bodies of water. The damage to NR availability refers to the extraction of scarce resources, such as mineral deposits and fossil energy carriers. This area of protection covers the concern about limited resource availability and the future possibilities to use the resources we have today.

Scenario 2.2 (Sc. 2.2) presents a significantly lower impact on the 3 Endpoints Areas of Protection when compared to Scenario 1 (Sc. 1) and Scenario 2.1 (Sc. 2.1) and for transport would be the most optimal situation with regards to Environmental Impact Assessment. Scenario 2.1 presents the highest environmental impact and was nearly 19 times higher than for scenario 2.2 on all 3 Endpoints.

System Level - Embodied vs Operational Impacts

Due to the complexity in drawing conclusions from midpoints environmental contributions (Appendix B), the end score areas of protection level are presented in Figure 5.6.

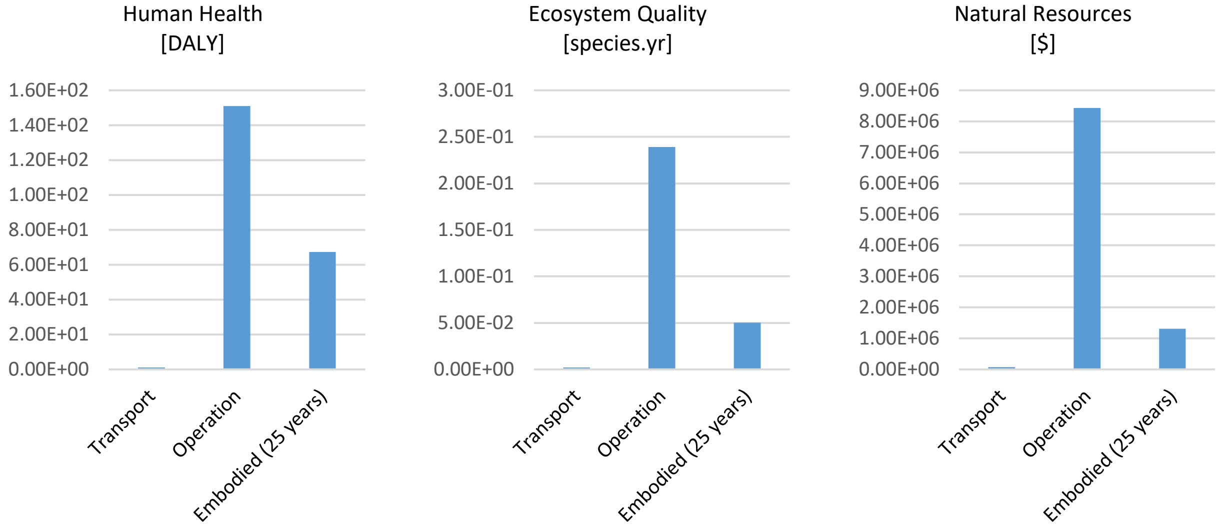

Figure 5.6. Comparative impact assessment for the different phases of the value chain based on damage to terrestrial ecosystems quality (EQ), human health (HH) and natural resources availability (NR).

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From the grouping procedure of the impact categories into normalized end score areas of protection, it was foreseeable that transport would also show negligible impact at this level of assessment; it is therefore omitted from this analysis. The impacts associated to the operational phase of the value chain presented lower performances on the three areas of protection. It was more than twice as harmful to HH compared to the embodied impacts, five times higher on damage to EQ, and 6.5 times higher regarding damage made to resource availability.

5.3.3 Comparison of PHA with alternative resource pathways

Comparative Impact Assessment: Operational Phase

This section focusses on the level of circularity of the different pathways considered during the research (PHA production, biogas production and incineration). It aims at comparing the processing of the dry matter content of 1 ton of primary sludge and excludes the transport and infrastructure phase. So only the production phase is included.

When looking at the environmental impacts of the production phase, these are the resultant of on the one hand the environmental impacts of the different routes and on the other hand the avoided burden. With the avoided burden (or impacts) we mean the environmental benefits that are associated to energy recovery and avoided use of oil-based materials. Specifically, these environmental benefits are:

- The recovery of heat and electricity for incineration;
- The production of PHA as replacement to produce virgin polyethylene and polypropylene and the production of biogas from the residual biomass replacing the extraction of natural gas;

- The production of biogas by processing the total amount biomass, as a replacement for the extraction of natural gas.

The environmental impacts of the different routes are presented in 3 ways in Figure 5.7, Figure 5.8 and Figure 5.9:

- The impact of PHA production, biogas production and incineration without avoided impacts;
- The avoided impacts that result from PHA production, biogas production and incineration;
- The net environmental impacts (sum of the impact of PHA production and the avoided impacts) of PHA production, biogas production and incineration.

This breakdown of the results allows to draw attention on the scenario which would benefit from further optimization, at operational level. In other words, a processing route showing relatively high amount of avoided burden while showing rather high environmental impacts due to operational parameters, can be highlighted as the processing route that would benefits from operational optimisation; Therefore, it also serves the purpose of hotspot analysis.

Comparative Impact Assessment: operational level without valorisation

Figure 5.10. shows that significant differences can be observed on the damage to HH, for the 3 processing routes. The incineration of the feedstock presents the lowest environmental impact, followed by conversion of the totality of the sludge into biogas. The production of PHA (and biogas) from the residual biomass within the same system is the highest contributor to damage to HH.

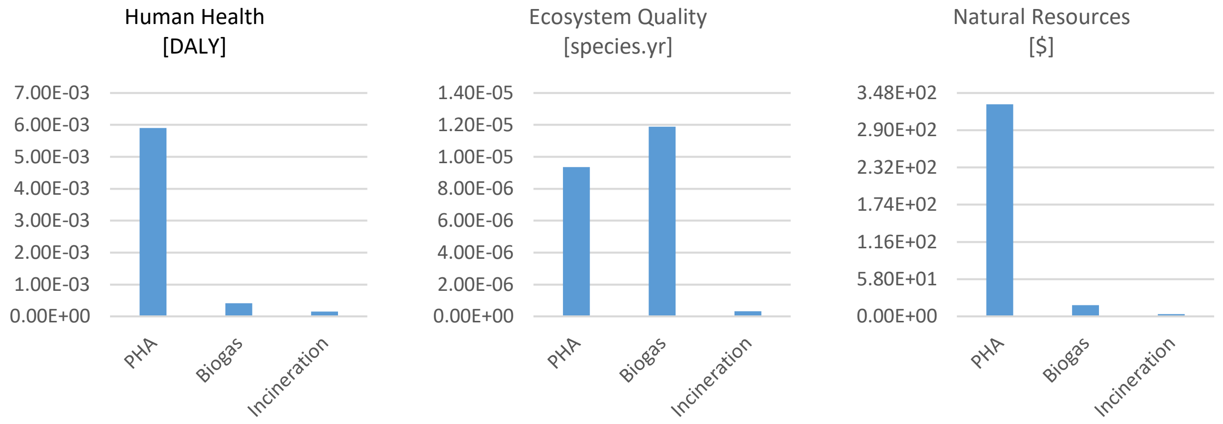

Figure 5.7. Impact Assessment: operational level without valorisation (production without avoided impacts) based on damage to terrestrial ecosystems quality (EQ), human health (HH) and natural resources availability (NR).

Regarding the damage to EQ, the biogas production route appeared to have the highest impact, while incineration is still displaying the lowest impact, and the PHA production with biogas from residual biomass performing slightly better on the same endpoint. Finally, both the incineration route as well as the biogas production route appeared significantly less impactful on the damage made to resource availability, the PHA production route presenting the highest impact.

Impact Assessment: Valorisation level

Figure 5.11 shows that the production of PHA has the highest avoided impact. This is due to the potential for producing 2 valuable outputs: PHA on one hand, and biogas from the left-over biomass, on the other hand.

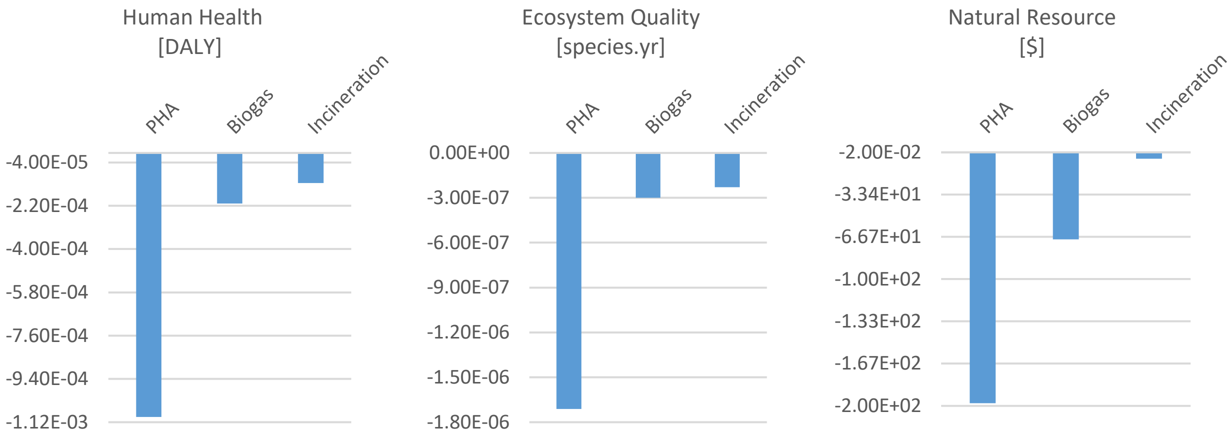

Figure 5.8. Impact Assessment: valorisation level (avoided Impacts due to fossil products replacement) based on damage to terrestrial ecosystems quality (EQ), human health (HH) and natural resources availability (NR).

The fermentation of the primary sludge towards biogas production solely was almost 5 times less beneficial to HH than the PHA production pathway, which also performed 6 times better in terms of avoided damage to EQ. Finally, it resulted in 3 times more savings on future NR availability.

The incineration scenario was used as a worst-case scenario and ranked, as expected, last on the amount of avoided impacts via the recovery of heat and electricity.

Impact Assessment: Net Environmental Impacts

Figure 5.12 shows the results of the net environmental impacts. The PHA production value chain performed the worst on the net damage to HH and net damage to resource availability. Both the biogas and incineration route presented low impacts on damage to HH (24 and 31 times lower than the PHA production route, respectively).

The biogas production pathway performed worse than the 2 other scenarios on damage to EQ (1.5 times higher than the PHA production route, and 135 times higher than the incineration route), however the study resulted in a negative net environmental impact regarding damage to resource availability. Incineration also presented a negative net impact.

Again, the midpoints impacts categories leading to this endpoint area of protection, regarding the PHA production process, are the largest contributors. The results showed to be the only scenario associated with a net burden on resource availability.

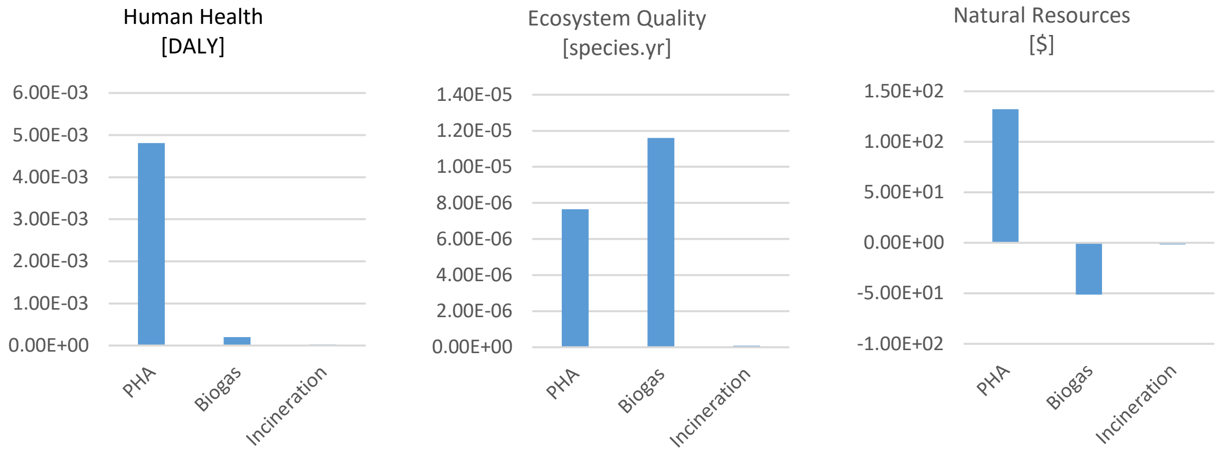

Figure 5.9. Impact Assessment: net environmental impact based on damage to terrestrial ecosystems quality (EQ), human health (HH) and natural resources availability (NR).

5.3.4 2023 vs 2030 Horizons

The PHA production process has a considerable electricity requirement that generates a significant contribution to the operational impacts of the process and production costs. As the decarbonisation of energy systems progresses and indeed accelerates over the coming years the magnitude and composition of the environmental impacts will also change. With the EU Renewable Energy Directive mandating a renewable energy target of at least 32% by 2030 (European Commission, 2022), and the United Kingdom's plan to fully decarbonise their electrical grid by 2035 (Department for Energy Security and Net Zero, 2023), the energy circularity of PHA production will invariably improve owing to the increase penetration of renewable energy sources in electricity generation. The environmental impacts will also change, under a future electricity network. The global warming potential and fossil fuel depletion arising from PHA production will also fall, due to the shift away from fossil fuels in the electrical grid (Baumgartner, 2021). Other less obvious impacts such as freshwater eutrophication and ionising radiation would also be expected to show significant reductions (Baumgartner, 2021). This, however, is not the case for all environmental impacts. Metal resource depletion and land use impacts of grid electricity are expected to increase significantly due to the development of wind and solar capacity and battery, which is likely to increase carcinogenic and non-carcinogenic HH burdens (Baumgartner, 2021). Therefore, passive changes to the impacts of PHA production will not necessarily improve under a low carbon electricity network.

The cost of electricity generation will also likely change in 2030, however there is a great deal of uncertainty as to the impact of grid decarbonisation on the cost of electricity. With the rapid decline in the cost of electricity production from renewable sources such as wind and solar, it is possible that the cost of grid electricity and, subsequently, PHA production will fall in the future (Heptonstall , 2020). However, the reduction in the cost of electricity depends on factors such as location, renewable energy resources and flexibility of the electricity system (Trondle, 2020), therefore it is not entirely certain what the impact of a future decarbonised electricity grid will have on the cost of production. However, it should be noted that PHA production from a wastewater stream is an immature process, therefore there is likely a potential for process improvements and efficiency gains as the process matures.

The impact of a changing electricity network will have mixed implications on the PHA production process with the process either improving or becoming more detrimental depending on the perspective of the assessment. To unconditionally improve the environmental and HH performance of PHA production, improvements should be made to the efficiency of the process to reduce the high energy demand currently arising from PHA production, rather than relying on passive improvements from regional strategies to reduce climate change.

5.3.5 Stakeholder reporting

From the findings of the CMA and complementary LCA and SDG analysis, specific results vary in their relevance and value to each stakeholder in the value chain. The CMA outputs present a benchmark in relation to the technical, economic, environmental, and social dimensions of PHA production, and offer a start-point to position itself as either an alternative to fossil-derived plastics, or to inform decision-making as to whether PHA production as compared to biogas or incineration pathways.

PHA producing company

For a PHA producing company, the CMA presents the clear differences between a centralised or decentralised system, with details regarding the energy intensity of PHA production, capital and operational expenditure, and incorporating a living wage when producing this bioplastic. Further LCA results demonstrated the embodied and operational burdens of a project considering energy, transport and infrastructural considerations.

Understanding the energy intensity of PHA production, and the associated breakdown of demands in the forms of electricity, heat and steam, helps inform a company on how to decarbonise and reduce the overall environmental burdens of these processes. It can inform decisions relation to the percentage of renewable energy ($RE_{\%}$) that can be achieved.

A breakdown of the operational costs per ton of PHA produced allows for prospective companies to identify measures that reduce the costs of the production process, providing a comparison to fossil-derived plastics and recycled plastics.

Furthermore, the LCA findings presents evidence of the embodied and operational burdens of delivering and using infrastructure for PHA production were evaluated fir different scenario, with 46-61% of the total impacts across all three areas of protection represented by the tanks. However, the operational burden results presented the largest endpoint burdens and therefore focusing on measures to reduce this through more sustainable energy sources can benefit the circularity of PHA production.

Local water authority / Waterboard

Waterboards or water authorities have the knowledge and data to quantify the burdens to implement infrastructure that supports PHA production. The net environmental impacts present information in relation to the options available to them in terms of choosing between PHA production, biogas, and incineration to manage sewage. The results also compare different centralised or decentralised scenarios which can inform the waterboards / water authorities of the differences that exist in relation to economic, environmental, and social impacts for each possible scenario.

Policy makers

Policy makers have access to important results that demonstrates the current challenges that PHA production faces, whether it is its excessive costs as compared to fossil-derived plastics and recycled plastics thus requiring incentivisation to accelerate the possibilities for PHA in the marketplace, or it is the reality that PHA will deviate primary sludge from alternative pathways such as biogas or incineration. The results can help guide policy makers who wish to deliver a circular economy and support measures to help improve the circular performance of PHA production.

6 Conclusions

This completed circularity measurement and assessment (CMA) quantifies the economic, environmental, and social impacts of PHA recovery from primary sludge. This CMA process is a first case study application of forthcoming ISO 59000 standards, accounting for the regional of Scotland within NWE. Data from previous WOW! deliverable reports provided the basis for much of the CMA process, with some additional variations on previous centralised/decentralised scenarios undertaken in this study to enhance the findings. PHA is recognised as only one possibility for a by-product from primary sludge, and CMA results can compare its burdens with biogas and incineration as alternative pathways of this resource. The CMA findings can therefore inform decision-makers of the economic, environment and social credentials of PHA production.

The CMA framework followed three key stages, namely setting the regional boundary conditions; undertaking a circularity measurement and data acquisition exercise; and evaluating results through a circularity assessment and reporting. Based on a capped 2 million p.e. for each scenario investigated, the initial resource flows were compared for several scenarios reflecting a decentralised, centralised or stand-alone system. An appropriate life cycle assessment (LCA) method and relevant sustainable development goal (SDG) mapping were also defined as complementary methods to produce additional outputs.

From the CMA, seven indicators were selected as the most appropriate for the evaluation of PHA, with one representing a core indicator (lifetime of product relative to industry average) and six additional indicators (energy, economic and social factors), all of which align with newly formed standards (ISO 59020). The evaluation of resource flows for PHA presented a wide-ranging set of results when compared to its comparator, a fossil-derived plastic e.g. polyethylene, as PHA has the potential to have short or long lifespans. In an economic sense, PHA derived plastics are not yet economically viable without incentivisation, regardless of centralised or decentralised scenarios. Furthermore, taking social factors into account, ensuring the living wage is provided will add a further 5% to the current costs of the product.

The LCA ReCiPe model was applied and indicators were selected to reflect resource flows, energy, and water, as well as economic and social metrics. The evaluation of embodied, transport and operational burdens over a 25-year system lifespan demonstrated that despite high impact attributed to tanks, the operational impacts represent the dominant burden across all three endpoint areas of protection. The net impact analysis did compare PHA production with biogas and incineration, and currently the findings highlights the greatest impacts for PHA for human health and natural resources, with ecosystem impacts more evident for biogas.

A set of specific and relevant SDGs (#7, 8#, #9, #10 & #12) were selected as complementary outputs for the CMA, as they addressed a range of technical, economic, social, environmental, and social factors. This informs the stakeholder pathways to the possibility of implementing PHA and provides information that can improve the performance of these systems.

The findings from the CMA was also mapped against stakeholder priorities, with PHA producing companies, local water authority / waterboards and policy-makers representing those who can benefit from or are the gatekeepers to success for PHA in the commercial market. Three primary themes emerged from the stakeholder reporting: (i) it can help determine the appropriateness of PHA production as opposed to alternative resource pathways (biogas or incineration), (ii) it provides a benchmark to support improvements in PHA production through implementing renewable energy sources, and (iii) identifying where incentivisation is required to accelerate PHA production as a circular resource on the market.

Abbreviations

Acidification: terrestrial	**TAP**
Climate change: freshwater ecosystems	CC:FW
Climate change: terrestrial ecosystems	CC:TE
Ecotoxicity: freshwater	FETP
Ecotoxicity: marine	METP
Ecotoxicity: terrestrial	TETP
Eutrophication: freshwater	FEP
Eutrophication: marine	MEP
Land use	LOP
Photochemical oxidant formation: terrestrial ecosystems	EOFP
Water use: aquatic ecosystems	WCP: AE
Water use: terrestrial ecosystems	WCP: TE
Climate change: HH	CC: HH
Human toxicity: carcinogenic	HTPc
Human toxicity: non-carcinogenic	HTPnc
Ionising radiation	IRP
Ozone depletion	ODP
Particulate matter formation	PMFP
Photochemical oxidant formation: HH	HOFP
Water use: HH	WCP:HH
Energy resources: non-renewable, fossil	FFP
Material resources: metals/minerals	SOP
Ecosystem quality (species.yr)	EQ (species.yr)
HH (dalys)	HH (DALYs)
Natural resources (USD 2013)	NR (USD 2013)

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Appendix A

Additional LCA Midpoint Results of Embodied Impacts

From Figure A1.1 it is evident that Terrestrial Ecosystem Climate Change category (CC:TE) is the greatest environmental burden arising from PHA plant infrastructure with a total impact of 4.3×10^{-10} species.yr/ton P.S processed. The CC:TE impact makes up 65% of the overall EQ Impact of 6.5×10^{-10} species.yr/ton P.S. This is over four times the magnitude of the next largest environmental burden coming from Terrestrial Acidification (TAP) at 8.8×10^{-11} which contributes 13% of the overall EQ burden.

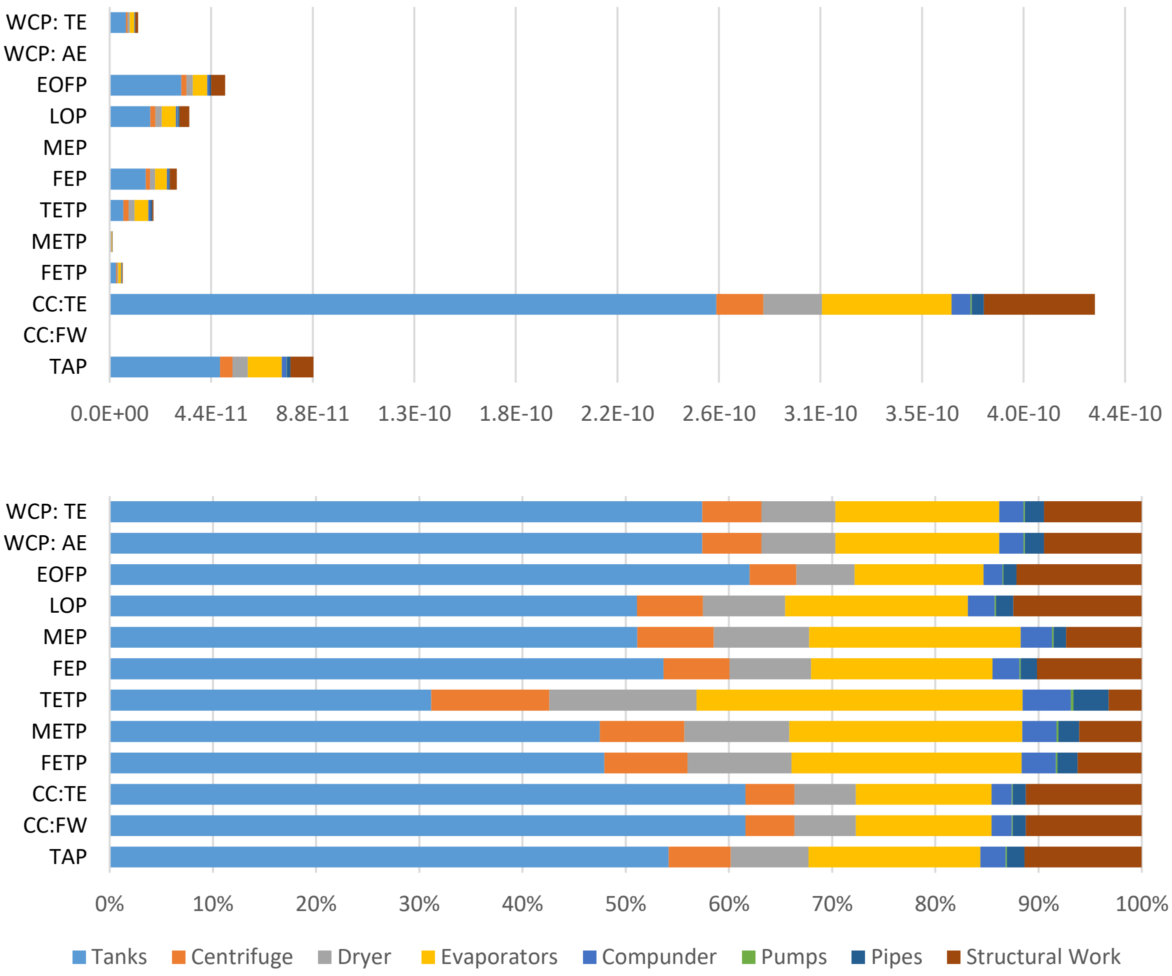

Figure A1.1. Breakdown of the contributions from emodied burdens across the EQ impact categories (measured in species.yr).

The carcinogenic human toxicity (HTPC) burden is the greatest burden arising from PHA infrastructure at 3.4×10^{-7} DALY or 49% of the overall burden on HH, as illustrated in Figure A1.2. Particulate matter formation

(PMFP) contributes the second highest burden of 1.7x10^{-7} DALY accounting for 25%, with Climate change: HH (CC:HH) making the third largest contribution of 1.4x10^{-7} DALY or 20% of the HH burden. The non-carcinogenic human toxicity (HTPnc) makes a smaller, yet appreciable contribution of 3.1x10^{-8} DALY or 4% of the overall burden. The remaining impact categories have negligible contributions <1% of the overall HH burden.

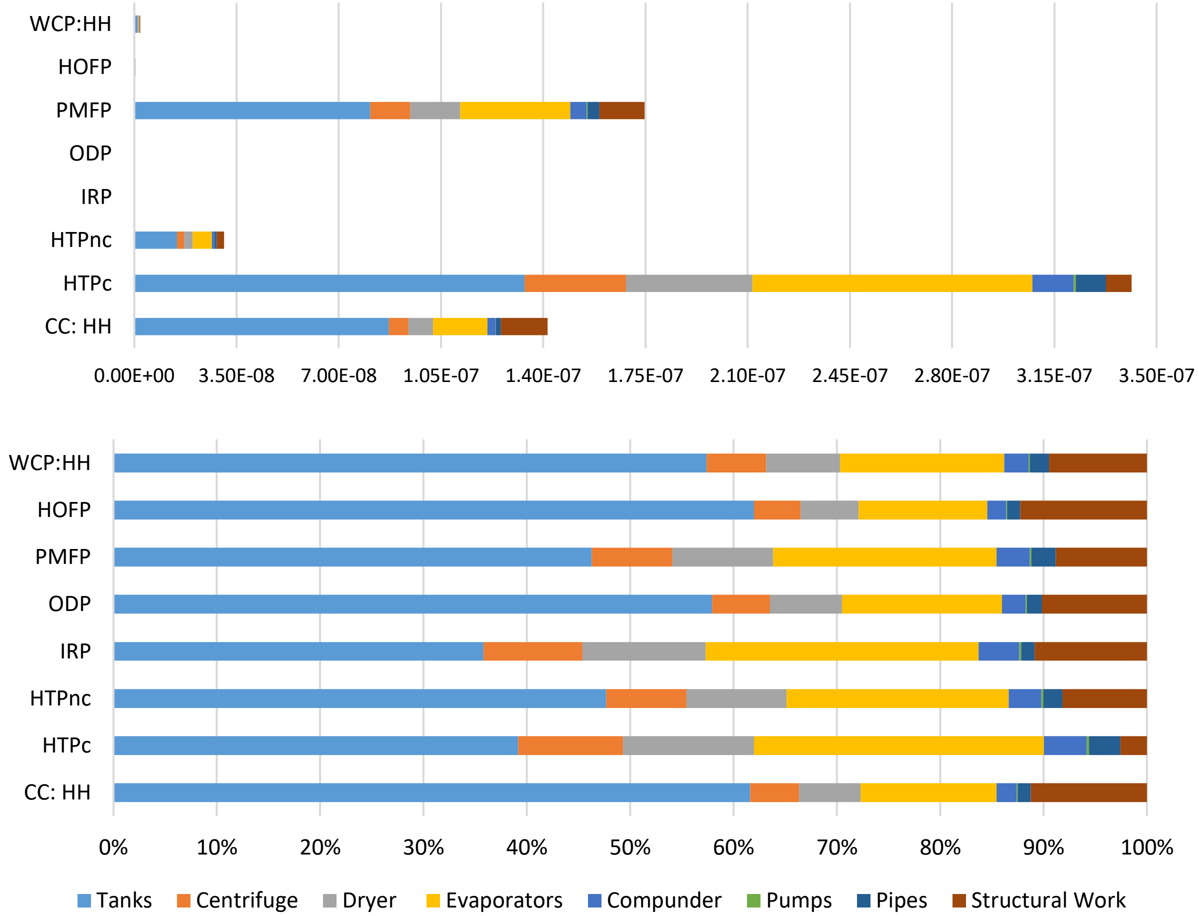

Figure A1.2. Breakdown of the contributions from emodied burdens across the HH impact categories (measured in DALY).

The burden on NR is shown in Figure A1.3Error! Reference source not found.. The depletion of fossil fuel resources is the dominant contributor to the overall NR burden contributing €0.0088/£0.0076 per tonne sludge processed, accounting for 67% of the overall burden of €0.013/£0.011. Mineral resource depletion makes a comparable much smaller, but appreciable contribution of €0.0044/£0.0038 or 33% of the overall NR burden.

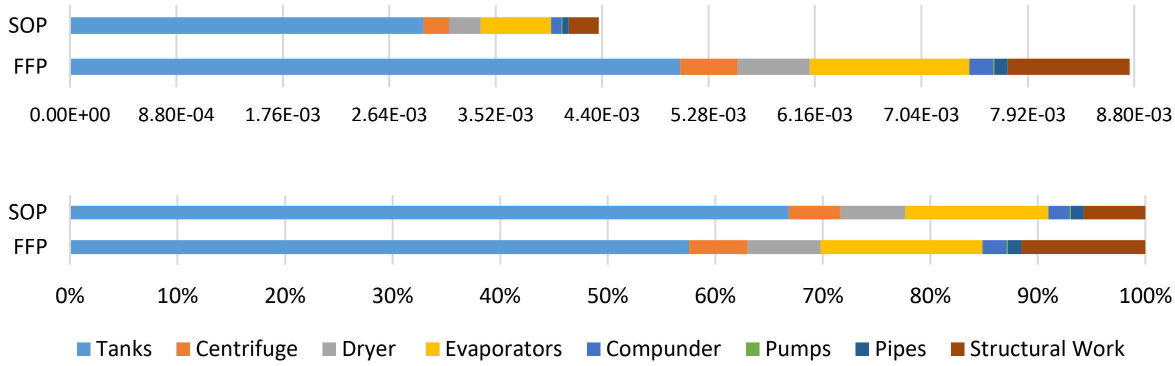

Figure A1.2. Breakdown of the contributions from emodied burdens across the natural resources impact categories (measured in Euros ($) in 2023).

Appendix B

Credits contribution of indicators for PHA production

The functional unit chosen for the assessment of the different transport scenarios, within the scope of the project, corresponds to the total amount of primary sludge as described in Tables 6.5-5.7. This basis for the impact calculations on the Endpoints Areas of Protection has been selected since evaluating the optimal scenario for transport can only be done by considering the actual trucks' capacities and distances, respective of scenario 1 (S1), scenario 2.1 (S2.1) and scenario 2.2 (S2.2). For all transport scenarios, a payload of 24.7 tons was chosen, with a mix of Euro 5 trucks (44%) and Euro 6 trucks (56%) and a utilisation rate of 61%. Scenario 3 corresponded to a centralized scenario that did not have any transport burdens. The results of the comparative assessment at midpoint level are shown in Table B1.1.

Table B1.1. Midpoint Impacts comparison of the three transports' scenarios.

Midpoints ReCiPe 2016	Value
Clim. Ch., default, excl. carbon [kg CO2 eq.]	9.07E+05
Clim. Ch., incl biogenic carbon [kg CO2 eq.]	9.03E+05
Fine Particulate Matter [kg PM2.5 eq.]	3.27E+02
Fossil depletion [kg oil eq.]	2.83E+05
Freshwater Consumption [m3]	7.94E+02
Freshwater ecotoxicity [kg 1,4 DB eq.]	1.69E+02
Freshwater Eutrophication [kg P eq.]	2.68E+00
Human toxicity, cancer [kg 1,4-DB eq.]	2.45E+02
Human toxicity, non-cancer [kg 1,4-DB eq.]	8.54E+04
Ionizing Radiation [kBq Co-60 eq. to air]	4.88E+02
Land use [Annual crop eq.·y]	4.06E+04
Marine ecotoxicity [kg 1,4-DB eq.]	4.68E+02
Marine Eutrophication [kg N eq.]	1.35E+01
Metal depletion [kg Cu eq.]	1.25E+03
Photo. Oz. Formation, Eco. [kg NOx eq.]	2.06E+03
Photo. Oz. Form., Hum. Hea. [kg NOx eq.]	2.05E+03
Strato. Ozone Depletion [kg CFC-11 eq.]	6.45E-01
Terrestrial Acidification [kg SO2 eq.]	1.02E+03
Terrestrial ecotoxicity [kg 1,4-DB eq.]	7.93E+04

The results of the analysis showed that transport S2.2 accounts for only 3.3% of the total impacts of all scenarios summed up, as compared to 37.8% and 58.9% for S1 and S2.1, respectively. This outcome is expected when looking back at Tables 5.6-6.1 as S2.2, in comparison to the analysed alternatives, presented the lowest impacts on all midpoints impact categories due to the difference in annual transport frequency as well as due to the dry matter content considered, by comparison to the other scenarios.

Figure B1.1 presents the breakdown of credit across each endpoint category for PHA production against LDPE, biogas, or PP production.

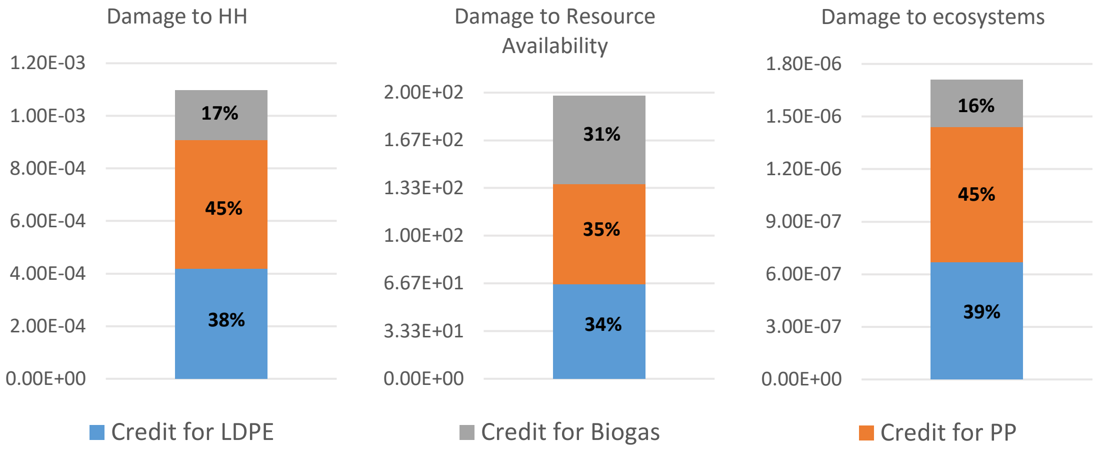

Figure B1.1. Breakdown of credits contribution for PHA production.

System Level – Transport vs Embodied vs Operational Impacts

Nearly 59% of the transport impact is allocated to S2.1. Therefore, this scenario is selected as the basis for the impact assessment of the separate parts of the value chain (transport impacts, operational impacts, and embodied impacts) route. This is considered a worst-case scenario since it presents the highest environmental impact from all transport scenarios.

The results are shown in Table B1.2 at midpoints level. This was done to draw conclusions with regards to the significance of the environmental impacts of transport compared to the environmental impacts of a yearly PHA production and the embodied impacts, assuming a lifetime of 25 years.

Table B1.2. Environmental impact contribution of transport compared to the production of PHA and embodied carbon impacts, at midpoints level.

Midpoints ReCiPe 2016	Midpoints			Relative Contribution			TOTAL
	Transport S2.1	Yearly PHA Ops	Embodied Impacts (25 yrs)	Transport S2.1	Yearly PHA Ops	Embodied Impacts (25 yrs)	
Clim. Ch., default, excl. carbon [kg CO2 eq.]	5.32E+05	7.56E+07	1.14E+07	1%	86%	13%	8.75E+07
Clim. Ch., incl biogenic carbon [kg CO2 eq.]	1.92E+02	1.64E+04	1.98E+04	1%	45%	54%	3.64E+04
Fine Particulate Matter [kg PM2.5 eq.]	1.67E+05	3.39E+07	2.55E+06	0%	93%	7%	3.66E+07
Fossil depletion [kg oil eq.]	4.68E+02	4.61E+05	1.09E+05	0%	81%	19%	5.71E+05
Freshwater Consumption [m3]	9.95E+01	1.83E+03	7.79E+05	0%	0%	100%	7.81E+05
Freshwater ecotoxicity [kg 1,4 DB eq.]	1.58E+00	2.65E+01	4.91E+03	0%	1%	99%	4.94E+03
Freshwater Eutrophication [kg P eq.]	1.44E+02	1.73E+04	9.41E+06	0%	0%	100%	9.43E+06
Human toxicity, cancer [kg 1,4-DB eq.]	5.03E+04	5.44E+05	9.85E+06	0%	5%	94%	1.04E+07
Human toxicity, non-cancer [kg 1,4-DB eq.]	2.87E+02	1.79E+06	4.09E+05	0%	81%	19%	2.20E+06
Ionizing Radiation [kBq Co-60 eq. to air]	2.39E+04	7.81E+05	2.04E+05	2%	77%	20%	1.01E+06

Land use [Annual crop eq.·y]	2.76E+02	8.59E+03	1.10E+06	0%	1%	99%	1.11E+06
Marine ecotoxicity [kg 1,4-DB eq.]	7.97E+00	3.33E+02	5.21E+02	1%	39%	60%	8.62E+02
Marine Eutrophication [kg N eq.]	7.33E+02	4.50E+04	3.43E+06	0%	1%	99%	3.48E+06
Metal depletion [kg Cu eq.]	1.22E+03	7.16E+04	3.08E+04	1%	69%	30%	1.04E+05
Photo. Oz. Formation, Eco. [kg NOx eq.]	1.21E+03	7.03E+04	2.85E+04	1%	70%	28%	1.00E+05
Photo. Oz. Form., Hum. Hea. [kg NOx eq.]	3.80E-01	6.33E+00	1.88E+00	4%	74%	22%	8.59E+00
Strato. Ozone Depletion [kg CFC-11 eq.]	6.03E+02	4.82E+04	3.04E+04	1%	61%	38%	7.92E+04
Terrestrial Acidification [kg SO2 eq.]	4.67E+04	1.23E+07	5.31E+07	0%	19%	81%	6.55E+07
Terrestrial ecotoxicity [kg 1,4-DB eq.]	5.32E+05	7.56E+07	1.14E+07	1%	86%	13%	8.75E+07

As can be seen, the environmental impact of transport is only a low contributor in comparison to PHA production and embodied impacts. It contributes to less than 2% of the total environmental impact on 17 of the 19 midpoints, and only shows a contribution of 4% on the Photochemical Ozone Formation and its effect on HH. Since transport does not contribute to more than 5% of the emissions on any of the midpoints, it can be omitted from the analysis from this point on. This is decided based on cut-off criteria rule regarding environmental significance (International Standard, 2006), and consequently the other transport scenarios (1 and 2.2) can also be considered negligible.

The yearly PHA operation presents significantly worse environmental impacts than the embodied impacts for 7 of the 19 midpoints impact categories. These include climate change excluding biogenic carbon (73% higher), fine particulate matter formation (86% higher), fossil depletion (62% higher), human toxicity, non-cancer (62% higher), Ionizing radiation (57% higher), photochemical ozone formation, ecotoxicity (42% higher) and terrestrial ecotoxicity (73% higher).

On the other hand, the embodied impacts show significantly worse environmental impacts for 7 of the 19 midpoints impact categories. These include freshwater consumption, freshwater eutrophication, freshwater ecotoxicity, Human toxicity, cancer, Marine Eutrophication, land use and terrestrial acidification.