Interreg North-West Europe WOW!

European Regional Development Fund

REPORT

DATE: December 2022

ACTION: A1 Site selection for centralized PHA compounding and processing

SUBJECT: D1.1 Report on selection of WWTPs in 3 NWE regions that are suitable for PHA production

D1.2 Report and GIS maps about most suitable locations to realize a centralized PHA compounding and processing facility

WOW! is supported by the Interreg North-West Europe program.

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Content

1 Introduction

Within the framework of WOW! Project, the market potential and technical feasibility for production of bioplastic from sewage with primary sludge as feedstock has been proved. The developed production process of bioplastic from primary sludge is shown in Figure 1-1, which can be divided into 3 stages including PHA-enrichment, PHA-extraction and PHA-compounding.

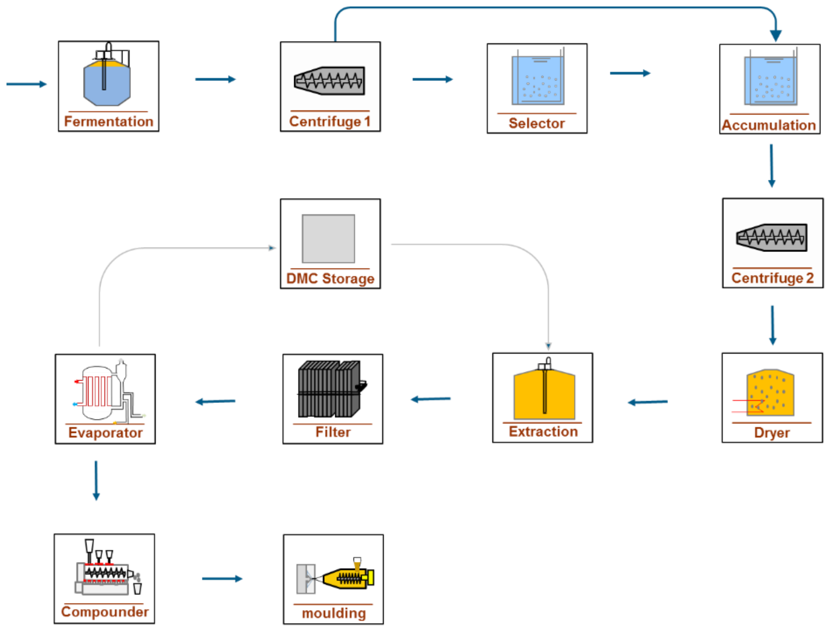


Figure 1-1: Flow diagram of PHA production

In the report of techno-economical assessment for bioplastic production from sewage (Khan, 2021), the economic feasibility of a theoretical large-scale plant with PHA-production capacity of 5000t/y has been assessed, which correspond to a demand of primary sludge from around 2,000,000 PE. In reality, a single WWTP with 2,000,000 PE isn't common. Therefore, for a practical capitalization of bioplastic production from sewage, possible concepts have to be studied with regard to the logistics, finances and sustainability.

This report is the deliverable 1.1 & 1.2 of Activity A1 of WOW! Capitalisation. The objective is to identify the most suitable location to realize PHA production and processing in 3 NWE regions including Scotland, Ireland and Saarland. The cost analysis serves as the basic for the location selection, which is conducted with the similar method in (Khan, 2021).

The possible concepts were firstly proposed based on preliminary cost analysis with consideration of the production process. With the help of Geographic Information System (GIS), the possible locations for the installation of system for different PHA production stages were selected to be considered as different variants. The variant - specific cost analysis was then conducted for the final determination.

2 Activity D1.1 – site selection

Before reporting on the most suitable locations to realize a centralized PHA facility – which is activity D1.2 and described further after this chapter – a site selection for this study was made.

Before the site selection, a region selection was done. It was decided to select Ireland, Scotland and Saarland in Germany as regions to analyze. The UWWTD (Urban Waste Water Treatment Directive) website was consulted to gather data for the selected regions:

- Ireland has 175 STPs spread around the country, exceeding a capacity > 2000 PE
- Scotland has 153 STPs spread around the country, exceeding a capacity > 2000 PE
- Germany has about 3800 STPs spread around the country

A cut-off criteria was set initially to select only treatment facilities which have a capacity over 2000 PE (People Equivalent). Due to the fact that Germany was too big as region for being a case study, initially it was chosen to focus on the region of Saarland with 60 STPs exceeding a capacity > 2000 PE.

The facilities were all processed through the Decision Support Tool (developed in WPT2 of the WoW project and to be downloaded here: https://www.coebbe.nl/projecten/wow/).

All treatment plant without primary treatment were erased from the selection, since primary treatment is essential for PHA production. The remaining selection was processed through the DST.

The BOD/COD ratio was not known for all STPs (sewage treatment plants), for the ones which were unknown, the assumption was made it is sufficient enough to stay in the site selection. For the known ones with a ratio under the required value, these were erased from the selection.

The results were as follows (as being able to produce PHA at a single STP):

Ireland: 12 STPs were promising, 14 STPs were not yet clear and 136 STPs seemed to be not suitable
Scotland: 23 STPs were promising, 11 STPs were not yet clear and 119 STPs seemed to be not suitable
Saarland: 3 STPs were promising, 6 STPs were not yet clear and 51 STPs seemed to be not suitable

As result, the decision was taken to continue only with STPs having 10.000 PE or more. The remaining selection for all 3 regions was taken as input for activity D1.2. Further developments regarding the selection is described in the corresponding chapters in this report.

3 Basis for cost analysis

The cost analysis is conducted on the basis of the method and results presented in (Khan, 2021), which include the mass/energy balance of the PHA production, CAPEX and OPEX for a centralized plant with a PHA production and processing capacity of 5000t/a as well as the method used for the cost estimation.

3.1 CAPEX

Table 3-1 shows the CAPEX breakdown for the centralized plant with the capacity of 5000t/a

Table 3-1: CAPEX breakdown for the centralized plant with the capacity of 5000t/a

	CAPEX breakdown [1)]	CAPEX (annulized)	Investment cost[2)]	Piping	Instrumentation /Electrical	Engineering cost	Civil works	Start-up	equipment cost
Plant equipment				15% E-cost [1)]	25% E-cost [1)]	10% E-cost [1)]	34% E-cost [1)]	12% E-cost[1)]	
Sum	101%	4,156,810 [1)]	64,257,052	4,917,632	8,196,053	3,278,421	11,146,631	3,934,105	32,784,210
Fermentation reactor	14%	581,953	8,995,987	688,468	1,147,447	458,979	1,560,528	550,775	4,589,789
Centrifuge 1	14%	581,953	8,995,987	688,468	1,147,447	458,979	1,560,528	550,775	4,589,789
Selection reactor	20%	831,362	12,851,410	983,526	1,639,211	655,684	2,229,326	786,821	6,556,842
Accumulation reactor	28%	1,163,907	17,991,975	1,376,937	2,294,895	917,958	3,121,057	1,101,549	9,179,579
Centrifuge 2	15%	623,522	9,638,558	737,645	1,229,408	491,763	1,671,995	590,116	4,917,632
Dryer	2%	83,136	1,285,141	98,353	163,921	65,568	222,933	78,682	655,684
Extraction reactor	1%	41,568	642,571	49,176	81,961	32,784	111,466	39,341	327,842
Filter[3)]									
Evaporator[3)]									
Compounder	3%	124,704	1,927,712	147,529	245,882	98,353	334,399	118,023	983,526
Injection moulding	4%	166,272	2,570,282	196,705	327,842	131,137	445,865	157,364	1,311,368

1) Data obtained from TEA

2) Investment cost was calculated based on the annulized CAPEX with the equation for cost annualisation obtained from TEA

3) There is no information about the investment cost of filter and evaporator in TEA

Together with the equation 1-1, in which A represent the equipment with a larger capacity than B, CAPEX for plant in other scale can also be estimated. The applied exponent for different equipment is also adopted from (Khan, 2021) as shown in Table 3-2. The capacity of equipment is represented by the feedstock amount of each equipment calculated with mass balance.

$$Cost\ of\ equipment\ A = (cost\ of\ equipment\ B) \times (\frac{Capacity\ of\ A}{Capacity\ of\ B})^{exponent} \qquad \text{Eq.(1-1)}$$

Table 3-2: exponent for different equipment

		Exponent
PHA-Enrichment		
1	Fermentation reactor	0.75
2	Centrifuge 1	0.6
3	Selection reactor	0.78
4	Accumulation reactor	0.78
5	Centrifuge 2	0.6
PHA-Extraction		
1	Dryer	0.6
2	Extraction reactor	0.66
3	Filter	
4	Evaporator	
PHA-Compounding		
1	Compounder	0.6
2	Injection moulding	0.6

In consideration of composition of CAPEX, 35%, 55% and 10% of total CAPEX are separately assigned to construction engineering, mechanical engineering and instrumentation/control engineering with a depreciation period of 25a, 15a and 10a respectively. With an interest rate of 2%, the annualized CAPEX can also be estimated.

3.2 OPEX

The energy, material and personal demand for each step during the PHA production and processing are also adopted from (Khan, 2021) summarized as in Table 3-3.

Table 3-3: specific energy, material and personal demand

	electricity		heat		steam		Personnel
	unit		unit		unit		(per shift)
Acidogenic Fermentation	kWh/m³ sludge	96.9	kWh/m³ sludge	23.4			0.02
centrifuge 1	kWh/m³ sludge	1.88					0.35
Selection reactor	kWh/m³ sludge	2.51					0.5
Accumulation reactor	kWh/m³ sludge	2.4					0.5
centrifuge 2	kWh/m³ sludge	1.88					0.35
dryer	KWh/kg evaporated water	0.16	kWh/ kg evaporated water	1.45			0.5
extraction	kW/m³	0.01			t /t dried PHA-rich biomass	1.1	0.2
DMC stored tank							
filter							0.15
evaporator					t /t filtrate	0.06	0.25
compounder	KWh/t	441.7					0.2
injection moulding	KWh /t	1503.4					0.2

For the determination of the material costs, the costs according to Table 3-4 from (Khan, 2021) and the amounts of raw materials calculated from the mass balance are taken into account.

Table 3-4: Unit price for different resource

Unit cost			
1	Electricity	93	€/MWh
2	Natural gas	34	€/MWh
3	Steam	24.6	€/t
4	Cooling water	0.5	€/m3
5	Process water	1	€/m3
6	Dimethyl carbonate	1	€/kg
7	Raw materials	3	€/kg
8	Labor	31.2	€/h

Furthermore, the insurance cost and maintenance cost were assumed to be 67% of labor cost and 0.5% of annualized CAPEX as in (Khan, 2021). The cost for primary sludge and PHA-biomass transport was assumed to be 10€/km for a truck with a loading capacity of 25t.

3.3 Mass balance

The mass balance for PHA production and processing was adopted from (Khan, 2021) for the case with 3% dry matter (DM) content in primary sludge (PS) input.

When the input primary sludge are extern from other plants, 5% DM-content is assumed. In this case, the mass balance for PHA production and processing is adjusted based on the assumption that PHA-rich biomass and PHA production amount with the same amount of DM input is constant. Table 3-1 shows the yield coefficient derived from the mass balance used in (Khan, 2021)

Table 3-5: Yield coeffient

Yield coefficient	
$tDM_{PHA\text{-}rich\ biomass}/tDM_{ps,input}$	0.36
$tPHA/tDM_{PHA\text{-}rich\ biomass}$	0.56

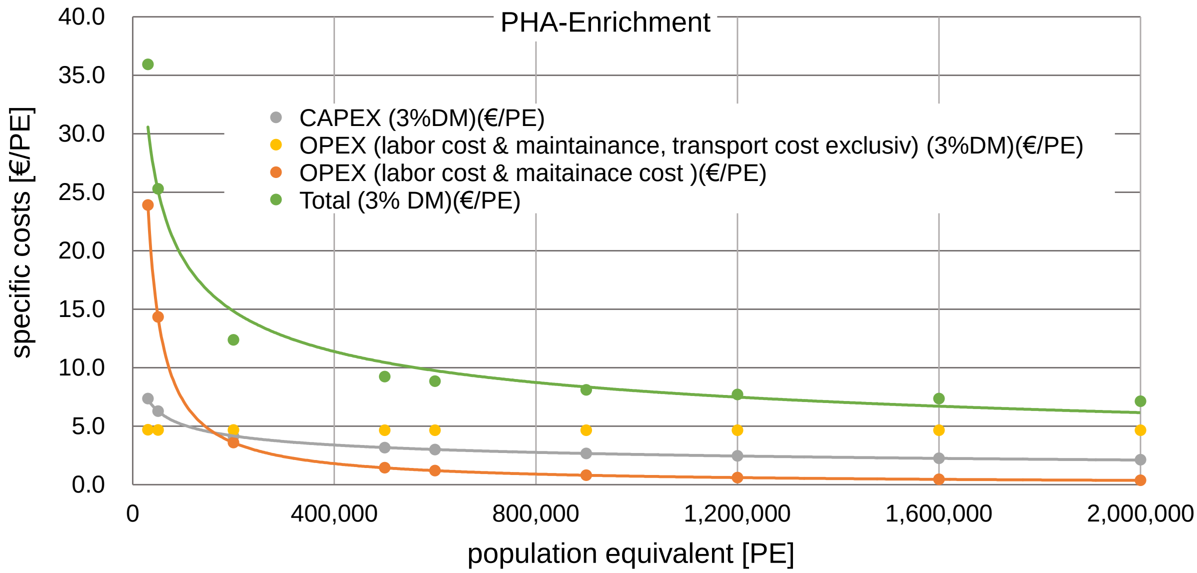
4 Cost analysis and initial concepts

4.1 Cost in dependence of size and number of involved plant

According to (Khan, 2021), a PHA production of 5000 t/a with a total annual investment of 26,252,362€ results in a minimum selling price lower than market price. For that, a total amount of PS-input of around 25,000 tDM/a is required, which correspond to around 2,000,000 PE with a specific PS-production of 35 gDM/PE/d. Since a single WWTP with this capacity is rare, the decentralized concept with PS or PHA-rich biomass transport is more practical.

In Figure 4-1, the specific cost for construction as well as operation a PHA-Enrichment system in dependence of the scale given in PE with 3% DM and 5% DM in PS-input is presented, which shows a higher specific cost for PHA-Enrichment in a small scale resulting from a higher CAPEX and constant labor cost independent of system scale. This indicates that the installation of PHA-Enrichment system should be as centralized as possible.

Furthermore, with the increasing of DM content in PS-input, the required size of system is reduced with the same amount of PHA-rich biomass produced, which lead to a significant reduction of CAPEX and OPEX with regard to the required material resource.



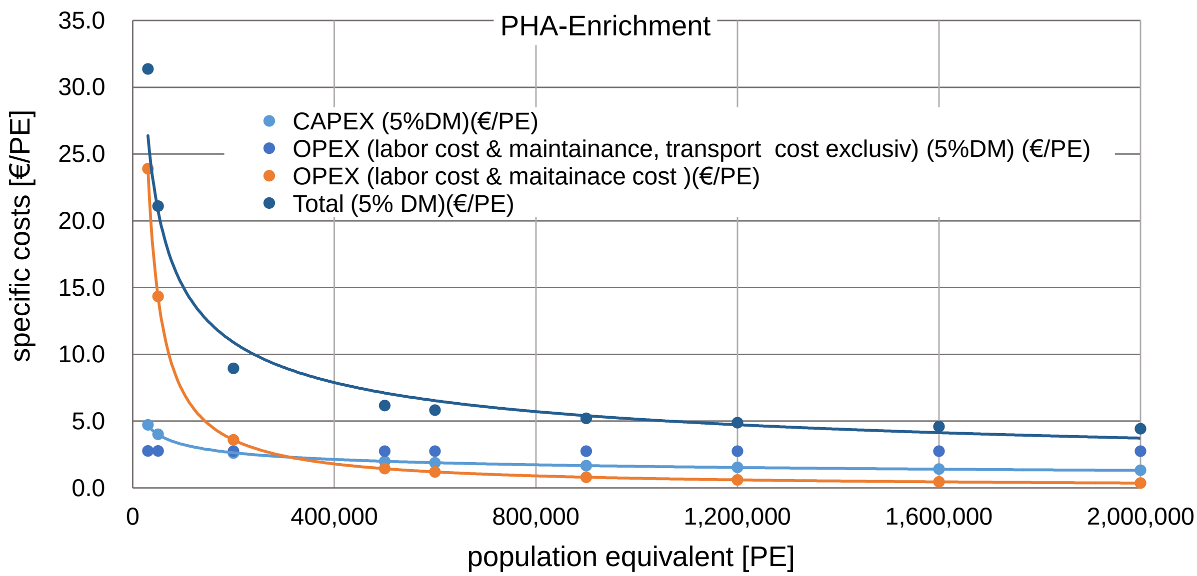


Figure 4-1: specific cost for construction as well as operation a PHA-Enrichment system

Figure 4-2 shows the specific cost for the PHA-extraction and PHA-compounding system with regard to the scale given in PE. Similar to PHA-Enrichment system, a less specific cost can be achieved with a larger scale system.

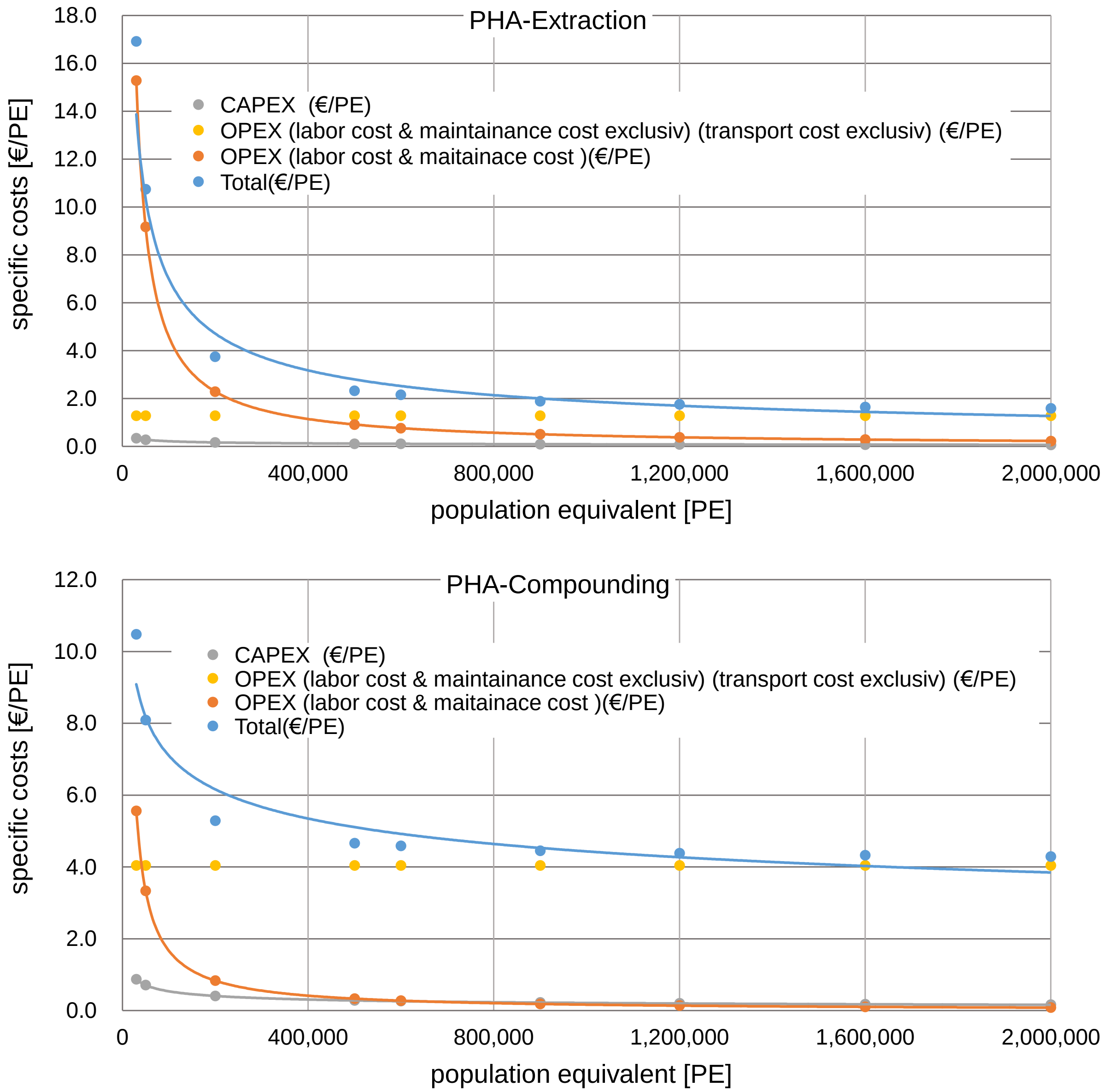


Figure 4-2: specific cost for the PHA-extraction and PHA-compounding system

Transport cost depends on the transport amount and distance. Whether a larger plant within a larger distance from central plant for the PS supply or several smaller near plants should be chosen should be assessed with specific data.

4.2 Concepts

The considered concepts can roughly be divided into two types. For the first type, the primary sludge produced in different WWTPs are transported to a central plant, while for the second type, the primary sludge produced in each WWTP are directly used for the production of PHA-rich biomass in the local constructed PHA-enrichment system and the produced PHA-rich biomass are transported to central plant for the further PHA production.

In consideration of the required primary sludge amount, WWTPs close to the single selected central plant may not be able to provide sufficient primary sludge. When the WWTPs not close to the central plant are involved, the transport cost will increase. Therefore, besides the concept, in which only one central plant receiving the primary sludge for the PHA-production is planned, another concept, in which one decentral PHA-enrichment system receiving primary sludge and providing PHA-rich biomass and one central plant receiving both primary sludge and PHA-rich biomass are planned. Through decentralization of the PHA-enrichment system, WWTPs near both the central plant and decentral PHA-enrichment system can be regarded as the primary sludge suppliers, WWTPs within a long distance from either central plant or decentral PHA-enrichment system probably don't need to be considered and the transport cost then may be saved. However, with the extra decentralized PHA-enrichment system, the size of two PHA-enrichment system will be smaller, which lead to higher specific cost for construction of PHA-enrichment system as well as higher total cost. Furthermore, the transportation of PHA-rich biomass also costs extra.

Since the primary sludge transport is not really practical for some regions due to e.g. high water content in primary sludge, concepts with decentralized PHA-enrichment system are considered, so that the produced PHA-rich biomass with less amount can be transported rather than primary sludge. Depending on the size of the decentralized PHA-enrichment systems, dryer for the PHA-rich biomass drying is also considered to be installed with the decentralized PHA-enrichment systems. Therefore, besides the concept, in which only dewatered PHA-rich biomass produced from decentralized PHA-enrichment systems is transported to the central plant for further extraction and compounding, another concept, in which dewatered PHA-rich biomass produced from some decentralized PHA-enrichment systems is firstly dried and then transported, is considered.

In Table 4-1, advantages and disadvantages of concepts are summarized. As the concepts with PHA-rich biomass transport require decentralized PHA-enrichment system, which leads to higher specific investment cost , the investment cost for these concepts will generally higher than the investment cost for concepts with primary sludge transport. However, since the required amount of primary sludge is much higher than the required amount of PHA-rich biomass, the transport cost for concepts with primary sludge transport will be higher than that for concepts with PHA-rich biomass transport.

Table 4-1: Advantages and disadvantages of concepts

	primary sludge transport		PHA rich biomass transport		Remarks
	One central plant	One central plant One decentral PHA-enrichment system	dewatered PHA rich biomass transport	dried PHA rich biomass transport	
Specific investment cost	++	+	-	--	
Transport cost	--	-	+	++	
Free capacity of original digesters	central plant: -- PS supplier: +	central plant: - PS supplier: + PHA-rich biomass supplier:-	central plant: + PHA-rich biomass supplier:+	central plant: + PHA-rich biomass supplier:+	assuming that digesters exist in all plants
Biogas production	central plant: ++ PS supplier:--	central plant: + PS supplier: -- PHA-rich biomass supplier:+	central plant: - PHA-rich biomass supplier:-	central plant: - PHA-rich biomass supplier:-	
Nitrogen load in reject water from digesters	central plant: -- PS supplier:+	central plant: - PS supplier: + PHA-rich biomass supplier:-	central plant: + PHA-rich biomass supplier:+	central plant: + PHA-rich biomass supplier:+	

For the plants receiving the primary sludge for PHA-enrichment, the load of the digester increase, which also lead to a higher nitrogen load in reject water. When the capacity of the digester is insufficient, the construction of new digester may also be necessary. However, due to the increased load, more biogas production can be expected in these plants.

For the plants providing primary sludge for PHA-enrichment system, the inflow of local digester is reduced, which leads to a lower nitrogen load in reject water. The freed capacity of digesters can be filled with e.g. co-substance with better degradability. Otherwise, the biogas production in these plants will decline.

For the plants with decentral PHA-enrichment system and only local primary sludge as inflow, since a part of primary sludge is fermented for PHA-production, the load of the original digester and the produced biogas amount decline.

5 Region-specific study

To create an analysis of ideal locations to place both decentralized enrichment plants and centralized PHA production plants, tables containing coordinates and all descriptive and numerical data are transformed to be visualized as point data on a map in ArcGIS. ESRI ArcGIS pro offers several toolboxes to solve network optimization problems. The data can then be used to calculate routes and weighted values, using the different networking tools.

The Location-Allocation tool chooses the best locations from a set of input locations, and a selected optimization method. Given a set of candidate points and supply points it generates the optimal location(s) for one or multiple facilities, minimizing the total distance or the weighted distance. The solution is the scenario that allocates the most supply to facilities and minimizes overall distance between supply points and facilities. The output includes the optimal locations for facilities, demand (or supply) points associated with their assigned facilities and lines connecting supply points to their facilities. The lines are depicted as straight lines, but a cloud based infrastructure network is used to calculate actual transport distances from supply points towards the facilities, that is used to calculate the complete distance term per supply point.

In addition, the location-allocation solver has options to solve a variety of location problems such as:

- minimizing weighted impedance (minimize the total weight multiplied by the total distance)
- maximize capacity (trying to fulfill the maximum capacity set by the user)
- maximizing coverage (aims to maximize the spread of the different locations)
- achieving a target market share

Independent on the location problem, the cut-off distance can be set, this is the maximum distance allowed to be in between the facility and a demand point. Demand-points are all the WWTP that need to be included in the analysis. All demand-points get transported towards Facilities, facilities are bigger WWTP's that are eligible to serve as a collection point for sludge and a PHA-extraction facility. The cut-off distance has been used to approximate a PE of 2.000.000, the pre-determined minimal required capacity for a technical and financial viable PHA production plant. Further information about the location allocation tool can be found through the following link.

For three different regions, Scotland, Saarland (Germany), Germany and Ireland, different variants with specific arrangement are developed based on the concepts mentioned in Chapter 0.

Primary sludge has a dry matter content of 3 to 5%, consequentially the other 97 to 95% is water. Due to this fact, a minimum capacity of demand points was set at 50.000 PE. The size would provide the financial opportunity to at least de-water the sludge before transportation. For the facility receiving the de-watered sludge, a dryer is necessary. Dryers are existing and feasible in bigger facilities with 300.000 PE or more.

For all the facilities and demand points (except Saarland), the assumption is that every WWTP with more than 300.000 PE will transport dried primary sludge, all smaller WWTP's will transport de-watered sludge.

5.1 Scotland

In Scotland, there are 153 WWTPs in total with a capacity of 7.698.322 PE. Among them, 30 WWTPs have capacity larger than 50.000 PE and 7 WWTPs have a capacity larger than 300.000 PE, shown in figure 5-1.

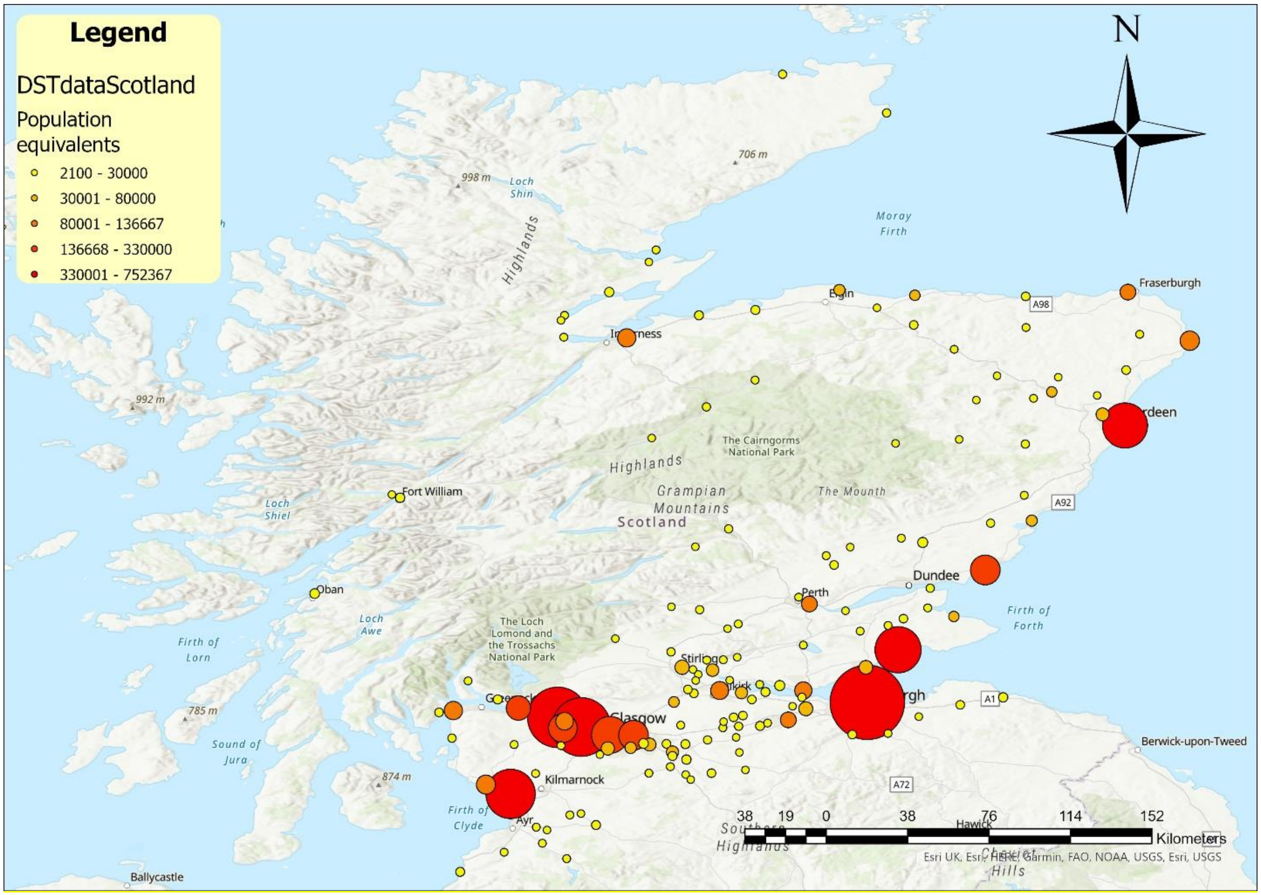


Figure 5-1: GIS map of all participating WWTPs in Scotland

Three separate locations were analysed as potential location for a PHA production facility, which are Aberdeen, Glasgow and Edinburgh.

5.1.1 Aberdeen

During the analysis, it was concluded that with the limitation of at least 50.000 PE per demand point, Aberdeen is not a viable location for a PHA extraction plant. Even with a cut-off distance of 160km Aberdeen only reaches a total amount of 864.172 PE, whereas 2.000.000 PE is required. Therefore, the Aberdeen scenario was not further analyzed and discarded as viable option.

5.1.2 Glasgow

For Glasgow, a cut-off distance was used to approach a PE of 2.000.000 as closely as possible. Where for Glasgow a selection was made by the algorithm between the two biggest facilities; Dalmuir PFI and Shieldall S.T.W, with a cut-off distance off 45km, a sum of 2.636.978 PE was reached. The analysis is visualized in figure 5-2 and the outcomes are shown in table 5-1.

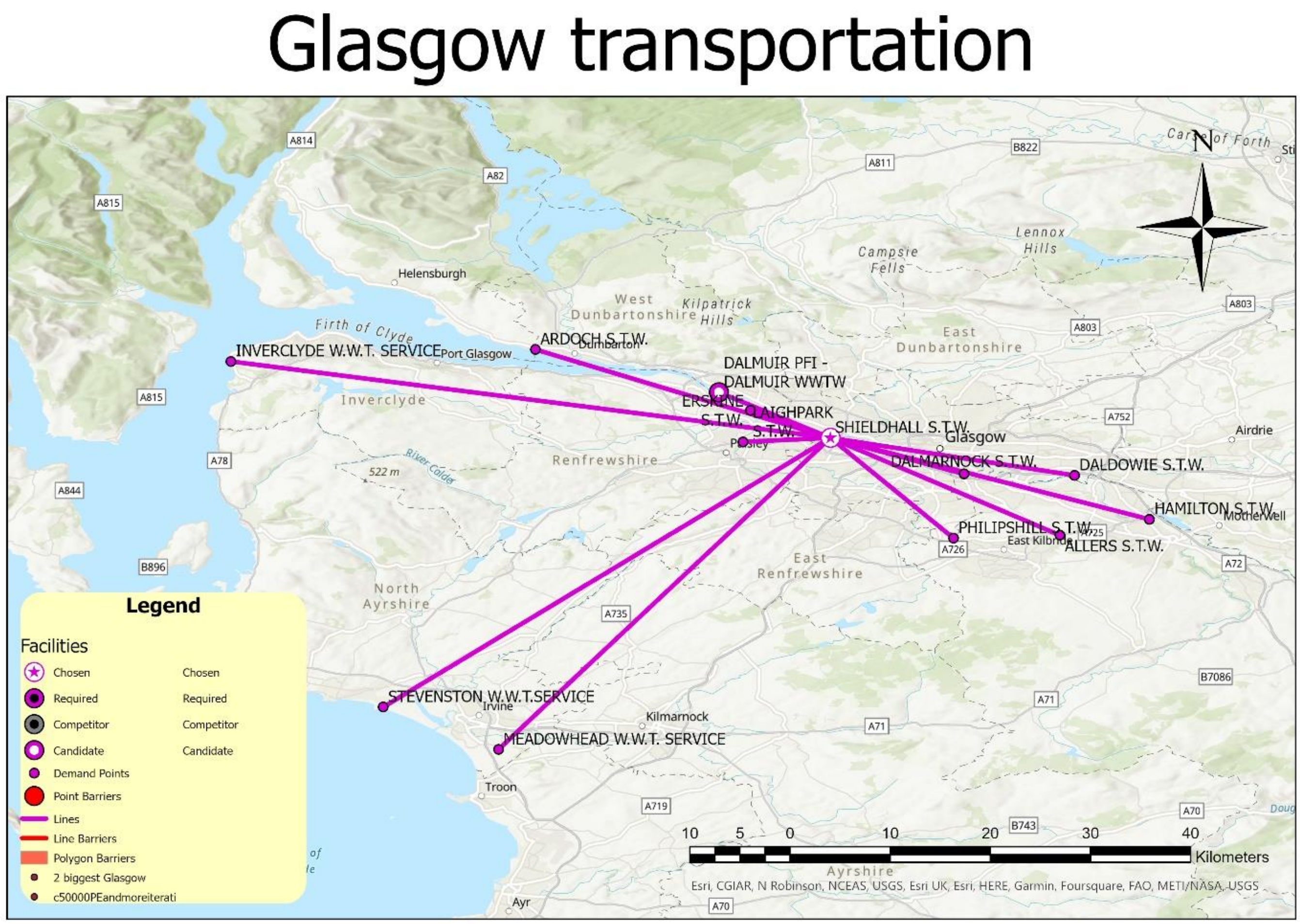


Figure 5-2: Chosen scenario after location-allocation analysis for Glasgow

Table 5-1: Participating facilities in Glasgow scenario

GLASGOW		
Name	**Weight (Load entering PE)**	**Total_Kilometers**
DALMUIR PFI - DALMUIR WWTW - SHIELDHALL S.T.W.	581.220	11,32
SHIELDHALL S.T.W. - SHIELDHALL S.T.W.	563.713	0,00
MEADOWHEAD W.W.T. SERVICE - SHIELDHALL S.T.W.	332.371	42,09
DALDOWIE S.T.W. - SHIELDHALL S.T.W.	317.927	16,98
DALMARNOCK S.T.W. - SHIELDHALL S.T.W.	232.840	9,87
LAIGHPARK S.T.W. - SHIELDHALL S.T.W.	126.440	7,00
INVERCLYDE W.W.T. SERVICE - SHIELDHALL S.T.W.	87.914	40,25
ERSKINE S.T.W. - SHIELDHALL S.T.W.	83.015	6,82
STEVENSTON W.W.T.SERVICE - SHIELDHALL S.T.W.	82.813	42,51
HAMILTON S.T.W. - SHIELDHALL S.T.W.	63.430	22,71
ARDOCH S.T.W. - SHIELDHALL S.T.W.	61.219	23,22
PHILIPSHILL S.T.W. - SHIELDHALL S.T.W.	54.258	15,97
ALLERS S.T.W. - SHIELDHALL S.T.W.	49.818	19,90

The load entering PE is the amount of people equivalents that enter the WWTP, the total kilometres is the amount of kilometres between the chosen facility and the specific demand point.

As visible in table 5-1, the chosen location is Shieldhall, despite the fact that Shieldhall is slightly smaller in capacity than Dalmuir. However, due to location optimalization, the software calculated the above scenario to be most efficient.

Hamilton is shown in red, because it is overlapping with the scenario for Edinburgh as explained in next paragraph.

It needs to be taken into account that the total kilometres does not equal the amount of kilometres that needs to be driven when implementing this scenario in practice. The total amount of transport is dependent on the weight too. Therefore, to calculate the total amount of kilometres, the PE should be multiplied by the weight of either the dry-matter or de-watered sludge (dependent on the process), followed by dividing that number trough the estimated capacity of a truck; 25 ton. These calculations will be shown in chapter 6 and 7.

5.1.3 Edinburgh

For Edinburgh, even with a cut-off distance of 70km, only a sum of 1.479.458 PE was reached, these results are shown in figure 5-3 and table 5-2Table 5-2. Within this cut-off distance, one of the water treatment facilities, HAMILTON S.T.W, overlaps with the Glasgow scenario selection. However, HAMILTON S.T.W., only accounts for 63.430 PE and can be easily missed from the Glasgow scenario which includes way more than 2 million PE. Then again, there might be a possibility for the Edinburgh scenario to reach 2 million PE when Perth, Hatton and Aberdeen (not visible figure 5-3 except for Perth) could contribute by boat. They would respectively add 100.353, 240.825 and 289.584 PE, ensuring a total PE of 2.110.220.

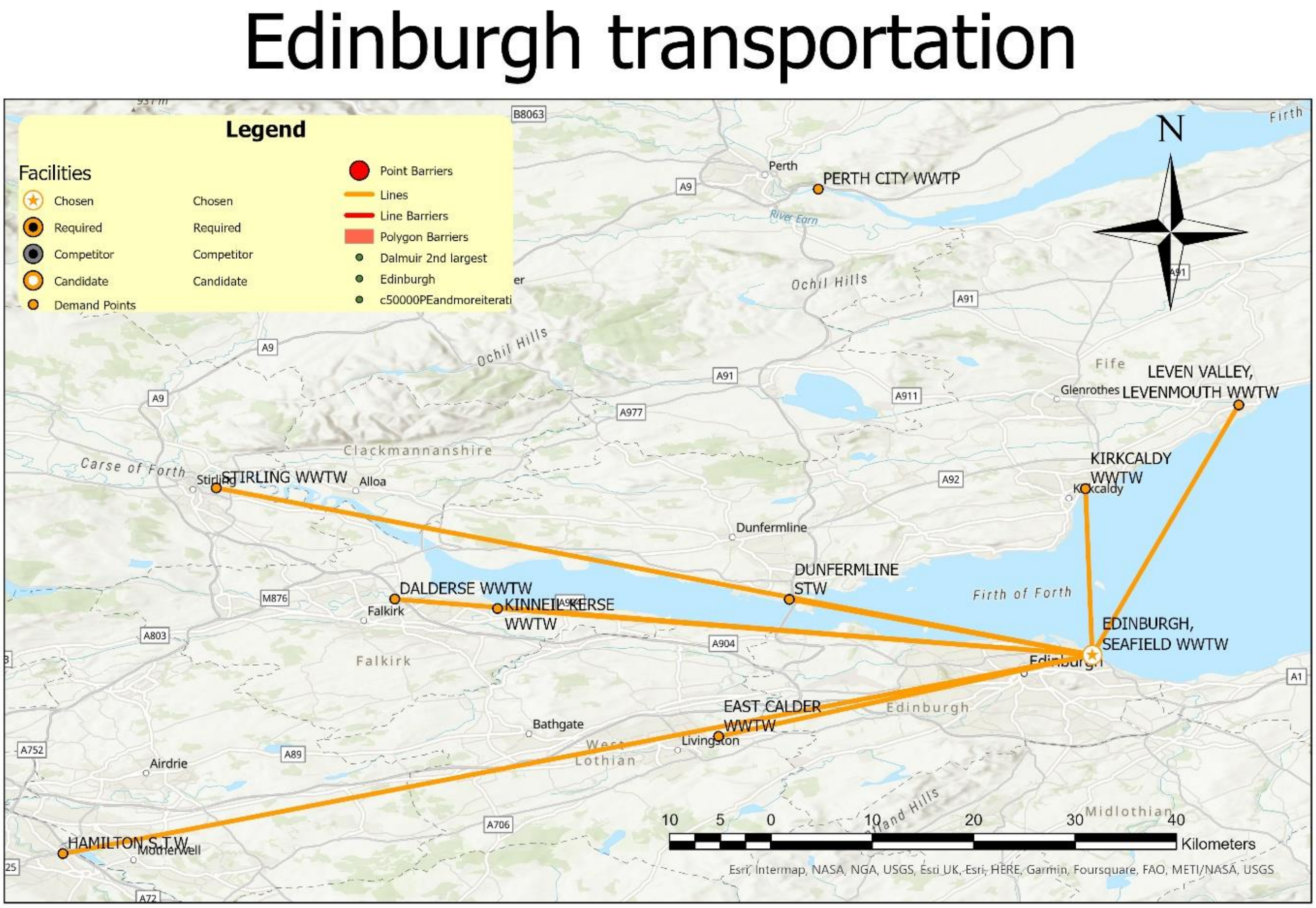


Figure 5-3: Chosen scenario after location-allocation analysis for Edinburgh

Table 5-2: Participating facilities in Glasgow scenario

EDINBURGH		
Name	**Weight (Load entering PE)**	**Total_Kilometers**
EDINBURGH, SEAFIELD WWTW - EDINBURGH, SEAFIELD WWTW	764.659	0,00
LEVEN VALLEY, LEVENMOUTH WWTW - EDINBURGH, SEAFIELD WWTW	172.355	60,18
EAST CALDER WWTW - EDINBURGH, SEAFIELD WWTW	115.185	26,08
DALDERSE WWTW - EDINBURGH, SEAFIELD WWTW	91.701	46,51
DUNFERMLINE STW - EDINBURGH, SEAFIELD WWTW	83.507	24,95
STIRLING WWTW - EDINBURGH, SEAFIELD WWTW	78.108	62,26
HAMILTON S.T.W. - EDINBURGH, SEAFIELD WWTW	63.430	67,00
KIRKCALDY WWTW - EDINBURGH, SEAFIELD WWTW	61.055	46,85
KINNEIL KERSE WWTW - EDINBURGH, SEAFIELD WWTW	49.458	38,65

As visible in table 5-2, the chosen location for the PHA production facility would be at Edinburgh Seafield WWTP. In total 8 other WWTPs would contribute to this scenario with a possible addition of Perth, Hatton and Aberdeen as mentioned previously. Again, the table does not show the total transport kilometres for this scenario.

5.2 Saarland (region Germany)

The Saarland region in Germany is a relatively small area. The total capacity of 60 WWTPs in Saarland are 1,477,900 PE. The largest WWTP is WWTP Burbach with 200,000 PE. Only 9 WWTPs have capacity above 50,000 PE, as show in figure 5-4.

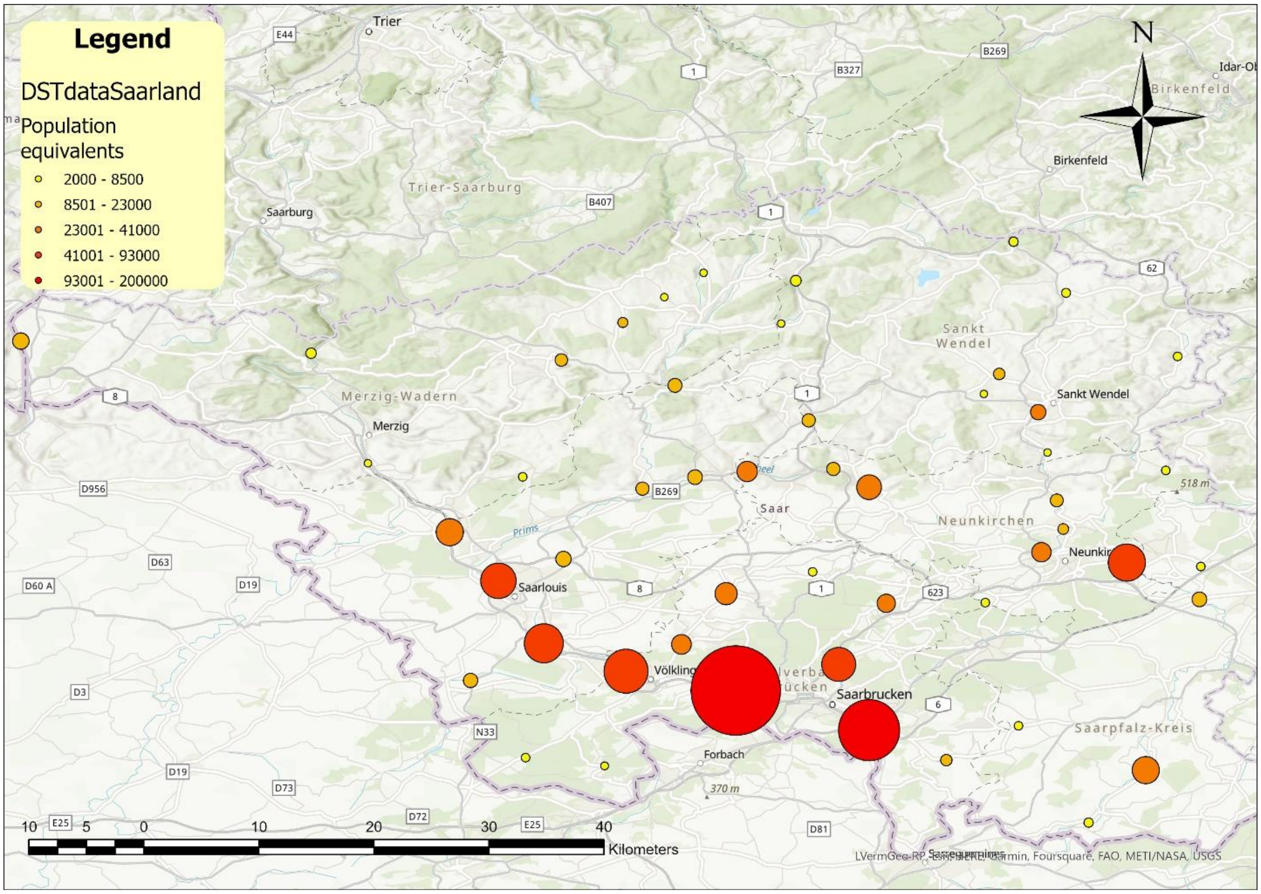


Figure 5-4: GIS map of all participating WWTPs in Saarland (Germany)

Within the original assignment, Saarland in Germany was one of the set areas to assess the feasibility of a PHA production plant. Initial research showed that within the region of Saarland too little PE is available to create a PHA production plant. To check how it would be feasible to have a PHA production facility in the region (or close surroundings) of Saarland, an analysis was performed including some additional WWTPs that are outside the borders of Saarland.

For this analysis, only WWTPs with 100.000 PE or more could be chosen as candidate point, all WWTPs above 50.000 PE (from all over Germany) were added as demand points. As the function maximize capacity was used with a cap of 3.500.000 PE, the cut-off distance was used to approach 2.000.000 PE afterwards. This cut-off distance ended up to be 125 km, providing a PE of 2.214.984. The results of this analysis are shown in figure 5-5 and table 5-3.

Saarland region and surroundings map

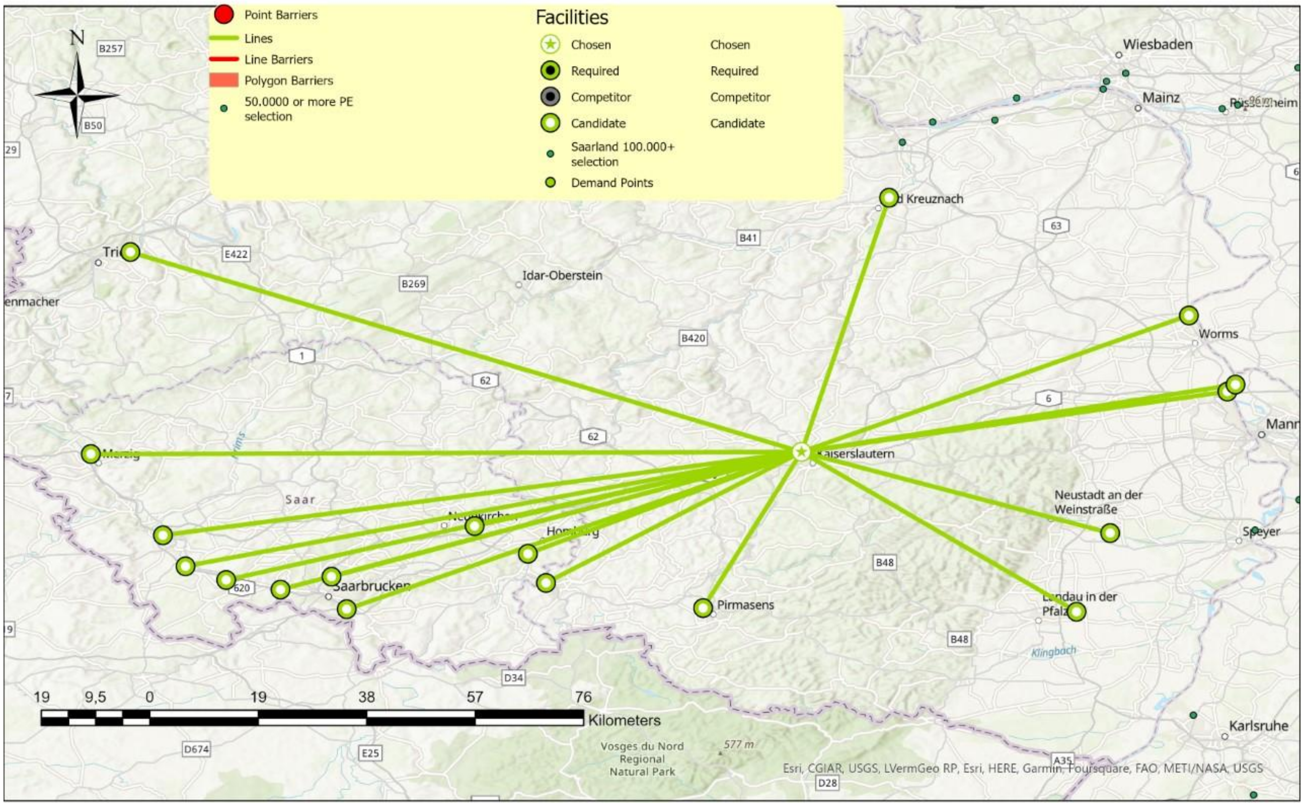


Figure 5-5: Chosen scenario after location-allocation analysis for Saarland and surroundings

Table 5-3: Participating facilities in Saarland scenario

Saarland (Germany)				
Name	**Weight**	**TotalWeighted_Kilometers**	**Total_Kilometers**	**Total_TruckTravelTime**
Worms - Kaiserslautern	179.000	11.233.945	62,76	64,56
Neustadt ZKA - Kaiserslautern	67.500	3.133.522	46,42	63,93
Landau - Kaiserslautern	57.686	3.471.606	60,18	76,69
Ludwigshafen - BASF AG - Kaiserslautern	285.000	15.983.972	56,08	49,94
Trier Hauptklärwerk - Kaiserslautern	142.740	15.472.702	108,40	109,14
Kläranlage Mannheim - Kaiserslautern	517.255	31.181.895	60,28	58,76
KA WELLESWEILER - Kaiserslautern	61.700	2.866.154	46,45	52,52
KA JÄGERSFREUDE - Kaiserslautern	52.860	3.541.488	67,00	72,81
KA BURBACH - Kaiserslautern	158.350	12.281.759	77,56	90,39
KA BREBACH - Kaiserslautern	133.300	9.048.013	67,88	62,35
KA HOMBURG - Kaiserslautern	68.550	2.876.949	41,97	49,73
KA SAARLOUIS - Kaiserslautern	75.150	6.675.394	88,83	80,93
KA ENSDORF - Kaiserslautern	55.350	4.872.190	88,03	85,63
KA VÖLKLINGEN - Kaiserslautern	67.000	5.650.412	84,33	95,94
KA MERZIG - Kaiserslautern	50.650	5.322.741	105,09	96,90
Kaiserslautern - Kaiserslautern	134.832	-	0,00	0,00
Pirmasens-Blümelstal - Kaiserslautern	54.594	2.105.118	38,56	47,28
Zweibrücken - Kaiserslautern	53.467	2.753.118	51,49	60,06
Bad Kreuznach - Kaiserslautern	99.061	6.263.309	63,23	76,17

As visible in table 5-3, the WWTP in Kaiserslautern with 134.832 PE was the chosen location for the PHA production facility. Kaiserslautern does not lay within Saarland, but relatively close to the borders of it. A total of 18 additional WWTPs are required to make this scenario work. As mentioned, a relative big cut-off distance was required. Again, table 5-3 does not show the total transport kilometres for this scenario.

5.3 Germany

Germany has a total of 3810 WWTPs and a sum of 118.304.154 PE. There are 50 WWTPs with a capacity higher than 300.000 PE which account together for 39.074.112 PE. Furthermore, 434 WWTPs have a capacity over 50.000 PE. The map showing all WWTPs in Germany is shown in figure 5-6Figure .

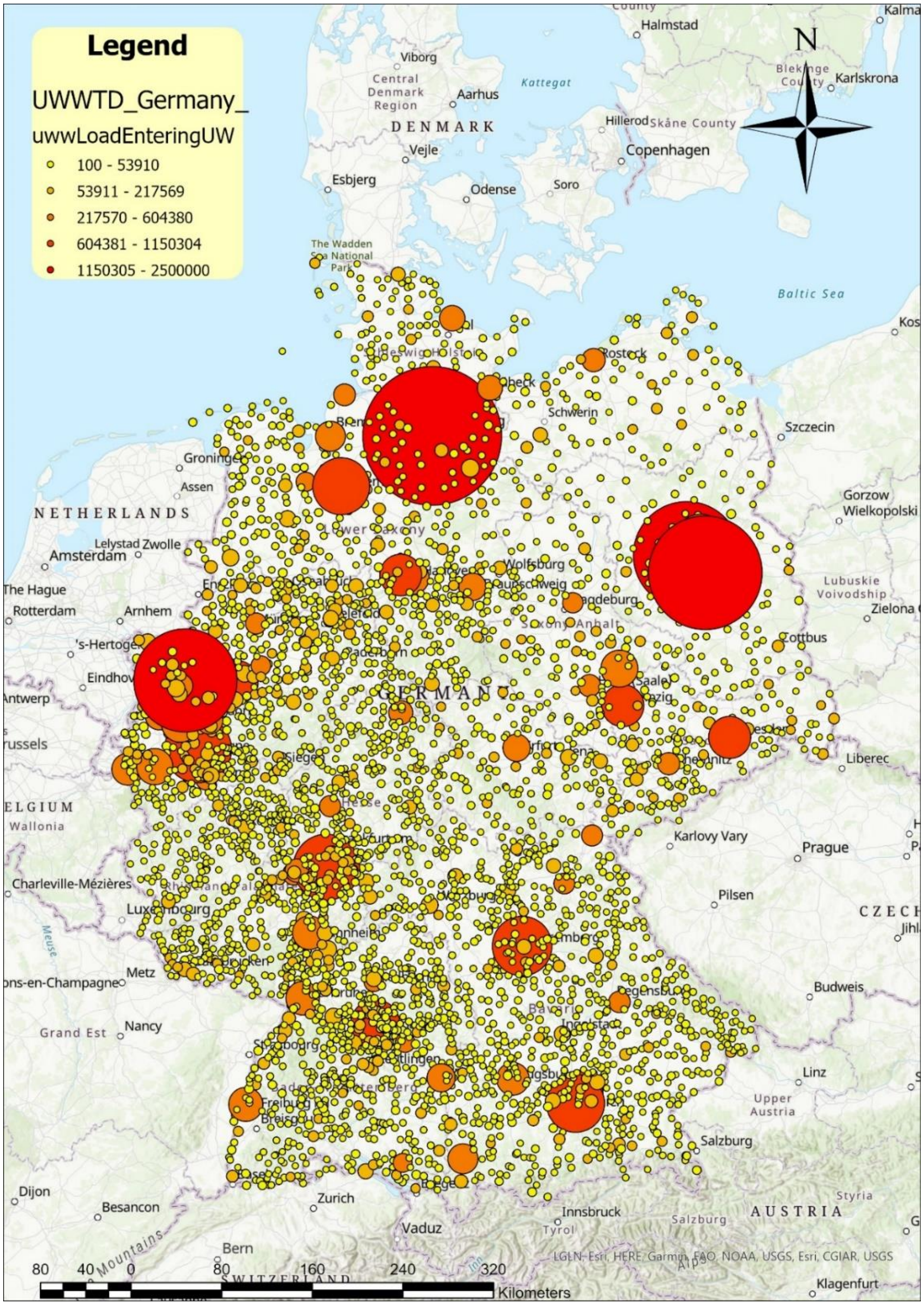


Figure 5-6: GIS map of all participating WWTPs in Germany

Additionally to the analysis for Saarland, an analysis was also performed for the whole of Germany. The limit was set to 8 PHA production facilities with a cut-off distance of 45 kilometres for WWTPs to supply dried primary sludge. This means for this analysis only WWTPs with 300.000 PE or more were part of this analysis. A maximum of 3.500.000 PE was set per potential PHA production facility. The outcomes of the analysis is shown in figure 5-7.

Germany possible locations

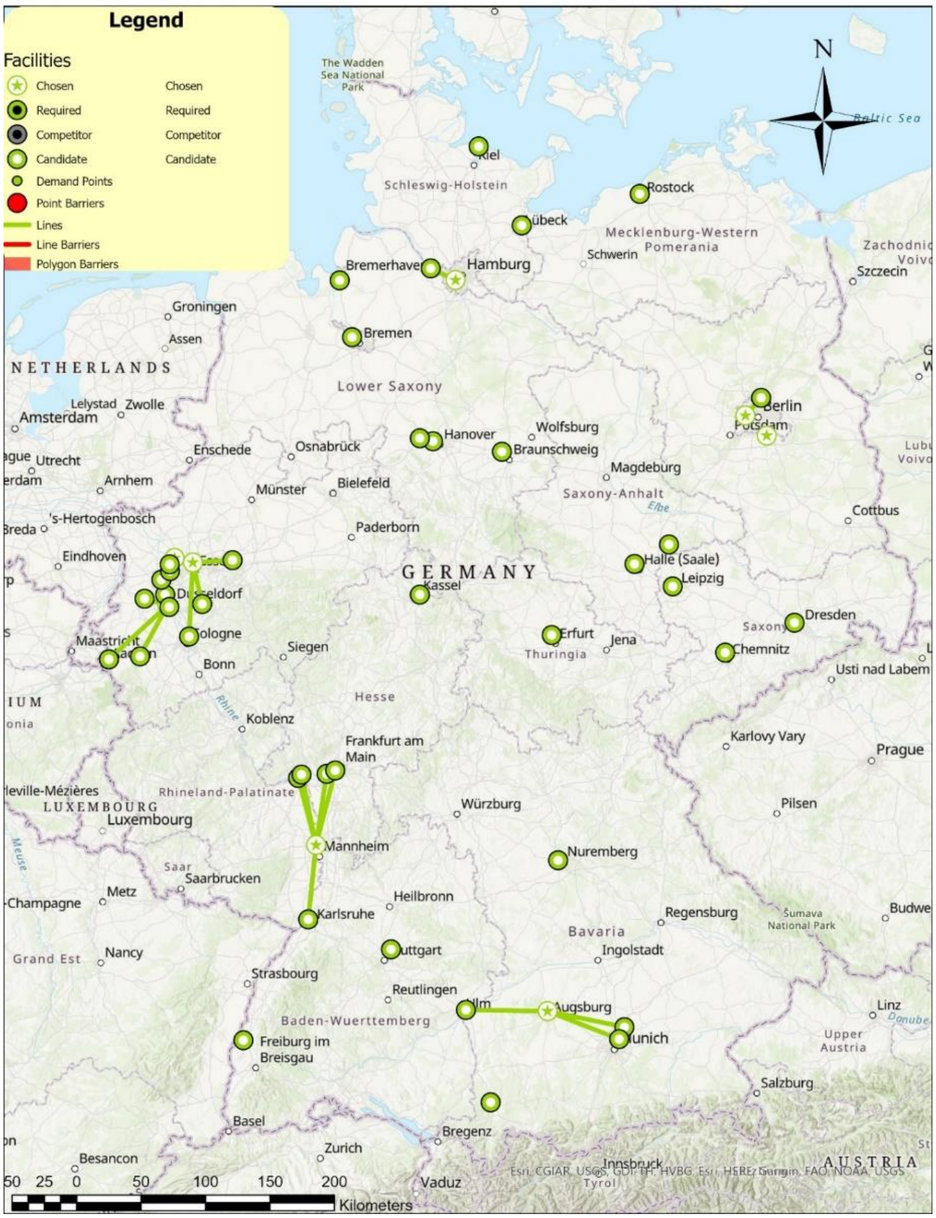


Figure 5-7: Chosen scenario after location-allocation analysis for Germany

Table 5-4: The 8 possibilities for PHA production facilities in Germany

Germany 300.000 PE or more only							
Name	**FacilityType**	**Weight**	**DemandCount**	**DemandWeight**	**Capacity**	**Total_Kilometers**	**TotalWeighted_Kilometers**
Kläranlage Mannheim	Chosen	517.255	6	3.266.266	3.500.000	354,31	193.159.748,51
Augsburg	Chosen	500.997	4	2.635.853	3.500.000	221,66	157.044.753,87
Neuss-Ost	Chosen	389.233	7	3.496.169	3.500.000	205,04	105.945.553,18
Bottrop	Chosen	1.150.304	4	3.392.448	3.500.000	159,72	129.374.553,42
Emscherkläranlage	Chosen	1.830.977	3	2.521.237	3.500.000	31,57	10.874.830,23
Klärwerksverbund Köhlbrandhöft Dradenau	Chosen	2.500.000	2	3.391.439	3.500.000	29,95	26.700.066,19
Ruhleben	Chosen	1.901.188	2	2.742.277	3.500.000	25,77	21.671.766,14
Waßmannsdorf	Chosen	2.023.000	1	2.023.000	3.500.000	0,00	0

Table 5-4 is showing the outcomes for Germany region where 8 potential PHA facilities were picked. All of the 8 outcome possibilities have a PE higher than 2.000.000 and one of them even has 0km driven, meaning to be self-supporting. Of course there are some other WWTPs in Germany with a PE above 2.000.000 that could already install a self-supporting PHA production facility, however these are not mentioned in this assessment since these speaks for itself.

Table 5-4 shows the different facilities, their own weight (in PE), the DemandCount which stands for the amount of demand-points from which dried primary sludge must be collected (including itself), DemandWeight which is the combined weight (in PE) of both the facility and the demand points. The capacity is the variable that was set as maximum PE per PHA production facility and total weighted kilometres which is weight*kilometres.

5.4 Ireland

Ireland has a total of 163 WWTPs with a total capacity 5.447.495 PE of which only Dublin and Cork have a PE over 300.000. Furthermore, Ireland only has 18 WWTPs with a PE over 50.000, with a total capacity of 3.751.840. All of this is shown in figure 5-8.

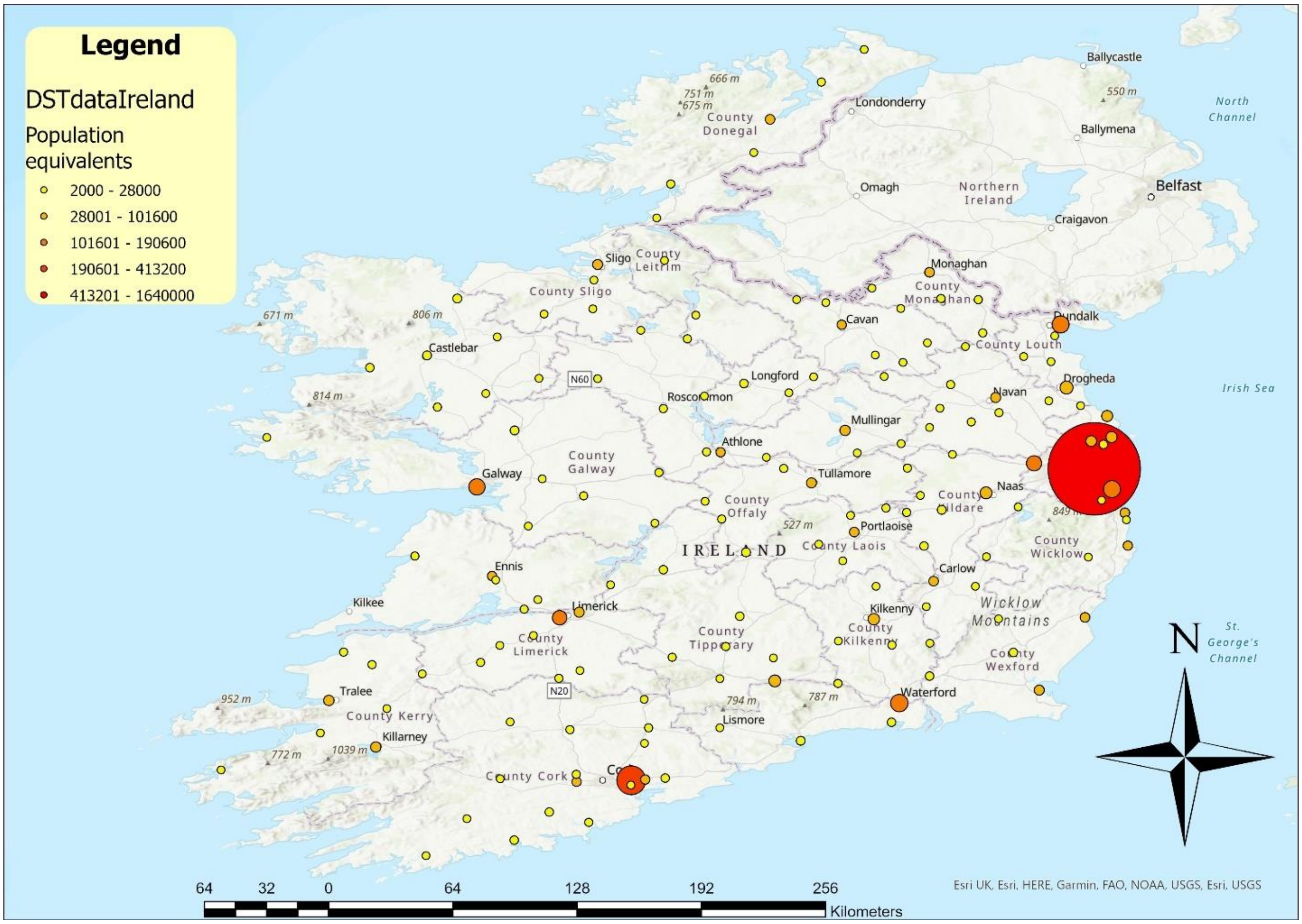


Figure 5-8: GIS map of all participating WWTPs in Ireland

Since Ireland has only 2 facilities with a capacity over 300.000 PE, consequentially only 2 facilities where set as potential candidate points. Using the maximize capacity setting, only Dublin was able to surpass the required 2.000.000 PE, while Cork was only able to reach 1.088.133. Since the setting tried to gain maximal capacity, Cork was assumed not to be a viable location for a PHA production plant. The next step entailed setting a cut-off distance for Dublin to approach the 2.000.000 PE as closely as possible, consequentially minimizing demand points and total kilometres driven. The analytical results are shown in figure 5-9.

Ireland: Dublin facility

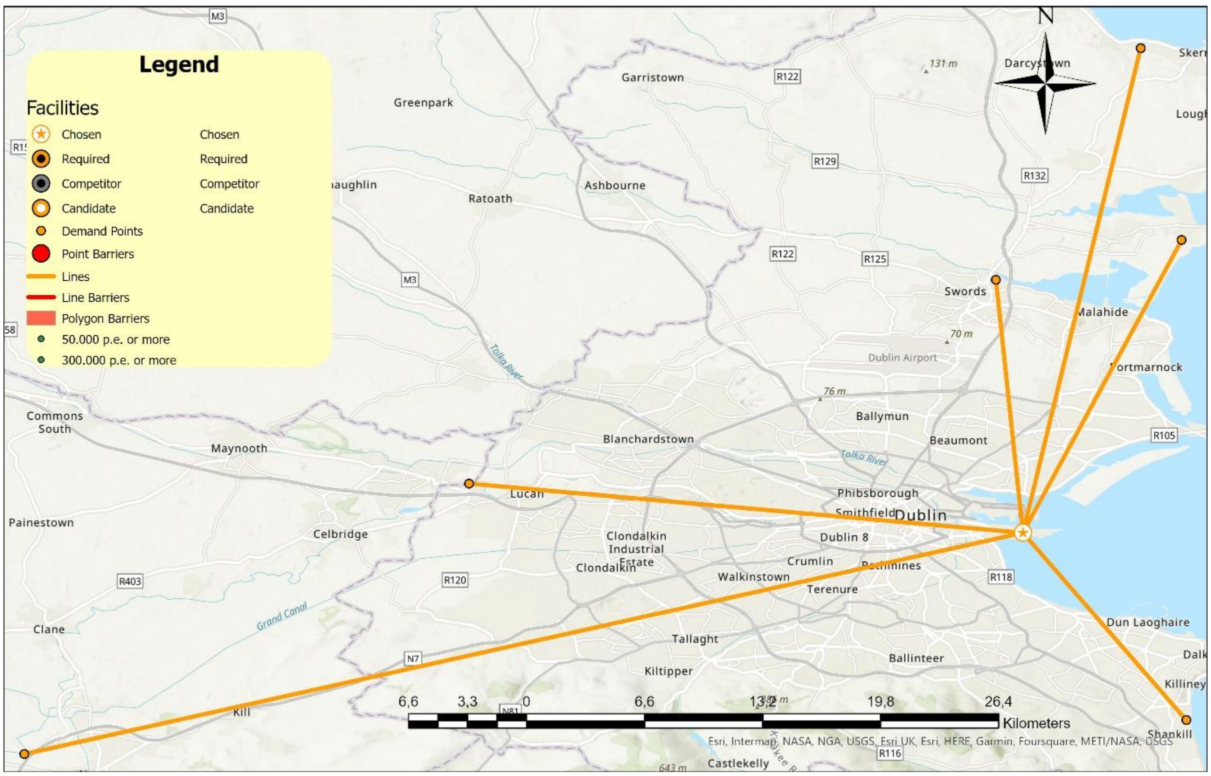


Figure 5-9: Chosen scenario after location-allocation analysis for Ireland

Table 5-5: Participating facilities in Saarland scenario

Ireland			
Name	**Weight**	**TotalWeighted_Kilometers**	**Total_Kilometers**
Ringsend Waste Water Treatment Plant - Ringsend Waste Water Treatment Plant	1.640.000	-	0,00
Shanganagh Waste Water Treatment Plant - Ringsend Waste Water Treatment Plant	186.000	3.124.601,59	16,80
Leixlip Waste Water Treatment Plant - Ringsend Waste Water Treatment Plant	150.000	3.167.669,37	21,12
Osberstown Waste Water Treatment Plant - Ringsend Waste Water Treatment Plant	80.000	3.169.021,69	39,61
Swords Wastewater Treatment Plant - Ringsend Waste Water Treatment Plant	60.000	1.104.465,46	18,41
Balbriggan Waste Water Treatment Plant - Ringsend Waste Water Treatment Plant	70.000	2.436.593,64	34,81
Portrane Waste Water Treatment Plant - Ringsend Waste Water Treatment Plant	65.000	1.658.235,33	25,51

Table 5-5 is showing the outcomes for the Ireland scenario in which Ringsend WWTP in Dublin was chosen as PHA production location, ending up with 2.251.000 PE from 6 demand points within a range of 40km.

5.5 Conclusions GIS analysis

Due to the costs connected to transport, the less kilometers driven the better. For Scotland, Aberdeen does not seem to be a viable location transport wise, while Edinburgh is optional but dependent on shipping feasibility. The best and only proven viable location in Scotland is Glasgow.

For Saarland, within the province there is not enough PE to build a PHA production facility. However, when including the surroundings, 18 demand-points together with Kaiserslautern as chosen location, come to a PE of 2.314.045. Despite that, those 18 demand-points have an average of 64 km distance to the facility. Although those kilometers are not weighted, relatively a lot of transport is required.

Germany as a country has 8 very viable options next to the WWTPs that could be self-supporting already. All of these are suitable for a PHA extraction facility, also since all of the demand points have 300.000 PE or higher and therefore only dried primary sludge will be transported instead of also dewatered primary sludge.

For Ireland, Dublin is the only viable location. Since it is the biggest facility within Ireland, the potential is there when 6 demand points contribute bringing their sludge towards the facility in Dublin. However, the distance towards these facilities is relatively high, then again, most of the required sludge is already at Dublin itself.

Concluding, from the original research locations (Scotland, Saarland and Ireland), Glasgow in Scotland is the most viable location in its region based on the GIS results. However, since Saarland was not able to gain enough PE by itself, Germany as a country was also analyzed. Within Germany, there are several options that would (transport wise) even be more aligned, especially since all demand-points taken into account are over 300.000 PE and thus would only need to transport dried primary sludge.

6 Region-specific study –Cost analysis

6.1 Scotland

The results of the GIS tool show that the Glasgow region has the shortest distances between the central PHA extraction plant and the decentralised plants. Therefore 6 potentially suitable variants for PHA-production were investigated for the Glasgow region. Two of them are with primary sludge transport to Dalderse STP, while the rest are with PHA-rich biomass transport to Shieldhall STP in Glasgow.

6.1.1 Primary sludge transport

<u>Central</u>

In this variant, the central plant with PHA-enrichment system, PHA-extraction system and compounding system is set in Dalderse WWTP with a physical capacity of 120,000 PE. Twelve other WWTPs within 55km from Dalderse WWTP are selected to provide primary sludge. The estimated dry matter amount in primary sludge from each WWTP in (Niels, 2022) was adopted for the calculation for this variant. The physical loading, primary sludge amount of central plant and primary sludge suppliers and distance from primary sludge suppliers to central plant are summarized in Table 6-1. According to the mass balance, the PHA production amount of this variant is estimated as 5,139 t/a.

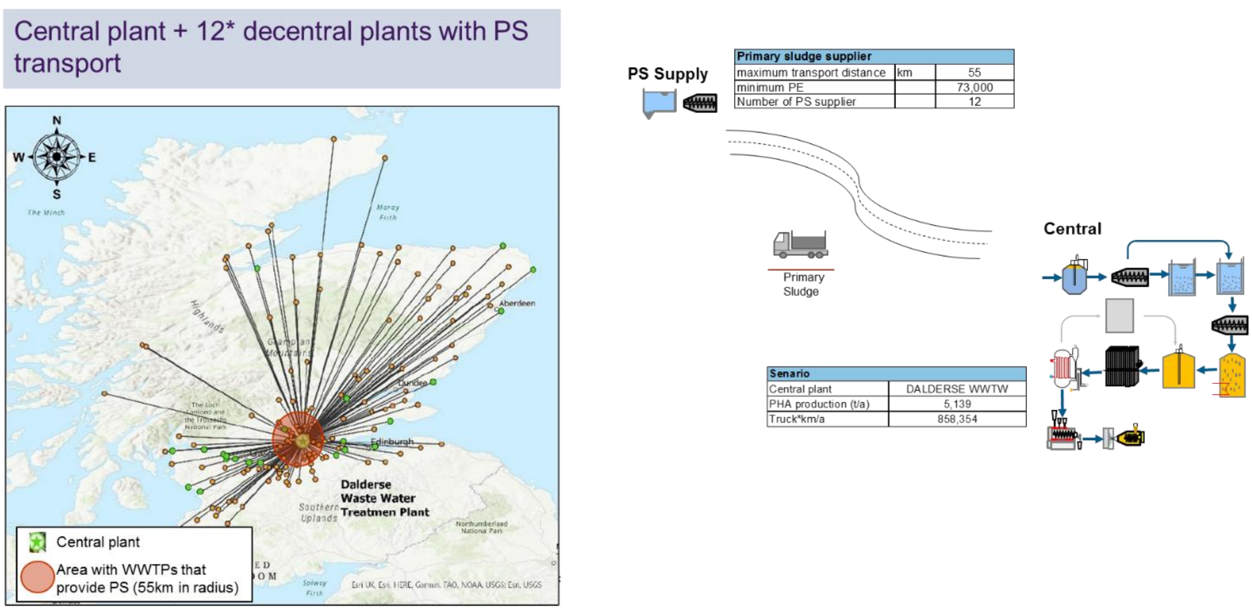


Figure 6-1: Senario with primary sludge transport and one central plant

Table 6-1: involved WWTPs in Variant 1.1

	WWTP	Physical loading (PE)	PS (tDM/a)	Distance to central plant (km)
Central plant				
0	DALDERSE WWTW	120,000	1,004	-
Primary sludge supplier				
1	DALDOWIE S.T.W.	250,000	1,800	36.616585
2	DALMARNOCK S.T.W.	330,000	2,550	41.168615
3	DALMUIR PFI - DALMUIR WWTW	593,802	4,275	53.582301
4	DUNFERMLINE STW	111,250	914	30.436074
5	EAST CALDER WWTW	95,000	684	30.293393
6	EDINBURGH, SEAFIELD WWTW	752,367	5,417	45.167159
7	ERSKINE S.T.W.	114,600	909	54.240297
8	KIRKCALDY WWTW	73,000	526	51.14444
9	LAIGHPARK S.T.W.	240,000	1,385	53.962904
10	NEWBRIDGE WWTW	76,133	548	30.62295
11	SHIELDHALL S.T.W.	574,000	4,133	47.153352
12	STIRLING WWTW	80,000	855	20.110444

Decentral

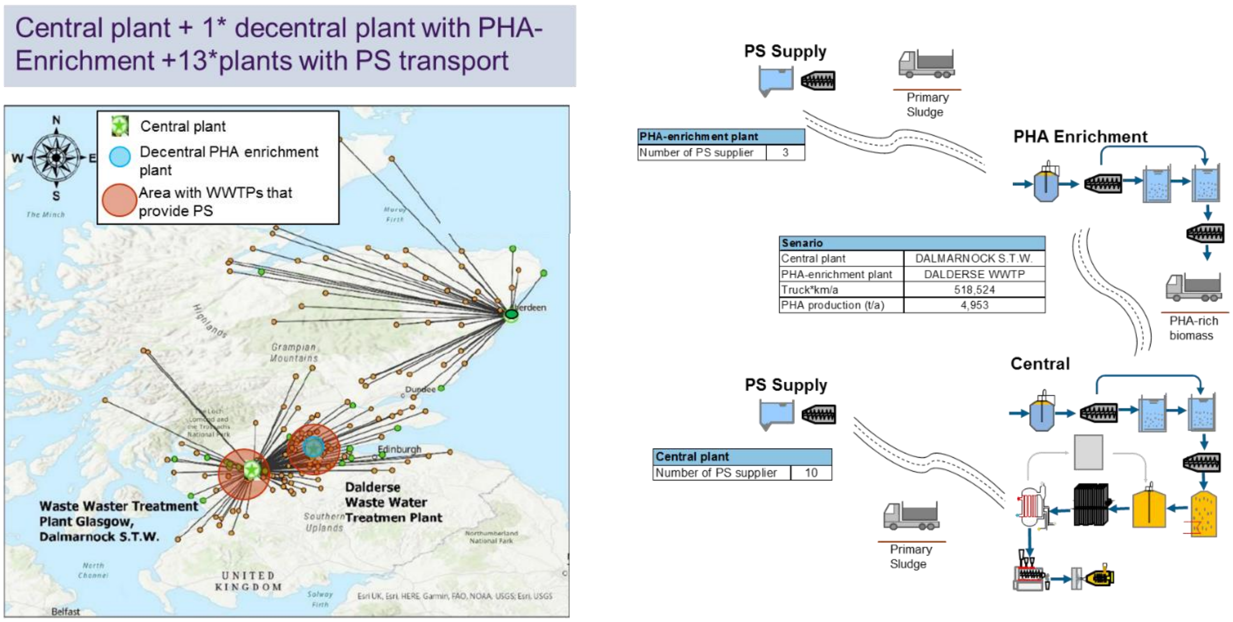


Figure 6-2: variant 1.2 with one central plant and one decentral PHA enrichment plant

In this variant, PHA-enrichment system, PHA-extraction system and compounding system is set in Dalmarnock STW with a physical capacity of 330,000 PE. Besides that, a decentral PHA enrichment plant is set in Dalderse WWTP with a physical capacity of 120,000 PE. Ten and three other WWTP are separately selected to provide primary sludge for central plant and decentral PHA enrichment plant. The dewatered PHA-rich biomass produced in decentral PHA enrichment plant in Dalderse WWTP will be transported to central plant in Dalmarnock STW for further extraction and compounding process. The primary sludge amount from each WWTPs used for the calculation for this variant are also obtained from (Niels, 2022). The physical loading, primary sludge amount of selected WWTPs, the distance from primary sludge suppliers to receivers and from decentral PHA enrichment plant to central plant are summarized in Table 6-2. According to the mass balance, the PHA production amount of this variant is estimated as 4,953 t/a.

Table 6-2: involved WWTPs in variant 1.2

	WWTP	Physical loading (PE)	PS (tDM/a)	Distance (km)	
				to central plant	to decentral PHA-enrichment plant
Central plant					
1	DALMARNOCK S.T.W.	330,000	2,550	-	-
Decentral PHA-enrichment plant					
2	DALDERSE WWTW	120,000	1,004	41.168615	-
Primary sludge supplier for central plant					
1.1	DALMUIR PFI - DALMUIR WWTW	593,802	4,275	18.585378	-
1.2	SHIELDHALL S.T.W.	574,000	4,133	9.955219	-
1.3	DALDOWIE S.T.W.	250,000	1,800	8.723437	-
1.4	LAIGHPARK S.T.W.	240,000	1,385	16.3994	-
1.5	ARDOCH S.T.W.	191,300	670	30.487304	-
1.6	ERSKINE S.T.W.	114,600	909	16.250562	-
1.7	PHILIPSHILL S.T.W.	67,590	487	10.412672	-
1.8	HAMILTON S.T.W.	63,106	695	14.577293	-
1.9	CARBARNS S.T.W.	54,035	529	23.128917	-
1.10	ALLERS S.T.W.	47,000	546	11.438858	-
Primary sludge supplier for decentral PHA-enrichment plant					
2.1	EDINBURGH, SEAFIELD WWTW	752,367	5,417	-	45.167159
2.2	KINNEIL KERSE WWTW	55,900	542	-	10.015822
2.3	BONNYBRIDGE WWTW	17,000	122	-	7.766735

6.1.2 PHA rich biomass transport

Based on the information from Scottish Water, the primary and secondary sludge from WWTPs with sludge production less than 1,000 t DM/a will be locally used. Therefore, assuming that the daily primary and secondary sludge production per population equivalent is 55g DM/g/d, WWTPs with a load less than 50,000 PE are not considered for PHA-production. Furthermore, primary sludge and secondary sludge are thickened and transported together in Scotland. Therefore, the separate primary sludge transport required in variant 1.1 and 1.2 isn't purposeful.

For this reason, variants with decentralized PHA enrichment plants and PHA-rich biomass transport are being developed for Scotland. In consideration of the common throughput of dryers used for sewage sludge drying, in some variants, the dewatered PHA-rich biomass is planned to be dried before being transported.

Dewatered PHA-rich biomass transport

The first two variants are separately shown in Figure 6-3 and Figure 6-4, in which only the dewatered PHA-rich biomass produced from the decentral PHA-enrichment plants are transported to the central plant.

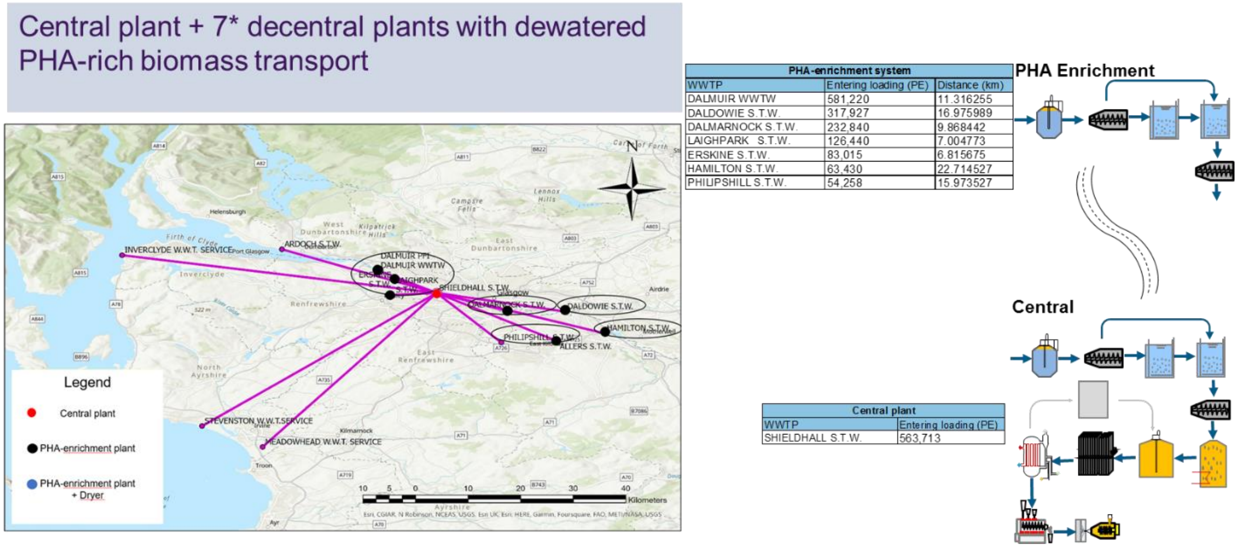


Figure 6-3: variant 2.1 with one central plant and 7 decentral plants providing dewatered PHA-rich biomass

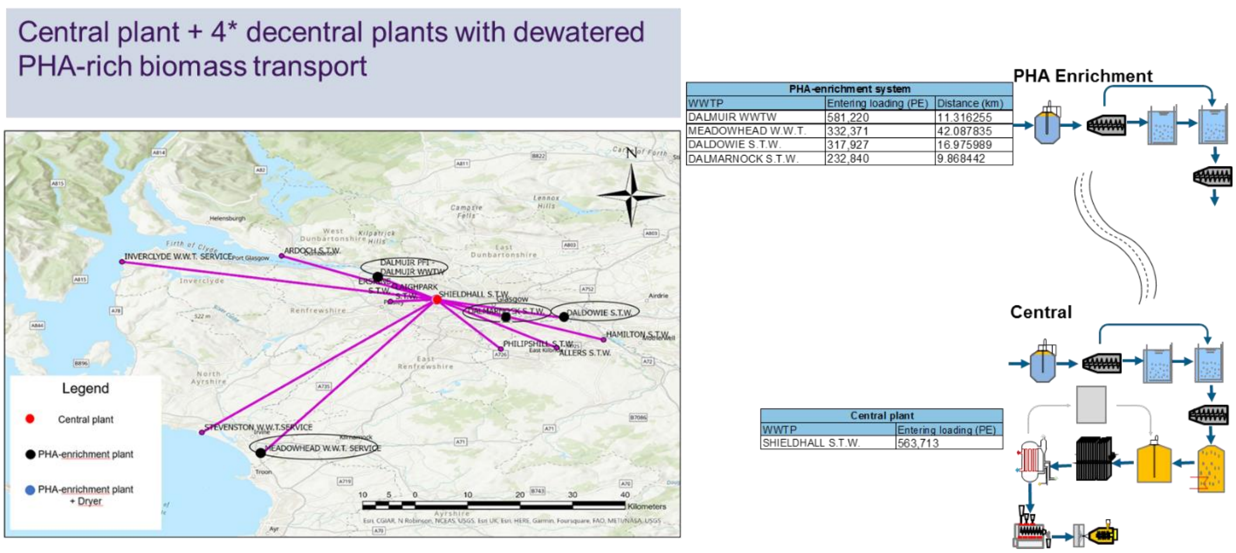


Figure 6-4: variant 2.2 with one central plant and 4 decentral plants providing dewatered PHA-rich biomass

In variant 2.1, seven WWTPs are chosen to be the site for the decentral PHA-enrichment system, which are all within the distance of 23km from central plant and with an load over 54,000 PE.

In variant 2.2, four WWTPs with entering loading below 230,000 PE in variant 2.1 are replaced by the WWTP named MEADOWHEAD W.W.T. with an entering loading of 332,371PE, which is around 42 km away from the central plant.

In Table 6-3 and Table 6-4, the entering loading, primary sludge amount of selected WWTPs, the distance from dewatered PHA-rich biomass suppliers to central plant in variant 2.1 and variant 2.2 are separately summarized. The produced primary sludge amount in each plant is estimated on the basis of the entering loading and two assumptions that the specific primary sludge production is 35gDM/PE/d and the DM-content in primary sludge is 3%.

According to the mass balance, a PHA production of 5,107 t/a can be expected with variant 2.1, while the PHA production amount of variant 2.2 is estimated to be 5,120 t/a.

Table 6-3: involved WWTPs in variant 2.1

	WWTP	Loading entering (PE)	PS (tDM/a)	Distance to central plant (km)
Central plant				
0	SHIELDHALL S.T.W.	563,713	240,048	-
Dewatered PHA-rich biomass supplier				
1	DALMUIR WWTW	581,220	247,503	11.316255
2	DALDOWIE S.T.W.	317,927	135,384	16.975989
3	DALMARNOCK S.T.W.	232,840	99,151	9.868442
4	LAIGHPARK S.T.W.	126,440	53,842	7.004773
5	ERSKINE S.T.W.	83,015	35,351	6.815675
6	HAMILTON S.T.W.	63,430	27,011	22.714527
7	PHILIPSHILL S.T.W.	54,258	23,105	15.973527

Table 6-4: involved WWTPs in variant 2.2

	WWTP	Loading entering (PE)	PS (tDM/a)	Distance to central plant (km)
Central plant				
0	SHIELDHALL S.T.W.	563,713	240,048	-
Dewatered PHA-rich biomass supplier				
1	DALMUIR WWTW	581,220	247,503	11.316255
2	MEADOWHEAD W.W.T.	332,371	141,535	42.087835
3	DALDOWIE S.T.W.	317,927	135,384	16.975989
4	DALMARNOCK S.T.W.	232,840	99,151	9.868442

Combination of dried and dewatered PHA-rich biomass transport

Since in variant 2.2, three of four WWTPs chosen to be the site for decentral PHA enrichment plant have the entering loading more than 300,000 PE, in variant 3.1, to install 3 dryers separately in these three decentral plants are considered as shown in Figure 6-5.

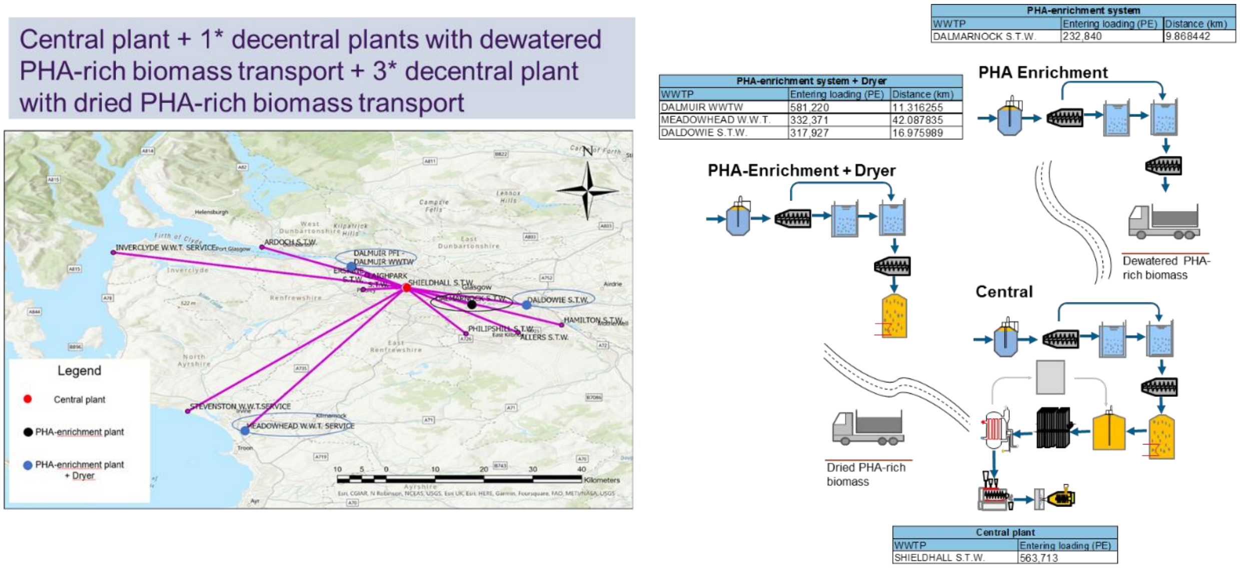


Figure 6-5: variant 3.1 with one central plant, 1 decentral plants providing dewatered PHA-rich biomass and 3 decentral plant providing dried PHA-rich biomass

In Table 6-5, the entering loading, primary sludge amount of selected WWTPs, the distance from dewatered as well as dried PHA-rich biomass suppliers to central plant in variant 3.1 are separately summarized. The produced primary sludge amount in each plant is also estimated on the basis of the entering loading and the assumed specific primary sludge production of 35gDM/PE/d as well as the assumed DM-content of 3% in primary sludge.

Table 6-5: involved WWTPs in variant 3.1

	WWTP	Loading entering (PE)	PS (tDM/a)	Distance to central plant (km)
		Central plant		
0	SHIELDHALL S.T.W.	563,713	240,048	-
		Dewatered PHA-rich biomass supplier		
1	DALMARNOCK S.T.W.	232,840	99,151	9.868442
		Dried PHA-rich biomass supplier		
2	DALMUIR WWTW	581,220	247,503	11.316255
3	MEADOWHEAD W.W.T.	332,371	141,535	42.087835
4	DALDOWIE S.T.W.	317,927	135,384	16.975989

In order to have a concept with even less number of involved WWTPs, the largest WWTPs in Scotland named SEAFIELD WWTW in Edinburgh is considered in the variant 3.2, which has an entering loading of 764,659 PE and a distance of around 85km from the central plant. In consideration of the loading and distance, a dryer is also planned in this WWTP. Besides, two other decentral PHA-enrichment system are planned in this variant to provide the dewatered PHA-rich biomass for central plant as shown in Figure 6-6.

A summary of the entering loading, estimated primary sludge amount of selected WWTPs, the distance from dewatered as well as dried PHA-rich biomass suppliers to central plant in variant 3.2 are shown in Table 6-6.

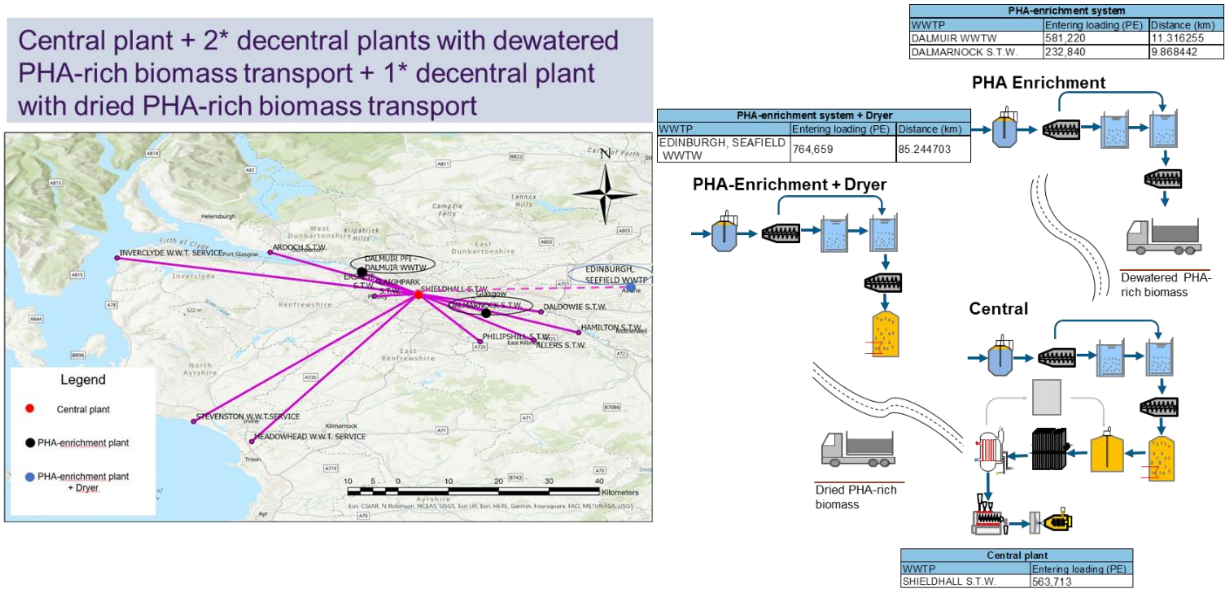


Figure 6-6: variant 3.2 with one central plant, 2 decentral plants providing dewatered PHA-rich biomass and 1 decentral plant providing dried PHA-rich biomass

Table 6-6: involved WWTPs in variant 3.2

	WWTP	Loading entering (PE)	PS (tDM/a)	Distance to central plant (km)
Central plant				
0	SHIELDHALL S.T.W.	563,713	240,048	-
Dewatered PHA-rich biomass supplier				
1	DALMUIR WWTW	581,220	247,503	11.316255
2	DALMARNOCK S.T.W.	232,840	99,151	9.868442
Dried PHA-rich biomass supplier				
3	SEAFIELD WWTW	764,659	325,617	85.244703

6.1.3 Estimated cost

The estimated cost for variant 1.1 and 1.2 with primary sludge transport are 29,718,589 €/a and 27,482,586 €/a, which are lower than the cost of other variants. With regard to the PHA production amount, the specific cost are separately 5,783 €/t PHA and 5,548 €/t. The reason for a lower cost for variant 1.2 than variant 1.1 are the reduced transport cost due to the partially decentralised PHA-enrichment system. Since the transported primary sludge has a higher dry matter content of 5%, the inflow and throughput in variant 1.1 and 1.2 is lower than other variant, which lead to a lower specific OPEX cost excluding cost for transport, labour, maintenance, and insurance. The cost breakdown for variant 1.1 and 1.2 are shown in Table 6-7 and Table 6-8.

Table 6-7: Cost for variant 1.1

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	DALMARNOCK S.T.W.	3,204,144	16,572,685	0	1,342,199	16,021	21,135,049
1-12	**Primary sludge suppliers for central plant**	0	0	8,583,541	0	0	8,583,541
Sum (€/a)		3,204,144	16,572,685	8,583,541	1,342,199	16,021	29,718,589
Specific cost (€/t PHA)		623	3,225	1,670	261	3	5,783

Table 6-8: Cost for variant 1.2

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
1	DALMARNOCK S.T.W.	2,700,883	14,690,298	0	1,342,199	13,504	18,746,884
Decentral PHA-enrichment plant							
2	DALDERSE WWTW	1,160,347	1,667,360	138,352	716,951	5,802	3,688,812
1.1 - 1.10	**Primary sludge suppliers for central plant**	0	0	3,038,511	0	0	3,038,511
2.1 - 2.3	**Primary sludge supplier for decentral PHA-enrichment plant**	0	0	2,008,378	0	0	2,008,378
Sum (€/a)		3,861,230	16,357,658	5,185,242	2,059,150	19,306	27,482,586
Specific cost (€/t PHA)		780	3,302	1,047	416	4	5,548

For variant 2.1, 2.2, 3.1 and 3.2, the estimated cost are from 31,811,048 €/a for variant 2.2 to 34,417,514 €/a for variant 2.1. In fact, the estimated cost for variant 2.2, 3.1 and 3.2 are in the same order of magnitude.

Variant 2.2 and variant 3.1 have the same WWTPs with the similar function involved. Only the dewatered PHA-rich biomass is transported in variant 2.2, while in variant 3.1, the dried PHA-rich biomass is transported. However, the estimated results shows that the reduced transport cost through drying the transported PHA-rich biomass in variant 3.1 can't offset the cost for extra dryer installation, therefore, the total cost for variant 3.1 is a little bit higher than that of variant 2.2.

The comparison of estimated cost for variant 2.1 and 2.2 shows that with eight WWTPs involved in total, the cost for the highly decentralised PHA-enrichment system plays the decisive role, even if the decentral PHA-enrichment system in variant 2.1 are all within the distance of 23km from central plant.

For variant 3.2, the highest cost for the PHA-rich biomass transport is determined due to the long distance for the dried PHA-rich biomass transport. However, since only 3 decentralised PHA-enrichment system with relatively large scale are planned and the PHA-production amount is the highest, the specific cost of 5,973 €/t PHA is the lowest among all variants with PHA-rich biomass transport.

Table 6-9: Cost for variant 2.1

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	SHIELDHALL S.T.W.	2,181,621	13,399,417	0	1,342,199	10,908	16,934,146
Dewatered PHA-rich biomass supplier							
1	DALMUIR WWTW	1,751,468	2,696,074	39,854	716,951	8,757	5,213,105
2	DALDOWIE S.T.W.	1,142,963	1,474,751	32,704	716,951	5,715	3,373,084
3	DALMARNOCK S.T.W.	917,859	1,080,062	13,923	716,951	4,589	2,733,385
4	LAIGHPARK S.T.W.	598,325	586,510	5,367	716,951	2,992	1,910,145
5	ERSKINE S.T.W.	446,246	385,077	3,428	716,951	2,231	1,553,934
6	HAMILTON S.T.W.	370,187	294,229	8,730	716,951	1,851	1,391,949
7	PHILIPSHILL S.T.W.	332,219	251,684	5,252	716,951	1,661	1,307,767
Sum (€/a)		7,740,890	20,167,805	109,258	6,360,856	38,704	34,417,514
Specific cost (€/t PHA)		1,516	3,949	21	1,246	8	6,739

Table 6-10: Cost for variant 2.2

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	SHIELDHALL S.T.W.	2,182,354	13,427,290	0	1,342,199	10,912	16,962,754
Dewatered PHA-rich biomass supplier							
1	DALMUIR WWTW	1,751,468	2,696,074	39,854	716,951	8,757	5,213,105
2	MEADOWHEAD W.W.T.	1,179,357	1,541,752	84,764	716,951	5,897	3,528,720
3	DALDOWIE S.T.W.	1,142,963	1,474,751	32,704	716,951	5,715	3,373,084
4	DALMARNOCK S.T.W.	917,859	1,080,062	13,923	716,951	4,589	2,733,385
Sum (€/a)		7,174,002	20,219,929	171,245	4,210,003	35,870	31,811,048
Specific cost (€/t PHA)		1,401	3,949	33	822	7	6,213

Table 6-11: Cost for variant 3.1

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	SHIELDHALL S.T.W.	2,142,144	12,629,072	0	1,342,199	10,711	16,124,126
Dewatered PHA-rich biomass supplier							
1	DALMARNOCK S.T.W.	917,859	1,080,062	13,923	716,951	4,589	2,733,385
Dried PHA-rich biomass supplier							
2	DALMUIR WWTW	1,795,729	3,072,796	13,285	925,367	8,979	5,816,156
3	MEADOWHEAD W.W.T.	1,211,007	1,757,180	28,255	925,367	6,055	3,927,865
4	DALDOWIE S.T.W.	1,173,782	1,680,818	10,901	925,367	5,869	3,796,737
Sum (€/a)		7,240,522	20,219,929	66,364	4,118,300	36,203	32,398,268
Specific cost (€/t PHA)		1,414	3,949	13	804	7	6,328

Table 6-12: cost for variant 3.2

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	SHIELDHALL S.T.W.	2,175,660	13,541,372	0	1,342,199	10,878	17,070,109
Dewatered PHA-rich biomass supplier							
1	DALMUIR WWTW	1,751,468	2,696,074	39,854	716,951	8,757	5,213,105
2	DALMARNOCK S.T.W.	917,859	1,080,062	13,923	716,951	4,589	2,733,385
Dried PHA-rich biomass supplier							
3	SEAFIELD WWTW	2,180,578	4,042,602	131,658	925,367	10,903	7,291,108
Sum (€/a)		7,025,566	21,360,111	185,435	3,701,468	35,128	32,307,708
Specific cost (€/t PHA)		1,299	3,949	34	684	6	5,973

6.1.4 Recommendation

In Table 6-13, the estimated cost for all variants are summarized. Based on estimated results, the variant 1.1 and 1.2 with primary sludge transport shows the least cost requirement. However, due to the current operation condition in WWTPs in Scotland, the operator Scottish Water would like to avoid primary sludge transport. Variant 1.1 and 1.2 are therefore not recommended.

Among the variants with PHA-rich biomass transport, variant 3.2 with less decentralized PHA-enrichment system requires the least specific cost with regard to PHA produced amount. Therefore, it is the most recommended. As alternative options, variant 2.2 and variant 3.1 with four decentralized PHA-enrichment system can also be considered.

Table 6-13: Cost for all variants

Cost							
		Primary sludge transport		PHA rich biomass transport			
		Var. 1.1	Var.1.2	Var. 2.1	Var. 2.2	Var.3.1	Var.3.2
CAPEX (€/a)		3,204,144	3,861,230	7,740,890	7,174,002	7,240,522	7,025,566
OPEX (€/a)	OPEX excluding cost for transport, labor, maintainance, insurance	16,572,685	16,357,658	20,167,805	20,219,929	20,219,929	21,360,111
	Transport cost	8,583,541	5,185,242	109,258	171,245	66,364	185,435
	Labor and maintainance cost	1,342,199	2,059,150	6,360,856	4,210,003	4,835,251	3,701,468
	insurance cost	16,021	19,306	38,704	35,870	36,203	35,128
Sum (€/a)		29,718,589	27,482,586	34,417,514	31,811,048	32,398,268	32,307,708
PHA production (t/a)		5,139	4,953	5,107	5,120	5,120	5,409
Specific cost (€/t PHA)		5,783	5,549	6,739	6,213	6,328	5,973

6.2 Germany / Saarland

Due to the low population density in the Saarland region and the associated high transport costs, the implementation of a central PHA extraction plant in this region is not economically viable and is therefore not considered in detail. Within the framework of the GIS analysis, potentially suitable wastewater treatment plants could be identified for Germany. The costs incurred are even more favourable compared to the Glasgow region in Scotland, as the transport kilometres and the wastewater treatment plants considered are lower.

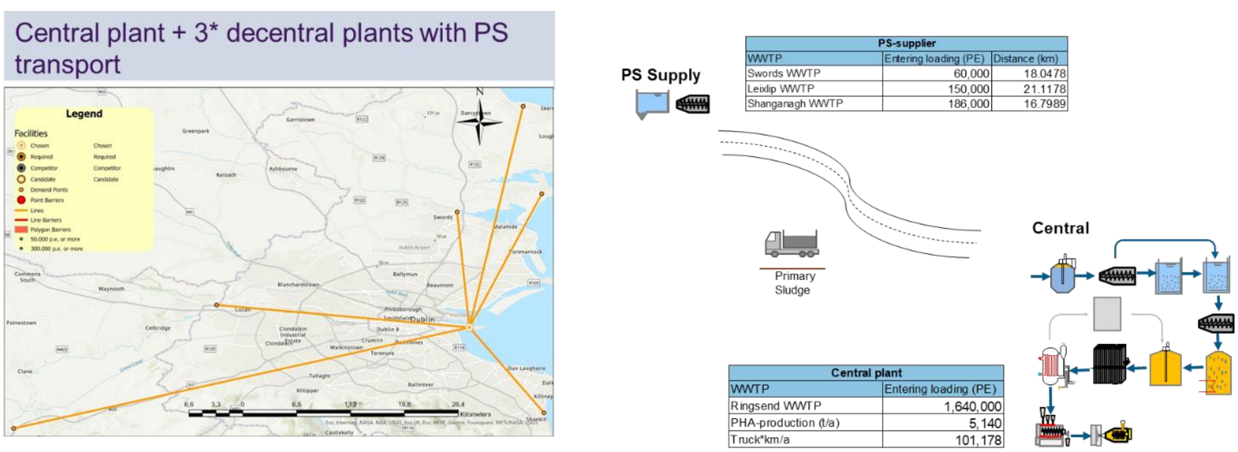
6.3 Ireland

The results of the GIS tool show that the Dublin region has the shortest distances between the central PHA extraction plant and the decentralized plants. Therefore 2 potentially suitable variants for PHA-production, one with primary sludge and one with PHA rich biomass transport, were investigated for the Dublin region.

6.3.1 Primary sludge transport

<u>Central</u>

In this variant, the central plant with PHA-enrichment system, PHA-extraction system and compounding system is set in Ringsend WWTP with a physical capacity of 1,640,000 PE. Three other WWTPs within 25km from Ringsend WWTP are selected to provide primary sludge. The physical loading, primary sludge amount of central plant and primary sludge suppliers and distance from primary sludge suppliers to central plant are summarized in Figure 6-7 and Table 6-14. According to the mass balance, the PHA production amount of this variant is estimated as 5,140 t/a.



PS-supplier		
WWTP	Entering loading (PE)	Distance (km)
Swords WWTP	60,000	18.0478
Leixlip WWTP	150,000	21.1178
Shanganagh WWTP	186,000	16.7989

Central plant	
WWTP	Entering loading (PE)
Ringsend WWTP	1,640,000
PHA-production (t/a)	5,140
Truck*km/a	101,178

Figure 6-7: Scenario with primary sludge transport and one central plant

Table 6-14: involved WWTPs in Variant 1.1

	WWTP	Loading entering (PE)	PS (tDM/a)	Distance to central plant (km)
Central plant				
0	Ringsend WWTP	1,640,000	698,367	-
primary sludge supplier				
1	Swords WWTP	60,000	25,550	18.05
2	Leixlip WWTP	150,000	63,875	21.12
3	Shanganagh WWTP	186,000	79,205	16.80

6.3.2 PHA rich biomass transport

In this variant there is one central plant and three decentralized PHA enrichment plants. The PHA-rich biomass is dewatered and transported to the central plant. Due to the relatively low capacity of the decentral PHA enrichment plants a dryer for the PHA enriched biomass is not considered at the decentral plants. In Table 6-15 the entering loading, primary sludge amount of selected WWTPs, the distance from dewatered PHA-rich biomass suppliers to central plant is separately summarized. The produced primary sludge amount in each plant is estimated based on the entering loading and two assumptions that the specific primary sludge production is 35 g DM/PE/d and the DM-content in primary sludge is 3%. According to the mass balance, a PHA production of 5,140 t/a can be expected.

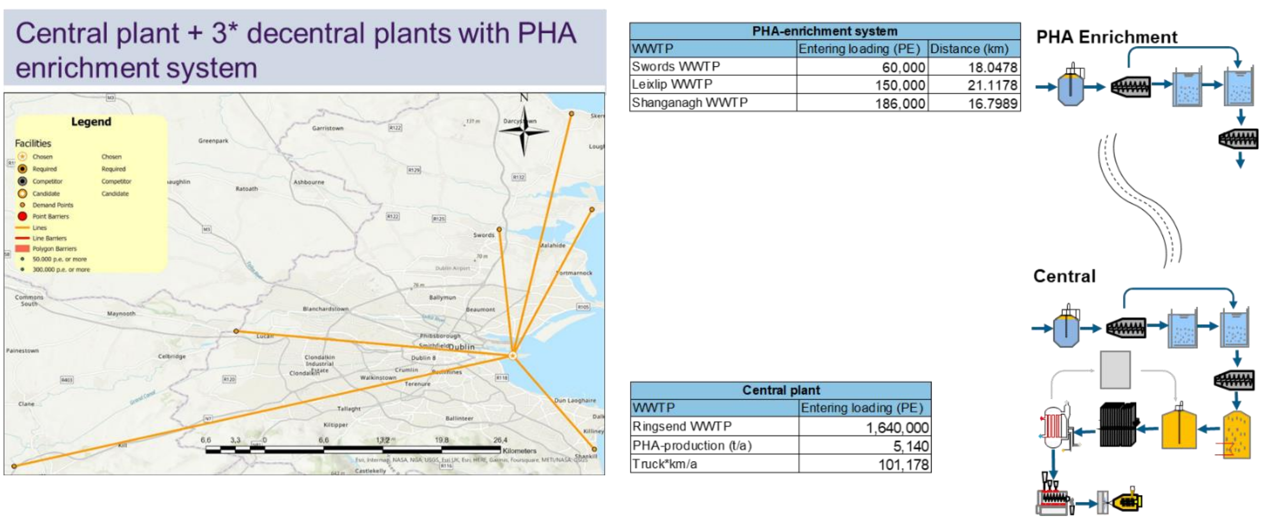


Figure 6-8: variant 1.2 with one central plant and 3 decentral plants providing dewatered PHA-rich biomass

Table 6-15: involved WWTPs in variant 1.2

	WWTP	Loading entering (PE)	PS (tDM/a)	Distance to central plant (km)
Central plant				
0	Ringsend WWTP	1,640,000	698,367	-
Dewatered PHA-rich biomass supplier				
1	Swords WWTP	60,000	25,550	18.05
2	Leixlip WWTP	150,000	63,875	21.12
3	Shanganagh WWTP	186,000	79,205	16.80

6.3.3 Estimated cost

The estimated cost for variant 1.1 with primary sludge transport is 5,082 €/t PHA, which are lower than the cost of the second variant with 5.688 €/t PHA. The cost breakdown for variant 1.1 and 1.2 are shown in Table 6-16 and Table 6-17.

Table 6-16: Cost for variant 1.1

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	Ringsend WWTP	4,461,915	19,545,865	0	1,342,199	22,310	25,372,289
Dewatered PHA-rich biomass supplier							
1	Swords WWTP	0	0	110,669	0	0	110,669
2	Leixlip WWTP	0	0	323,736	0	0	323,736
3	Shanganagh WWTP	0	0	319,334	0	0	319,334
Sum (€/a)		4,461,915	19,545,865	753,739	1,342,199	22,310	26,126,028
Specific cost (€/t PHA)		868	3,802	147	261	4	5,082

Table 6-17: Cost for variant 1.2

	WWTP	CAPEX (€/a)	OPEX (€/a)				Sum (€/a)
			OPEX excluding cost for transport, labor, maintainance, insurance	Transport cost	Labor and maintainance cost	Insurance cost	
Central plant							
0	Ringsend WWTP	4,139,997	18,462,077	0	1,342,199	20,700	23,964,973
Dewatered PHA-rich biomass supplier							
1	Swords WWTP	356,192	278,319	6,562	716,951	1,781	1,359,805
2	Leixlip WWTP	674,253	695,797	19,194	716,951	3,371	2,109,566
3	Shanganagh WWTP	783,928	294,229	8,730	716,951	1,851	1,805,690
Sum (€/a)		5,954,370	19,730,422	34,486	3,493,052	27,703	29,240,034
Specific cost (€/t PHA)		1,158	3,838	7	680	5	5,688

6.3.4 Recommendation

In Table 6-18 the estimated cost for all variants is summarized. Based on estimated results, the variant 1.1 with primary sludge transport shows with 5,082 €/t PHA the least cost requirement, because only one PHA-enrichment plant at the central plant is necessary. However, this is associated with high efforts for the transport of the primary sludge of the decentral plants. In contrast, variant 1.2 with three decentralized PHA plants has low transport costs, but higher capital costs for the installation of the PHA plants on the decentralized WWTPs. The specific costs amount to 5,688 €/t PHA.

Table 6-18: Cost for all variants

Cost			
		Primary sludge transport	PHA rich biomass transport
		Var. 1.1	Var.1.2
CAPEX (€/a)		4,461,915	5,954,370
OPEX (€/a)	OPEX excluding cost for transport, labor, maintainance, insurance exclusive	19,545,865	19,730,422
	Transport cost	753,739	34,486
	Labor and maintainance cost	1,342,199	3,493,052
	insurance cost	22,310	27,703
Sum (€/a)		26,126,028	29,240,034
PHA production (t/a)		5,140	5,140
Specific cost (€/t PHA)		5,082	5,688

7 Conclusions

Within the framework of WOW! Project, the market potential and technical feasibility for production of bioplastic from sewage with primary sludge as feedstock has been proved. However, an estimate of economic viability has shown that this requires a WWTP size of approximately 2 million PE (Nazeer Khan, 2020). Since in most regions in NWE, WWTP connection sizes are typically below 2 million PE. The following concepts for an economic production of PHA considering several WWTP sites were developed:

- Transport of primary sludge to a central plant for the enrichment, extraction and compounding of PHA.

- Decentralized plants for the enrichment of PHA and transport of PHA-rich biomass to a and a central plant for PHA extraction and compounding

The advantages and disadvantages with respect to the operation of the treatment plants and the required technical equipment were discussed. Due to the poor data basis for the individual sites such as sludge production, digester size, capacity of the biological stage and sludge digestion, it was not possible to perform a detailed analysis on the effects on each WWTP. However, these aspects have to be considered monetarily when planning a PHA production plant.

Using the GIS tool, optimal sites for PHA production could be identified for three different catchment areas in NWE. For the Scotland region, 3 sites for a centralized treatment plant were analyzed, of which Glasgow was most viable. The Glasgow region had the best boundary conditions due to the high population density, a high number of wastewater treatment plants with a capacity greater than 50,000 PE and a single driving distance to the central site of less than 70 km.

For the Saarland region, a very rural area, it was shown that only by taking into account wastewater treatment plants outside the catchment area, a sufficient amount of primary sludge can be acquired for a central PHA extraction plant. Also the chosen location for the PHA production facility was chosen outside the area of Saarland. Also, this involves long transport distances of up to 125 km single driving distance. Therefore, a site search for the whole of Germany was carried out within the framework of the GIS study. It was found that there are 8 target locations for the whole of Germany next to the single facilities that could already be self-supporting having over 2 million PE. The important is here the boundary condition of taking into account only WWTPs over 300.000 PE, so only dries sludge is being transported.

For the region of Ireland, only one central WWTP location could be identified. However, the Dublin region has an ideal location for a PHA production plant with the Ringsend WWTP with 1.6 million PE. With the surrounding wastewater treatment plants, sufficient primary sludge can be provided.

An economic feasibility study was carried out for the Glasgow and Dublin regions. For the rural region of Saarland, no detailed economic feasibility analysis was carried out. Due to the long transport distances between the decentral and central plant, the specific costs were very high.

Five different variants were investigated for the Glasgow region. The lowest specific costs of 5,500 €/t PHA result from a central PHA enrichment and extraction plant. However, this involves high cost for the transport of the primary sludge from the decentralized plants to the central site. This requires storage of the primary sludge at both sites. Furthermore, sufficient capacity in the biological stage and sludge digestion at the central site is required to treat the reject water of the additional primary sludge from the decentralized sites. Therefore, this alternative is not recommended for implementation.

Slightly higher specific costs of 6.200 €/t PHA result from the implementation of decentralized plants for PHA enrichment and transport of the dewatered PHA-enriched biomass. The advantage of this variant is that the reject water from the PHA enrichment can be treated directly at the site. In addition to the transport of the dewatered PHA enriched biomass, the transport of dried sludge was also considered for long distances between the decentral plant and the central plant. Hereby, the transport costs can be reduced significantly. Due to the additional costs for the dryer, specific costs of 6,000 €/t PHA result in the investigated case.

Two variants were investigated for the Dublin region. Due to the high connection size of the central plant of 1.6 million PE, only three additional wastewater treatment plants have to be considered to reach the required connection size of 2 million PE. The transport of primary sludge from the decentralized plants to the central plant results in specific costs of 5.100 €/t PHA. With the consideration of PHA enrichment plants on the decentralized plants, specific costs of 5,700 €/t PHA result.

Due to the decrease of the specific investment costs in dependence of the plant size, the most cost-effective solutions result especially for densely populated regions like Glasgow and Dublin. The Saarland region shows unfavorable boundary conditions for a PHA production plant due to the high number of wastewater treatment plants with a relatively small connection size. Considering industrial wastewater streams from the food industry with higher PHA yield rates, the specific costs can be reduced. This can result in economic solutions also for regions with WWTP with a size.

8 Literature

Nazeer Khan; M; Uhrig, T.; Steinmetz, H.; de Best, J.; Raingue, A.: WOW (2020): Techno-economic assessment of producing bioplastics from sewage https://www.nweurope.eu/media/16741/1wpt1_deliverable_3_1_pha_tea_final.pdf, Zugriff am 13.12.2022

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9 Abbreviations

NWE	North West Europe
PHA	Polyhydroxyalkanoate
GIS	Graphical Information systems
PE	People Equivalent
WWTP	Wate water treatment plant

Contribution to this report

DE: Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH, WiW

NL: Avans University of Applies Sciences, Avans