P-REX

Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency

Project supported by the European Commission within the Seventh Framework Programme Grant agreement No. 308645

Report on LCC of European P recovery processes

Work package	WP10 Life cost analysis of treatment-recovery paths
Deliverable number	D 10.1
Deliverable title	Report on LCC of European P recovery processes
Due date	Month 32
Actual submission date	11.11.2015
Start date of project	01.09.2012
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Dissemination level: (**PU**blic, Restricted to other **P**rogrammes **P**articipants, **RE**stricted to a group specified by the consortium, **CO**nfidential- only for members of the consortium)	PU
Deliverable Status:	Version 1.0

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1 Introduction

1.1 Goal and scope

The goal of this financial Life Cycle Costing (LCC) is to calculate process costs from the investor's perspective for selected processes for phosphorus recovery from municipal sewage sludge, sludge liquor, or sludge incineration ash, taking into account all relevant side-effects on the sludge treatment or the WWTP. The cost of all inputs and outputs is considered, although the cost of the recovered phosphorus materials only if a defined marketing channel is offered by the technology provider. The study uses cost data directly from technology suppliers or from case studies. All prices are reported to a reference country (Germany) and reference raw materials. This cost analysis should reveal the distribution of cost types for a given process and the cost of processes relative to one another and to other environmental technologies.

One target group of this report is investors considering phosphorus recovery, such as WWTP or incinerator operators. Other target groups are policymakers needing information on the cost of regulations of phosphorus recovery and engineers and researchers interested in the commercial perspectives of different recovery technologies to better orient their research.

1.2 Background

The phosphorus recovery processes that are the subject of this cost assessment were assessed and described by the P-REX project from a technical and environmental point of view (Herzel (ed.) et al., 2015; Niewersch (ed.) et al., 2014; Remy & Jossa, 2015).

A few previous comparative cost assessments of phosphorus recovery processes have been performed (Egle, Rechberger, & Zessner, 2014; A Nättorp, Lüscher, & Unpublished, 2010; Rheinisch-Westfälische Technische Hochschule Aachen, Fraunhofer IME, Fraunhofer ISI, Justus Liebig Universität, 2011; Wetsus, 2014). The most recent comparison (Egle et al., 2014) is very thorough, trying to provide an evaluation of many available technologies. P-REX focuses on a limited set of technologies with reasonable likelihood of implementation and spends considerable time consolidating mass and energy balances and cost assumptions.

There are different types of LCC. Hoogmartens et al. (2014) distinguish between:

- financial LCC accounting for costs borne by the investor
- environmental LCC accounting for the above costs plus externalities related to the product or process that are borne by other actors e.g. global warming adaptation costs
- societal LCC accounts for costs borne by the society rather than for one actor. This approach is thus based on complete monetarisation of LCA resource demand and emissions

As said, the LCC of P-REX is financial.

2 Methodology

2.1 System definition

Nine scenarios for phosphorus recovery were investigated. Three baseline models without recovery were used as reference (Table 1). The scenarios are named by their approach of phosphorus recovery rather than with their process name, so that the reader can relate directly to the type of process/pathway which is assessed. However, the direct link between scenarios and process names enables the clear identification of original processes, which is explicitly not avoided in this report. Flow schemes and main features of the processes are given in the P-REX factsheets (Annex).

The recovery processes will be integrated in the overall wastewater and sludge treatment trains.

Depending on the raw material used by the processes (sludge, sludge liquor or sludge ash) they intervene in different parts of the treatment trains. For the nine processes evaluated, six different treatment trains with phosphorus recovery can be distinguished (Figure 1). The three most common treatment trains without technical phosphorus recovery (Reference treatment trains R1-R3 in Figure 2) serve as a baseline.

Figure 3 shows the system evaluated for treatment train 1-3. A common mass and energy balance is established for cost analysis and LCA. These flows and other inputs are evaluated in the different cost components Infrastructure (CAPEX), Energy, Raw materials and Personnel. The Output values are also calculated for Waste and By-products.

The revenue from the phosphoric material is in general not included in the cost calculation. Most materials do not yet have a market and their legal status and quality criteria are still developing. The integration of these materials in production of fertilizer and other products is only just beginning. Thus the revenue from the recovered materials is uncertain and will evolve over time. Marketing efforts might very much increase the revenue, but will on the other hand represent additional costs if output of recovery processes is not directly suitable for sale (e.g. quality, physical properties). Due to these uncertainties in product market value, it was decided not to mix rough estimations of revenue in the calculation with the more certain cost data of the process. Revenue will only be included if, as in the case of Ecophos and Pearl, the technology provider offers offtake of product at fixed conditions. For the other processes the income potential from phosphorus material sales made in the pre-normative matrix (Anders Nättorp (ed.)et al., 2014) will be compared to process costs.

Table 1: Short description of recovery and reference scenarios including process names and state of development.

No	Scenario	Description	Process name	Data quality
1	Sludge Precipitation	Precipitation of struvite with Mg dosing in sludge before dewatering and pH increase via CO2 stripping.	Airprex™	Commercial operation
2	Liquor precipitation 1	Precipitation of struvite with Mg in sludge liquor after dewatering and pH increase via NaOH	Pearl®	Commercial operation
2	Liquor precipitation 2	Precipitation of struvite with Mg in sludge liquor after dewatering and pH increase via NaOH	Struvia™	Pilot
3	Sludge leaching 1	Leaching of digested sludge and dewatering P recovery from the resulting sludge liquor by pH increase and Mg dosing, simultaneous precipitation of metals with Na2S.	Gifhorn process	Test operation
3	Sludge leaching 2	Leaching of digested sludge and dewatering. P recovery from the resulting sludge liquor by pH increase and Mg dosing, metal complexation with citric acid	Stuttgarter process	Pilot
4	Sludge metallurgic, integrated	Drying followed by a thermal treatment of sludge in a shaft furnace (1’450°C) with coke addition and energy recovery via burning of off-gas in municipal solid waste incinerator. Recovery of P as slag and metals in a metal phase.	Mephrec®	Pilot
5	Ash leaching 1	Leaching of ash with H2SO4, solid-liquid separation, pH increase and precipitation of CaP with Ca(OH)2	LeachPhos	Test operation
5	Ash leaching 2	Leaching of ash with H3PO4, separation of H3PO4 and metal ion fractions via staged ion exchange regenerated by HCl. Concentration of the H3PO4.	Ecophos	Commercial operation with P rock. Pilot with ash.
6	Ash thermo-chemical, integrated	Treatment of ash from mono-incineration in rotary kiln (950°C). Addition of dried sewage sludge as reducing agent to remove metals via off-gas and Na salts to improve plant availability.	Ashdec	Test operation
R1	Mono-incineration	Mono-incineration and landfill		Commercial operation
R2	Co- incineration	Co-incineration in power plants and MSWI. Landfill of slag or ash.		Commercial operation
R3	Conventional recycling in agriculture	Valorisation of digested sludge in agriculture.		Commercial operation

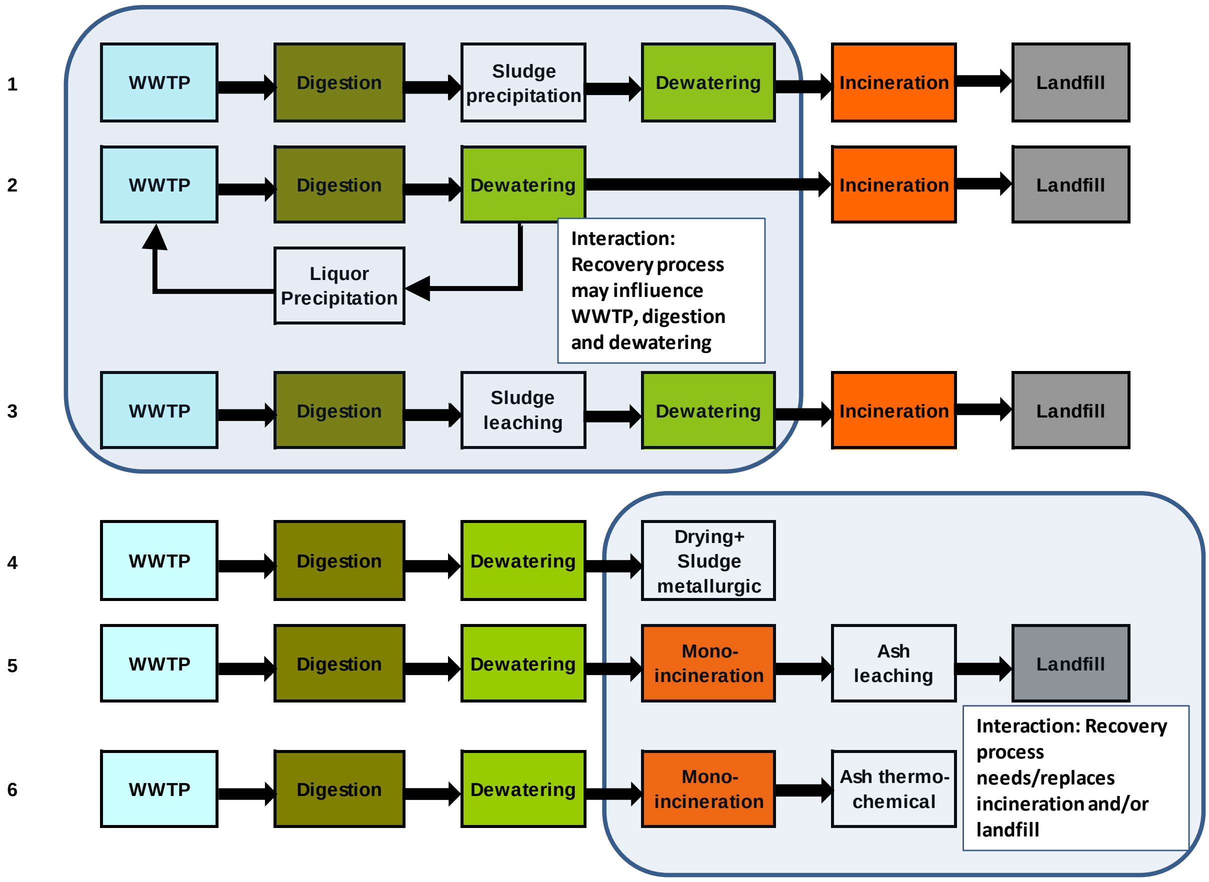


Figure 1: The treatment trains investigated by P-REX. Interactions between sludge/sludge liquor based processes (1-3) and the WWTP and interactions between dried sludge/ash based processes (4-6) and the incineration/landfill shown.

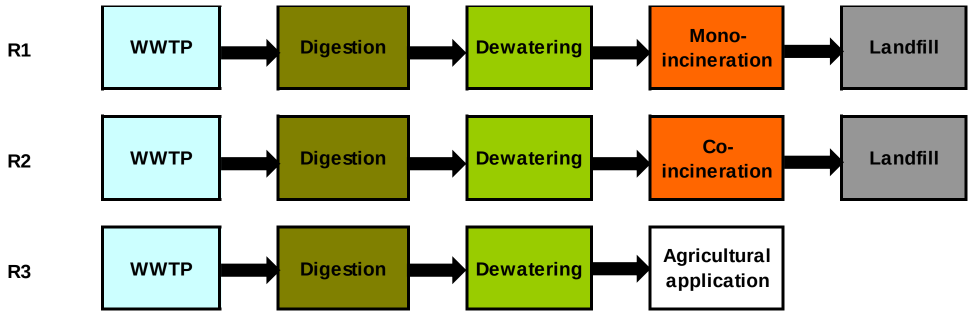


Figure 2: The reference treatment trains used as a baseline in P-REX. Only sludge disposal is monetarized.

As indicated in Figure 1 the phosphorus recovery influences the existing treatment trains. The sludge/sludge liquor treated in the first three treatment trains is modified. The removed phosphorus and the chemical treatment of the sludge may have beneficial or negative influence on the functioning of the WWTP and the ensuing sludge disposal. These process benefits are also quantified in the cost calculation (Figure 3).

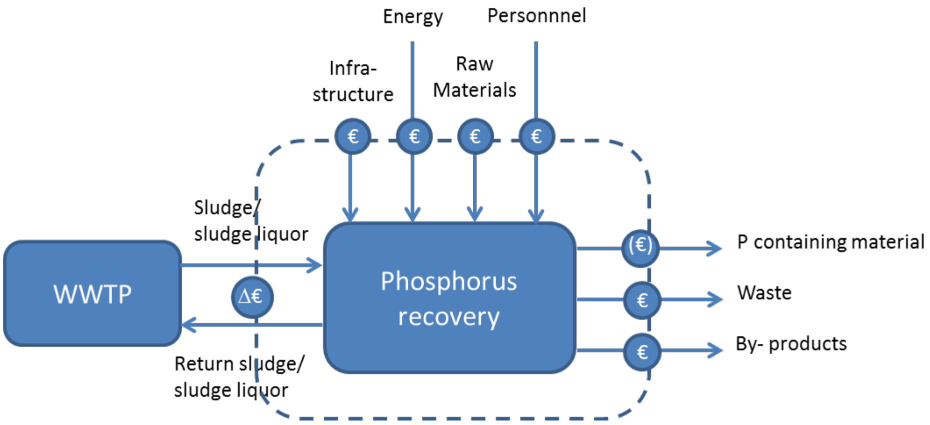


Figure 3: System evaluated for treatment train 1-3

The process cost treatment trains 4-6 are evaluated much as the treatment trains 1-3, by evaluating all inputs and outputs required for P recovery (Figure 4). Thus the **Process cost** is obtained. Only the interaction between the recovery process and the other processes is more pronounced for these treatment trains. As the waste stream is accounted for in the evaluation of the recovery process, the landfill of the reference treatment train is replaced. One recovery process (4) also replaces the mineralization step (see Figure 4), working directly with dried sludge as input. The others (5-6) need mono-incineration as an obligatory upstream mineralization step. If the sludge is currently not mono-incinerated the introduction of these recovery technologies will require a switch to this technology as pre-requisite, which will generate additional costs. By including the costs/benefits of necessary changes between one of the reference treatment trains R1, R2 or R3 the **Transition cost** from this treatment train to one of the treatment trains 4-6 is obtained.

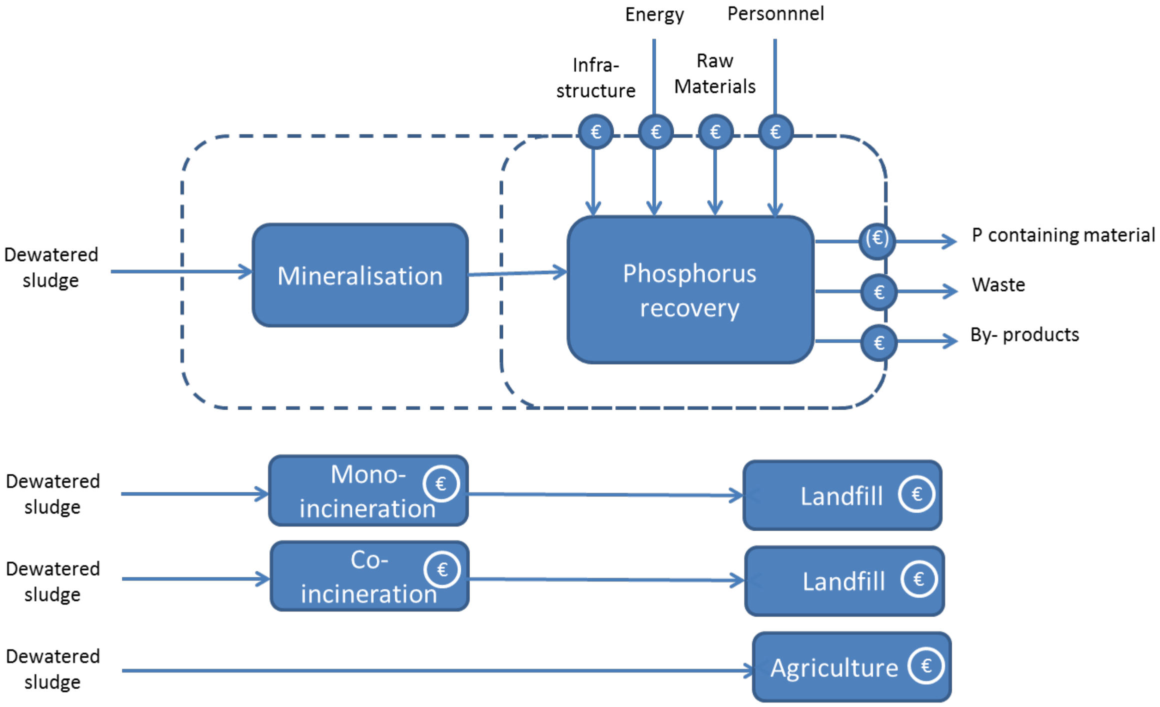
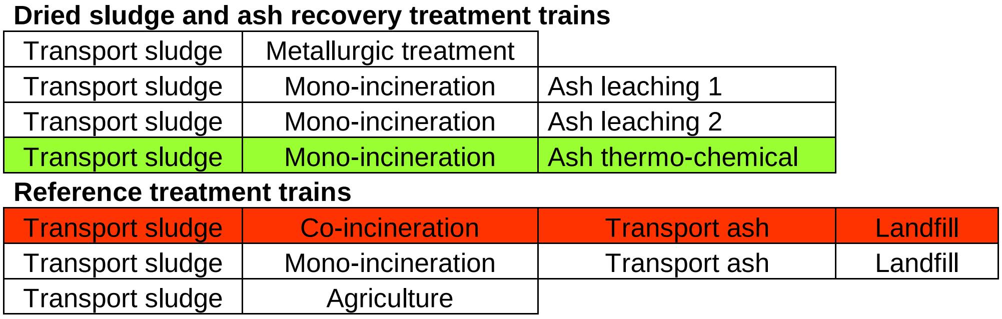


Figure 4: System evaluated for treatment train 4-6

The elements of treatment trains including transport are shown in Figure 5. The cost of an element is calculated per kg of phosphorus. With the recovery process yield the cost per kg of recovered phosphorus is calculated. The specific cost for e.g. transport of sludge is namely higher if the yield is low (because more sludge transport is then needed per kg of recovered phosphorus). Transition cost is thereafter calculated as the recovery process cost plus required elements from the reference treatment trains (Figure 5).



Dried sludge and ash recovery treatment trains

Transport sludge	Metallurgic treatment	
Transport sludge	Mono-incineration	Ash leaching 1
Transport sludge	Mono-incineration	Ash leaching 2
Transport sludge	Mono-incineration	Ash thermo-chemical

Reference treatment trains

Transport sludge	Co-incineration	Transport ash	Landfill
Transport sludge	Mono-incineration	Transport ash	Landfill
Transport sludge	Agriculture		

Figure 5: Exemplary elements for calculation of the transition cost from the reference scenario “co-incineration” to “thermo-chemical recovery from ash”. The elements of the resulting path are in green, red cells are subtracted.

2.2 Sensitivity analysis

Sensitivity analysis checks the influence of assumptions for calculation or input data variation on the outcomes. Regarding the multitude of assumptions and input data that have been included in this cost analysis; sensitivity analysis had to be restricted to a defined set of parameters that were identified as valuable for this exercise together with experts in the consortium. A systematic analysis of uncertainty and sensitivity of all parameters (e.g. via Monte-Carlo-Analysis) is out of the scope of this study and would require significant efforts in time and modelling. The effects of the variation of three parameters were investigated. Ranges were as small as possible, but should still be large enough to encompass almost every case (Table 2).

Table 2: Parameters and ranges for sensitivity analysis

	Standard	Min	Max
Plant size	Standard size	20%	500%
Phosphorus in raw material	Standard concentration (DE)	50%	200%
Interest rate	3%	50%	200%

The costs of the sludge based processes were assessed for 1 Mio PE as a standard WWTP size. Ash processes were assessed for an approximate minimum size of a plant of 2.5-2.7 Mio PE for which the tech providers made their simulations and their cost estimations based on engineering. To investigate sensitivity to plant size costs are extrapolated to other sizes assuming that personnel costs remain unchanged, that the investment cost changes with the square root of the plant size change (Prasad, 2011) and that other costs types change proportionally to the plant size (Table 3)

Table 3: Size power per cost type. The cost is recalculated to a target size from standard size as $(S/S_0)^a+(S/S_0)^b+(S/S_0)^c+\dots$ S being the target size and S_0 being the standard size.

Cost type	Power
Capex	0.5
Energy	1
Materials	1
Personnel cost	0
Other operational costs	1
WWTP operational benefits	1

2.3 Data collection, treatment and quality

Reference processes for WWTP and sludge treatment up to mono-incineration are defined with flows and compositions of streams (sludge liquor, sludge, ash etc.; Annex: Table 19A). Process data are transferred to this reference composition as the boundary conditions, for example phosphorus concentration in sludge, liquor or ash might influence the performance (e.g. yield) of a process and most certainly its specific cost. Conditions both for chemical elimination of phosphorus and EBPR are defined and processes using sludge with different phosphorus elimination methods can thus be compared. The reference ash concentration was the average of the concentration in the 12 mono-incineration plants treating essentially municipal sludge. Other mono-incineration plants treat a mix of industrial and municipal sludge which leads to lower concentrations. The sludge concentration was chosen to lead to this ash composition. The sludge concentration thus obtained is 30% higher than the German average.

The collection of input data for the different processes of P recovery relies mainly on primary data collected from technology providers and operators (Table 1). Data are thus seen representative of the individual technologies at the time of data collection (end 2014). Most processes realized a regular production campaign (test or commercial; Table 1) and the quality of these data is seen as high. If no production data were available input data from pilot operation were used. Careful upscaling was done in close contact with technology providers and operators and the data quality is estimated to be medium. In addition, transfer of site-specific process data to the defined conditions in the reference model was required to reflect process performance and efficiencies in a most realistic way. Mass balances and cost data were cross-checked internally and intensively validated within the project team and with the data providers to ensure valid input datasets and high quality and representativeness of results.

2.4 Material and energy consumption

The general characteristics and performance of the plant, its input and output as well as WWTP process benefits is summarized for the nine assessed processes in Table 4 below. In the following the data of individual processes will be commented upon.

2.4.1 Sludge precipitation- Airprex

P recovery ratio is defined based on P balances in full-scale plants in Berlin-Wassmannsdorf and Mönchengladbach (90% precipitation efficiency for dissolved PO4-P, 50% harvesting of formed struvite crystals into the product). Electricity demand is calculated in relation to aeration time (8h). $MgCl_2$ is dosed in molar excess to dissolved PO_4-P (ratio 2.1). Based on operators experience, dewatering of output sludge is improved by +2% TS (mean), and polymer demand can be reduced by 25%.

2.4.2 Liquor precipitation 1- Pearl

Process data is based on the Rock Creed plant (US), assuming a recovery of 83% of total P load in the liquor into the final product. Electricity demand is mainly for recirculation pump, while heat is used for product drying in belt drier. $MgCl_2$ is dosed in equimolar ratio to P, and NaOH is used for pH control.

2.4.3 Liquor precipitation 2- Struvia

P recovery ratio is calculated from pilot plant results in Brussels to 80% of total P load in the liquor into the final product. Electricity demand is estimated by the provider to 0.2 kWh/m^3 liquor, mainly for the turbomix in the reactor, while heat is used for product drying. Equimolar Mg dosing and NaOH for pH control are defined comparable to the Pearl® process, as both processes use the same principle.

2.4.4 Sludge leaching 1- Gifhorn

Process data is based on extensive studies of the Gifhorn full-scale plant with EBPR sludge. Phosphorus recovery potential is calculated by overall P balances to 48.7% related to the total P load in sludge, assuming an extraction pH of 4.5 and related demand of H_2SO_4. Mg is dosed as $Mg(OH)_2$ below stochiometric ratio, so phosphorus precipitates mainly as calcium phosphate. NaOH demand for pH control is based on a final pH of 9.3, and Na_2S demand is directly taken from Gifhorn data. Electricity demand for the entire process is based on detailed engineering of all aggregates (pumps, mixers, dosing), including the second centrifuge for dewatering. Additional polymer demand for second dewatering is assumed with 2 g/kg TS.

2.4.5 Sludge leaching 2- Stuttgart

Phosphorus recovery potential is calculated to 45% based on latest experience (Feb 2015) at the large pilot plant in Offenburg working on ChemP sludge, assuming an extraction pH of 4 with respective dosing of H_2SO_4. Citric acid is used to complex metals (4 L/m^3 filtrate). Mg dosing is equimolar to dissolved PO_4-P after extraction to precipitate phosphorus mainly as struvite at pH = 8.5, adjusted with NaOH.

2.4.6 Sludge metallurgic, integrated solution - Mephrec

The Mephrec process can be implemented for treatment of ash or sludge and the sludge treatment can either be stand-alone or integrated with an incineration plant. Here the drying and mineralisation of sludge to produce a calorific gas which is then incinerated to produce electricity in an existing incineration plant is assessed. This integrated solution is the least costly thus has the highest chances to be implemented.

Mass energy balances are based on modelling data of Ingitec for a full-scale plant (12'000 t dry sludge/y). Based on the few pilot trials 80% of the phosphorus is assumed to be recovered in the slag. The losses in metal alloy and off-gas still need to be thoroughly quantified in continuous trials. The electricity demand for the Mephrec reactor is estimated with 0.05 kWh/kg input material, while briquetting requires 0.035 kWh/kg briquettes. Electricity and heat demand for low temperature sludge drying to 80% DM upstream of the Mephrec reactor is estimated from other studies (0.09 kWh/kg evaporated H_2O for electricity, 0.875 kWh/kg evaporated H_2O for heat). Excess heat from MSWI plant is used for drying. Electricity output (0.45 kWh/kg briquettes) is based on electrical efficiency of MSWI steam turbine (20%) in relation to heating value of Mephrec off-gas. Coke and oxygen demand of the furnace is estimated based on the thermal simulation of the reactor. Beside the P-rich slag, an iron alloy can also be recovered from the process. The cost for the incineration and gas cleaning capacity is included in the calculation as well as the drying cost. Not included is the wet sludge bunker (2 x 200 m^3) and dry sludge silo.

2.4.7 Ash leaching 1- Leachphos

Process data is based on a test production in Berne complemented by mass balance from lab trials in Basel at FHNW, which quantify the phosphorus recovery yield at 70%. Electricity demand is estimated based on detailed engineering of the process (mixing, pumping) and dewatering steps. Chemical demand for acidic leaching (H_2SO_4) and pH increase ($Ca(OH)_2$, NaOH) is based on the lab scale mass balance results.

2.4.8 Ash leaching 2- Ecophos

Mass and energy balances are based on lab and pilot trials (Louvain-la Neuve) of Ecophos upscaled to plan a full-scale plant. The treatment of all streams to defined by-products and an inert solid as well as the pre-treatment and standard treatment of wastewater is included.

2.4.9 Ash thermochemical, integrated solution - Ashdec

The Ashdec process can be implemented either as stand-alone or integrated with a mono- incineration plant. The integrated solution where hot ash from the incineration is treated directly and the off-gas is treated by the incineration plant has been assessed. This integrated solution is the least costly thus has the highest chances to be implemented.

Process data are based on pilot trials with mono-incineration ash and thermal simulation of the process with the ASPEN Plus software. Phosphorus losses with off-gas are estimated to 2%. Electricity demand for the rotary kiln and off-gas cleaning is assumed with 0.104 kWh/kg ash. Dosing of $NaSO_4$ is transferred from pilot plant results, while $Ca(OH)_2$ and NaOH required for off-gas cleaning are estimated from BAT on dry gas cleaning. The cost of the material required for gas cleaning is included in the calculation, but not the amortisation of the treatment capacity required.

The cost includes a granulation unit where other nutrients can also be added to make complex fertilizer granules.

Table 4: General characteristics of the plant, energy and materials input and output as well as WWTP process benefits for the nine assessed processes.

	Sludge precipitation 1	Liquor precipitation 1	Liquor precipitation 2	Sludge leaching 1	Sludge leaching 2	Metallurgic, integrated	Ash leaching 1	Ash leaching 2	Ash thermo-chem, integrated
Plant size (t/a)	418'800	372'500	372'500	418'800	418'800	11'905	15'000	15'000	13'800
Raw material	digested sludge	sludge liquor	sludge liquor	digested sludge	digested sludge	dry sludge	ash	ash	ash
Phosphorus Elimination at WWTP	EBPR	EBPR	EBPR	EBPR	Chem-P	Chem-P	Chem-P	Chem-P	Chem-P
Calculatory operation duration (h/y)	8'000	8'000	8'000	8'000	8'000	8'000	7'500	7'800	8'000
Recovered material	struvite	struvite	struvite	struvite	Struvite	slag	CaP	H3PO4	treated ash
Potential phosphorus amount (t/y)	524	524	524	524	524	524	1'425	1'425	1'376
Recovered phosphorus amount (t/y)	38	62	60	255	236	421	999	1'382	1'349
Yield (%)	7	12	11	49	45	80	70	97	98
Personnel (full time equivalents)	0.13	0.26	0.26	0.50	0.36	11.00	2.00	6.00	6.00
Energy									
Electricity (MWh/y)	387	134	75	1'759	709	-2'185	1'590	450	1'104
Natural gas (MWh/y)	-	7	3	-	-	-	-	-	5'392
Steam (MWh/y)	-	-	-	-	-	-	-	28'250	-
Raw materials									
Calcium hydroxide 90% (t/y)	-	-	-	-	-	-	1'927	450	210
Citric Acid 50% (t/y)	-	-	-	-	1'852	-	-	-	-
Coke (t/y)	-	-	-	-	-	1'137	-	-	-
Dolomite (t/y)	-	-	-	-	-	560	-	-	-
Dry sludge (t/y)	-	-	-	-	-	-	-	-	1'892
Hydrochloric acid 30% (t/y)	-	-	-	-	-	-	-	*	-
Ion exchange filling (t/y)	-	-	-	-	-	-	-	5	-
Magnesium chloride 30% (t/y)	1'828	633	633	-	-	-	-	-	-
Magnesium hydroxide 53% (t/y)	-	-	-	97	-	-	-	-	-
Magnesium oxide 100% (t/y)	-	-	-	-	355	-	-	-	-
Raw materials cont.									

	Sludge precipitation 1	Liquor precipitation 1	Liquor precipitation 2	Sludge leaching 1	Sludge leaching 2	Metallurgic, integrated	Ash leaching 1	Ash leaching 2	Ash thermo-chem, integrated
Oven lining (t/y)	-	-	-	-	-	14	-	-	-
Oxygen (VPSA) (t/y)	-	-	-	-	-	318	-	-	-
Polymer for dewatering (t/y)	-	-	-	1.50	-	-	-	-	-
Polymer for heavy metal elimination (t/y)	-	-	-		-	-	1	-	-
Sodium hydroxide 50% (t/y)	-	13	13	881	751	-	1'223	-	309
Sodium sulphite 15% (t/y)	-	-	-	1'277	-	-	-	-	-
Sodium sulphate (t/y)	-	-	-	-	-	-	-	-	5'106
Sulphuric acid 98% (t/y)	-	-	-	2'084	2'793	-	5'730	-	-
Water (t/y)	-	-	-	-	-	-	116'820	36'600	4'000
Output									
Al/Fe-Solution 4% (t/y)	-	-	-	-	-	-	-	29'250	-
Ca/Mg-Solution 35% (t/y)	-	-	-	-	-	-	-	13'050	-
Phosphoric acid 85% (t/y)	-	-	-	-	-	-	-	*	-
Raw iron (t/y)	-	-	-	-	-	803	-	-	-
Solid waste DK1- DE** (t/y)	-	-	-	-	-	-	-	8'100	-
Solid waste DK 2-3- DE (t/y)	-	-	-	-	-	-	25'325	-	-
Solid waste DK 3-4 DE (t/y)	-	-	-	-	-	560	-	840	346
Wastewater (t/y)	-	-	-	-	-	32'725	124'478	33'750	-
Process benefits									
Reduced sludge volume (t/y)	4'152	-	-	-	-	-	-	-	-
Reduced P return load (t/y)	66	62	60	71	-4	-	-	-	-
Reduced N return load (t/y)	12	28	27	43	105	-	-	-	-
Reduced energy P&N treatment (MWh/y)	26	58	56	86	200	-	-	-	-
Reduced polymer demand (t/y)	37	-	-	-	-	-	-	-	-

*Provision of hydrochloric acid (19'725 t/y) and take-off of phosphoric acid (4'000 t/y) by tech provider. ** Landfill class, DK1 is inert, DK2-3 is for sewage sludge ash and DK3-4 for metal concentrates etc.

2.5 Calculation of the different cost types

2.5.1 Capex

Investment costs are in general based on detailed engineering made by the technology providers. As no investment cost was given for the Sludge leaching 2 process, it was estimated to be slightly lower than the similar Sludge leaching 1 process.

By common agreement in the consortium and the amortisation for equipment was set to 10 years. 10- 15 years would be in accordance with German practice, so 10 years is on the safe side. This can be justified as the technology is new and the actual wear thus less well known and for some technologies the wear is actually estimated to correspond to a 10 year depreciation period. Assuming a public investor, which in general have a high creditworthiness the interest rate was estimated at 3%. Thus an annuity for equipment of 11.7% could be calculated.

Building costs for basic steel halls were estimated at 250 EUR/m^3 by the consortium. According to common practice in Germany and by common agreement in the consortium the amortisation for the building was set to 30 years, leading to an annuity of 5.1%. Land cost in industrial zones is about 100 EUR/m^2 and its annual cost thus negligible compared to the building cost (Table 5).

Table 5: Basis for calculation of capital cost

Interest rate (%)	3.0
Amortisation period equipment (y)	10
Annuity equipment (%)	11.7
Building cost, including land (EUR/m^3)	250
Amortisation period building (y)	30
Annuity building (%)	5.1

2.5.2 Material and energy cost and income

The material and energy costs (Table 6) were in general given by the technology providers as they usually know the market prices relevant to the materials of their process. The costs can be considered as accurate, also because the inputs were considered as an offer to the customer and the tech providers would like to preserve their credibility. However, the prices are averages for a certain region (DE) and a certain point in time (end 2014). They thus vary depending on the location and over time. They are also subject to negotiation. The hydrochloric acid price for example is very low; the specific price per acidity equivalent is lower than for sulphuric acid. This is because Ecophos is already ordering hydrochloric acid for another full-scale plant and thus has excellent negotiating power respectively access to integrated solutions with the supplier.

Two electricity prices were used. Most processes use the market price paid by an industrial customer. Processes which will likely be placed on an incineration plant site (those based on dried sludge or ash) use the price at which the incineration plant can sell its excess electricity on the market.

The average current sludge and ash transport costs in Germany were given by Veolia and landfill costs were based on both the experience of the tech providers and published offers.

Table 6: Material and energy costs

Description	Cost	Description	Cost
Al/Fe-solution 4%Me (EUR/t)	20	Magnesium oxide 100% (EUR/t)	280
Ca/Mg-solution 35% (EUR/t)	5	Natural gas (EUR/MWh)	62
Calcium hydroxide 90% (EUR/t)	90	Oven lining (EUR/t)	1'500
Citric Acid 50% (EUR/t)	600	Oxygen (VPSA) (EUR/t)	110
Coke (EUR/t)	400	Phosphoric acid 85% (EUR/t)	517
Pearl struvite offtake (EUR/t)	375	Polymer dewatering (EUR/t)	4'000
Dolomite (EUR/t)	50	Polymer heavy metal elimination (EUR/t)	2'500
Dry sludge (EUR/t)	0	Raw iron (EUR/t)	200
Electricity (EUR/MWh)	140	Sludge/residue to disposal/landfill, 50 km (EUR/t)	15
Electricity internal price (EUR/MWh)	50	Sludge disposal (EUR/t)	35
Hydrochloric acid 30% (EUR/t)	25	Sodium hydroxide (50%; EUR/t)	90
Ion exchange resin (EUR/t)	2'500	Sodium sulphite 15% (EUR/t)	925
Landfill DK1(EUR/t)	30	Sodium sulphate (EUR/t)	130
Landfill SSA DK2-3 (EUR/t)	50	Steam, 3.5 bar (EUR/MWh)	8
Landfill metal conc. DK3-4 (EUR/t)	120	Sulphuric acid (98%;EUR/t)	90
Magnesium chloride 30% (EUR/t)	75	Wastewater (EUR/t)	2
Magnesium hydroxide 53% (EUR/t)	150	Water (EUR/t)	0.20

2.5.3 Process benefits

Sludge and sludge liquor based processes provide process benefits for the WWTP (Table 4):

- reduced sludge volume
- reduced energy consumption since phosphorus and nitrogen are precipitated as struvite and not recycled to the WWTP where they would have to be eliminated once again
- less demand for polymer

These can be monetarized using the sludge disposal, energy and polymer cost. Also cost for chemicals and maintenance due to encrustation are saved. These were assessed for Airprex based on data from the plants in Mönchengladbach, Berlin and Amsterdam (0.16 MEUR/y for a 1 Mio PE plant). The liquor precipitation processes also observe lower encrustation costs. However, these could not be conclusively quantified by P-REX.

2.5.4 Personnel cost

The number of operators needed to run the plant 24/7 was estimated by the tech providers. These were multiplied by 50'000 EUR, the typical annual salary of a WWTP operator including social costs (Tarif Vertrag öffentlicher Dienst, Entgeltstufe 7, Durchschnittswert).

2.5.5 Other costs

Insurance against fire, breakdown, damages was approximated as 0.5% of the investment cost for all processes except metallurgic and thermochemical treatment which were slightly lower.

Annual maintenance was approximated as 2% of the investment per year for some processes. Ecophos and ASH DEC counted slightly higher maintenance costs, Leachphos half as high and Stuttgart none.

For the metallurgic treatment also the cost for the briquetting unit and the cost participation in the gas turbine of the MSWI were included under other costs.

2.6 German cost and extrapolation to Europe

All costs were calculated for Germany, mostly based on cost data coming from Germany. The costs can be extrapolated to other countries. This was done in the regional studies of P-REX: for each cost type a country factor was estimated based on price data of the country.

3 Results and discussion

3.1 Results per Process

Below on the one hand the main characteristics of the plant including investment and annual cost as well as the repartition of the annual cost will be presented and discussed for each process.

3.1.1 Sludge precipitation- Airprex

The Airprex (Table 7) process was calculated for 1 Mio person equivalents, which is a plant of average capacity. The recovered phosphorus amount is comparatively low, but the process is in general profitable (negative process costs) for a WWTP with EBPR due to the process benefits.

Table 7: Main characteristics of Airprex

Capacity (t/a)	418'800
Raw material	digested sludge
Plant size (Mio PE)	1.0
Recovered phosphorus (t/y;%)	38/7
Investment (MEUR)	1.3
Sum of process costs (MEUR/y)	-0.14

The capex for the Airprex process (Figure 6) comprises amortization of a 35 m^3 airlift reactor, compressor, washing line and instrumentation. The energy cost is for electricity for the compressors and materials cost is essentially the $MgCl_2$ used for precipitation. Personnel cost is limited to 0.13 Full Time Equivalents (FTE). Process benefits are substantial. Reduced return load of phosphorus and nitrogen, reduced polymer demand for sludge conditioning and reduced cost for encrustation each contribute about a third to the total process benefits.

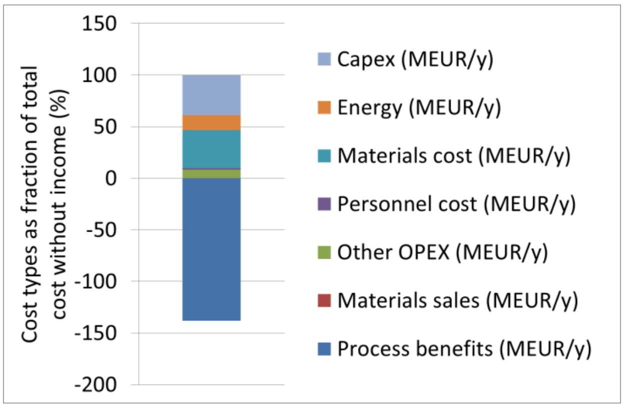


Figure 6: Repartition of cost types for Airprex

3.1.2 Liquor precipitation 1- Pearl

The Pearl process was calculated for 1 Mio person equivalents (Table 8), which is a plant of average capacity. The recovered phosphorus amount is comparatively low for a substantial investment. Ostara offers off-take of product which leads to moderate process costs if guaranteed revenues for product sale to OSTARA are counted.

Table 8: Main characteristics of Pearl

Capacity (t/a)	372'500
Raw material	sludge liquor
Plant size (Mio PE)	1.0
Recovered phosphorus (t/y;%)	62/12
Investment (MEUR)	2.5
Sum of process costs (MEUR/y)	0.23

The capex for the Pearl process comprises mainly the amortization of the custom reactor ensuring large and uniform crystals (Figure 7). The energy cost is for electricity for the compressors and materials cost is essentially the $MgCl_2$ used for precipitation. Process benefits include reduced return load. Pearl (and Struvia) also saves encrustation costs (less than Airprex). These could not be quantified within P-REX.

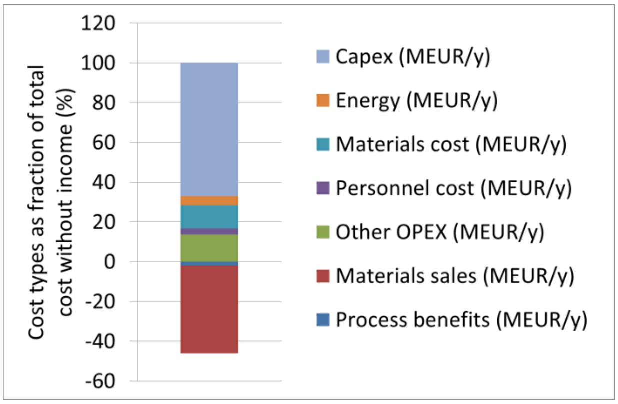


Figure 7: Repartition of cost types for Pearl

3.1.3 Liquor precipitation 2- Struvia

The Struvia process was calculated for 1 Mio person equivalents (Table 9). The recovered phosphorus amount is comparatively low, but so are investment and process costs.

Table 9: Main characteristics of Struvia

Capacity (t/a)	372'500
Raw material	sludge water
Plant size (Mio PE)	1.0
Recovered phosphorus (t/y;%)	60/11
Investment (MEUR)	1.0
Sum of process costs (MEUR/y)	0.19

The capex for the Struvia process comprises the amortization of the crystallization reactor, decanters and instrumentation (Figure 8). The materials cost is essentially the $MgCl_2$ used for precipitation.

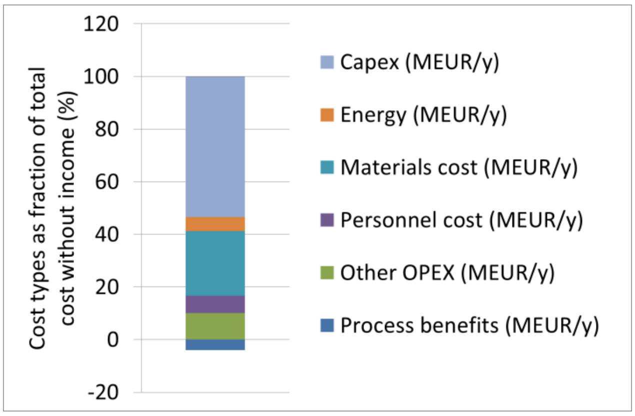


Figure 8: Repartition of cost types for Struvia

3.1.4 Sludge leaching 1- Gifhorn

The Gifhorn process was calculated for 1 Mio person equivalents (Table 10). The recovered phosphorus amount is higher than in the precipitation processes. However, the investment and resulting process costs are even higher compared to the aforementioned processes.

Table 10: Main characteristics of Gifhorn

Capacity (t/a)	418'800
Raw material	digested sludge
Plant size (Mio PE)	1.0
Recovered phosphorus (t/y;%)	255/49
Investment (MEUR)	6.1
Sum of process costs (MEUR/y)	2.57

The capex for the Gifhorn process comprises the amortization of two parallel 16 m^3 reactors for leaching and the centrifuges for separating leached sludge and the precipitated struvite respectively (Figure 9). Substantial electricity costs results from the use of the centrifuges. The largest cost item is the sodium sulfite used for separation of heavy metals for a pure and plant available product, and the second largest the sulphuric acid for leaching.

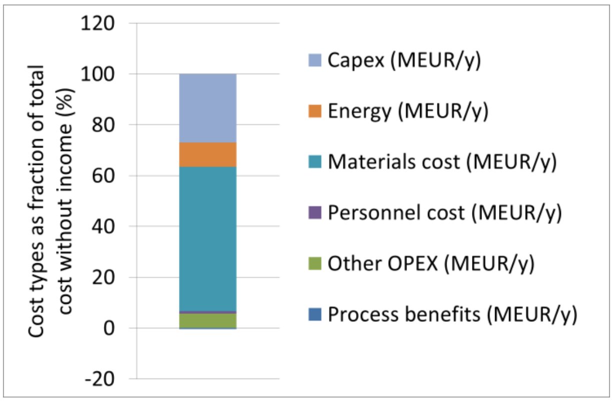


Figure 9: Repartition of cost types for Gifhorn

3.1.5 Sludge leaching 2- Stuttgart

The Stuttgart process was calculated for 1 Mio person equivalents (Table 11). The recovered phosphorus amount is higher than the precipitation processes. However, the investment and resulting process costs are even higher compared to the aforementioned processes.

Table 11: Main characteristics of Stuttgart

Capacity (t/a)	418'800
Raw material	digested sludge
Plant size (Mio PE)	1.0
Recovered phosphorus (t/y;%)	236/45
Investment (MEUR)	5.3
Sum of process costs (MEUR/y)	2.24

The investment for the Stuttgart process was estimated from that of the Gifhorn process and assumed to be slightly lower due to the use of filter presses instead of centrifuges (Figure 10). The use of filter presses also saves electricity costs compared to the Gifhorn process. The largest cost item is the citric acid used for complexation of heavy metals for a pure product, and the second largest the sulphuric acid for leaching.

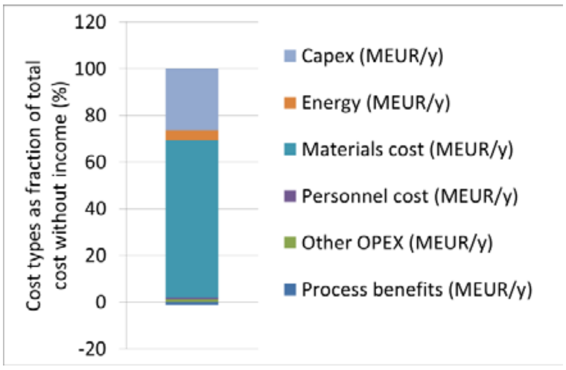


Figure 10: Repartition of cost types for Stuttgart

3.1.6 Sludge metallurgic, integrated solution - Mephrec

The Mephrec process was calculated for 1 Mio person equivalents (Table 12). The recovered phosphorus amount is higher than both sludge precipitation processes. The investment and resulting process costs are also much higher compared to the aforementioned processes. However, the process both separates phosphorus and mineralises the sludge which leads to cost advantages in other parts of the treatment train (see 3.2.2 Transition costs). The Mephrec process may also be used to treat ash, but the cost structure is less attractive due to the lacking mineralization function.

Table 12: Main characteristics of Mephrec

Capacity (t/a)	11'905
Raw material	dry sludge
Plant size (Mio PE)	1.0
Recovered phosphorus (t/y;%)	421/81
Investment (MEUR)	23.6
Sum of process costs (MEUR/y)	4.05

The option assessed by P-REX includes low-temperature drying and is integrated with a MSWI plant or with cement works where the calorific gas produced by Mephrec is incinerated to produce electricity and heat. Also a standalone unit would be possible, but the integrated plant is the most favorable option.

Capex is the dominating cost type of the Mephrec process, caused mainly by the amortization of the metallurgical reactor (Figure 11). Smaller amortization costs included in the calculation are proportional contribution to the MSWI incineration and gas cleaning capacity used as well as sludge drying and briquetting. The main material cost is coke. Personnel costs are substantial for this complex process; 11 FTE are necessary to run it, even though it is integrated with the operation of an incineration plant. The Mephrec process produces more electricity than it uses, covering a small part of the costs.

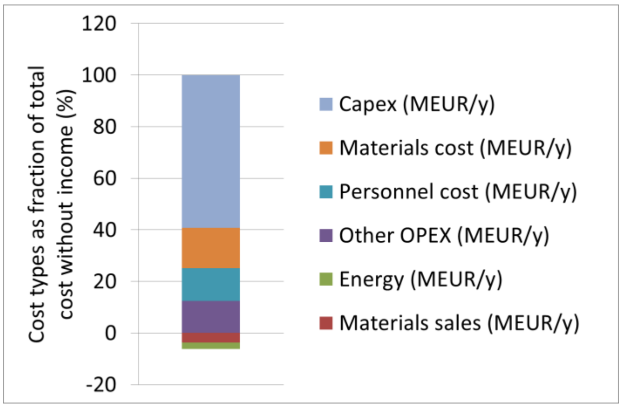


Figure 11: Repartition of cost types for Mephrec

Also sale of the metal phase as scrap iron generates a benefit.

3.1.7 Ash leaching 1- Leachphos

The Leachphos process was calculated for 2.7 Mio person equivalents, or 15'000 to of ash which is a rather small plant (Table 13). The recovered phosphorus amount is double that of the Mephrec plant for the same investment. However, the Leachphos process does not offer additional mineralization as Mephrec does.

Table 13: Main characteristics of Leachphos

Capacity (t/a)	15'000
Raw material	ash
Plant size (Mio PE)	2.7
Recovered phosphorus (t/y;%)	999/70
Investment (MEUR)	23.2
Sum of process costs (MEUR/y)	5.61

The capex covers amortization of reactors for leaching, precipitation and workup of wastewater (Figure 12). Reactors in parallel and buffer tanks ensure continuous operation of the belt filters for solid liquid separation. The main cost type is the materials cost that in turn is dominated by the need to landfill extracted ash. The workup of this residue to reach inert quality represents an important optimization potential for Leachphos. Other substantial materials costs are acid and base for pH adjustment.

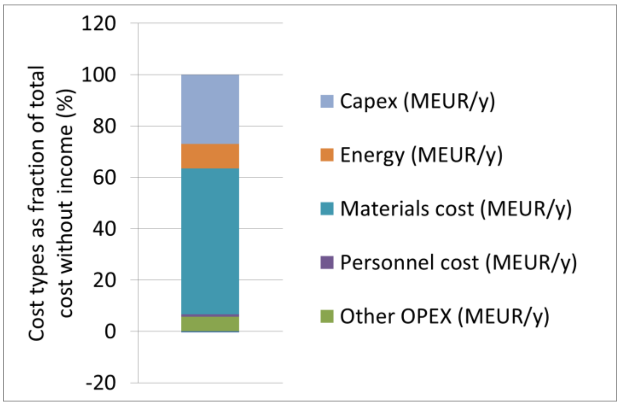


Figure 12: Repartition of cost types for Leachphos

3.1.8 Ash leaching 1- Ecophos

The Ecophos process was calculated for 2.7 Mio person equivalents, which is a rather small plant (Table 14). Almost all the contained phosphorus can be recovered. The necessary investment is only half as high as that of Mephrec and Leachphos. Ecophos covers most of the investment, provides the hydrochloric acid, but still makes some overall profit thanks to sales of the highly purified phosphoric acid that is produced. Ecophos counts an amortization rate of 15 years and reaches a payback time for the project of 10 years, which they deem acceptable.

Table 14: Main characteristics of the Ecophos process

Capacity (t/a)	15'000
Raw material	ash
Plant size (Mio PE)	2.7
Recovered phosphorus (t/y;%)	1382/97
Invest customer (MEUR)	0.5
Invest tech provider (MEUR)	11.1
Sum of costs investor (MEUR/y)	0.87
Sum of costs tech provider (MEUR/y)	-0.57

The very low cost at which Ecophos can procure hydrochloric acid is essential for this profitability.

Looking at the customer cost structure, the capex needed is very low (building, precleaning of wastewater; Figure 13). The materials cost is the largest cost type due to landfill costs. A team of 6 FTE are sufficient, under the assumption that they work together with a team running an incineration plant on the same site. The customer is expected to be able to considerably lower the overall costs by selling 4% AlFeCl-solution as coagulant and 35% MgCaCl-solution (e.g. as thawing agent).

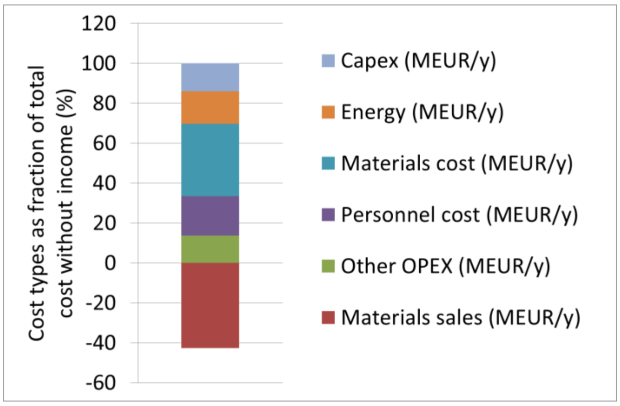


Figure 13: Repartition of cost types for the Ecophos process

3.1.9 Ash thermochemical, integrated solution - ASH DEC

The Ash-dec process was calculated for 2.5 Mio person equivalents, a rather small plant (Table 15). Almost all the contained phosphorus can be recovered. The necessary investment is only half as high as that of Mephrec and Leachphos.

Table 15: Main characteristics of ASH DEC

Plant size (t/a)	13'800
Material	ash
Plant size (Mio PE)	2.5
Recovered phosphorus (t/y;%)	1349/98
Investment (MEUR)	11.7
Sum of process costs (MEUR/y)	3.21

Capex is the main cost type of ASH DEC (Figure 14). It covers amortization of the rotary kiln, dosing equipment and instrumentation. The non-negligible cost for energy is caused by the natural gas needed to reach the reaction temperature of 950°C. The substantial materials cost is essentially the sodium sulphate used to make the phosphate plant available. As the recovery and the incineration plant will be operated in a joint team an additional 6 FTE are sufficient.

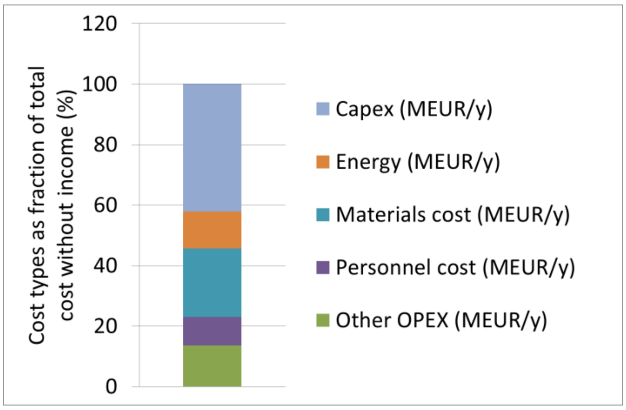


Figure 14: Repartition of cost types for ASH DEC

3.2 Comparison of processes

3.2.1 Process costs

The process costs vary between -3.81 (savings) and 10.05 EUR/kg phosphorus (Figure 15). Most expensive are the sludge leaching processes and one ash leaching process. The other ash leaching process is in contrast very economical. This process has 0.63 EUR/kg P investor cost including material sales and 2.18 EUR/kg P when summing up the investor and tech provider costs and not counting sales. A rough approximation of most costs indicates that Single Super Phosphate (SSP) from sewage sludge ash can be produced in the fertilizer industry at 1.00 €/kg P, cheaper than most of the processes assessed by P-REX. When comparing the different types of specific costs (per kg P), capex and the related maintenance are the highest for ash leaching. Also sludge precipitation and liquor precipitation 1 have high costs in this category. They require a couple of unit operations and because of the low yield the specific capex and maintenance costs become substantial. Specific material costs are the highest for sludge leaching, which can be explained by the need to dissolve from a comparatively dilute matrix and subsequently precipitate. Sale of phosphoric material is counted only for sludge precipitation 1 and ash leaching 2 (see 2.1 System definition). In both cases it makes an important contribution to the attractiveness of the process (see 3.4 Materials sales). For processes based on ash dried sludge (scenario 4-6), the process cost is only part of the picture, the transition cost taking into account the current sludge disposal (see 3.2.2) must be used for comparisons.

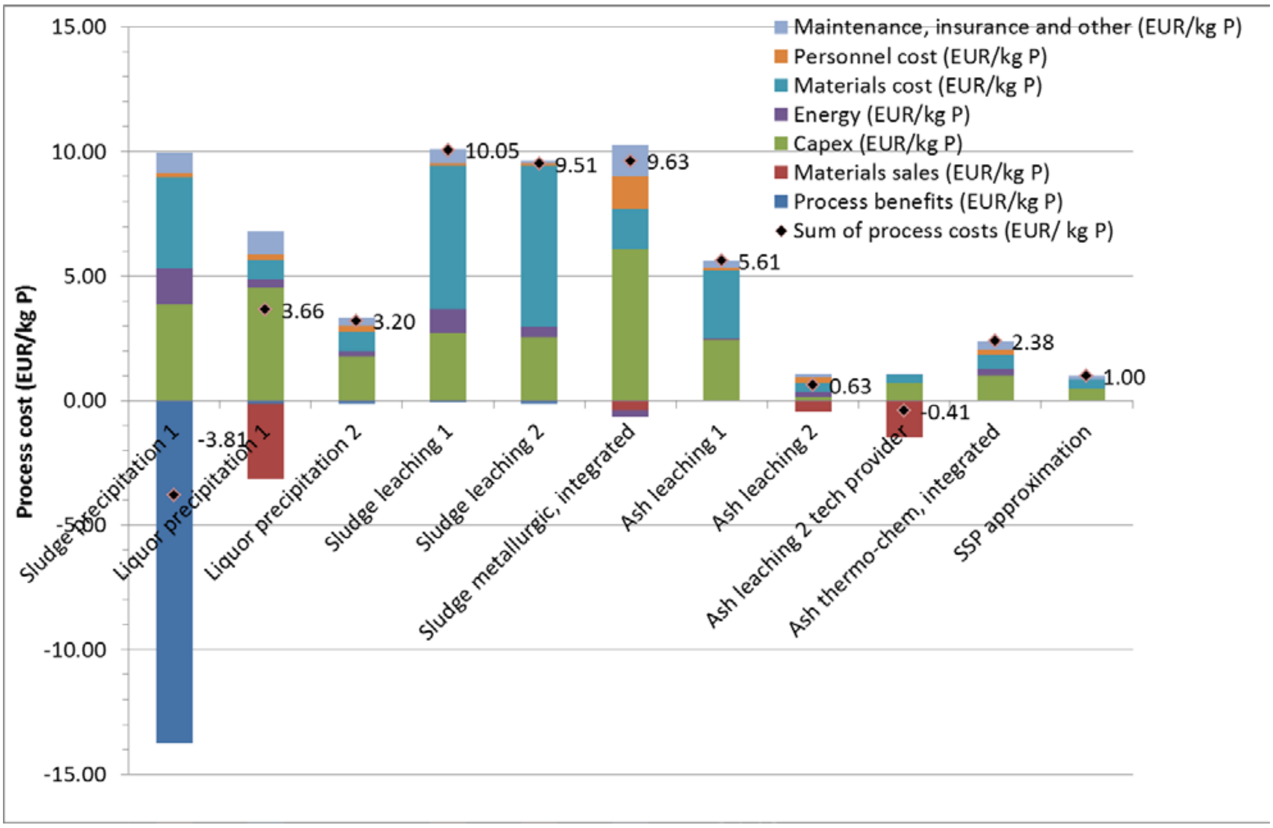


Figure 15: Specific process costs for recovery processes divided into cost types. Comparison with approximated main costs (invest, acid) of single-superphosphate production from sewage sludge ash.

3.2.2 Transition costs

Based on the German sludge properties, transport distances and unit costs (see Annex: Table 23A), the costs of the sludge disposal can be calculated. The most expensive sludge disposal is mono-incineration and the least expensive is agricultural application. The sludge transport costs for typical disposal transport distances are not negligible, which explains why often the nearest disposal location is preferred (Table 16).

Table 16: Cost elements of German reference treatment paths

	Cost (EUR/t)
Monoincineration + Landfill	65
Co-incineration + Landfill	50
Agricultural application	35
Landfill of ash	50
Sludge to agriculture (35 km)	14
Sludge to incineration (35 km)	14
Ash to landfill (50 km)	15

The cost of transition from wastewater and sludge treatment trains of today to wastewater and sludge treatment trains with phosphorus recovery can now be calculated. If the recovery is made from sludge or sludge liquor (scenario 1-3) the transition cost is identical to the process costs discussed in the preceding paragraph.

If phosphorus is recovered from dried sludge or ash (scenario 4-6) the cost of transition depends of the current sludge disposal as shown with specific costs for phosphorus in Figure 16. It is the least expensive if the sludge is currently mono-incinerated, more expensive if a transition from co-incineration or use in agriculture is required. Metallurgic recovery will generate a calorific gas which is then burnt for heat and electricity in an existing plant. This use of incineration capacity is already included in the process cost. Thus this solution including mineralization will replace current infrastructure, whose costs are deduced. The process costs of metallurgical recovery are among the highest, but as said it includes the mineralization and thus its transition costs are among the lowest.

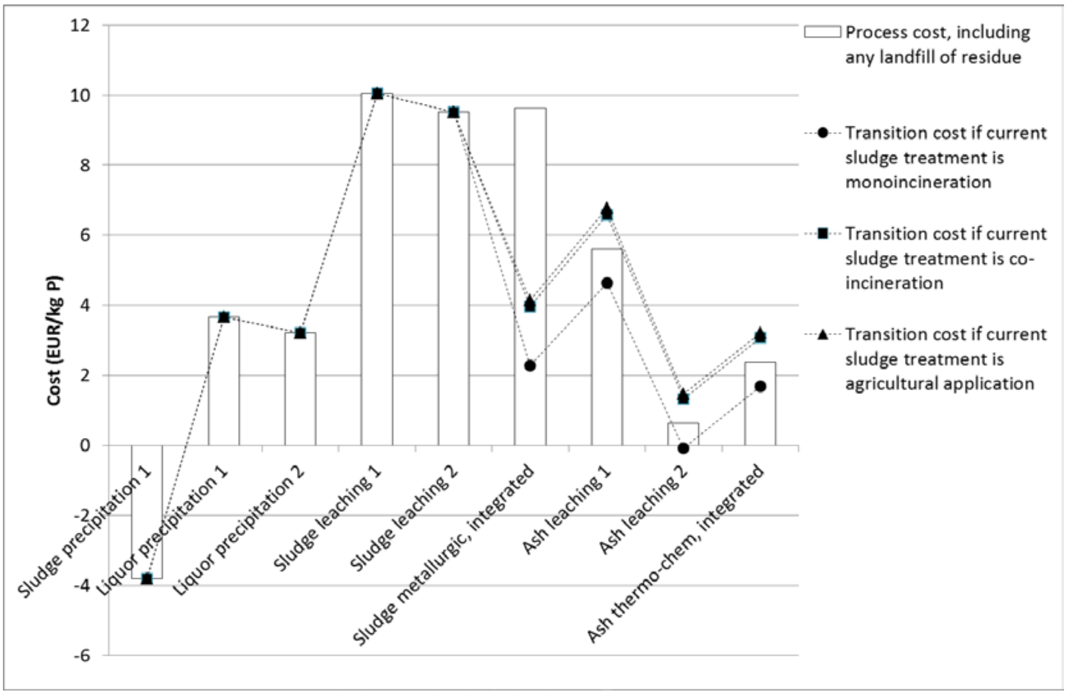


Figure 16: Specific process cost and transition cost from the three reference treatment trains. Expressed per amount of recovered phosphorus.

Figure 17 compares the transition cost of standard sized plants with the amount of phosphorus that they can recover. Again the cost influence of the current sludge disposal (mono-incineration, co-incineration or use in agriculture) is visible. Ash based plants recover the most phosphorus (1'000-1'400 t/y) at very varying costs (-0.1 MEUR/y to 6.8 MEUR/y). A standard sized plant for metallurgical treatment of sludge recovers only about a fourth of this amount, but is also less costly. Still less phosphorus, but at a higher cost, is recovered by the standard sized sludge leaching plants. The precipitation plants recover very little phosphorus compared to the ash based plants (up to 36 times less) but come at a low or even negative cost.

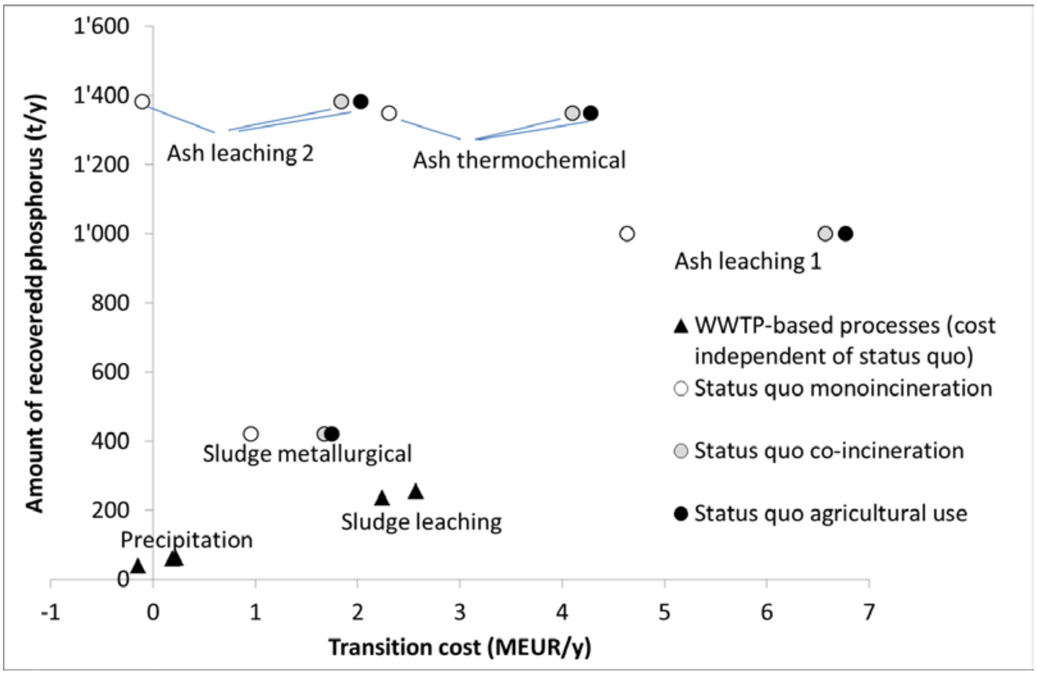


Figure 17: Transition cost and amount of recovered phosphorus for standard sized plants. Cost of dried sludge and ash based processes are differentiated according to the current sludge disposal.

In Table 17 these same data are shown together with specific costs per person equivalent and per amount of sludge treated. The transition cost per person equivalent range between -0.14 EUR/y and 2.57 EUR/y. This can be compared to the total cost for wastewater, both net and treatment, in Germany of 108 EUR/PE y (Lamp & Grundmann, 2009). The introduction of phosphorus recovery, even with the most expensive process studied, would increase the total cost for wastewater with less than 3%. The specific transition cost per kg P ranges between -3.81 EUR and 10.05 EUR. Thus the transition cost of some processes can compete with the market price of for example phosphorus rock (0.90 EUR/kg P: World bank, 2015) or struvite (0.30 EUR/kg P- 1.00 EUR/kg P). Others are more expensive, up to a factor 11. These processes are thus not profitable in the current legal framework, which explains why essentially only sludge precipitation is operated commercially today. The specific transition cost per t of sludge ranges between -1 and 25 EUR/t. If the sludge is currently disposed of in agriculture (at 49 EUR/t), the overall cost (recovery+ disposal) would consequently decrease if the low cost process is implemented or increase 50% if the most costly process is implemented.

Table 17: Plant characteristics, plant cost and transition costs from three reference treatment trains. Specific transition cost in relation to person equivalents, to recovered phosphorus amount and to equivalent treated sludge amount. A reference for comparison is given for each specific cost type.

	Sludge precipitation 1	Liquor precipitation 1	Liquor precipitation 2	Sludge leaching 1	Sludge leaching 2	Sludge metallurgic, int.	Ash leaching 1	Ash leaching 2	Ash thermochem, int.	Reference comparison
Standard plant size (Mio. PE)	1.0	1.0	1.0	1.0	1.0	1.0	2.7	2.7	2.5	
Recovered phosphorus (t/y)	38	62	60	255	236	421	999	1'382	1'349	
Investment (MEUR)	1.3	2.5	1.0	6.1	5.3	23.6	23.2	2.4	11.7	
For standard plant (MEUR/y)										
Process cost						4.05	5.61	0.87	3.21	1.43[1]
Transition monoincineration	-0.14	0.23	0.19	2.57	2.24	0.96	4.63	-0.11	2.31	
Transition from co-incineration						1.67	6.57	1.84	4.10	
Transition from agricultural use						1.74	6.77	2.03	4.28	
Specific per person equivalent (EUR/PE y)										
Transition monoincineration						0.96	1.70	-0.04	0.92	
Transition from co-incineration	-0.14	0.23	0.19	2.57	2.24	1.67	2.42	0.67	1.64	108[2]
Transition from agricultural use						1.74	2.49	0.75	1.71	
Specific per amount of P recovered (EUR/ kg P)										
Transition monoincineration						2.28	4.64	-0.08	1.68	
Transition from co-incineration	-3.81	3.66	3.20	10.05	9.51	3.97	6.58	1.33	3.07	0.90[3] 0.3-1.0[4]
Transition from agricultural use						4.14	6.78	1.47	3.21	
Specific per amount of sludge (EUR/t)										
Transition monoincineration						9	16	0	9	79[5]
Transition from co-incineration	-1	2	2	25	21	16	23	6	16	64[5]
Transition from agricultural use						17	24	7	16	49[5]

[1] SSP production cost [2] Wastewater cost assuming average 40m3 drinking water, 33 m3 rainwater (Lamp & Grundmann, 2009) [3] P rock market price 082015 (World bank, 2015) [4] struvite market price [5] sludge disposal in mono-incineration, co-incineration and agriculture including typical transport cost

3.3 Sensitivity

At higher phosphorus content of the raw material most cost types remain unchanged, only some chemicals must be dosed proportionally to the phosphorus content. Higher phosphorus content leads to more recovered material with basically the same process cost. Thus the specific process cost is almost inversely proportional to the phosphorus content (Figure 17). Sludge precipitation is a special case, where the recovery represents a moderate cost, which is outweighed by the larger benefits for WWTP processes (encrustation, dewatering, nutrient return flow) generated by the removal of phosphorus resulting in overall cost benefits. For this process higher phosphorus content of the raw material means more costs, so the cost benefit becomes smaller or even disappears.

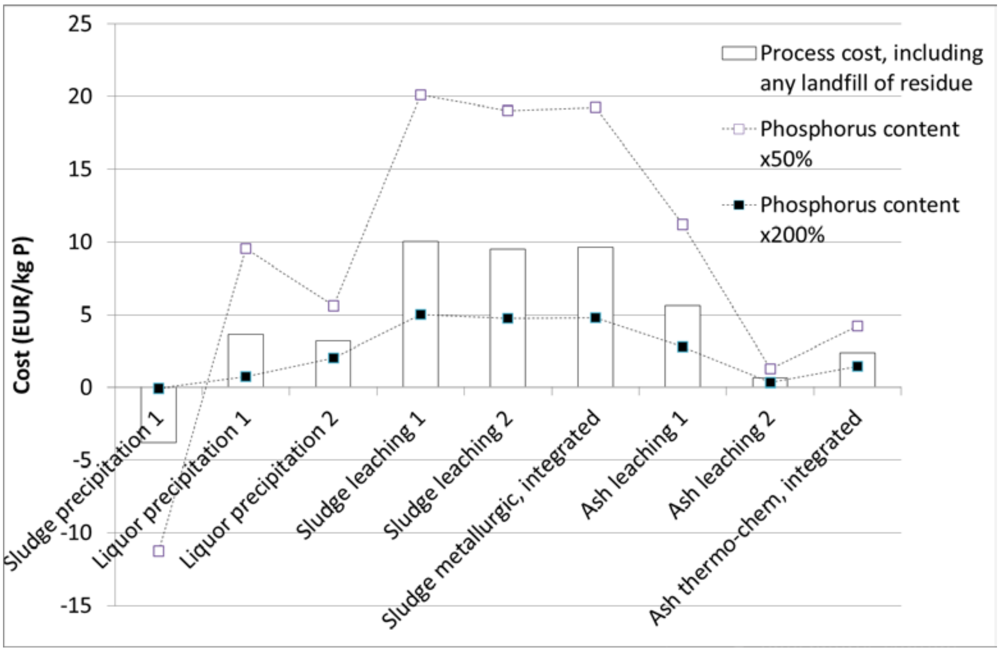


Figure 18: Specific process cost for recovery processes at halved, standard and doubled phosphorus content in the raw material

The specific process cost is lower in larger plants due to economies of scale (Figure 18). This is explained by the constant personnel cost and under-proportional investment cost increase in larger plants. The effect of plant size is the highest where investment is high (liquor precipitation, metallurgic and thermo-chemical recovery) and the lowest where material costs dominate (sludge leaching).

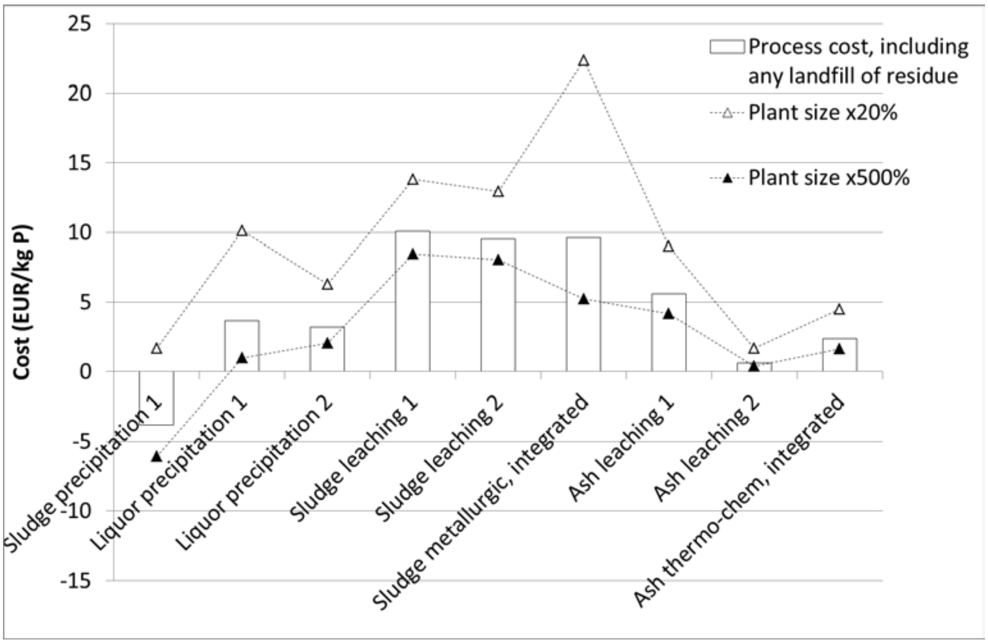


Figure 19: Specific process cost for recovery processes at 20%, 100% and 500% of the standard plant size.

The specific process cost is little influenced by the interest rate (Figure 19). The amortization period, which was set to 10 years by common agreement among project partners and tech providers, has more influence on the CAPEX.

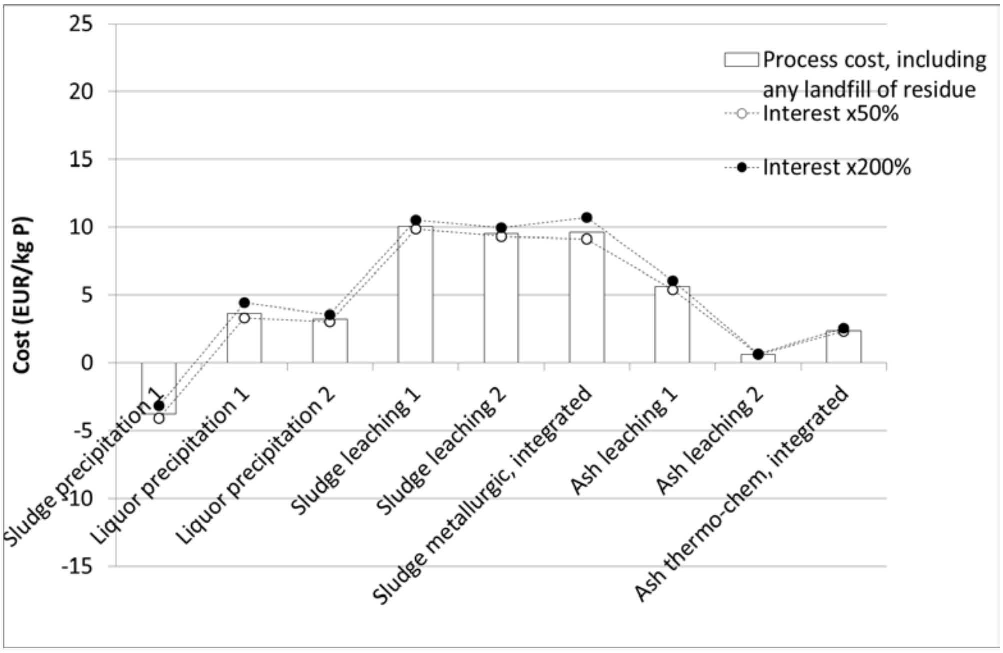


Figure 20: Specific process cost for recovery processes 1.5%, 3% (standard), and 6% interest rate

3.4 Materials sales

The sale of recovered phosphoric materials could cover part of the recovery costs and even lead to profitability of the process as in the case of Ecophos. Typical price ranges and quality requirements for different markets were analyzed in the pre-normative matrix of P-REX (P-REX). With the exception of the Ecophos outputs the output materials only fulfil the fertilizer contaminants requirements.

In Figure 20 the transition cost from the mono-incineration reference treatment train (white) is compared to market prices for fertilizer raw materials (black). Processes for which the transition cost already include materials sales are marked in grey.

The sludge and sludge liquor based processes produce struvite. The struvite market is developing. Typical prices up to now lie between 0.30 EUR/ kg P and 1.00 EUR/ kg P. Sales could thus make a small contribution to the overall profitability of the precipitation processes. The contribution of materials sales to the cost of sludge leaching processes would also be small, maximum 10%.

The income from sales of materials recovered from dry sludge or ash can be estimated by comparison of quality (heavy metal contamination, phosphorus concentration and plant availability) to phosphorus rock (0.90 EUR/kg P, harbor bulk price; World bank, 2015).

Sale of material as P rock would cover 40% of the transition costs of the metallurgic treatment. However, the material recovered by metallurgic treatment is more contaminated than P rock and also has a lower concentration, so materials sales contribution must be less.

The material recovered by Ash leaching 1 (Leachphos) is more plant available and more contaminated than P rock and thus might have a similar market price. In that case material sales would cover 20% of the transition costs.

Sale of output material at the price of P rock would cover 50% of the transition costs of the thermochemical ash treatment. However, although more plant available than P rock, the material recovered by thermochemical ash treatment is more contaminated and less concentrated. Consequently, the materials sales contribution would likely be below 50%.

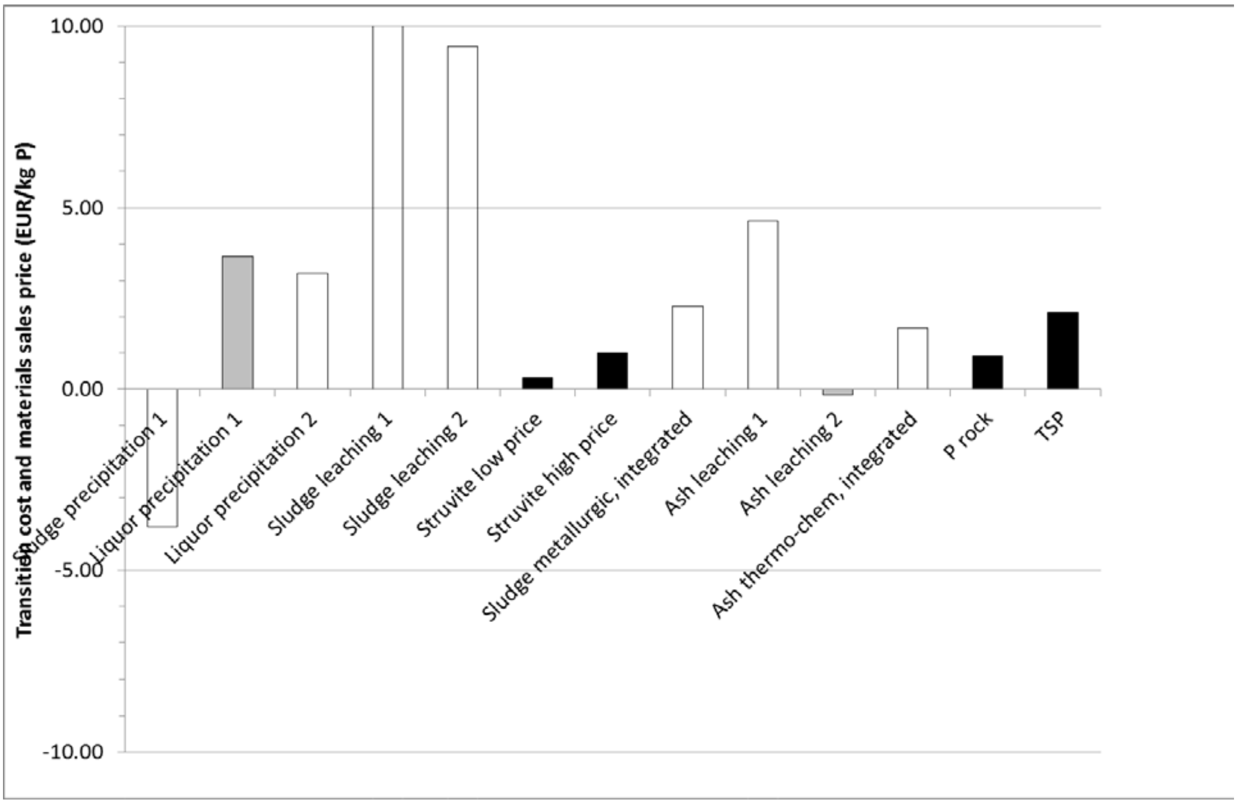


Figure 21: Transition cost from the mono-incineration reference treatment train (white) compared to market prices for fertilizer raw materials (black). Transition cost of grey colored processes already include phosphoric materials sales.

4 Conclusion

Process costs from an investor's perspective were calculated for selected processes for phosphorus recovery from municipal sewage sludge, sludge liquor, or sludge incineration ash, taking into account all relevant side-effects on the sludge treatment or the WWTP. We see that the different cost types capex, materials cost and revenue, energy cost and revenue and personnel all play a more or less important role for the cost of the different processes. Three different groups can be distinguished: precipitation processes, sludge leaching processes and processes based on dry sludge or ash (Table 18).

The process costs do not take into account the treatment train necessary for recovery from ash or dried sludge. For these processes the Cost of Transition from the current sludge and wastewater treatment train to a treatment train with phosphorus recovery must be considered. This calculation of Cost of Transition in turn reveals additional cost necessary for example for building mono-incineration plants.

The resulting Cost of Transition per person equivalent is low compared to for example the wastewater treatment cost (108 EUR/PE y; Table 18) for all three groups. The specific transition cost per amount of phosphorus for precipitation processes ranges from negative up to 150% of current market prices for phosphorus from triple-superphosphate (TSP). For sludge leaching it is about 500% of the current TSP price. For processes based on dry sludge or ash the transition cost ranges from negative (cost including product sales) up to the current twice the current TSP price. If the mono-incineration plant must also be constructed the price range is from half to three times the current TSP price.

Table 18: Comparison of transitions cost ranges per processes group to annual cost of WWTP and fossil fertilizer market price.

	Approx. yield	Transition cost	Reference
Precipitation processes. Require EBPR	5-15%	-0.14 to 0.23 EUR/ PE y -3.81 to 3.66 EUR/ kg P	WWTP cost: 108 EUR/ PE y Triplesuper-phosphate, harbour, bulk: 2.10 EUR/ kg P
Sludge leaching	~50%	~2.50 EUR/ PE y ~10 EUR/ kg P	
Dry sludge, ash treatment, mono-incineration existing	70-100%	-0.04 to 1.70 EUR/ PE y -0.08 to 4.64 EUR/ kg P	
Dry sludge, ash treatment, no existing mono-incineration		0.67 to 2.49 EUR/ PE y 1.33 to 6.78 EUR/ kg P	

In sum the cost of recovery, even with the most expensive process assessed, is less than 3% of the wastewater cost and thus implementing a P recovery process will not lead to a large cost increase of the whole WWTP, so it seems to be a useful investment for a society.t least one precipitation process is profitable and one ash based process on the verge of being profitable. Other processes based on ash or sludge can recover at costs comparable to or even lower than the market price of TSP. However, they are not yet profitable as the produced product is of lower quality than TSP with regards to for example plant availability, concentration or heavy metal content.

In most cases, and especially in large scale, phosphorus recovery and recycling would come with a cost. However, we have shown that these cost are very much affordable for the society. Policy makers will have to set priorities and choose between the extremely low cost of today's fertilizers and somewhat higher costs with the benefit of higher supply security for Europe as phosphorus rock is a critical raw material.

The P-REX cost assessment is unique because of the quality achieved through primary data from processes and validation in the consortium. To simplify data have in general been standardized for German prices, for a certain plant size and for a certain phosphorus concentration in the raw materials. They are thus useful to show the importance of various parameters on the total cost and to compare processes. They will have to be updated or complemented for other countries and over time. The influence of boundary conditions has been considered in the P-REX regional studies, providing more specific decision support for four different regions. In these studies and in general it is necessary to use also other criteria than cost for decision making, in particular the environmental impact, as phosphorus recovery is among other things motivated by environmental concern. As mentioned some of the data are less certain, as no production campaign has yet been performed. This might change in the future. The processes might also be further developed or others might reach pilot or production scale.

In the future political decisions would be important for the further development of phosphorus recycling. This study has shown that the costs are affordable, but that phosphorus recycling as many environmental technologies is not profitable unless boundary conditions provide a driver. Technology developers will try to develop the best possible solutions for phosphorus recovery. This study and the business models analysed by P-REX (Hukari, Nättorp, & Kabbe, 2015) show that both outputs (phosphoric product and by-products) and other services (mineralisation, better control of EBPR) can contribute to cover the process costs. So to improve overall profitability both increased income and decreased costs can be helpful. As the example of Ecophos shows, achieving high output quality can also hugely improve profitability.

As discussed the market for recovered mineral phosphorus is not yet developed. Currently essentially 1000 t of P in the form of raw struvite somehow finds its way to agriculture. When the volume of recovery increases we can expect that quite a few new materials will be offered as the number of processes will increase. These products will not necessarily be 100% water soluble, as this could mean additional process steps and cost. This will lead to a discussion about the needed solubility and the necessary quality required to ensure maximum crop yields. Another dimension which will influence the development of market and prices in the coming years is the extent to which current production plants, market channels and product categories will absorb the recovered materials. Another possibility is regional solutions driven by technology start-ups collaborating with farmers coops, which are already creative when it comes to solutions for organic fertilizers.

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6 Annex

Table 19A: Adjustment of process costs to calculate transitions costs.

Process	Yield (kg P recovered/kg P; %)	Process cost including landfill and influence on WWTP (EUR/kg P recovered)	Reference scenario: Monoincineration and landfill			Reference scenario: Coincineration and landfill			Reference scenario: Agricultural application		
			Adjustment (EUR/ kg P)	Adjustment (EUR/ kg P recovered)	Adjusted (EUR/ kg P recovered)	Adjustment (EUR/kg P)	Adjustment (EUR kg P recovered)	Adjusted (EUR/ kg P recovered)	Adjustment (EUR/ kg P)	Adjustment (EUR/ kg P recovered)	Adjusted (EUR/ kg P recovered)
Sludge precipitation 1	7	-3.81			-3.81			-3.81			-3.81
Liquor precipitation 1	12	3.66			3.66			3.66			3.66
Liquor precipitation 2	11	3.20			3.20			3.20			3.20
Sludge leaching 1	49	10.05			10.05			10.05			10.05
Sludge leaching 2	45	9.51			9.51			9.51			9.51
Sludge metallurgic integrated	80	9.63	-5.91	-7.35	2.28	-4.55	-5.65	3.97	-4.41	-5.48	4.14
Ash leaching 1	70	5.61	-0.68	-0.98	4.64	0.68	0.97	6.58	0.82	1.16	6.78
Ash leaching 2	97	0.63	-0.68	-0.71	-0.08	0.68	0.70	1.33	0.82	0.84	1.47
Ash thermo-chem integrated	98	2.38	-0.68	-0.70	1.68	0.68	0.69	3.07	0.82	0.83	3.21

Explanation of adjustment procedure per process

Sludge precipitation 1	No interaction with the reference scenarios as the sludge can be used as before after recovery.
Liquor precipitation 1	No interaction with the reference scenarios as the sludge can be used as before after recovery.
Liquor precipitation 2	No interaction with the reference scenarios as the sludge can be used as before after recovery.
Sludge leaching 1	No interaction with the reference scenarios as the sludge can be used as before after recovery.
Sludge leaching 2	No interaction with the reference scenarios as the sludge can be used as before after recovery.
Sludge metallurgic integr.	Mono- or co-incineration capacity and landfill capacity or agricultural application is replaced.
Ash leaching 1	Additional cost for switch from co-incineration or agricultural application to mono-incineration, landfill adjustment.
Ash leaching 2	Additional cost for switch from co-incineration or agricultural application to mono-incineration, landfill adjustment.
Ash thermo-chem integr.	Additional cost for switch from co-incineration or agricultural application to mono-incineration, landfill adjustment.

Table 20A: Sensitivity of process cost to variations in interest rate, phosphorus content and recovery plant size

	Sludge precipitation 1	Liquor precipitation 1	Liquor precipitation 2	Sludge leaching 1	Sludge leaching 2	Sludge metallurgic, integrated	Ash leaching 1	Ash leaching 2	Ash thermo-chem, integrated
Process cost	-3.81	3.66	3.20	10.05	9.51	9.63	5.61	1.99	2.38
Interest rate x50%	-4.10	3.30	3.05	9.85	9.31	9.13	5.40	1.94	2.30
Interest rate x200%	-3.19	4.44	3.54	10.50	9.93	10.70	6.06	2.11	2.54
Phosphorus content x50%	-11.24	9.53	5.59	20.11	19.02	19.25	11.22	3.98	4.21
Phosphorus content x200%	-0.09	0.72	2.01	5.03	4.75	4.81	2.81	0.99	1.46
Plant size x20%	1.66	10.14	6.29	13.81	12.96	22.36	9.01	3.68	4.51
Plant size x500%	-6.08	0.97	2.04	8.47	8.04	5.22	4.19	1.45	1.65

Table 21A: Materials cost factors. 1 indicates that materials cost are considered proportional to phosphorus content of the raw material. 0 indicates that materials cost is considered independent of the phosphorus content of the raw material.

Process	Material cost factor
Sludge precipitation 1	1
Liquor precipitation 1	1
Liquor precipitation 2	1
Sludge leaching 1	0
Sludge leaching 2	0
Sludge metallurgic integr	0
Ash leaching 1	0
Ash leaching 2	0
Ash thermo-chem integr	1

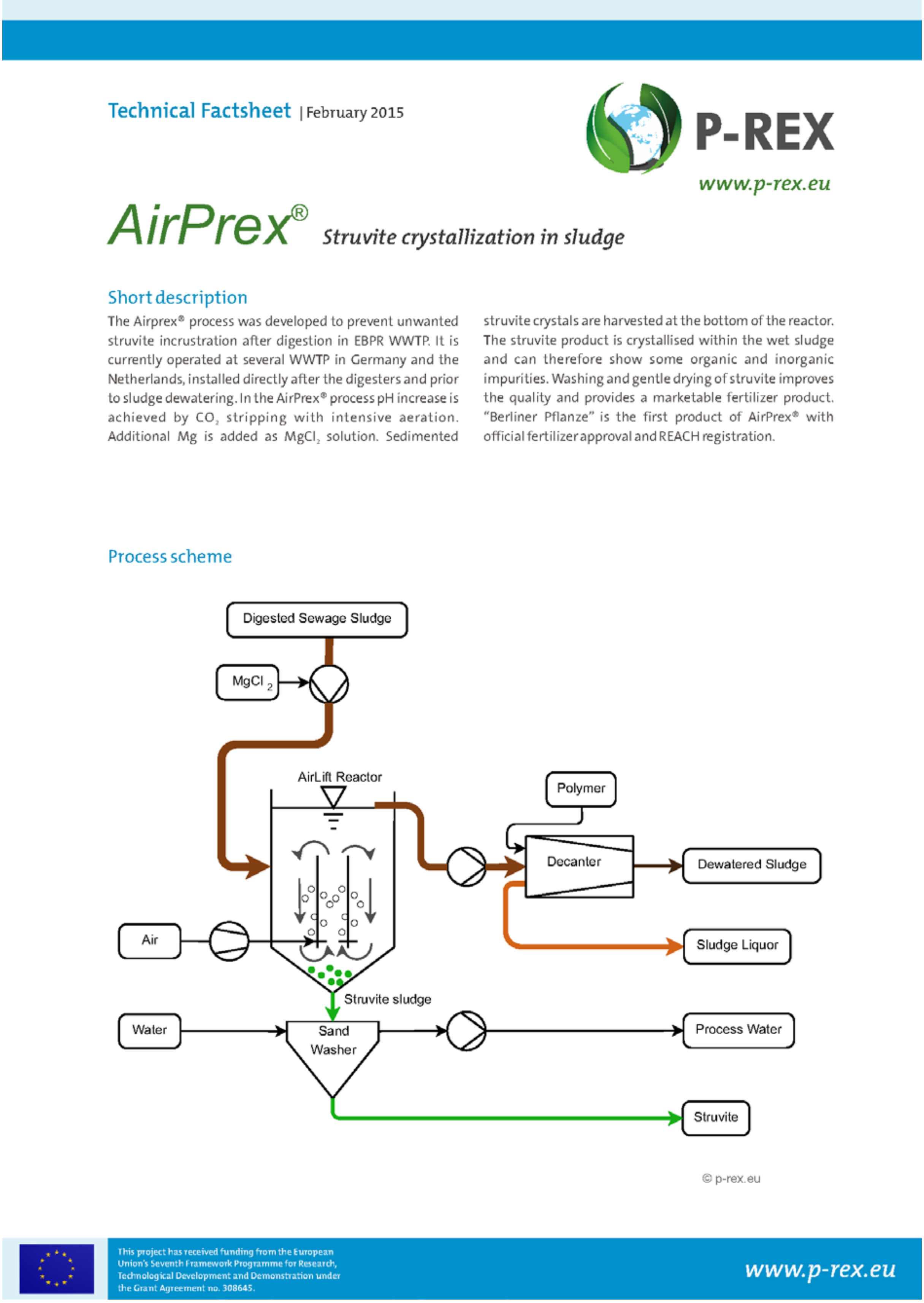
Table 22A: Concentrations of streams in the reference WWTP used for the cost assessment and the LCA

EBPR liquor content	**0.01%**	
Digested sludge content	**0.12%**	
Sludge DM content	**25%**	
Sludge phosphorus content (on DM)	**4.4%**	**German average is 3.3%(Budewig, 2014; Statistisches Bundesamt (Publisher), 2013; Umweltbundesamt (Publisher), 2014)**
Ash phosphorus content	**9.5%**	**Average ash from municipal sludge. Industrial/municipal sludge ash is also common and has about 5% content (Krüger, Roskosch, & Adam, 2014).**

Table 23A: Distances and cost data for calculation of reference scenarios

Monoincineration (EUR/t sludge)	65
Co-incineration (EUR/t sludge)	50
Agricultural application (EUR/t sludge)	35
Landfill (EUR/t)	50
Dewatering cost (EUR/t sludge)	1700
Sludge to agriculture (km)	35
Sludge to incineration (km)	50
Ash to landfill (km)	50
Transport > 100 km	5 cts/km t + 10 €/t
Transport < 100 km	10 cts/km t + 10 €/t

Factsheets



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P-REX
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AirPrex® Struvite crystallization in sludge

Short description

The Airprex® process was developed to prevent unwanted struvite incrustration after digestion in EBPR WWTP. It is currently operated at several WWTP in Germany and the Netherlands, installed directly after the digesters and prior to sludge dewatering. In the AirPrex® process pH increase is achieved by CO_2 stripping with intensive aeration. Additional Mg is added as $MgCl_2$ solution. Sedimented struvite crystals are harvested at the bottom of the reactor. The struvite product is crystallised within the wet sludge and can therefore show some organic and inorganic impurities. Washing and gentle drying of struvite improves the quality and provides a marketable fertilizer product. "Berliner Pflanze" is the first product of AirPrex® with official fertilizer approval and REACH registration.

Process scheme

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This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308645.

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AirPrex® Struvite crystallization in sludge

General Data

Type of Process	crystallisation
Type of Plant	airlift reactor
Input Material	sewage sludge after digestion
Product	struvite
P-concentration	21 % P_2O_5 of DM
P recovery performance[1]	7 % of P in sludge input

Supply

Average total electricity demand[1]	10.3 [kWh/kg $P_{recovered}$]
Average chemical demand[1] (as 100% concentrate)	14.5 [kg $MgCL_2$/kg $P_{recovered}$] 4.7 [molar ratio Mg:$P_{recovered}$] 2.1 [molar ratio Mg:$P_{dissolved}$]

Advantages

- Improvement of sludge dewatering (+2 to 5% DM)
- Savings of polymer in dewatering (up to 25%)
- Prevention of down-stream struvite precipitation (pipe clogging, damage of centrifuge)
- WWTP retrofit possible by implementation after digestion
- Proportional reduction of phosphorus and nitrogen return load from sludge liquor

Remarks

- Process is limited to WWTP with enhanced biological P removal and concentrations of more than 50 mg/L PO_4-P in sludge liquor
- Product yield can be enhanced by thermal or chemical hydrolysis prior to digestion (increase of PO_4-P concentration in liquor)

Patents and Licenses

Patent held by	Berliner Wasserbetriebe (BWB)
Licenses	CNP-Technology Water and Biosolids GmbH
Contact	Rudolf Bogner Merkurring 46, 22143 Hamburg
Phone	+49 40 669968020
Mail	rudolf.bogner@cnp-tec.com
Website	www.cnp-tec.com

References

Berlin Wassmannsdorf

(BWB, andreas.lengemann@bwb.de)

Start of operation	2009
Annual struvite capacity	~ 600 - 1,000 tons

Mönchengladbach Neuwerk (Niersverband)

Start of operation	2009
Annual struvite capacity	~ 600 tons

Waternet, NL, RWZI Amsterdam-West

Start of operation	2014
Annual struvite capacity	~ 1,500 tons (projected)

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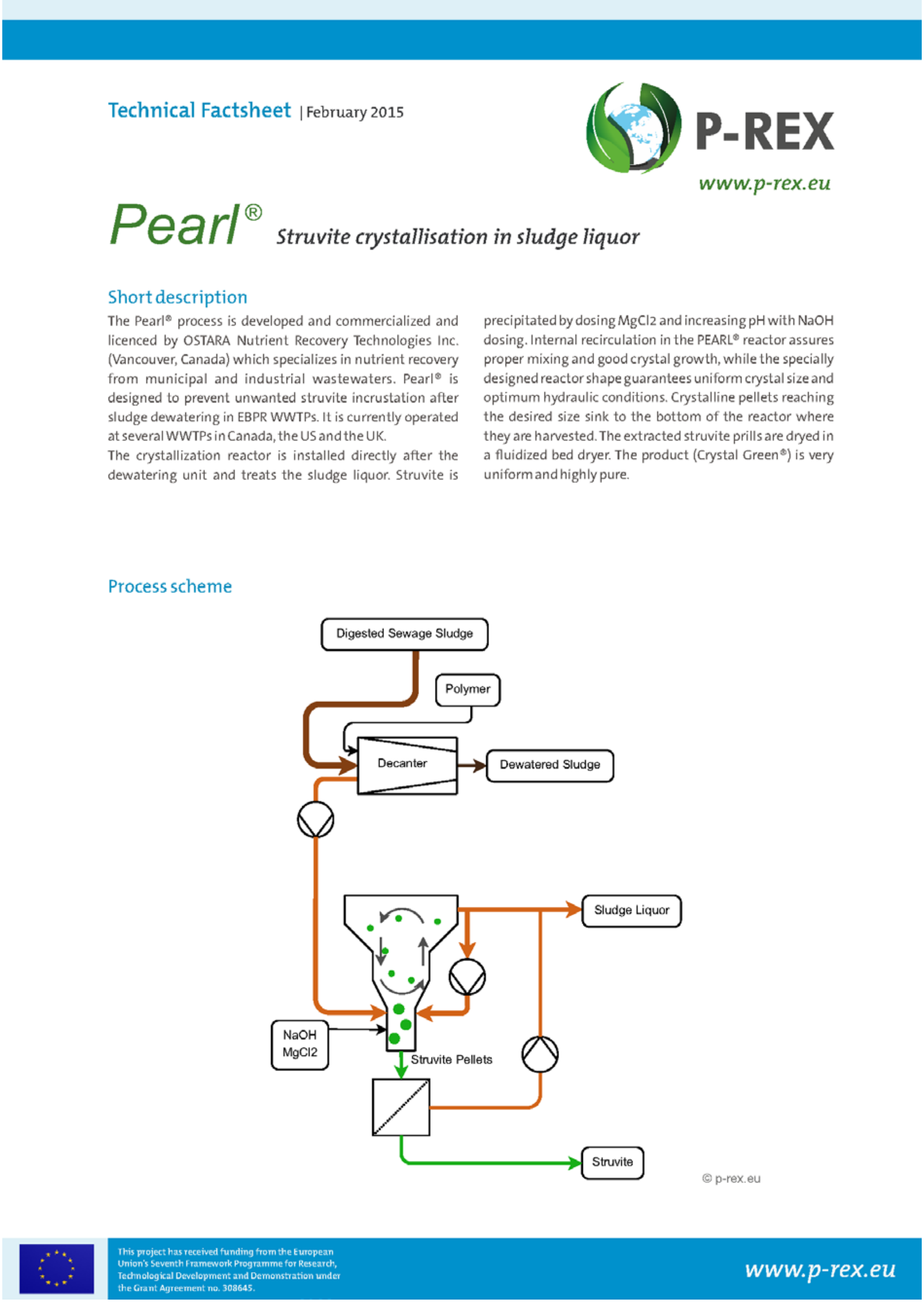
[1] Process data related to reference sludge line defined in **P-REX** (digested sludge of wastewater treatment plant for 1 Mio inhabitant equivalents, dry matter (DM) content: 3%, **P** content: 4.2% of DM, PO_4-**P** in liquor: 200 mg/**L** (**EBPR**) or 10 mg/**L** (ChemP), **Fe** content: 2% (**EBPR**) or 6.6% (ChemP)).More information on modelling can be found in **P-REX LCA** report.

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308645.

www.p-rex.eu



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P-REX
www.p-rex.eu

Pearl® Struvite crystallisation in sludge liquor

Short description

The Pearl® process is developed and commercialized and licenced by OSTARA Nutrient Recovery Technologies Inc. (Vancouver, Canada) which specializes in nutrient recovery from municipal and industrial wastewaters. Pearl® is designed to prevent unwanted struvite incrustation after sludge dewatering in EBPR WWTPs. It is currently operated at several WWTPs in Canada, the US and the UK.

The crystallization reactor is installed directly after the dewatering unit and treats the sludge liquor. Struvite is precipitated by dosing MgCl2 and increasing pH with NaOH dosing. Internal recirculation in the PEARL® reactor assures proper mixing and good crystal growth, while the specially designed reactor shape guarantees uniform crystal size and optimum hydraulic conditions. Crystalline pellets reaching the desired size sink to the bottom of the reactor where they are harvested. The extracted struvite prills are dryed in a fluidized bed dryer. The product (Crystal Green®) is very uniform and highly pure.

Process scheme

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308645.

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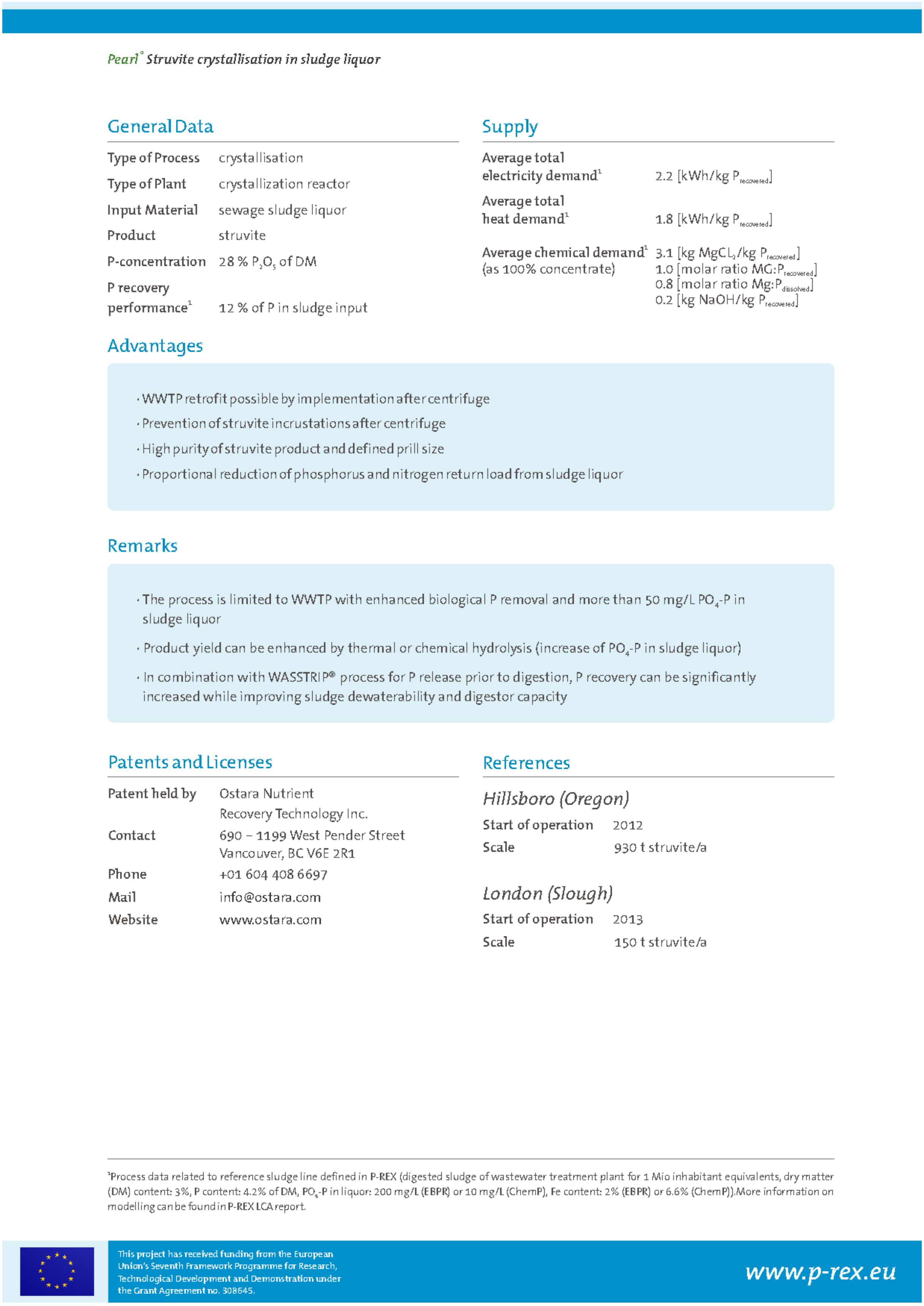

Pearl° Struvite crystallisation in sludge liquor

General Data

Type of Process	crystallisation
Type of Plant	crystallization reactor
Input Material	sewage sludge liquor
Product	struvite
P-concentration	28 % P_2O_5 of DM
P recovery performance[1]	12 % of P in sludge input

Supply

Average total electricity demand[1]	2.2 [kWh/kg $P_{recovered}$]
Average total heat demand[1]	1.8 [kWh/kg $P_{recovered}$]
Average chemical demand[1] (as 100% concentrate)	3.1 [kg $MgCL_2$/kg $P_{recovered}$] 1.0 [molar ratio MG:$P_{recovered}$] 0.8 [molar ratio Mg:$P_{dissolved}$] 0.2 [kg NaOH/kg $P_{recovered}$]

Advantages

- WWTP retrofit possible by implementation after centrifuge
- Prevention of struvite incrustations after centrifuge
- High purity of struvite product and defined prill size
- Proportional reduction of phosphorus and nitrogen return load from sludge liquor

Remarks

- The process is limited to WWTP with enhanced biological P removal and more than 50 mg/L PO_4-P in sludge liquor
- Product yield can be enhanced by thermal or chemical hydrolysis (increase of PO_4-P in sludge liquor)
- In combination with WASSTRIP® process for P release prior to digestion, P recovery can be significantly increased while improving sludge dewaterability and digestor capacity

Patents and Licenses

Patent held by	Ostara Nutrient Recovery Technology Inc.
Contact	690 – 1199 West Pender Street Vancouver, BC V6E 2R1
Phone	+01 604 408 6697
Mail	info@ostara.com
Website	www.ostara.com

References

Hillsboro (Oregon)

Start of operation	2012
Scale	930 t struvite/a

London (Slough)

Start of operation	2013
Scale	150 t struvite/a

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[1] Process data related to reference sludge line defined in P-REX (digested sludge of wastewater treatment plant for 1 Mio inhabitant equivalents, dry matter (DM) content: 3%, P content: 4.2% of DM, PO_4-P in liquor: 200 mg/L (EBPR) or 10 mg/L (ChemP), Fe content: 2% (EBPR) or 6.6% (ChemP)).More information on modelling can be found in P-REX LCA report.

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308645.

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P-REX
www.p-rex.eu

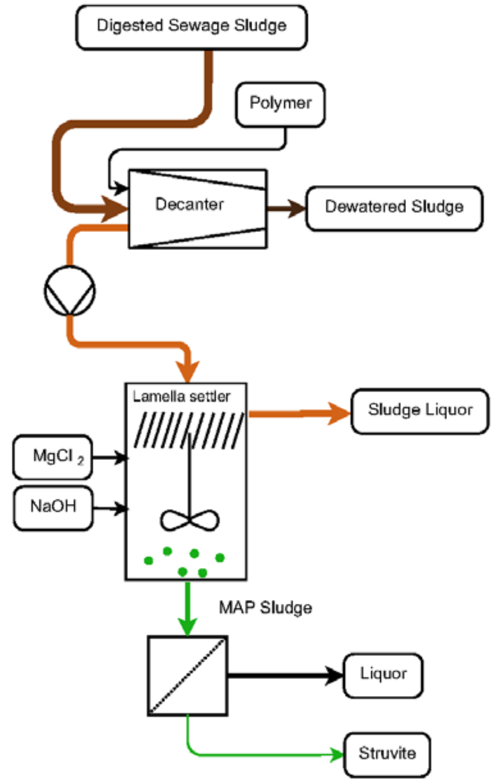
Struvia™ *Struvite crystallisation in sludge liquor*

Short description

The STRUVIA™ process is a modification of the phosphorus recovery technology Phostrip, originally developed by the Japanese company Showo Kankyo Systems K.K. (SKS). Since 2011, SKS is owned by Veolia Water which has developed the process into the current state and renamed the process to STRUVIA™.

For recovering struvite from sludge liquor, a continuous stirred tank reactor (CSTR) combined with a lamella settler on top are installed after the dewatering unit of a WWTP with enhanced biological P removal. Rapid mixing in the CSTR is enabled by a special mixing technology (Turbomix®). After dosing of $MgCl_2$ and NaOH for pH adjustment to 8-9, struvite is precipitated and can be harvested as a clean powder at the bottom of the reactor. Struvite can be dried at low temp (40-50°C) before storage.

Process scheme



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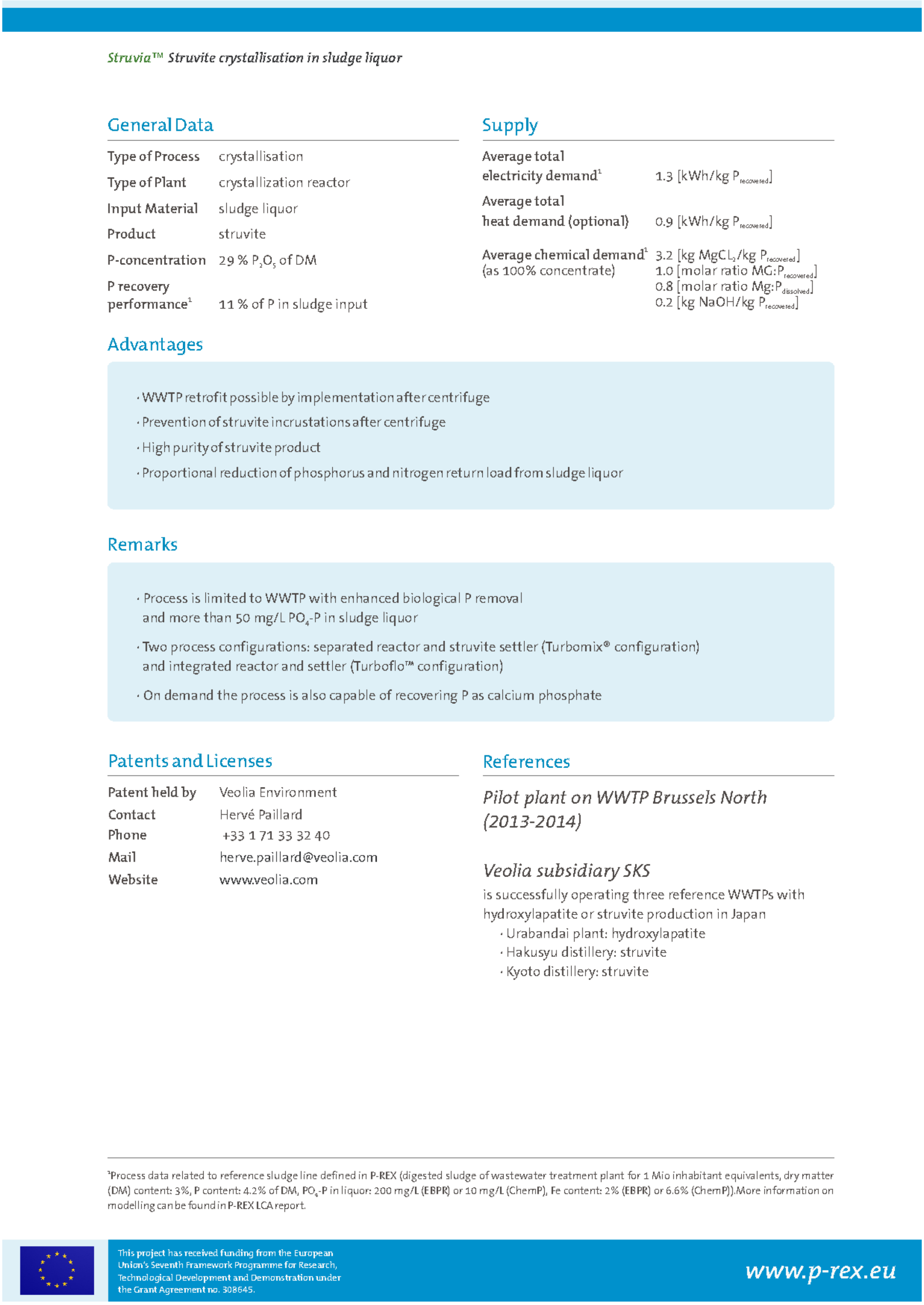

Struvia™ Struvite crystallisation in sludge liquor

General Data

Type of Process	crystallisation
Type of Plant	crystallization reactor
Input Material	sludge liquor
Product	struvite
P-concentration	29 % P_2O_5 of DM
P recovery performance[1]	11 % of P in sludge input

Supply

Average total electricity demand[1]	1.3 [kWh/kg $P_{recovered}$]
Average total heat demand (optional)	0.9 [kWh/kg $P_{recovered}$]
Average chemical demand[1] (as 100% concentrate)	3.2 [kg $MgCL_2$/kg $P_{recovered}$] 1.0 [molar ratio MG:$P_{recovered}$] 0.8 [molar ratio Mg:$P_{dissolved}$] 0.2 [kg NaOH/kg $P_{recovered}$]

Advantages

- WWTP retrofit possible by implementation after centrifuge
- Prevention of struvite incrustations after centrifuge
- High purity of struvite product
- Proportional reduction of phosphorus and nitrogen return load from sludge liquor

Remarks

- Process is limited to WWTP with enhanced biological P removal and more than 50 mg/L PO_4-P in sludge liquor
- Two process configurations: separated reactor and struvite settler (Turbomix® configuration) and integrated reactor and settler (Turboflo™ configuration)
- On demand the process is also capable of recovering P as calcium phosphate

Patents and Licenses

Patent held by	Veolia Environment
Contact	Hervé Paillard
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Mail	herve.paillard@veolia.com
Website	www.veolia.com

References

Pilot plant on WWTP Brussels North (2013-2014)

Veolia subsidiary SKS

is successfully operating three reference WWTPs with hydroxylapatite or struvite production in Japan

- Urabandai plant: hydroxylapatite
- Hakusyu distillery: struvite
- Kyoto distillery: struvite

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[1] Process data related to reference sludge line defined in P-REX (digested sludge of wastewater treatment plant for 1 Mio inhabitant equivalents, dry matter (DM) content: 3%, P content: 4.2% of DM, PO_4-P in liquor: 200 mg/L (EBPR) or 10 mg/L (ChemP), Fe content: 2% (EBPR) or 6.6% (ChemP)).More information on modelling can be found in P-REX LCA report.

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308645.

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Gifhorn Phosphorus recovery from sludge

General Data

Type of Process	acidic dissolution and precipitation
Type of Plant	precipitation reactor
Input Material	sewage sludge
Product	mix of struvite and hydroxylapatite
P-concentration	28 % P_2O_5 of DM
P recovery performance[1]	49 % of P in sludge input

Supply

Average total electricity demand[1]	6.9 [kWh/kg $P_{recovered}$]
Average chemical demand[1] (as 100% concentrate)	8.2 [kg H_2SO_4/kg $P_{recovered}$] 2.9 [kg NaOH/kg $P_{recovered}$] 0.2 [kg $Mg(OH)_2$/kg $P_{recovered}$] 0.1 [molar ratio Mg:$P_{recovered}$] 0.1 [molar ratio Mg:$P_{dissolved}$] 0.8 [kg Na_2S/kg $P_{recovered}$]

Advantages

- Process can be applied with EBPR or Chem-P sludge (acid demand calculated with 4% Fe)
- Separate heavy metal precipitation as sulfides
- Proportional reduction of phosphorus and nitrogen return load from sludge liquor
- Downstream recovery of nitrogen possible (air stripping) in the form of diammonium sulfate

Remarks

- Al coagulants in WWTP reduce P recovery rate. Higher rates of P recovery are possible at pH < 4.5, but with reduced dewaterability and increased chemical consumption. High Fe content in sludge leads to an increase in Na_2S dosing (FeS precipiation).
- Product contains small fractions of iron phosphate and larger fractions of hydroxylapatite.

Patents and Licenses

Patent held by	Seaborne EPM AG
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Website	www.asg-gifhorn.de

References

Owschlag (pilot)

Start of operation	2000
Scale	10.000 p.e., 50 kg struvite/d

Gifhorn (full scale)

Start of operation	2007
Scale	50.000 p.e., 270 kg struvite/d *(currently limited performance due to economic reasons)*

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[1] Process data related to reference sludge line defined in P-REX (digested sludge of wastewater treatment plant for 1 Mio inhabitant equivalents, dry matter (DM) content: 3%, P content: 4.2% of DM, PO_4-P in liquor: 200 mg/L (EBPR) or 10 mg/L (ChemP), Fe content: 2% (EBPR) or 6.6% (ChemP)).More information on modelling can be found in P-REX LCA report.

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under the Grant Agreement no. 308645.

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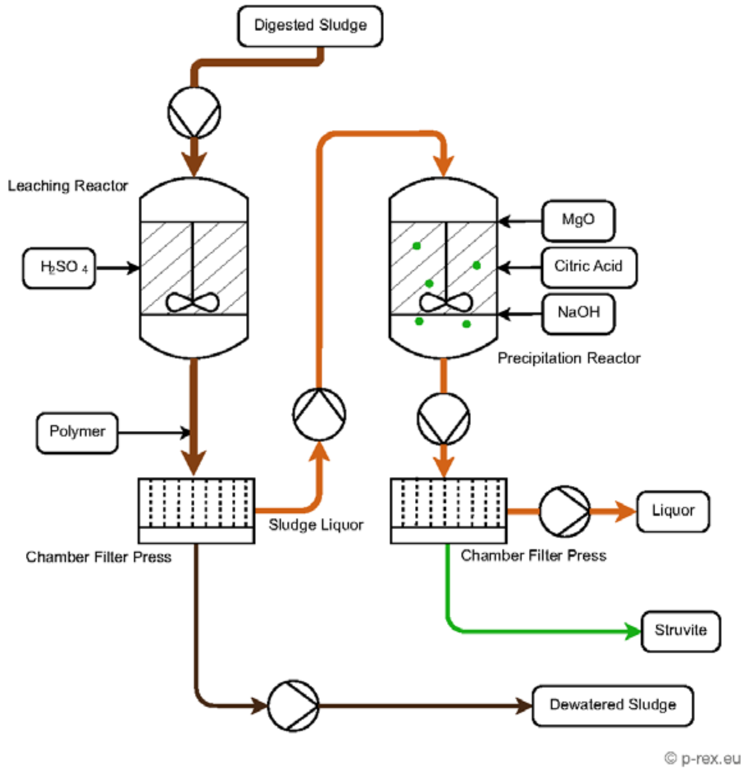
Stuttgart Sludge leaching

Short description

The STUTTGART process for P recovery from digested sludge of chemical P removal WWTPs was developed at University of Stuttgart by the Institute for Sanitary Engineering (ISWA). The process is based on acidic extraction of P from digested sludge at pH 4 with addition of H_2SO_4. After solid/liquid separation, dissolved Fe and heavy metals in liquor are masked by citric acid to prevent their transfer into the P product. Struvite precipitation is initiated by dosing of MgO and raising pH to 8, adjusted with NaOH. Finally, struvite is harvested as a powder by solid/liquid separation and dewatering/drying.

Process scheme



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Stuttgart Sludge leaching

General Data

Type of Process	acidic dissolution and precipitation
Type of Plant	extraction and precipitation reactors
Input Material	sewage sludge
Product	struvite
P-concentration	27 % P_2O_5 of DM
P recovery performance[1]	45 % of P in sludge input

Supply

Average total electricity demand[1]	4.8 [kWh/kg $P_{recovered}$]
Average chemical demand[1] (as 100% concentrate)	11.9 [kg H_2SO_4/kg $P_{recovered}$] 1.5 [kg MgO/kg $P_{recovered}$] 1.2 [molar ratio Mg:$P_{recovered}$] 1.0 [molar ratio Mg:$P_{dissolved}$] 2.7 [kg NaOH/kg $P_{recovered}$] 3.9 [kg $C_6H_8O_7$/kg $P_{recovered}$]

Advantages

- Process applicable for WWTP sludge from enhanced biological or chemical P removal
- Complexation of Fe and heavy metals with citric acid
- Proportional reduction of phosphorus and nitrogen return load from sludge liquor

Remarks

- Higher rates of P recovery are possible at a pH lower than 4, but with reduced dewaterability and increased chemicals consumption
- Citric acid consumption depends on metal concentration (Fe) in input sludge

Patents and Licenses

Contact	Universität Stuttgart ISWA Bandtäle 2, D-70569 Stuttgart
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Website	www.iswa.uni-stuttgart.de/lsww

References

Offenburg (Pilot plant)

Start of operation	2011
Scale	8.000 PE
P yield	50 kg struvite/d

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[1] Process data related to reference sludge line defined in **P-REX** (digested sludge of wastewater treatment plant for 1 Mio inhabitant equivalents, dry matter (DM) content: 3%, P content: 4.2% of DM, PO_4-P in liquor: 200 mg/L (EBPR) or 10 mg/L (ChemP), Fe content: 2% (EBPR) or 6.6% (ChemP)).More information on modelling can be found in **P-REX LCA** report.

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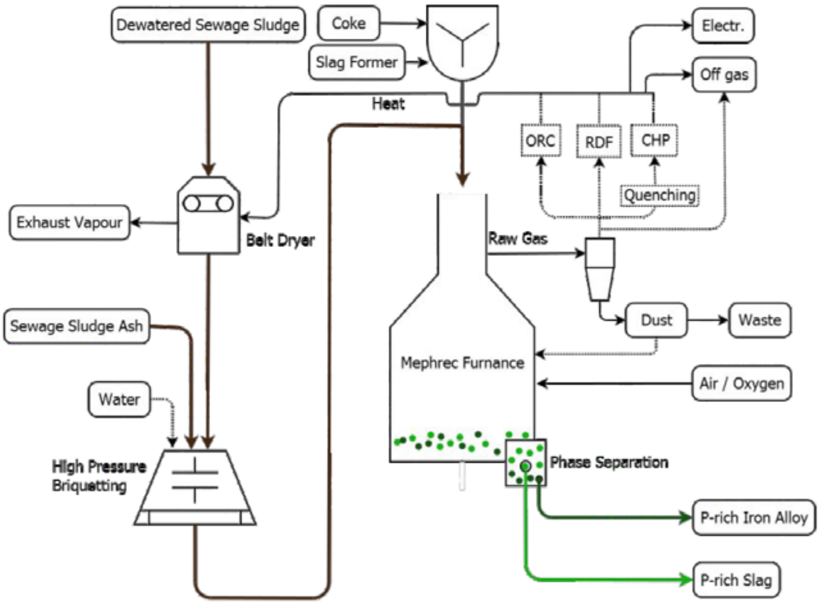
Mephrec® *Metallurgical sludge or ash treatment*

Short description

The Mephrec process was developed by the German company Ingitec for recovery of phosphorus from sewage sludge and/or ash. Dewatered sewage sludge (>25 % dry matter (DM)) is dried to 80 % DM and pressed into briquettes. The briquettes of sludge and/or ash are thermally treated (gasification) in a shaft furnace at temperatures above 1450 °C. Heavy metal compounds are reduced under these conditions into their elemental form. Volatile metals (Cd, Hg, Pb, Zn) are evaporated and separated via gas phase whereas non-volatile heavy metals are separated from the slag in form of a liquid metal phase. The phosphates present in sewage sludge are transformed into silico-phosphates (comparable to "thomas phosphate"). The Mephrec process with sludge as raw material also produces electricity and heat with the highly caloric raw gas. The raw gas can be directly injected into an Organic Rankine Cycle (ORC) process or municipal waste incineration plant, or refined in multiple steps to feed a combined heat and power (CHP) plant.

Process scheme



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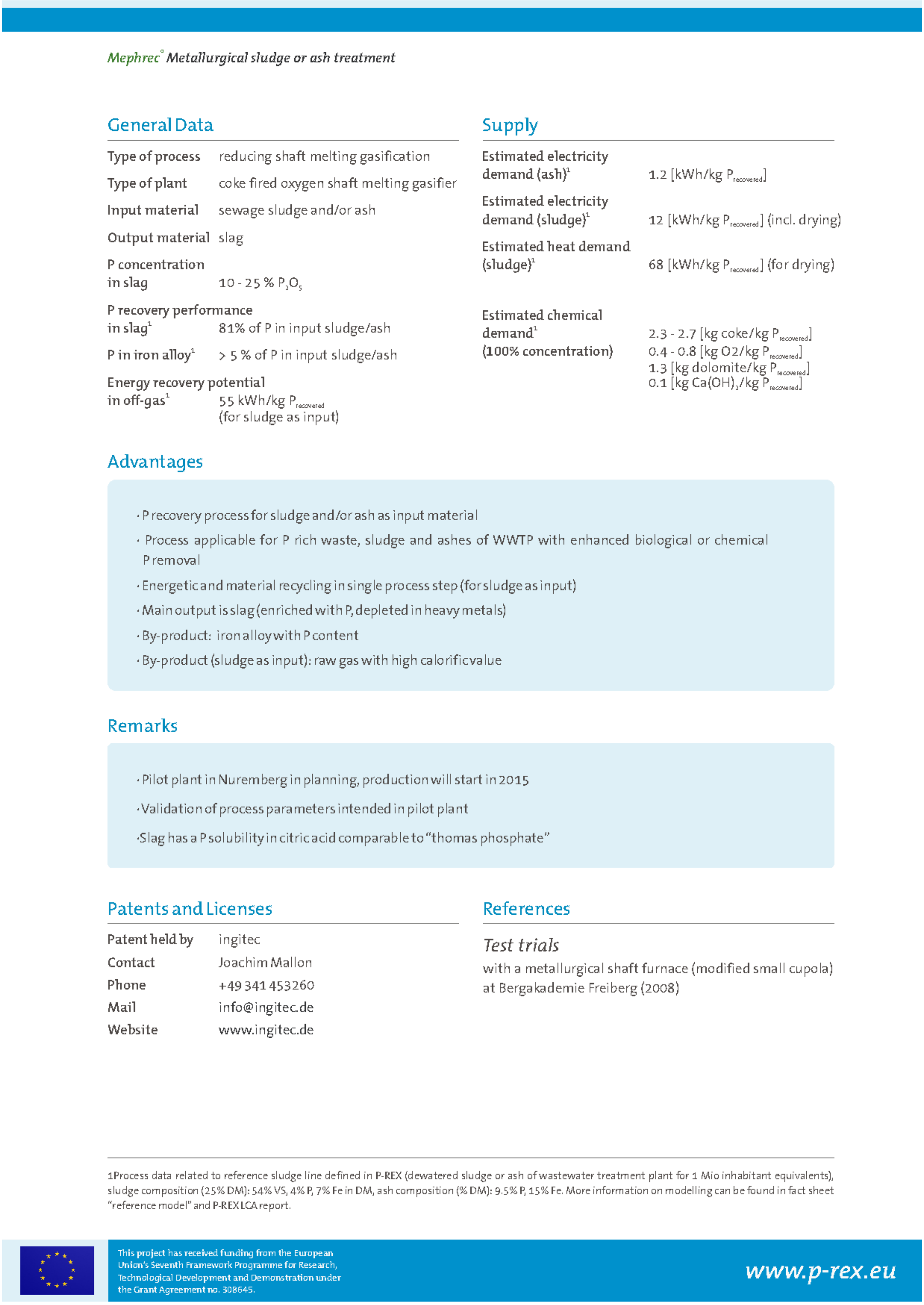

Mephrec° Metallurgical sludge or ash treatment

General Data

Type of process	reducing shaft melting gasification
Type of plant	coke fired oxygen shaft melting gasifier
Input material	sewage sludge and/or ash
Output material	slag
P concentration in slag	10 - 25 % P_2O_5
P recovery performance in slag[1]	81% of P in input sludge/ash
P in iron alloy[1]	> 5 % of P in input sludge/ash
Energy recovery potential in off-gas[1]	55 kWh/kg $P_{recovered}$ (for sludge as input)

Supply

Estimated electricity demand (ash)[1]	1.2 [kWh/kg $P_{recovered}$]
Estimated electricity demand (sludge)[1]	12 [kWh/kg $P_{recovered}$] (incl. drying)
Estimated heat demand (sludge)[1]	68 [kWh/kg $P_{recovered}$] (for drying)
Estimated chemical demand[1] (100% concentration)	2.3 - 2.7 [kg coke/kg $P_{recovered}$] 0.4 - 0.8 [kg O2/kg $P_{recovered}$] 1.3 [kg dolomite/kg $P_{recovered}$] 0.1 [kg $Ca(OH)_2$/kg $P_{recovered}$]

Advantages

- P recovery process for sludge and/or ash as input material
- Process applicable for P rich waste, sludge and ashes of WWTP with enhanced biological or chemical P removal
- Energetic and material recycling in single process step (for sludge as input)
- Main output is slag (enriched with P, depleted in heavy metals)
- By-product: iron alloy with P content
- By-product (sludge as input): raw gas with high calorific value

Remarks

- Pilot plant in Nuremberg in planning, production will start in 2015
- Validation of process parameters intended in pilot plant
- Slag has a P solubility in citric acid comparable to "thomas phosphate"

Patents and Licenses

Patent held by	ingitec
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Website	www.ingitec.de

References

Test trials

with a metallurgical shaft furnace (modified small cupola) at Bergakademie Freiberg (2008)

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[1] Process data related to reference sludge line defined in P-REX (dewatered sludge or ash of wastewater treatment plant for 1 Mio inhabitant equivalents), sludge composition (25% DM): 54% VS, 4% P, 7% Fe in DM, ash composition (% DM): 9.5% P, 15% Fe. More information on modelling can be found in fact sheet "reference model" and P-REX LCA report.

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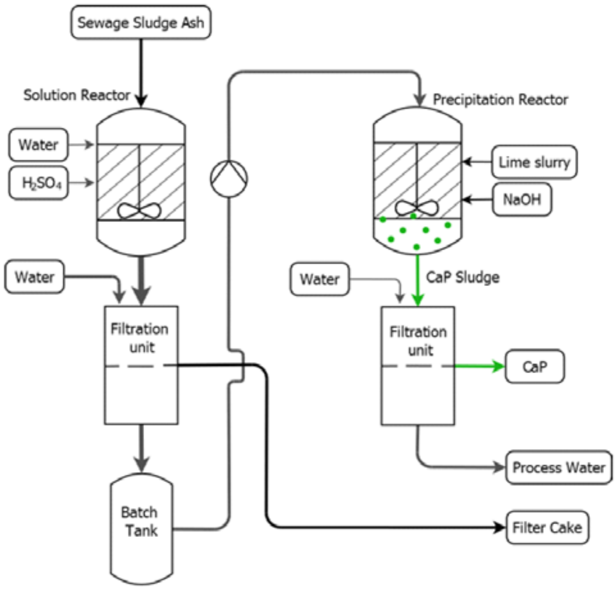
Leachphos® Ash leaching

Short description

LeachPhos was developed by BSH Umweltservice GmbH. Phosphorus (P) is extracted from sewage sludge ash (SSA) by addition of diluted sulfuric acid. 80-95 % of P is transferred into the leachate. The pH is subsequently increased by addition of sodium hydroxide or lime until target $P_{recovery}$ is achieved. Heavy metals such as cadmium, copper, and zinc are only partially dissolved and precipitated, leading to acceptable mass fractions in the output material. A mixture of aluminum-, ferric- and calciumphosphate is separated by filtration. The remaining heavy metals in the filtrate are quantitatively precipitated at pH >9 with a precipitating agent and are separated for disposal. Calcium phosphates or magnesium ammonium phosphate (struvite) are targeted output materials for future industrial-scale plants.

Process scheme



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Leachphos® Ash leaching

General Data

Type of Process	wet chemical
Type of Plant	leaching and crystallisation reactors
Input Material	sewage sludge ash
Product	CaP or struvite (wet)
P-concentration	20 - 40 % P_2O_5 of DM
P recovery performance[1]	70% of P in sewage sludge ash

Supply

Average total electricity demand[1]	1.6 [kWh/kg $P_{recovered}$]
Average chemical demand[1] (as 100% concentrate)	5.6 [kg H_2SO_4/kg $P_{recovered}$] 0.6 [kg NaOH/kg $P_{recovered}$] 3.9 [kg $Ca(OH)_2$/kg $P_{recovered}$]

Advantages

- Output material comparable to dicalcium phosphate
- High P content of output material
- Reduction of heavy metal content
- High process flexibility

Remarks

- Wet residual filter cake (60% DM) requires disposal (1.7 kg wet waste/kg ash) or additional treatment.
- Process data does not include a potential finishing (e.g. drying, granulation) of the wet LeachPhos output material (40-50 % DM).
- Higher recovery rates can be reached depending on ash composition and output quality requirements

Patents and Licenses

Patent held by	BSH Umweltservice AG
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References

Pilot study BSH 2012/2013

Amount	40 t sewage sludge ash
Throughput	2 t ash/h

Pilot plant at FHNW

Batch process with 50 kg ash

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[1] Process data related to reference sludge line defined in P-REX (ash of wastewater treatment plant for 1 Mio inhabitant equivalents), ash composition (% DM): 10.7% P, 5% Fe (EBPR ash) or 15% Fe (ChemP ash). More information on modelling can be found in fact sheet "reference model" and P-REX LCA report.

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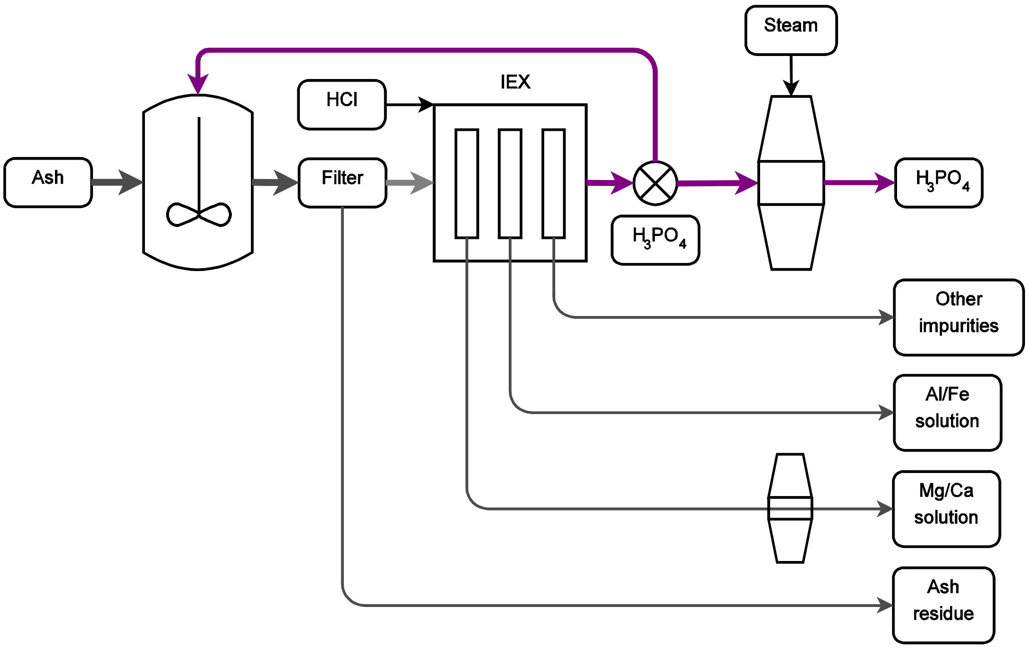
Ecophos

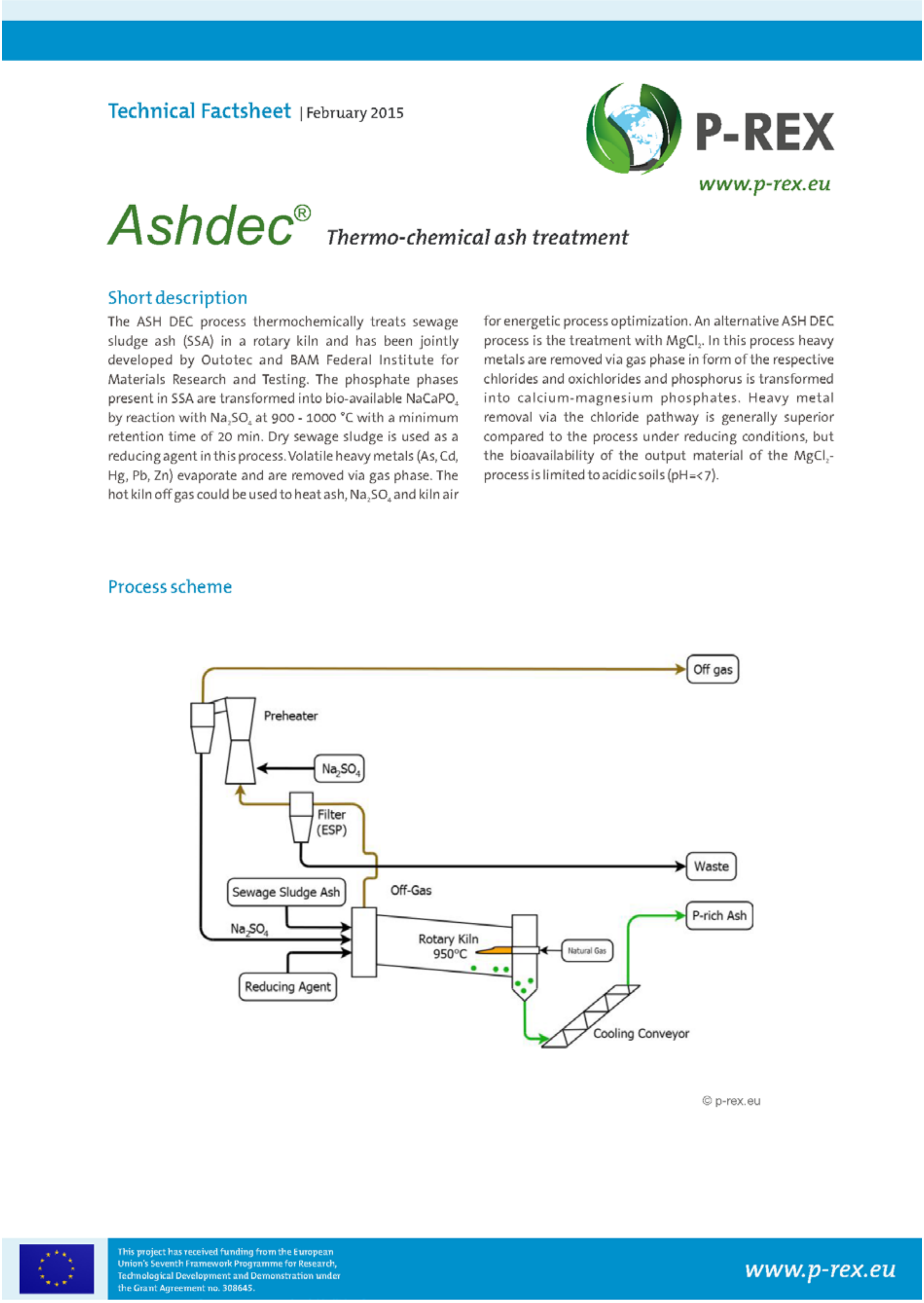
The EcoPhos process is used commercially in a handful of plants to process low-grade phosphorus rock (e.g. with less phosphorus content) into a high-quality phosphorus product (phosphoric acid in feed-grade quality). Recently, it has been modified and tested for mono-incineration ash as input material. A full-scale plant capable of processing mono-incineration ash by digestion with sulfuric acid is under construction in Dunquerque (FR).

The Ecophos process assessed by P-REX is based on the digestion of ash with a large excess of H_3PO_4 (see Figure below), which is recycled from the product side. After digestion, insoluble residues are removed via filtration and disposed as inert material. The filtrate contains a high concentration of H_3PO_4 and dissolved impurities from the ash. This solution is purified by a multi-stage ion exchange (IEX) process, removing separately major ions. These are fractionated as the ion exchange resins are regenerated with hydrochloric acid. The hydrochloric acid introduces the acidity into the process that is required for ash digestion. The different chloride salt solutions from the IEX can be valorized as Ca/MgCl solution or Al/Fe Cl solution, whereas other metal salts are precipitated and landfilled.

After purification, part of the phosphoric acid is recycled back to the ash digestion, whereas another part is further concentrated using steam into the final product



Process scheme of the Ecopho



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Ashdec® *Thermo-chemical ash treatment*

Short description

The ASH DEC process thermochemically treats sewage sludge ash (SSA) in a rotary kiln and has been jointly developed by Outotec and BAM Federal Institute for Materials Research and Testing. The phosphate phases present in SSA are transformed into bio-available $NaCaPO_4$ by reaction with Na_2SO_4 at 900 - 1000 °C with a minimum retention time of 20 min. Dry sewage sludge is used as a reducing agent in this process. Volatile heavy metals (As, Cd, Hg, Pb, Zn) evaporate and are removed via gas phase. The hot kiln off gas could be used to heat ash, Na_2SO_4 and kiln air for energetic process optimization. An alternative ASH DEC process is the treatment with $MgCl_2$. In this process heavy metals are removed via gas phase in form of the respective chlorides and oxichlorides and phosphorus is transformed into calcium-magnesium phosphates. Heavy metal removal via the chloride pathway is generally superior compared to the process under reducing conditions, but the bioavailability of the output material of the $MgCl_2$-process is limited to acidic soils (pH=<7).

Process scheme

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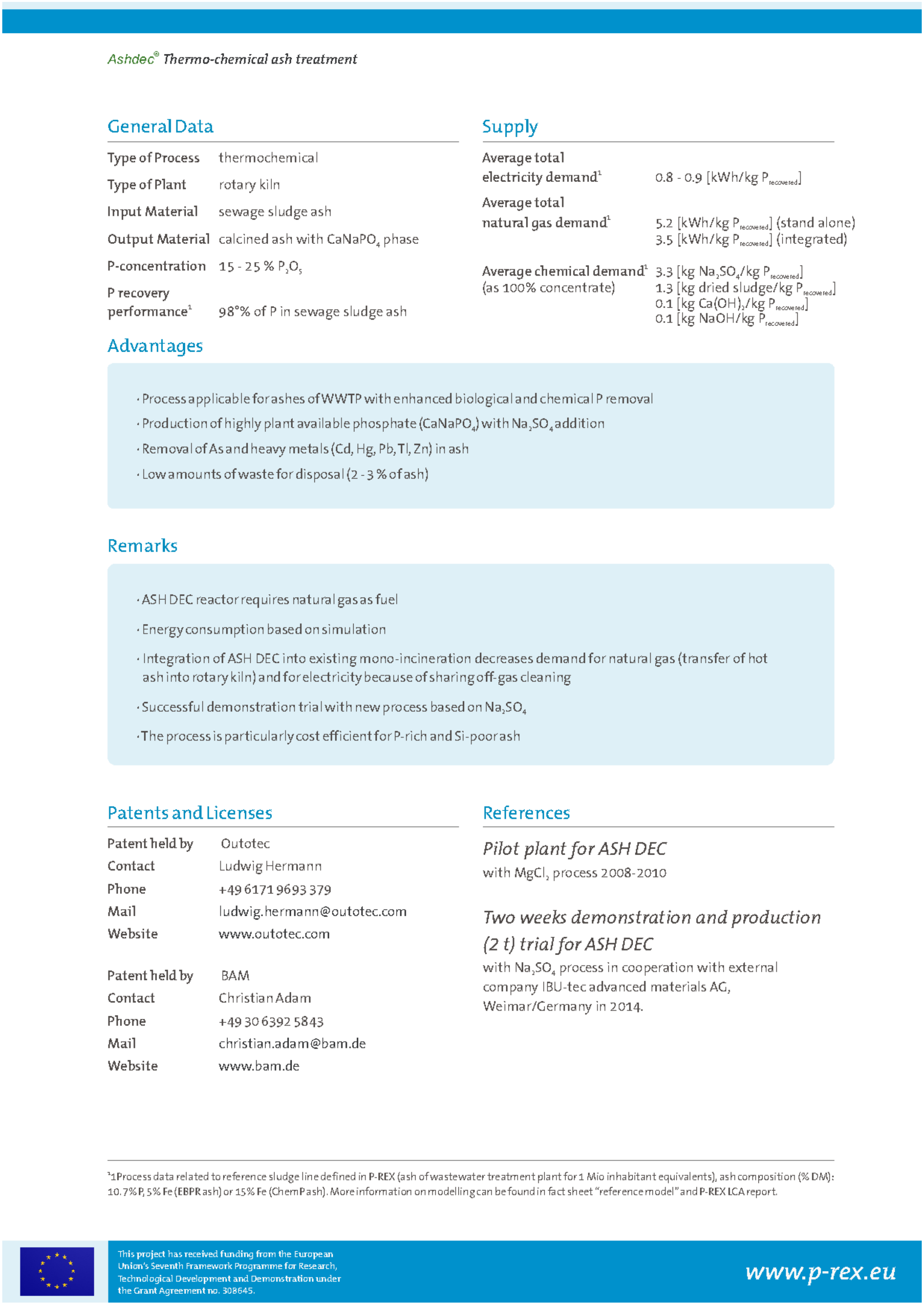

Ashdec® Thermo-chemical ash treatment

General Data

Type of Process	thermochemical
Type of Plant	rotary kiln
Input Material	sewage sludge ash
Output Material	calcined ash with $CaNaPO_4$ phase
P-concentration	15 - 25 % P_2O_5
P recovery performance[1]	98°% of P in sewage sludge ash

Supply

Average total electricity demand[1]	0.8 - 0.9 [kWh/kg $P_{recovered}$]
Average total natural gas demand[1]	5.2 [kWh/kg $P_{recovered}$] (stand alone) 3.5 [kWh/kg $P_{recovered}$] (integrated)
Average chemical demand[1] (as 100% concentrate)	3.3 [kg Na_2SO_4/kg $P_{recovered}$] 1.3 [kg dried sludge/kg $P_{recovered}$] 0.1 [kg $Ca(OH)_2$/kg $P_{recovered}$] 0.1 [kg NaOH/kg $P_{recovered}$]

Advantages

- Process applicable for ashes of WWTP with enhanced biological and chemical P removal
- Production of highly plant available phosphate ($CaNaPO_4$) with Na_2SO_4 addition
- Removal of As and heavy metals (Cd, Hg, Pb, Tl, Zn) in ash
- Low amounts of waste for disposal (2 - 3 % of ash)

Remarks

- ASH DEC reactor requires natural gas as fuel
- Energy consumption based on simulation
- Integration of ASH DEC into existing mono-incineration decreases demand for natural gas (transfer of hot ash into rotary kiln) and for electricity because of sharing off-gas cleaning
- Successful demonstration trial with new process based on Na_2SO_4
- The process is particularly cost efficient for P-rich and Si-poor ash

Patents and Licenses

Patent held by	Outotec
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Patent held by	BAM
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References

Pilot plant for ASH DEC

with $MgCl_2$ process 2008-2010

Two weeks demonstration and production (2 t) trial for ASH DEC

with Na_2SO_4 process in cooperation with external company IBU-tec advanced materials AG, Weimar/Germany in 2014.

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*1Process data related to reference sludge line defined in P-REX (ash of wastewater treatment plant for 1 Mio inhabitant equivalents), ash composition (% DM): 10.7% P, 5% Fe (EBPR ash) or 15% Fe (ChemP ash). More information on modelling can be found in fact sheet “reference model” and P-REX LCA report.

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