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Nutrient recovery from municipal wastewater for sustainable food production systems: An alternative to traditional fertilizers

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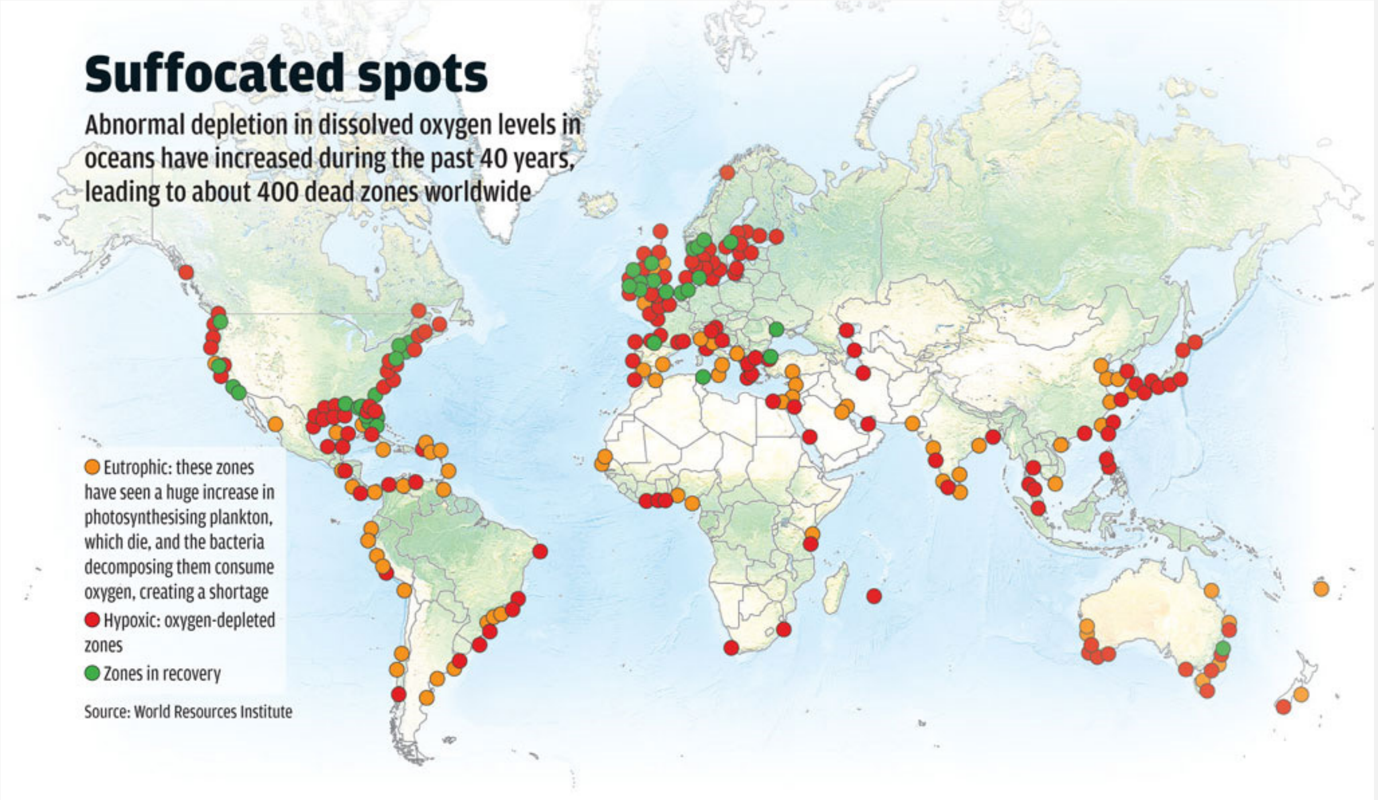
Importance of Nutrient Management



Source: World Resources Institute, 2015

- Eutrophication - enrichment of an ecosystem with chemical nutrients, typically compounds containing nitrogen (N), phosphorus (P), or both.

- Clean Water Act (CWA) requires wastewater treatment plants (WWTPs) to reduce nutrient discharge levels to prevent eutrophication

Study Objectives and Approach

- Aims to address

  1) how regulations drive system changes;

  2) how conventional systems can be transitioned to more cost effective and sustainable alternatives using nutrient management.

- Use emergy to provide system analysis
  - Emergy quantifies direct and indirect contributions from the elemental resource flow to the entire treatment plant operational requirements.

- Influent wastewater flow and nutrient levels, capital, and operational data were collected from previous nutrient removal studies and for nutrient recovery from Ostara Nutrient Recovery Technologies, Inc.

- All UEVs used and given hereafter (including those referenced in the text) were normalized to the **1.20 E25 sej/yr (solar emjoules/year)** global emergy baseline (Brown et al., 2016)

Nutrient Recovery and Benefits

- Nutrient recovery - practice of recovering nutrients (N and P) from wastewater and converting them into an environmental friendly fertilizer

- Industrial phosphate (PO_4^{3-}) fertilizers - manufactured using PO_4^{3-} rock (non-renewable resource)

- Nutrient recovery provides a self-sustainable solution to WWTPs
  - revenue generation from fertilizers
  - reduces fouling of equipment with involuntary precipitation of struvite
  - helps meet discharge limits

- PO_4^{3-} precipitation from wastewater is less energy intensive and economical compared to manufacture of phosphate fertilizers

Struvite Formation and Production

- Recovered from municipal wastewater (MWW)/urine source - slow-release mineral fertilizer given by the simplified equation

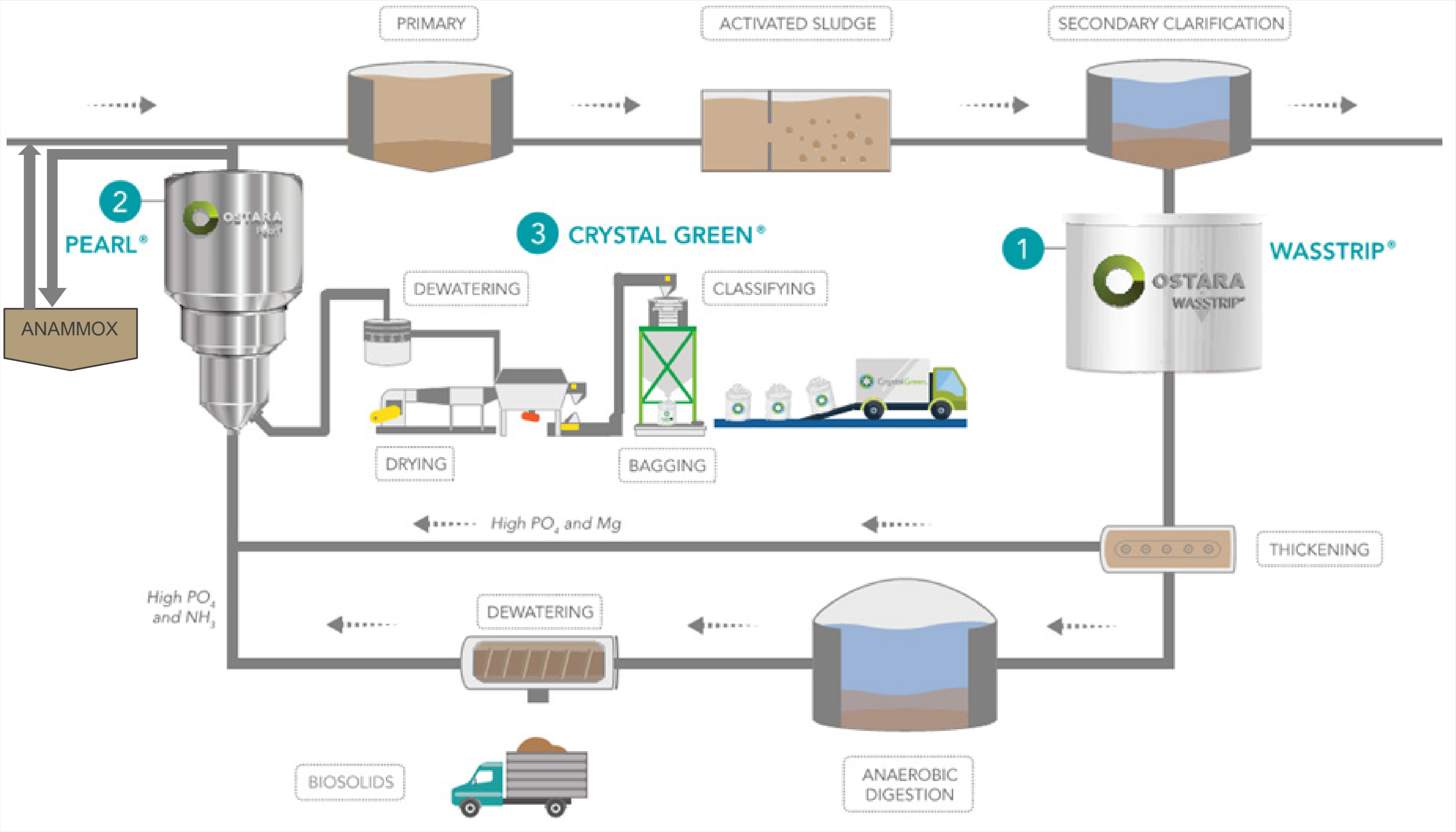
$$\mathrm{Mg}_2^{+} + \mathrm{NH}_4^{+} + \mathrm{PO}_4^{3-} + 6\mathrm{H}_2\mathrm{O} \rightarrow \mathrm{MgNH}_4\mathrm{PO}_4 \bullet 6\mathrm{H}_2\mathrm{O}\ \text{(solid)}$$

Magnesium Ammonium Phosphate

- Methods of struvite recovery from MWW have been under development, this study cites WASSTRIP™ and PEARL® process by Ostara Nutrient Recovery Technologies, Inc.

- Marketed fertilizer - 5% N, 28% PO_4^{3-}, and 0% potash, with 16.6% MgO (10% Mg)

Nutrient Recovery Technology Considered



PEARL® process by Ostara Nutrient Recovery Technologies, Inc, 2016

- In addition to P precipitation, partial nitration anammox was considered for nitrogen reduction in the nutrient recovery alternative.

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Emergy definition and concept

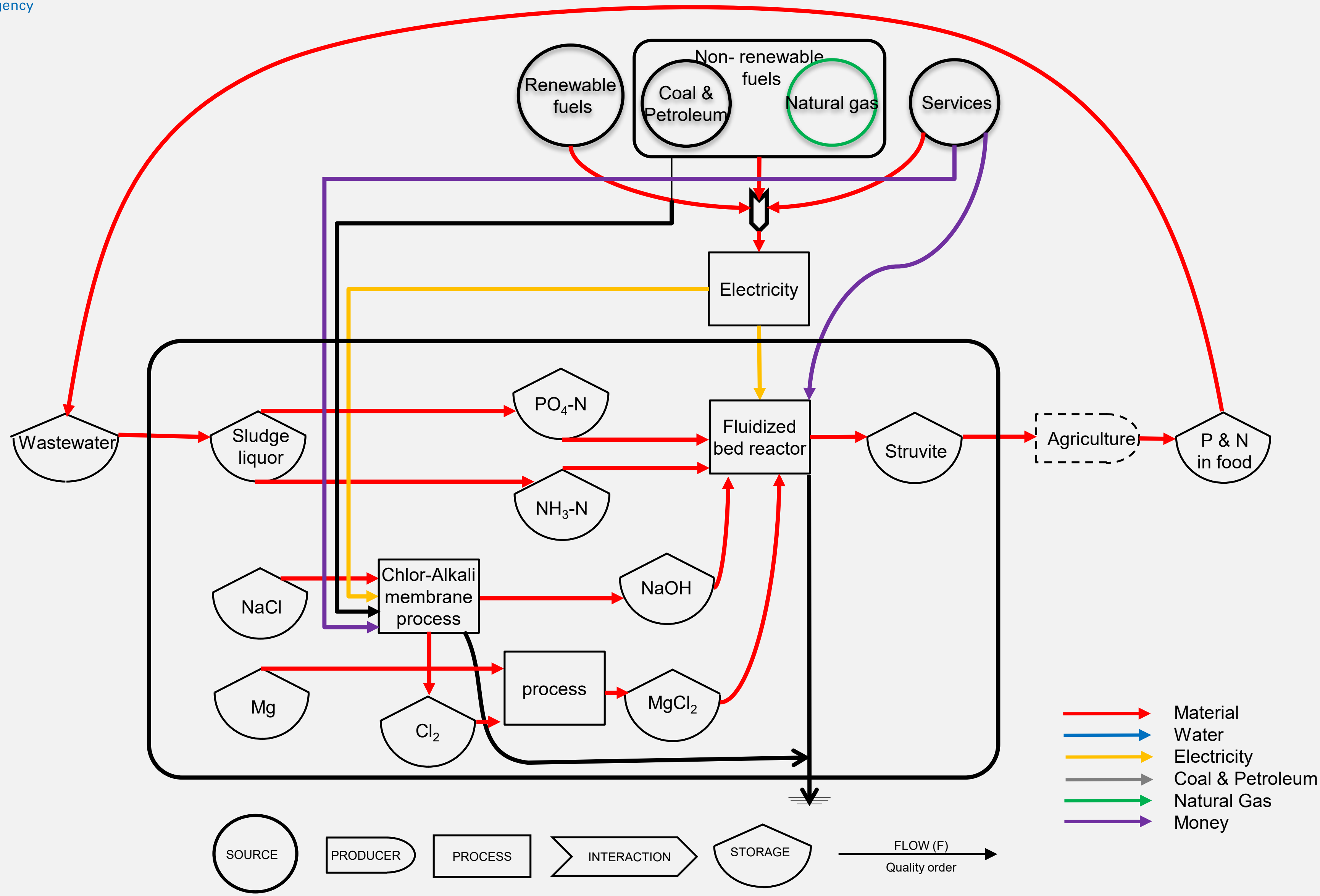
- Available energy of any kind previously used both directly and indirectly to make another form of energy, product or service

- Evolution of the theory during the past thirty years was documented by H.T Odum in Environmental Accounting, 2016

- Emergy (emjoules/yr or emjoules/unit) synthesis strives for understanding by grasping the wholeness of system.

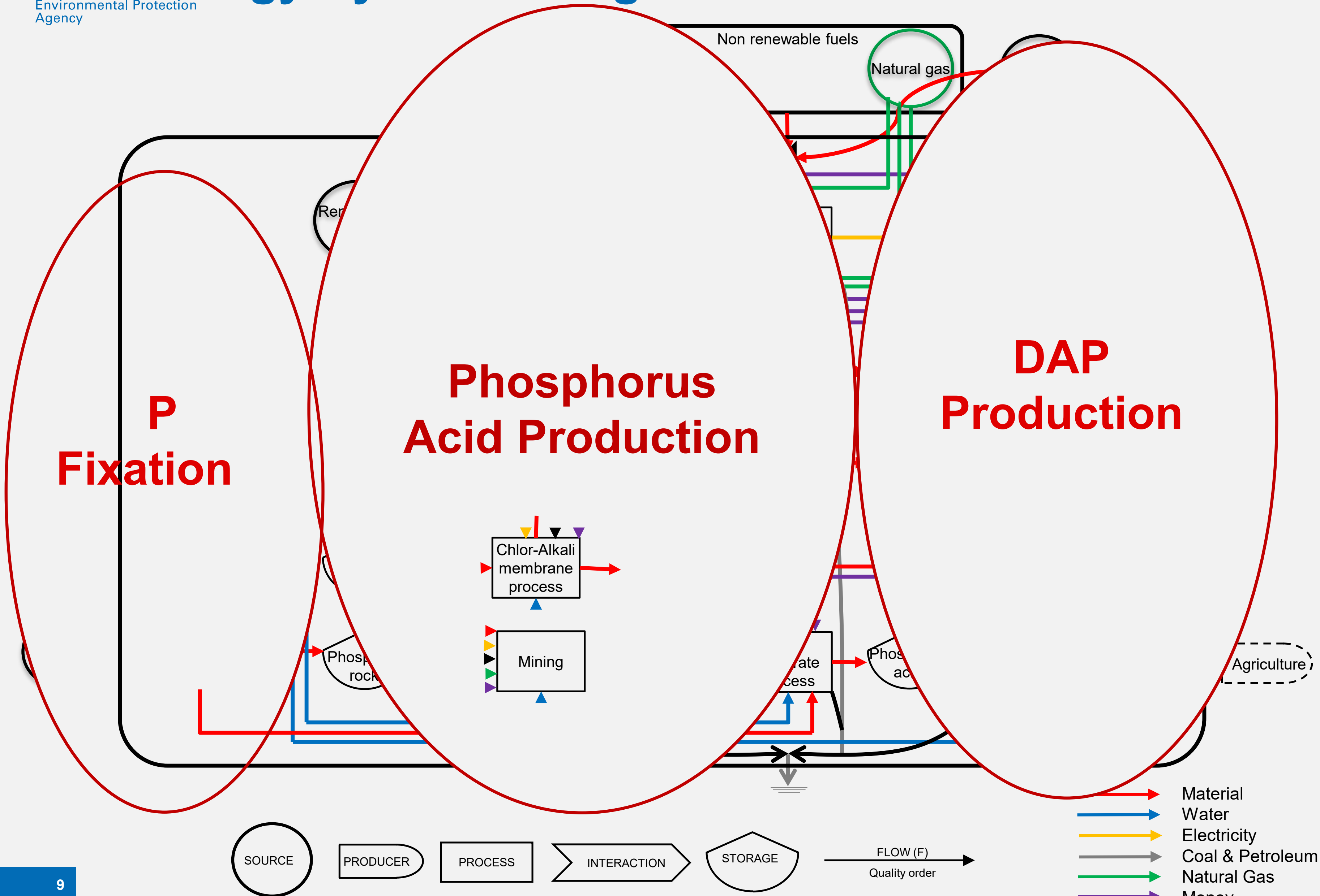
- Able to investigate systems that are outside of human activities and evaluate in a quantitative way (metrics) the quality of resource flows and storages.

Emergy Systems Diagram for Nutrient Recovery



External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

Energy Systems Diagram for DAP Production



External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown

Results of Traditional Fertilizer Vs. Nutrient Recovery

Diammonium Phosphate (DAP)

Chemical formula: $(NH_4)_2HPO_4$ Composition: 18% N, 46% P_2O_5 (20% P)					
		Data	Unit	UEV	EMERGY
Note	Description			(sej/unit)	(E sej/yr)
Infrastructure input					
*	Capital	1.14E+01	$	2.02E+12	2.31E+13
Operational inputs per year (2013)					
1	Materials				
1a	Phosphate Rock	1.50E+06	g	3.61E+09	5.40E+15
1b	Ammonia	1.44E+05	g	6.48E+09	9.35E+14
1c	Sulfur	3.97E+05	g	9.50E+10	3.77E+16
1d	Limestone	3.02E+04	g	2.20E+08	6.65E+12
2	Energy				
2a	Electricity	1.16E+08	J	7.26E+05	7.85E+12
2b	Fuels	4.34E+08	J	6.13E+05	4.01E+13
3	Services	5.12E+02	$	2.02E+12	1.04E+15
4	Water	3.56E+01	m^3	8.22E+11	1.23E+13
	Total EMERGY				**5.03E+16**
5	Transformity	w/o capital invest		5.03E+10	sej/g DAP
		with capital invest		5.03E+10	sej/g DAP
		w/o capital invest		1.18 E+10	sej/g P

Struvite

Chemical Formula: Crystal Green®, $NH_4MgPO_4{\cdot}6H_2O$ (5-28-0 +10% Mg)					
		Data	Unit	UEV	EMERGY
Note	Description			(sej/unit)	(E sej/yr)
Infrastructure input					
*	Capital	2.47E+02	$	2.02E+12	5.01E+14
Operational inputs per year (2013)					
1	Materials				
1a	Phosphate, eq. to elemental phosphorus (PO_4-P)	1.40E+05	g		0.00E+00
1b	Ammonia, equivalent to elemental Nitrogen (NH_3-N)	2.10E+05	g		0.00E+00
1c	Sodium hydroxide (NaOH)	4.90E+04	g	4.14E+09	2.03E+14
1d	Magnesium chloride ($MgCl_2$) as Mg	1.47E+05	g	4.34E+10	6.38E+15
2a	Electricity	6.40E+08	J	2.21E+05	1.41E+14
3	Services	5.33E+01	$	2.02E+12	1.08E+14
4	Wastewater	2.63E+02	g	3.26E+05	8.56E+07
	Total EMERGY				**7.10E+15**
5	Transformity	w/o capital invest		7.10E+09	sej/g CG
		with capital invest		7.60E+09	sej/g CG
		w/o capital invest		8.96 E+08	sej/g P

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Struvite

Chemical Formula: Crystal Green®, $NH_4MgPO_4 \cdot 6H_2O$ (5-28-0 +10% Mg)					
Note	Description	Data	Unit	UEV (sej/unit)	EMERGY (E sej/yr)
	Infrastructure input				
*	Capital	2.47E+02	$	2.02E+12	5.01E+14
	Operational inputs per year (2013)				
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1a	Phosphate, eq. to elemental phosphorus (PO_4-P)	1.40E+05	g		0.00E+00
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		w/o capital invest		8.96 E+08	sej/g P

Biological Nutrient Removal (BNR)

- BNR treatments remove TN and TP from wastewater through the use of chemicals and microorganisms under different environmental conditions (Metcalf and Eddy, 2003)
- Levels of nutrient removal processes :

Treatment Level (Effluent Limits)	Removal/Recovery Process Name	Processes Chosen for this Study
Recovery	Phosphorus Recovery	Phosphorus Recovery - Anammox
Level 2 TN – 8 mg/L, TP – 1 mg/L	Nitrification or Oxidation Ditch with or without Phosphorus Precipitation (chemical addition)	Nitrification
Level 3 TN – 4-8 mg/L, TP – 0.1-0.3 mg/L	Modified Ludzack Ettinger (MLE) 4 Stage and 5 Stage Bardenpho (Bardenpho), Modified University of Cape Town (MUCT), Sequential Batch reactor (SBR) + Phosphorus Precipitation (chemical addition)	MLE MLE - High Energy Bardenpho - No Chemical Addition Bardenpho - Chemical Addition Bardenpho - High Energy MUCT - No Chemical Addition MUCT - Chemical Addition MUCT - High Energy
Level 4 TN – 3 mg/L, TP – 0.1 mg/L	Level 3 process with either Denitrification Filter Membrane Filter, Membrane Bioreactor (MBR) + Phosphorus Precipitation (chemical addition)	Bardenpho - Denitrification Filter Bardenpho - Membrane Filter MUCT - Membrane Filter Bardenpho - MBR
Level 5 TN - <2 mg/L, TP<0.02 mg/L	Level 3 or Level 4 processes with Sidestream Reverse Osmosis	Bardenpho - RO Bardenpho - Membrane Filter & RO MUCT - Membrane Filter & RO

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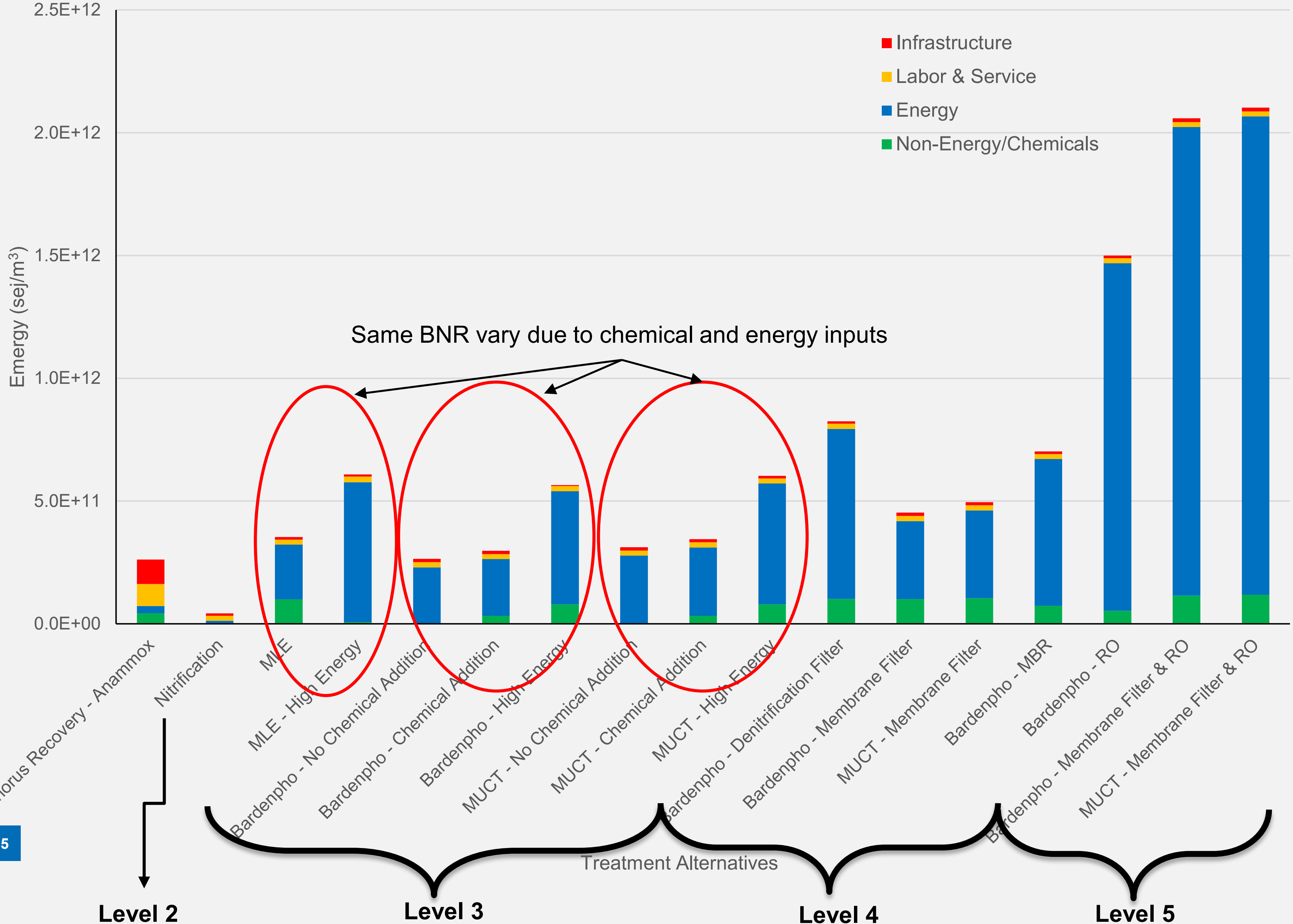
Processes Considered for the Study

Treatment Level (Effluent Limits)	Nutrient Removal/Recovery Process	Energy (kWh/m³)	Influent Ammonia (mg/L as NH_3-N)	Influent P (mg/L as P)
Recovery	Phosphorus Recovery - Anammox	0.14	20	7
Level 2 (TN – 8 mg/L, TP – 1 mg/L)	Nitrification	0.23	24	10
Level 3 (TN – 4-8 mg/L, TP – 0.1-0.3 mg/L)	MLE	0.28	23	8
	MLE - High Energy	0.59	32	8
	Bardenpho - No Chemical Addition	0.29	23	8
	Bardenpho - Chemical Addition	0.29	23	8
	Bardenpho - High Energy	0.58	22	5
	MUCT - No Chemical Addition	0.35	23	8
	MUCT - Chemical Addition	0.35	23	8
	MUCT - High Energy	0.56	22	5
Level 4 (TN – 3 mg/L, TP – 0.1 mg/L)	Bardenpho - Denitrification Filter	0.53	22	5
	Bardenpho - Membrane Filter	0.4	23	8
	MUCT - Membrane Filter	0.45	23	8
	Bardenpho - MBR	0.53	22	5
Level 5 (TN - <2 mg/L, TP<0.02 mg/L)	Bardenpho - RO	0.60	22	5
	Bardenpho - Membrane Filter & RO	2.4	23	8
	MUCT - Membrane Filter & RO	2.45	23	8

Total Emergy Comparison between Different Nutrient Removal and Recovery Technology



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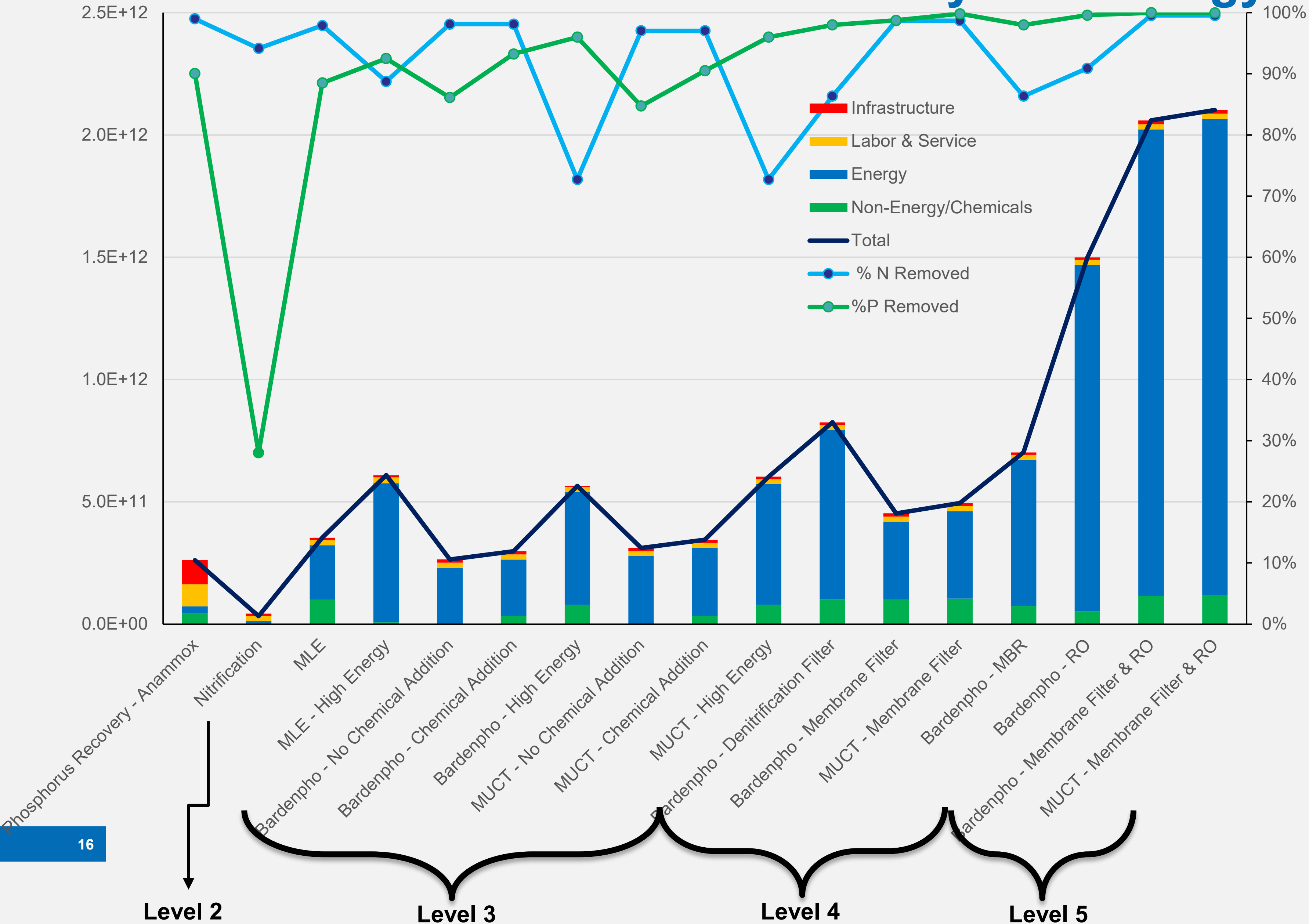

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Results and Discussions

- Stringent nutrient reduction regulations lead to trade-offs that need further evaluation to choose the most sustainable treatment alternative

- Emergy analysis justifies nutrient recovery from wastewater sludge and provides sound economic and ecological comparison of removal and recovery treatment alternative independent of perceived monetary value

- DAP process depends ~70% on non-renewable energy sources and a scarce material (phosphate rock), Struvite has potential of utilizing 100% of renewable sources, making recovery of phosphorus as fertilizer less emergy intensive

- DAP with an order of magnitude higher total emergy relative to struvite, displays a bigger environmental ‘footprint’.

- Among the nutrient removal treatment alternatives, the study results show that energy and non-energy (chemicals) inputs can lead to significant variation in process emergy

Selected References

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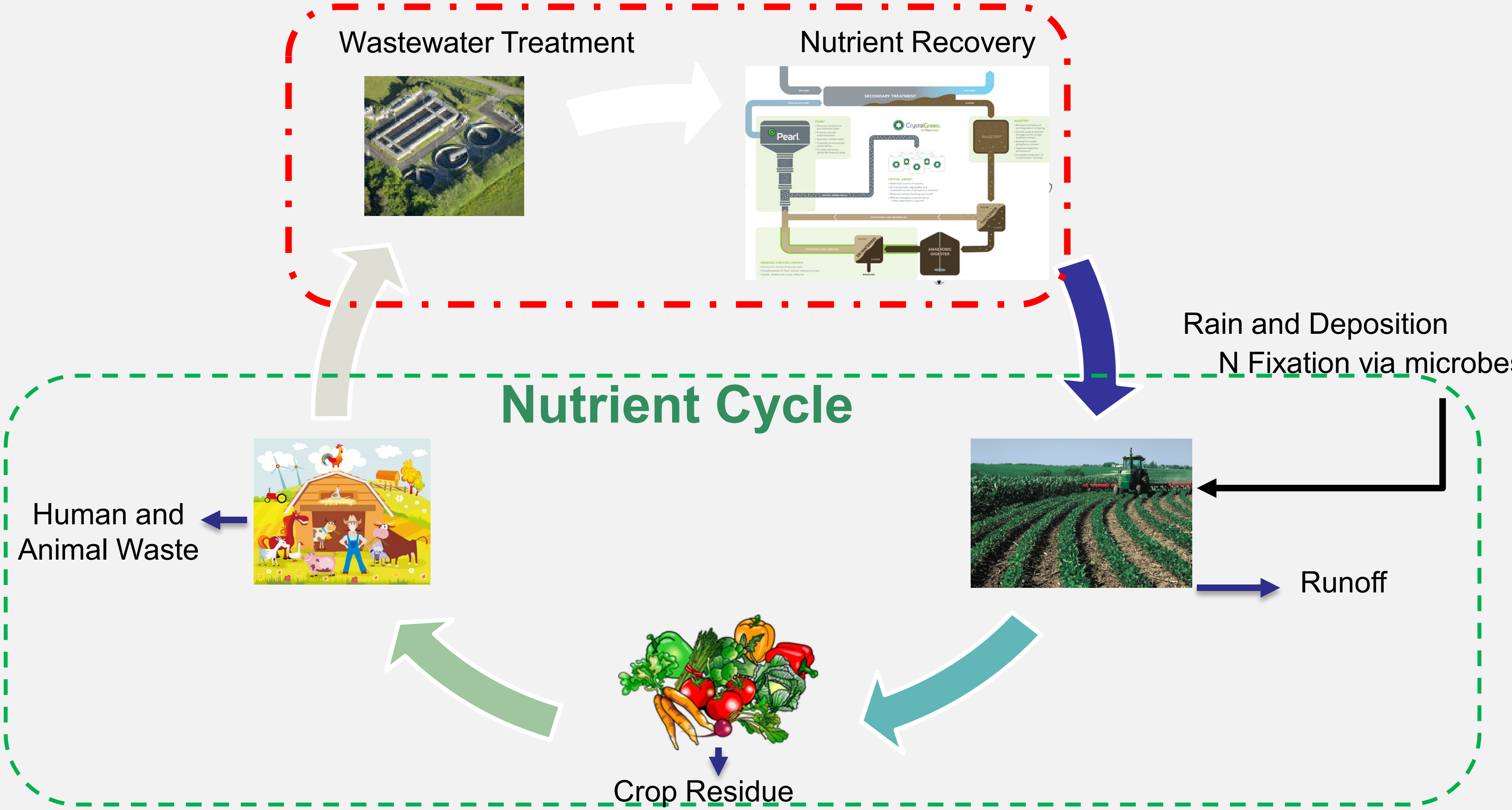
Future or Continued Work



Account for the benefits of nutrient recovery via efficient use of the struvite fertilizer and the flow of N and P nutrients in the food system, the economic, environmental and societal benefits of struvite recovery would be more perceptible.

Acknowledgements

- Research Adviser - Dr. Xin (Cissy) Ma
- Safe and Sustainable Water Resources National Research Program in the EPA's Office of Research and Development
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- U.S.EPA Graduate Student Program – Sam Arden
- ORISE Research Associate Program (Alejandra M. González-Mejía's appointment)
  - This project was supported in part by an appointment to the Internship/Research Participation Program at the NRMRL, U.S. Environmental Protection Agency, administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and EPA.
- Ostara Nutrient Recovery Technologies, Inc., The Mosaic Company and Agrium, Inc.

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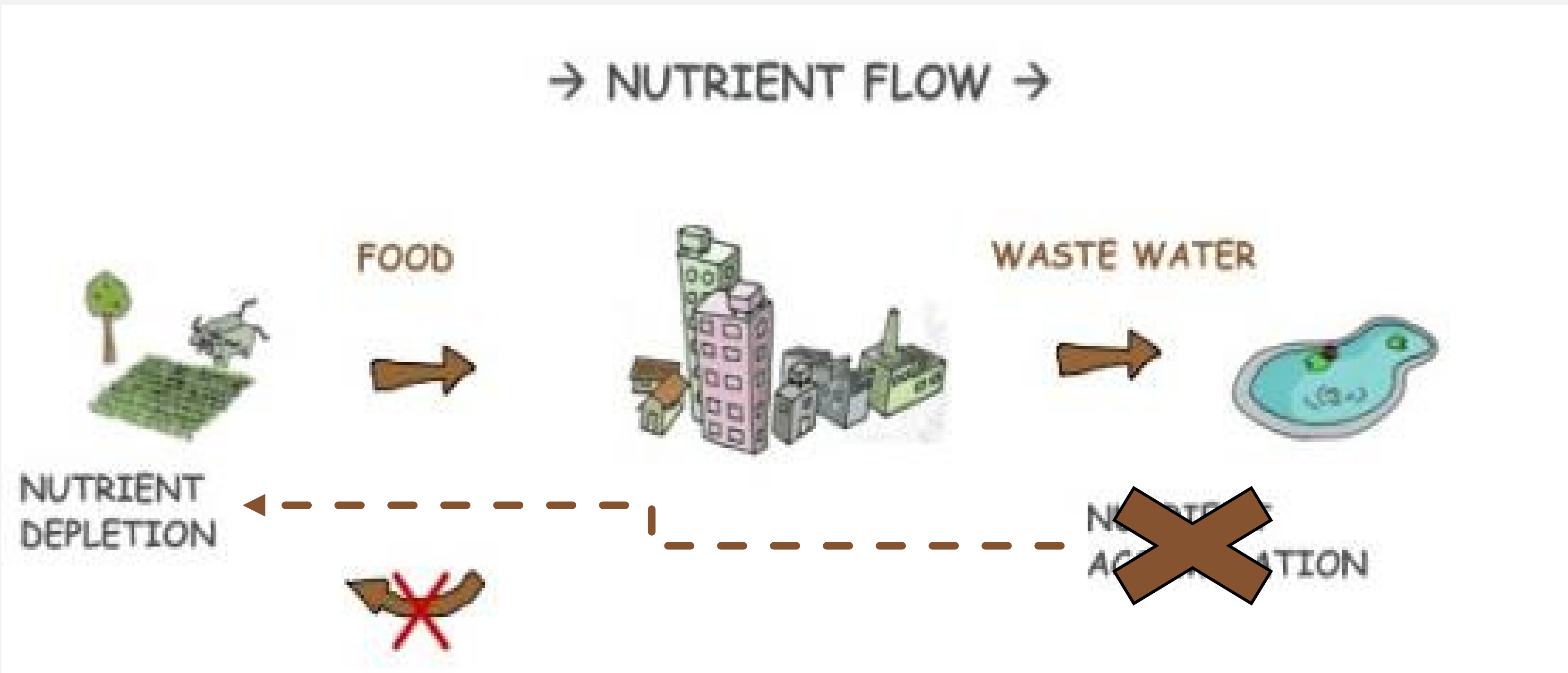
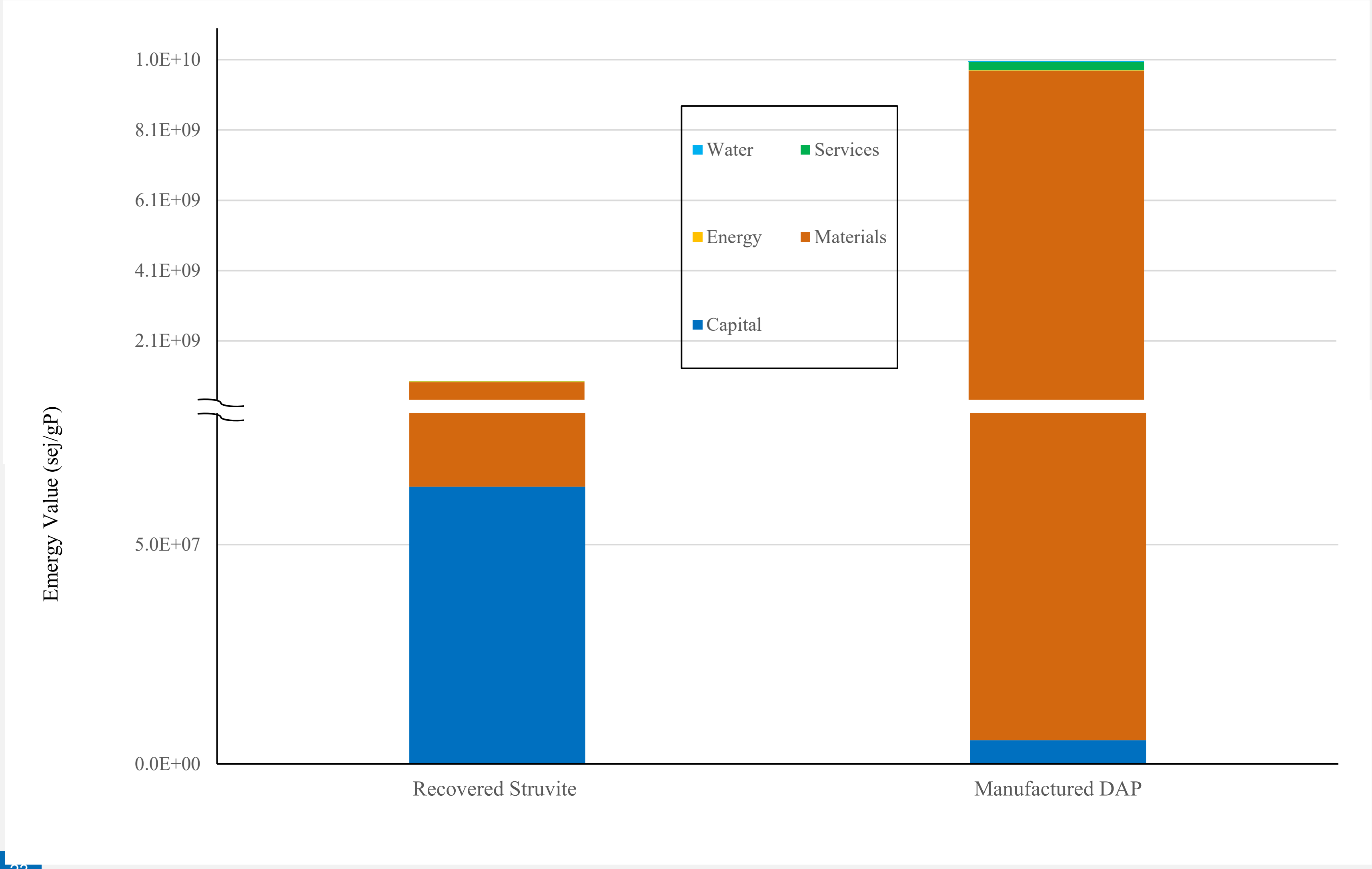
Thank you! Questions?

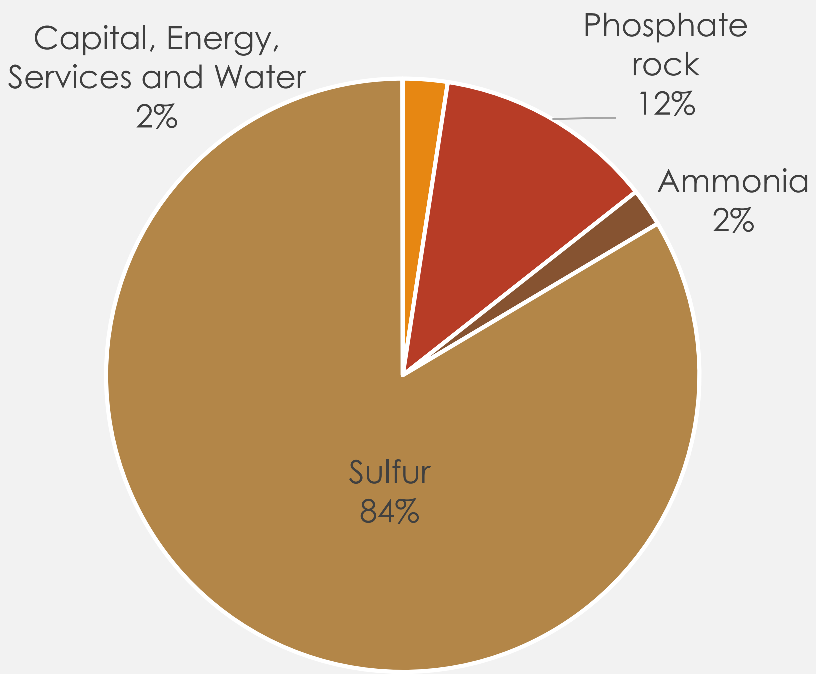


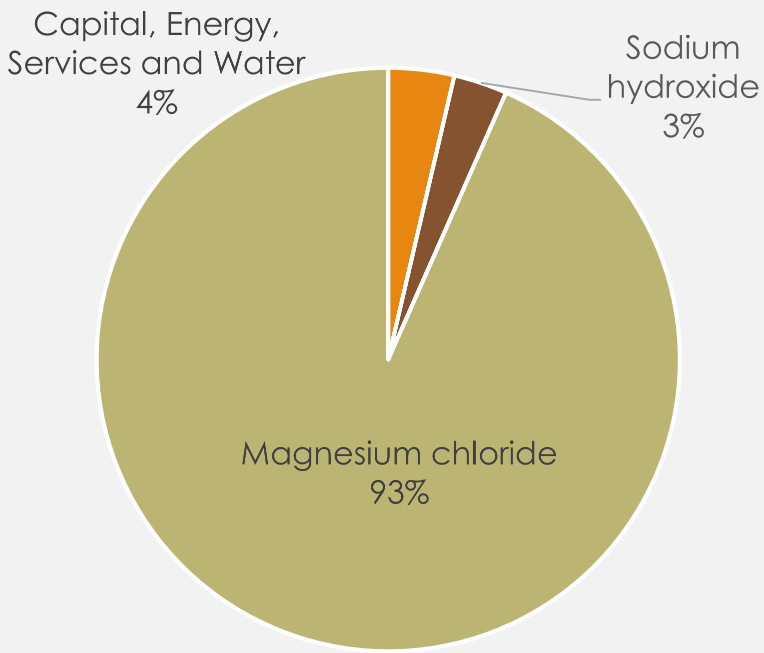
Backup Slides

Struvite vs. DAP

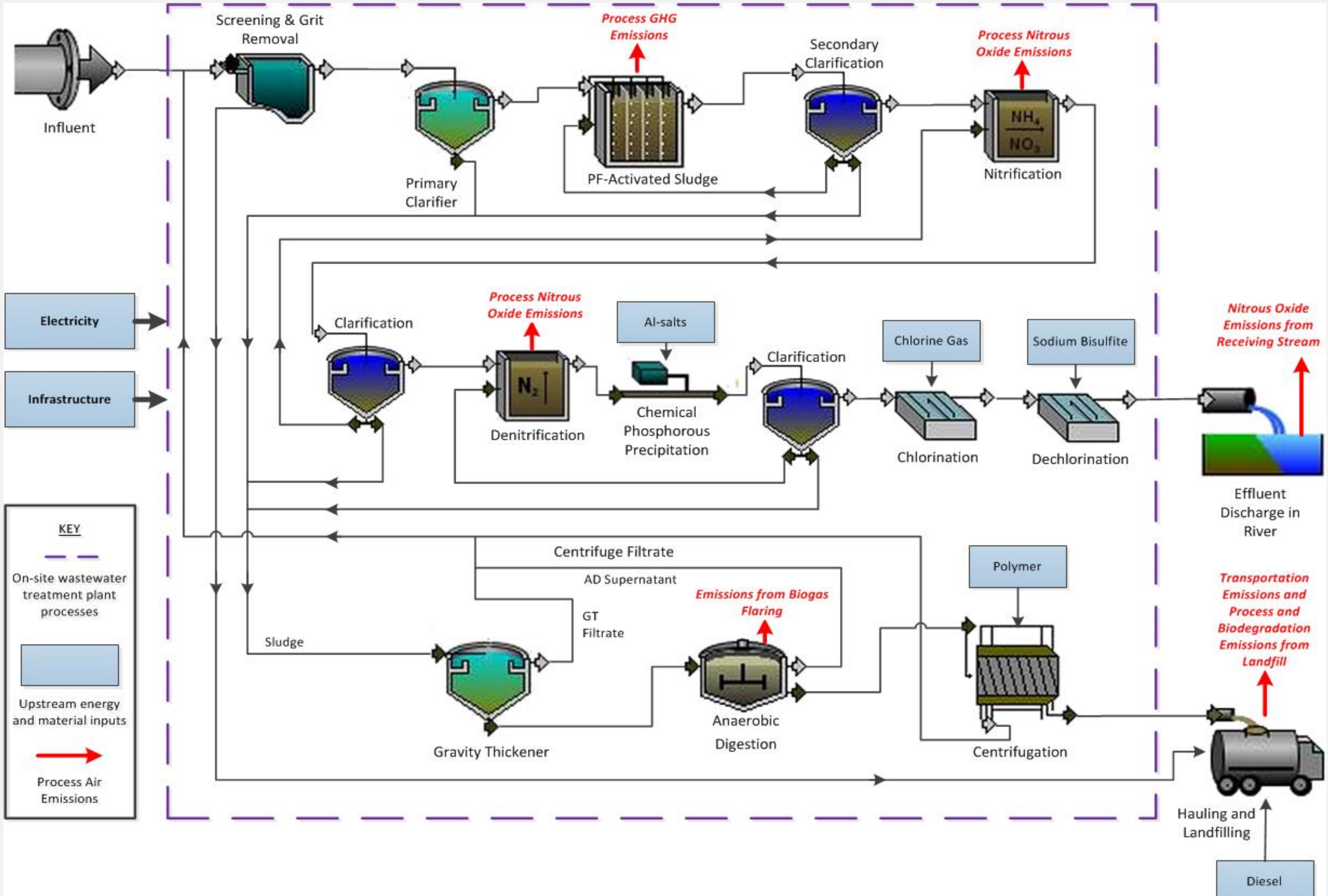


Struvite vs. DAP - Major emergy contributors





Level 2-2 (3-Sludge System)



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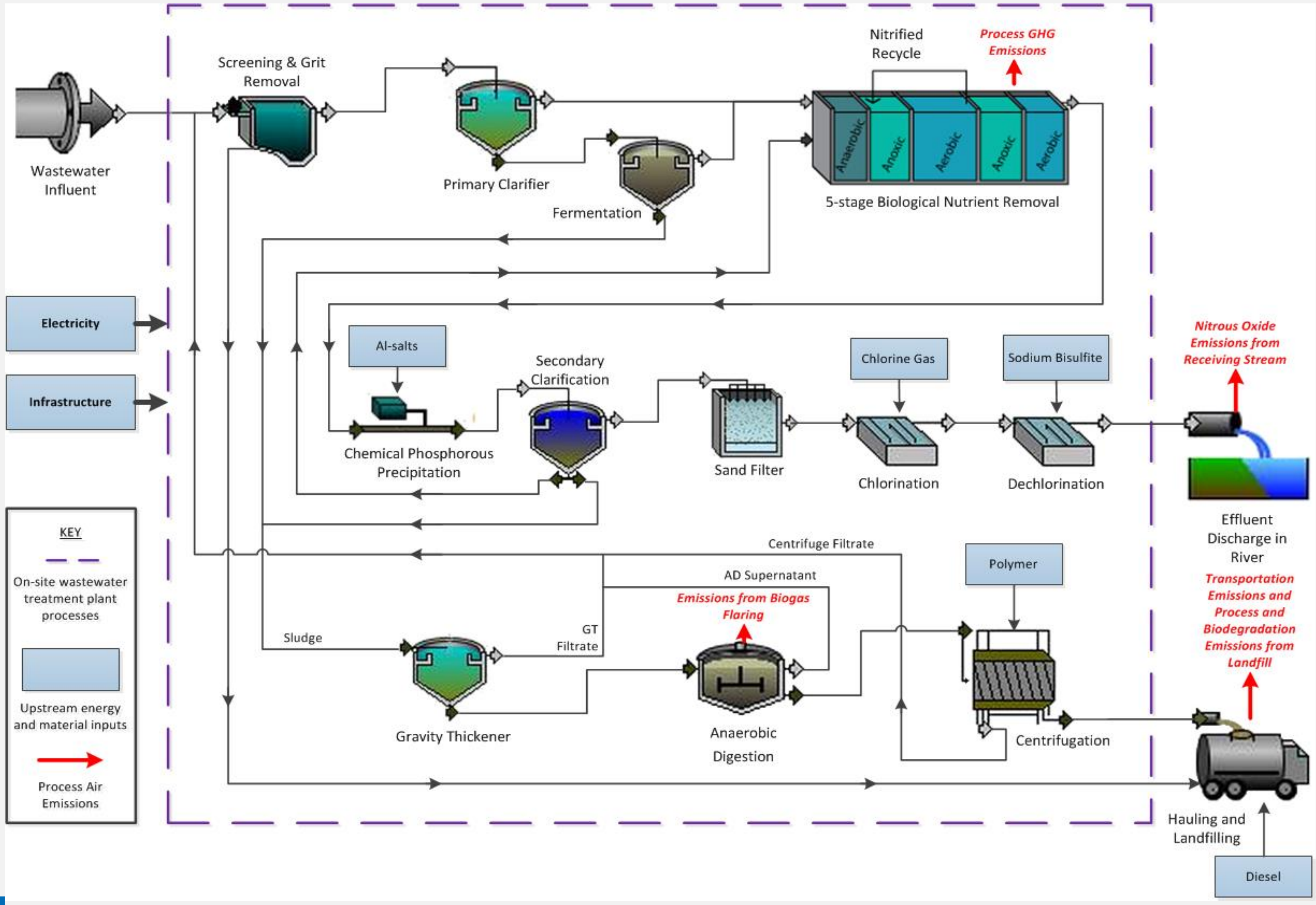
Level 3-1 (5-Stage Bardenpho)



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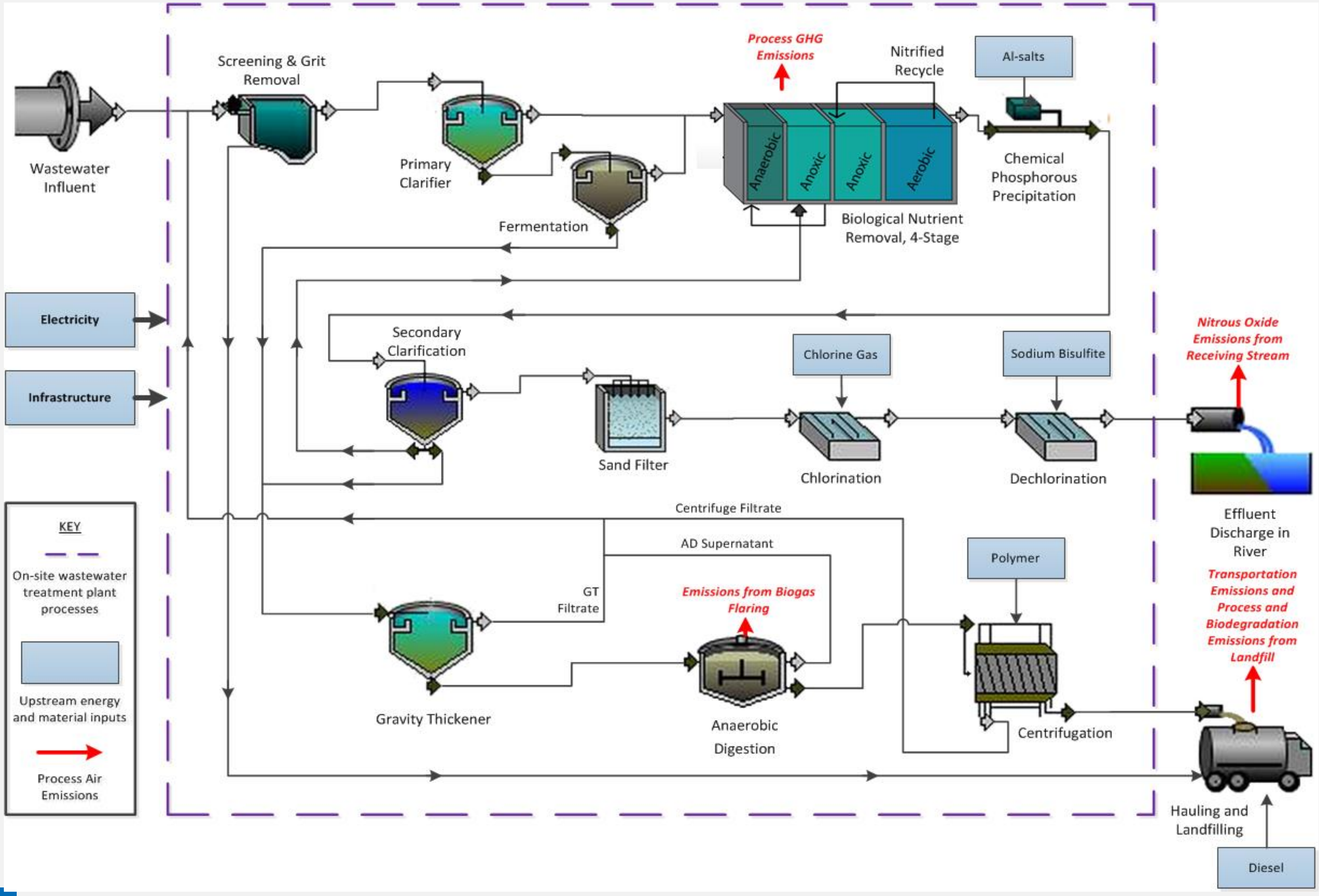
Level 3-2 (Mod, U of Cape Town)



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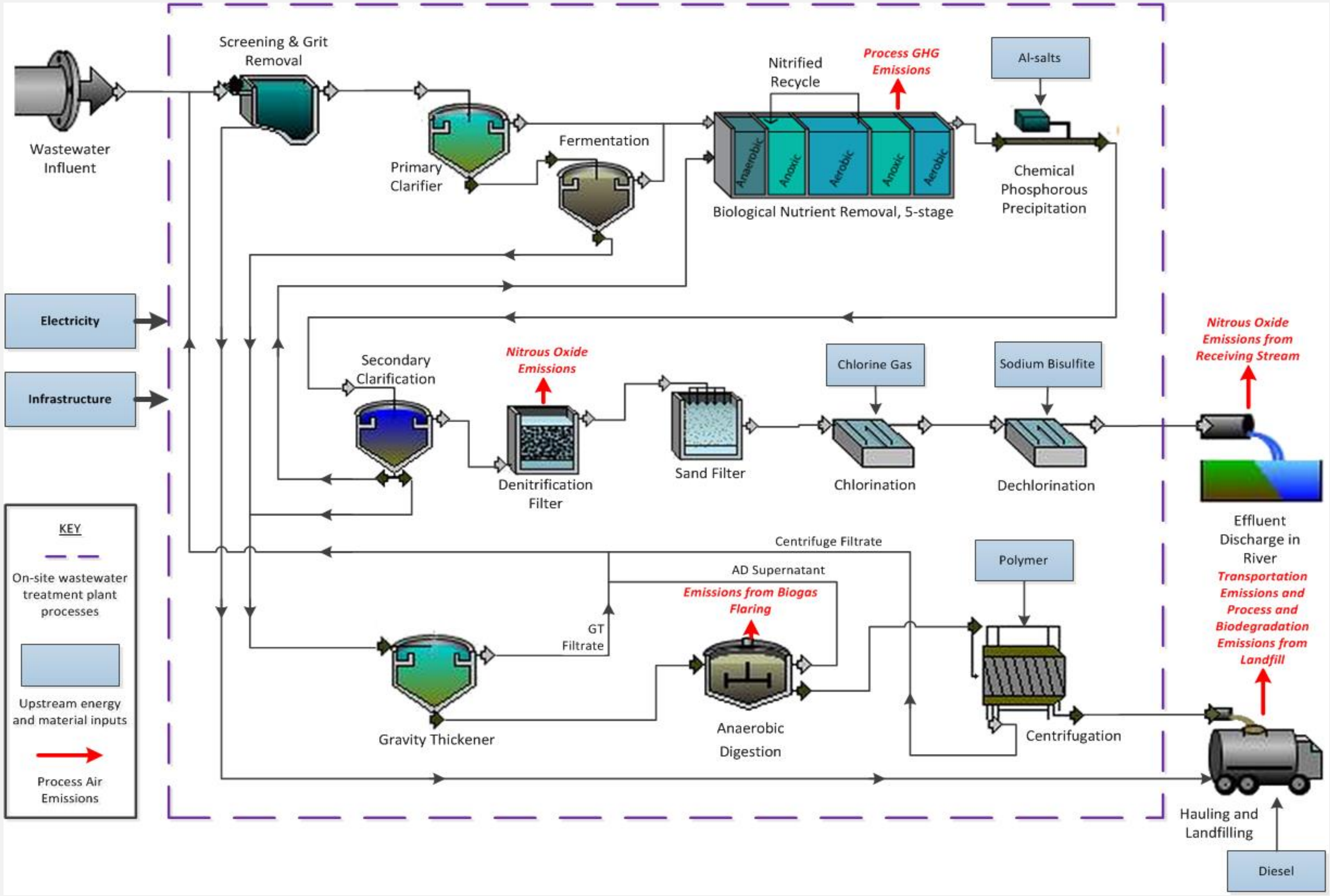
Level 4-1 (5-S Bardenpho+DenitFil)



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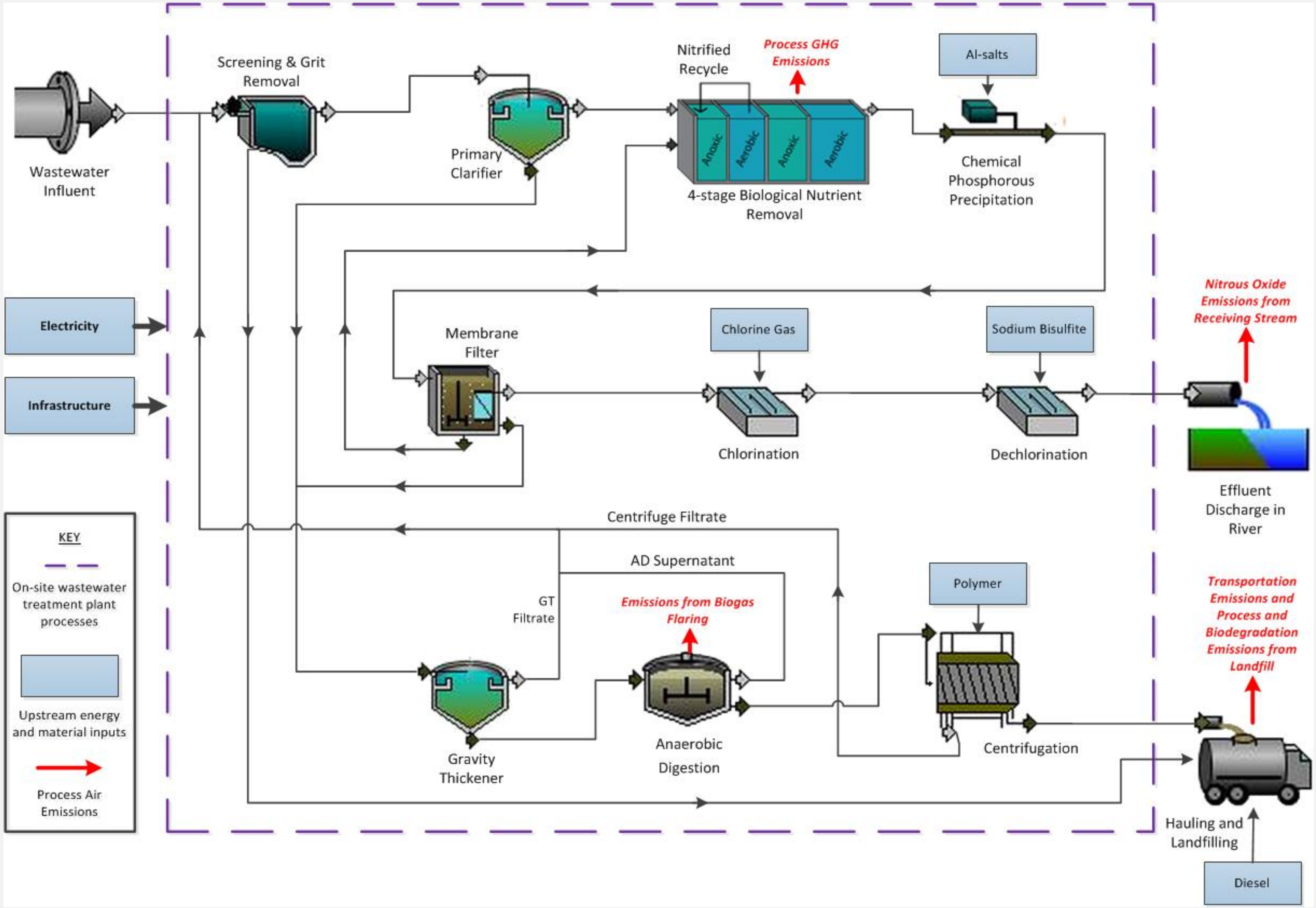
Level 4-2 (4-Stage Bardenpho MBR)



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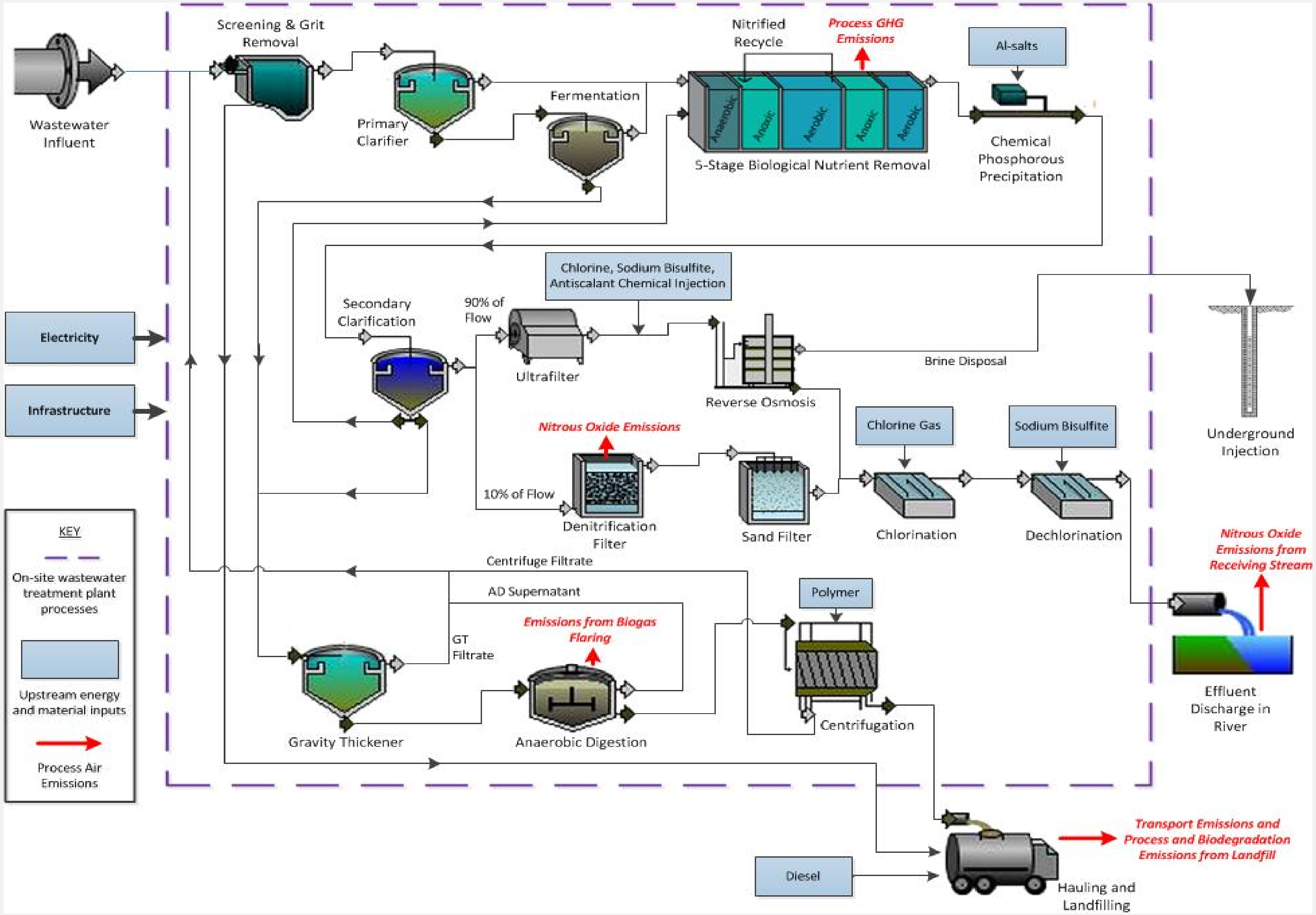
Level 5-1 (5-S Bardenpho+UF/RO)



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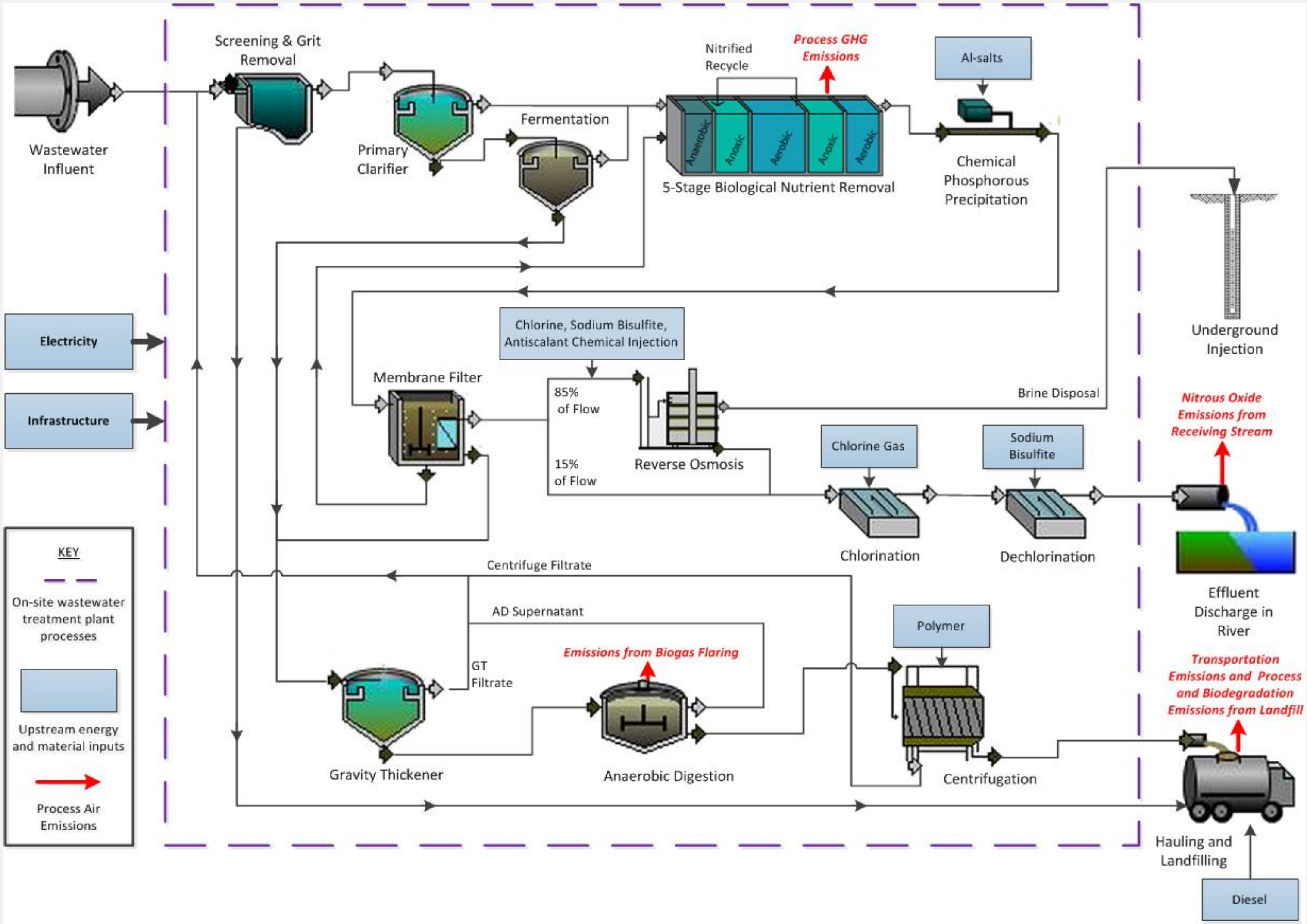
Level 5-2 (5-S Bardenpho MBR+RO)



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Emergy Comparison between Nutrient Removal and Recovery Technology- Percent Contribution