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From wastewater treatment to water resource recovery: Environmental and economic impacts of full-scale implementation

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ABSTRACT

To reduce greenhouse gas emissions and promote resource recovery, many wastewater treatment operators are retrofitting existing plants to implement new technologies for energy, nutrient and carbon recovery.
In literature, there is a lack of studies that can unfold the potential environmental and economic impacts of the transition that wastewater utilities are undertaking to transform their treatment plants to water resource recovery facilities (WRRFs). When existing, literature studies are mostly based on simulations rather than real plant data and pilot-scale results. This study combines life cycle assessment and economic evaluations to quantify the environmental and economic impacts of retrofitting an existing wastewater treatment plant (WWTP), which

The role of N_2O emissions in the life cycle assessment of a water resource recovery facility in Copenhagen

Maria Faragò, PhD fellow & consultant at Rambøll

BACKGROUND & MOTIVATION

- Wastewater treatment in Denmark **contributes to 10%** of the total waste sector's GHG emissions (Nielsen et al., 2020)
- **N_2O emissions** from nitrification/denitrification are a **major source of GHG** from wastewater

- Wastewater is also a **resource**.
- Residual sludge contains nutrients such as **phosphorous** (app. 5,000 ton P/year). **24% of sludge** is incinerated and hence lost (Jensen et al., 2015)
- Ca. 51 WWTPs in Denmark produce **biogas** hence **energy** from sludge [1]

[1] https://xn--kkkenkvrnen-g9a1u.dk/affaldssortering/biogasproduktion-i-danmark/

CASE STUDY

- Capacity of 400,000 PE
- Energy recovery plant
- Exporting biogas, heat

Future strategy:

- Retrofitting the plant to a water resource recovery facility **(WRRF)** in the **year 2025[1]**

Major goals:

- Reduce CO_2 emissions
- Recover more energy
- Recover phosphorus and other resources like sand and metals

[1] https://projekt-varga.dk/en/about-varga/

THE "VARGA" PROJECT

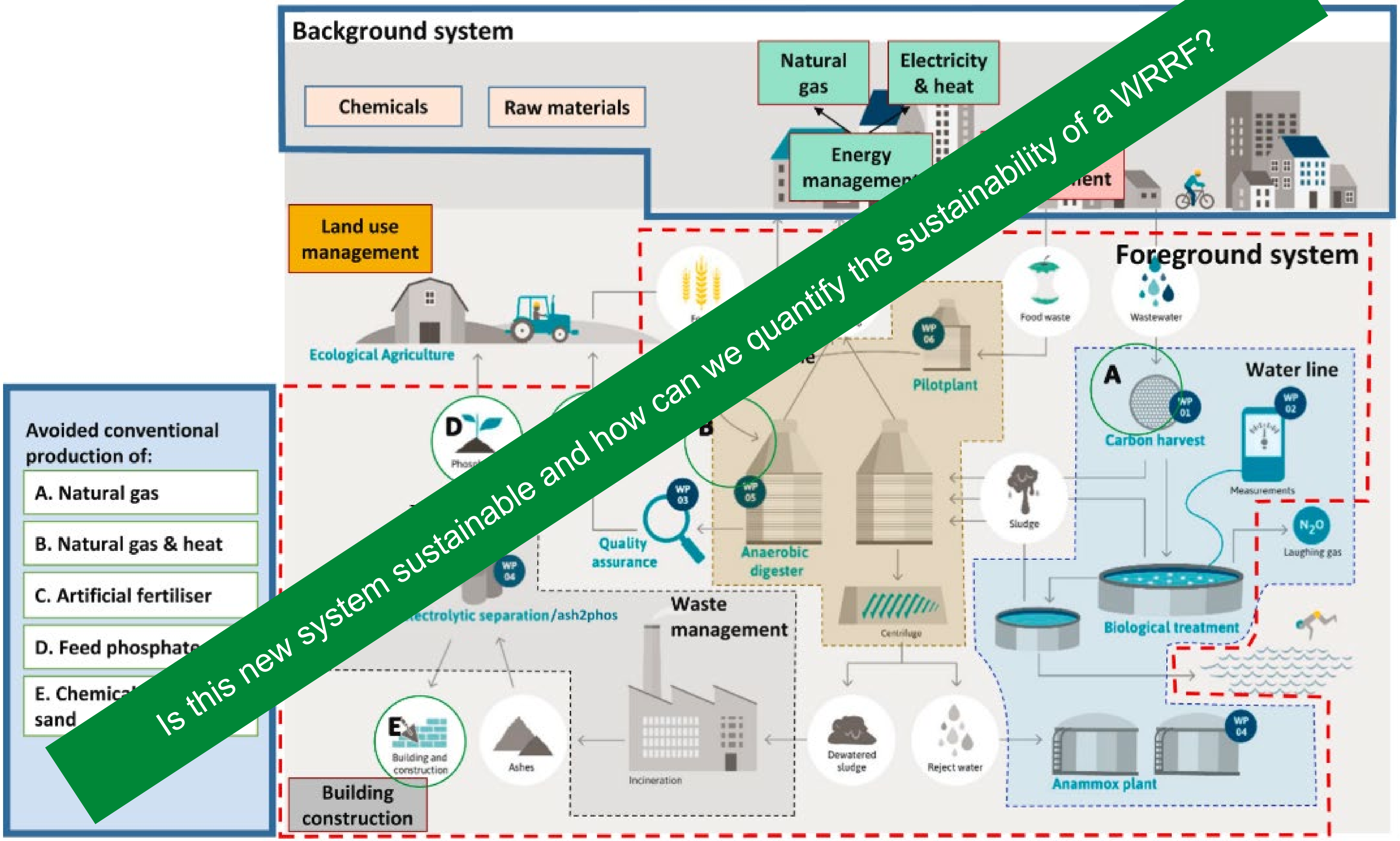
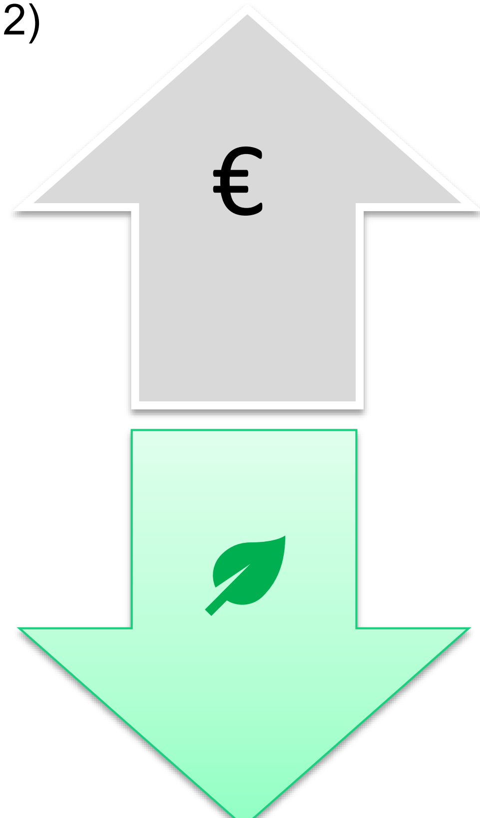


Fig. 1. Main system components/boundaries of the full-scale water resource recovery facility (WRRF). WP: work packages for implementing different resource recovery technologies. Figure edited from https://projekt-varga.dk/en/front/

ECO-EFFICIENCY METHODOLOGY

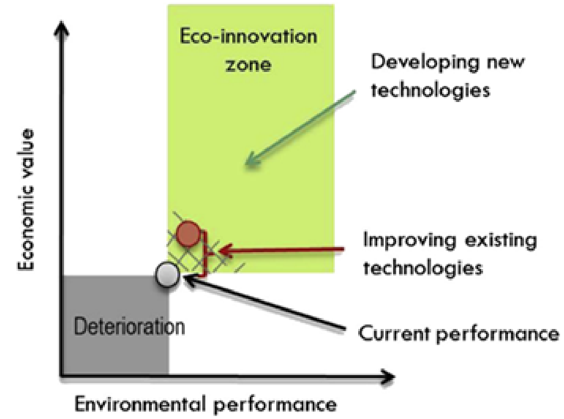
1) Goal & Scope Definition

2)



Economic added value assessment

+ CO_2 Abatement costs



Environmental impact assessment

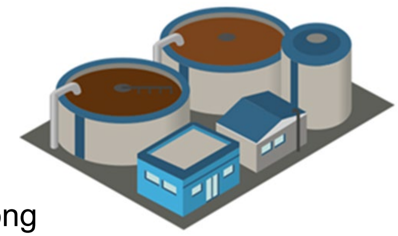
+ Mass/Energy balances

3) Interpretation

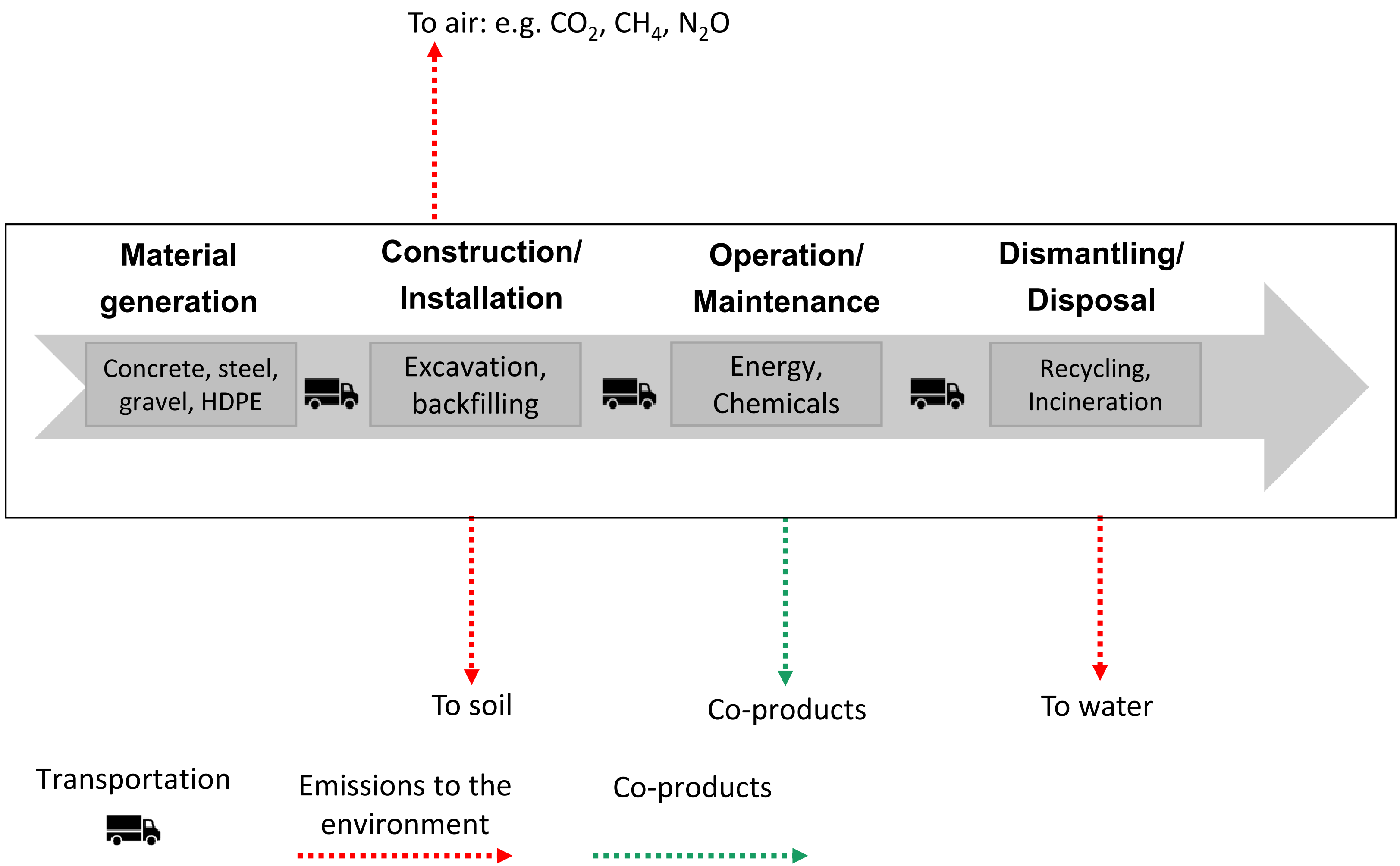
(ISO 14045, 2012)

What is LCA?

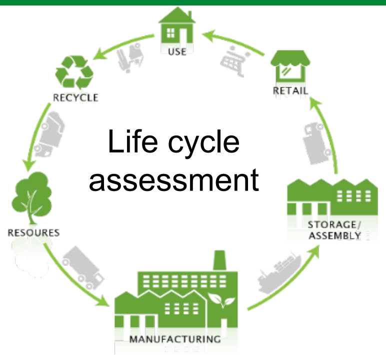
ENVIRONMENTAL IMPACT ASSESSMENT: LIFE CYCLE ASSESSMENT

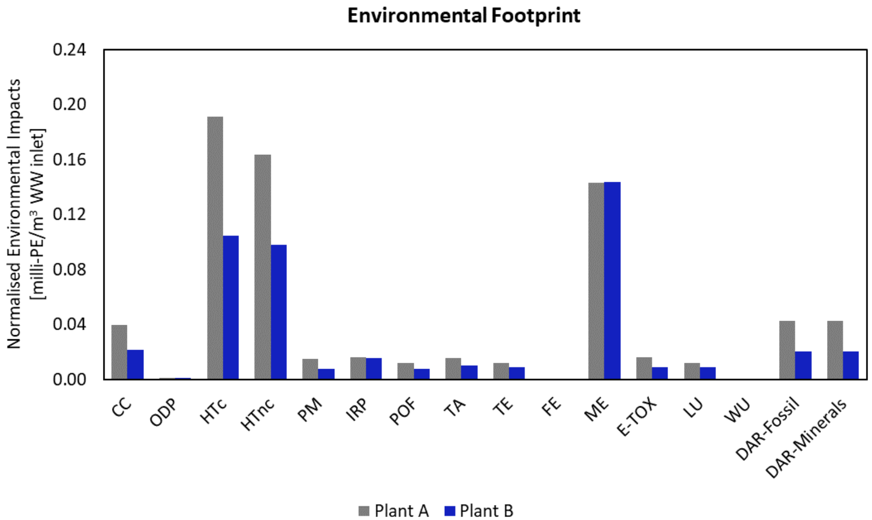


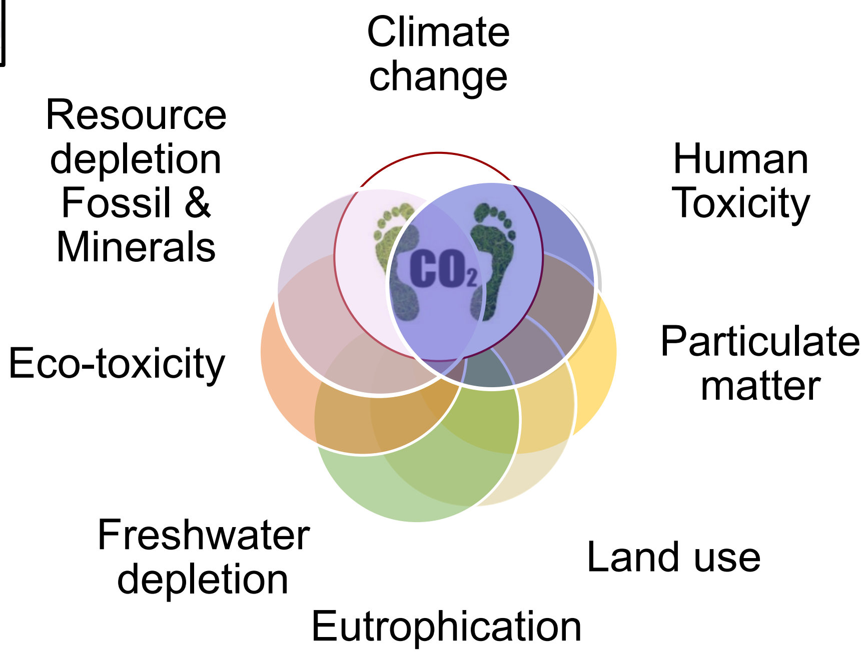
Cradle to grave approach: Inventory of materials' consumption and emissions along the life cycle of the system



FROM CARBON FOOTPRINT TO HOLISTIC DECISION SUPPORT TOOLS







INVENTORY DATA FOR N_2O SENSORS

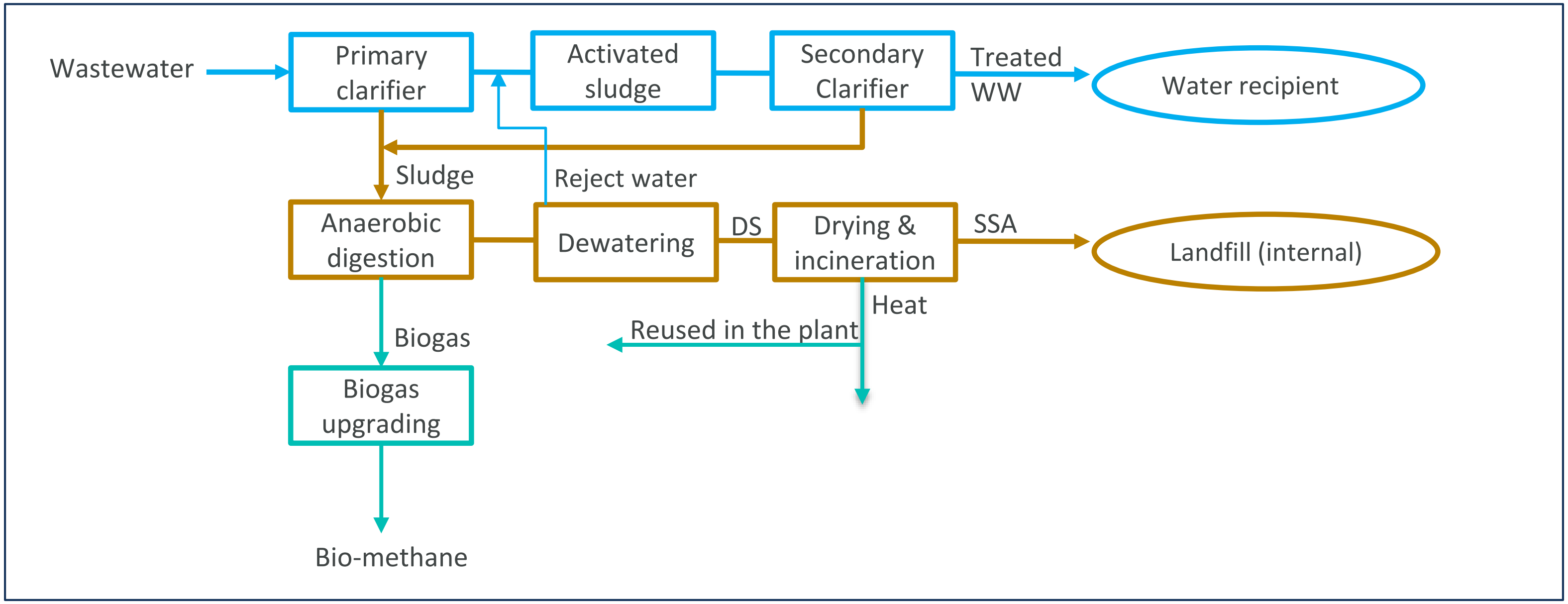
N_2O WASTEWATER SYSTEM

# of UNISENSE sensors	**4**
# of controllers	2

Life cycle stage	Parameter	Amount	Unit
Material	Controller: TFT (Thin-film-transistor) touch screen + electronics	0.064	kg
Material	Controller: Housing (case made of plastic (ABC))	0.33	kg
Material	Controller: Housing (electronics)	0.33	kg
Material	Sensor body: aluminium alloy	0.24	kg
Material	Sensor head POM acetylcopolymer	1.20	kg
Transport	Distance from the production location to Avedøre WRRF	700	km
Transport	Transport (sensor + controller) to Avedøre WRRF	1515	kg.km
Operation	Electricity for the sensors	negligible	negligible
Operation	Chemicals during calibration	negligible	negligible
Disposal	Controller: TFT + electronics - electronic waste recycling	0.39	kg
Disposal	Controller: Housing (plastic) - recycling	0.33	kg
Disposal	Sensor body: aluminium - recycling	0.24	kg
Disposal	Sensor head: POM – recycling	1.20	kg
Transport	Transport sensors and controllers to recycling stations	65	kg.km
Lifetime	Controller (housing, TFT touch screen + electronics)	10	years
Lifetime	Sensor body	5	years
Lifetime	Sensor head	6	months
Emissions (RF Baseline)	N_2O emissions – Activated Sludge	52.7	tons
Emissions (RF alternatives)	N_2O emissions – Activated Sludge	31.6	tons
Costs	CAPEX: initial investment	113,799 (one-time cost)	€2019
Costs	CAPEX: re-investments	7,800 (yearly)	€2019

ALTERNATIVES DEFINITION & SYSTEM BOUNDARIES

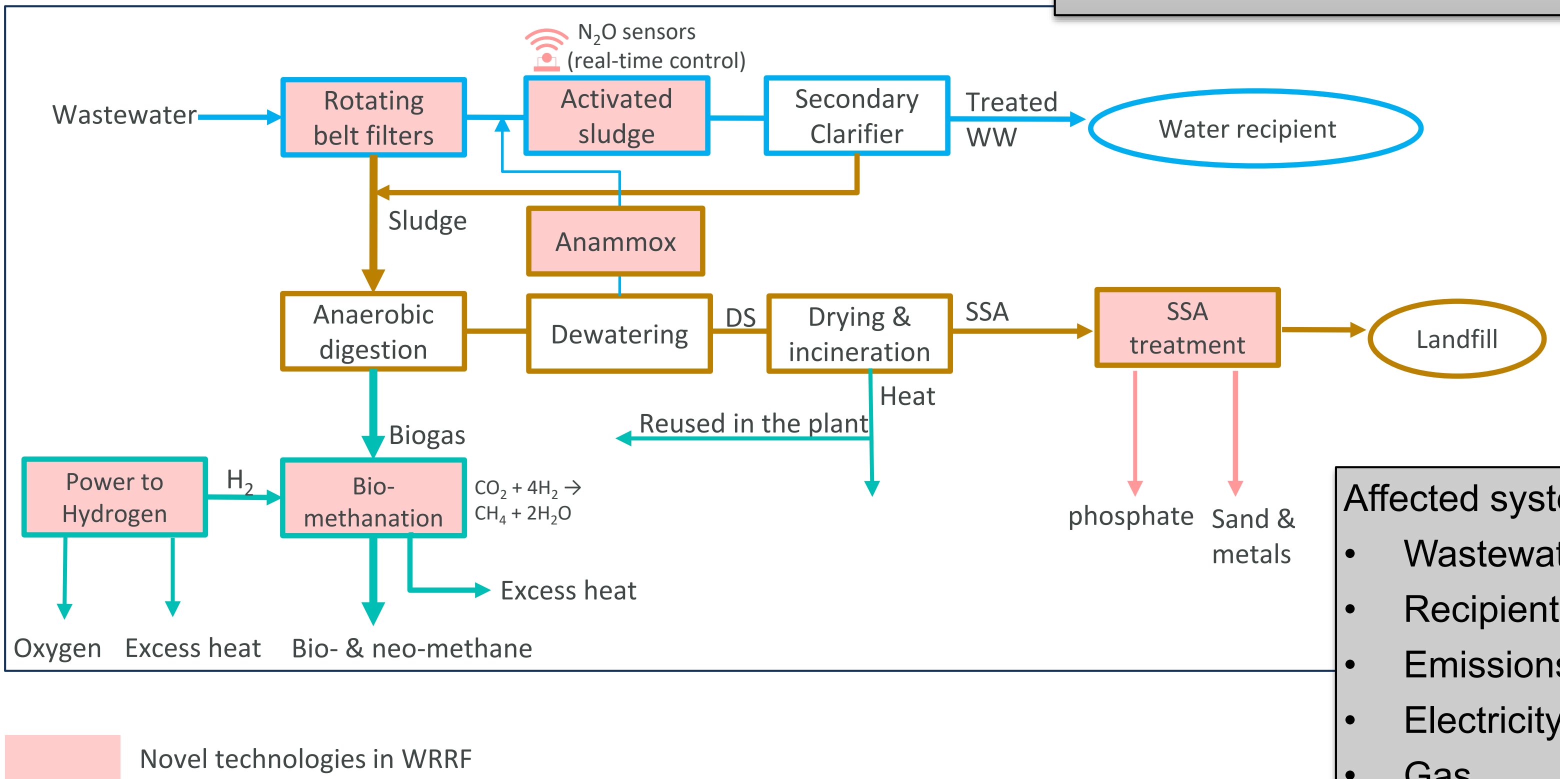
- RF-Baseline



ALTERNATIVES DEFINITION & SYSTEM BOUNDARIES

THE COMPLEXITY INCREASES

- WRRF



Affected systems:

- Wastewater treatment
- Recipient
- Emissions to air
- Electricity
- Gas
- District heating
- Cement production
- & more…

ALTERNATIVES’ DEFINITION

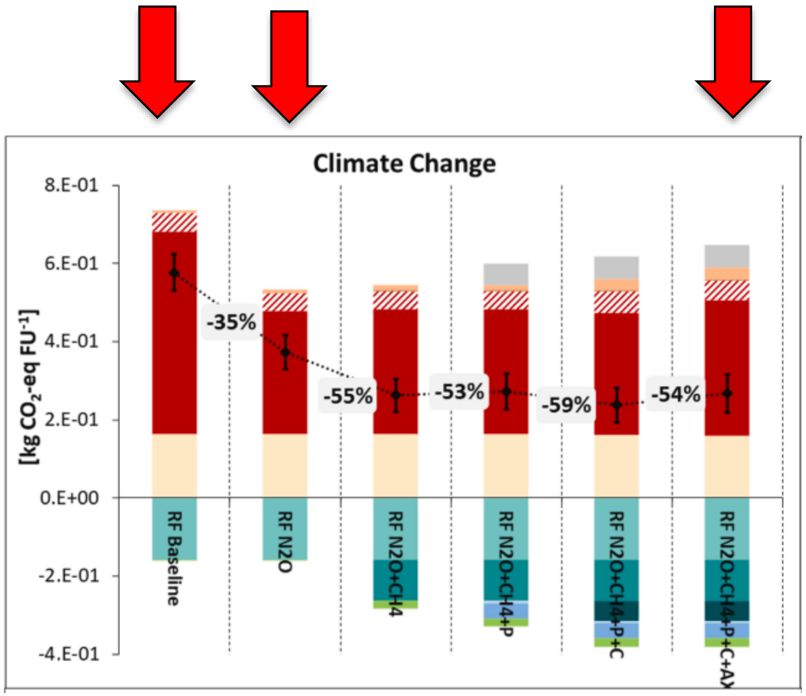
Alternative	Description
RF BASELINE	**Primary clarifier + conventional AS for nitrogen removal and chemical phosphate removal. Sludge treatment: AD+DW+INC.**
RF N2O	**+ Four sensors for online N_2O measurement & control installed in the aeration tanks**
RF N2O+CH4	+ Biologically upgrading of biogas through bio-methanation + P2H (electrolysis)
RF N2O+CH4+P	+ P recovery (MCP) and Al, Fe and sand from sludge ashes
RF N2O+CH4+P+C	+ A pre-filtration (PF) unit with 16 filters with aid of flocculants
RF N2O+CH4+P+C+AX	**+ A sidestream anammox (anaerobic ammonium oxidation) to remove nitrogen from the sidestream to the activated sludge system**

MASS BALANCE: FATE OF N,P, COD

Table 4
The fate of total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) in wastewater. Inlet loads: TN: 1,300 ton/year; TP: 193 ton/year; COD: 16,484 ton/year.

		RF Baseline	RF N2O	RF N2O+CH4	RF N2O+CH4+P	RF N2O+CH4+P+C	RF N2O+CH4+P+C+AX
TN-fate	N to cleaned effluent	8%	8%	8%	8%	8%	7%
	N to air (converted to N_2-N)	76%	77%	77%	77%	77%	78%
	N to air (converted to N_2O-N)	2.6%	1.6%	1.6%	1.6%	1.6%	1.7%
	N to landfill (sludge ashes)	[illegible]	[illegible]	13%	13%	13%	[illegible]
TP-fate	P to cleaned effluent	[illegible]	[illegible]	7%	7%	7%	[illegible]
	P to landfill (sludge ashes)	[illegible]	[illegible]	93%	5%	5%	[illegible]
	P recovered in feed phosphate	[illegible]	[illegible]	0%	89%	89%	[illegible]
COD-fate	COD to cleaned Effluent	4%	4%	4%	4%	4%	4%
	COD in activated sludge/aeration (used by microorganisms)	33%	33%	33%	33%	21%	21%
	COD anaerobically digested (converted to biogas)	34%	34%	34%	34%	42%	42%
	COD In dewatered sludge to incineration	30%	30%	30%	30%	34%	34%

ENVIRONMENTAL IMPACT ASSESSMENT



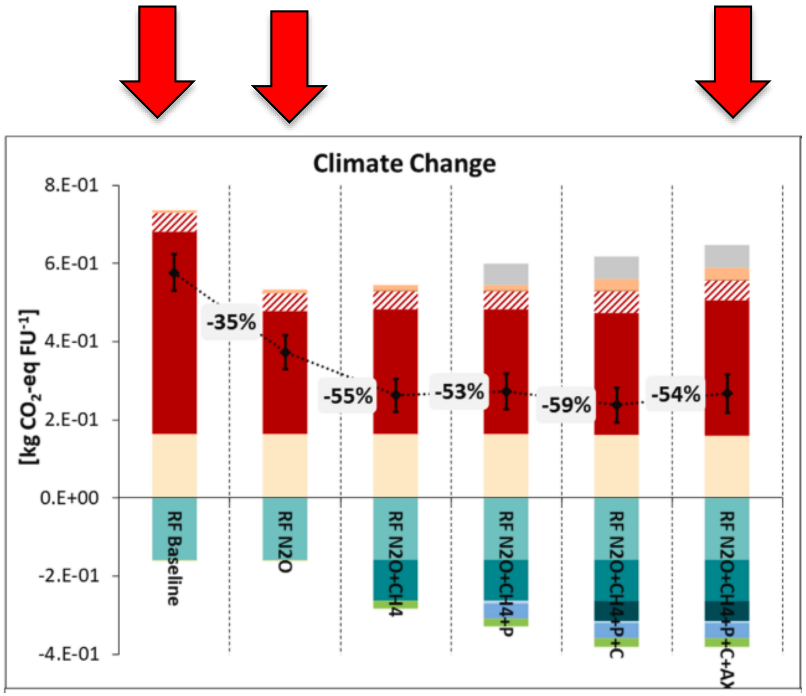
[FU: 1 m^3 wastewater inlet]

- N_2O emissions -> the major contributor to CC impacts
- Online control of N_2O reduced CC impacts by app. 35%
- A specific control was developed during a monitoring campaign between 2018 and 2019 by Chen et al. (2019)
- Side-stream anammox saved electricity consumption for aeration but increased N2O emissions (EF : 3% of TN removed) (Andersen et al., 2016; Uri Carreno, 2016).

- Wastewater treatment: baseline operation
- GHG direct emissions: CH4
- GHG direct emissions: N2O
- P-recovery: other co-products substitution
- P-recovery: chemicals & electricity consumption, landfill and transp
- Materials: new infrastructures
- Others
- Discharge to sea: water pollution
- Biomethane --> Natural gas substitution
- Neomethane (P2H) --> Natural gas substitution
- Additional bio- and neomethane (pre-filtration)
- P-recovery: Monocalcium phosphate (MCP) substitution
- Heat substitution
- ◆ Net impacts

ENVIRONMENTAL IMPACT ASSESSMENT

Equipment for real-time measurement and control of N_2O achieved no significant impacts in other environmental categories (<0.4%).



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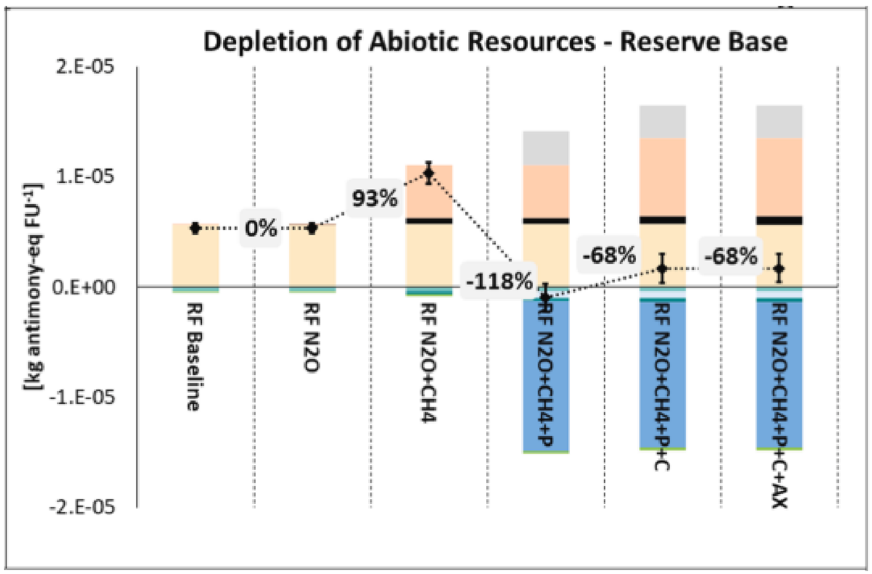

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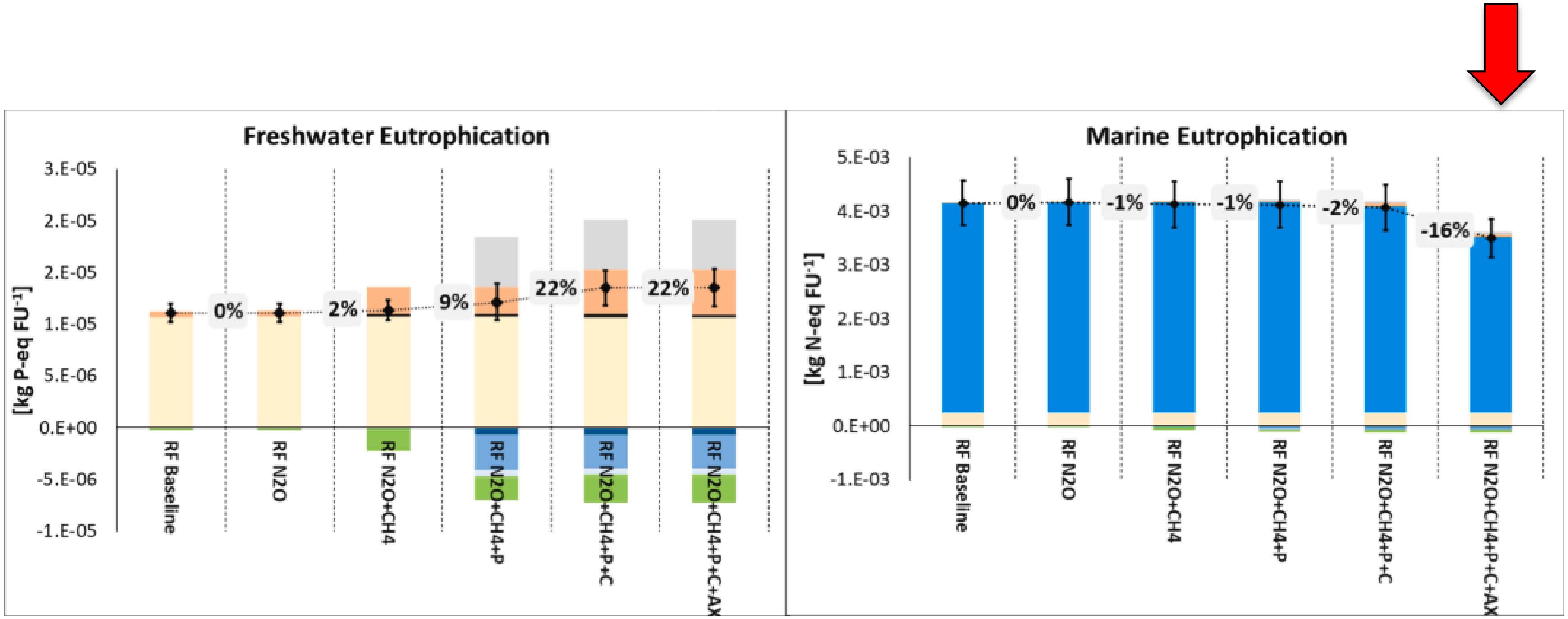
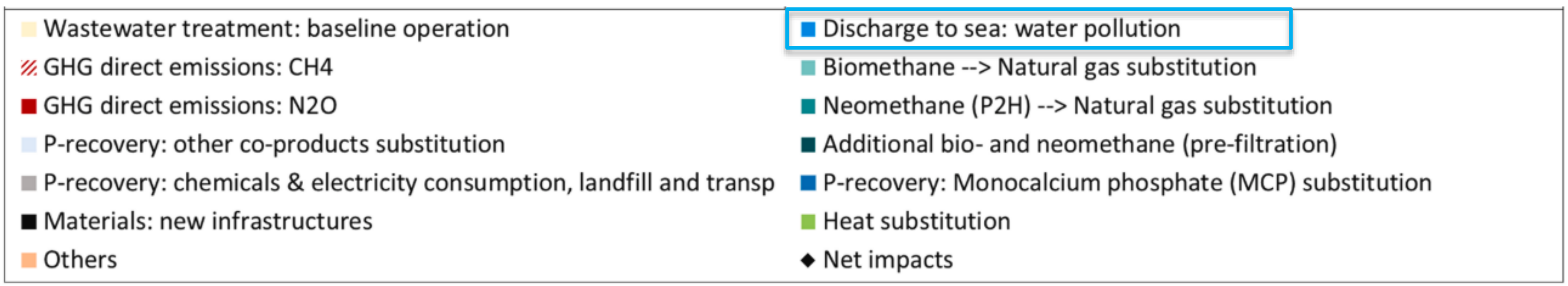
ENVIRONMENTAL IMPACT ASSESSMENT

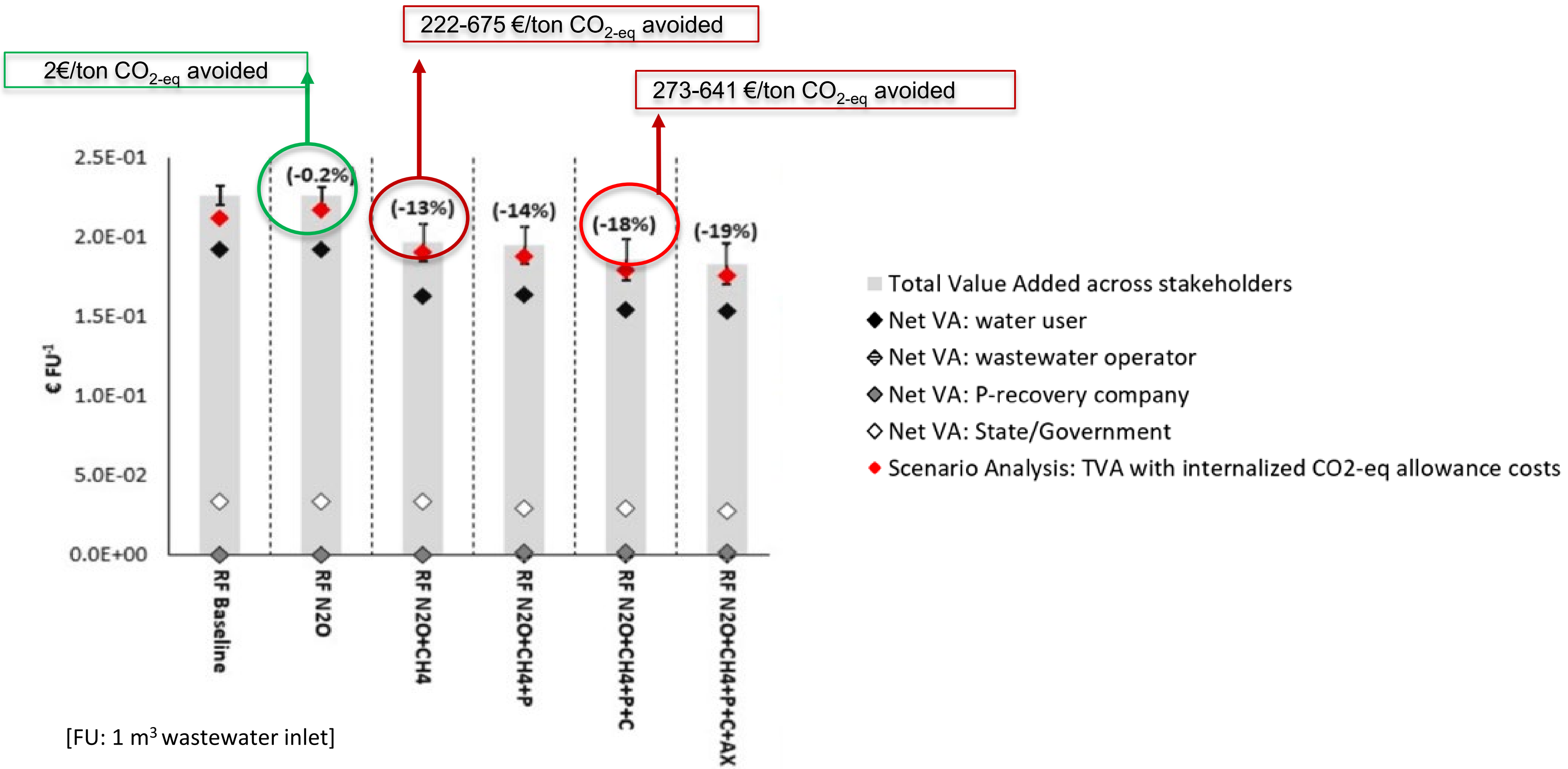
Anammox in the sidestream reject flow of the dewatering process alleviates activated sludge system load and improves N removal



[FU: 1 m^3 wastewater inlet]



ECONOMIC IMPACTS:
VALUE CREATION COMPARED TO WILLINGNESS TO PAY



[FU: 1 m^3 wastewater inlet]

- The TVA decreased with the implementation of resource recovery technologies by 19**%, <u>primarily due to the increase in operational costs (+70%)</u>** that counterbalanced **<u>the increase in revenue (+26%).</u>** The real-time measuring and control of N2O emissions was the cheapest technology.

- Internalising the CO_2-eq emissions did not significantly decrease the TVA in RF-Baseline suggesting that the current CO_2-eq allowance price is either too low or that wastewater operator should take further actions to reduce emissions.

CONCLUSIONS

- The implementation of the **real-time measurement and control of N_2O** achieved the **highest reduction in direct CO_2-eq emissions (-35%),** with no significant impacts in other environmental categories (<0.4%).
- **Real-time measurement and control of N_2O** was the cheapest solution and did not significantly decrease the economic value (0.2%).
- Wastewater operators **are in control of** reducing direct N_2O emissions (scope 1 emissions) and the equipment used (scope 3).
- Energy consumption (scope 2) and avoided impacts (scope 4) due to improved on-site energy efficiency **depend on the background energy mix** which is **outside the wastewater operator's control** and total $CO_{2\text{-eq}}$ emissions may increase if background electricity providers reduce their share of renewables.
- **LCA assessments** are **necessary to evaluate** technological advances in a WRRF and the **potential impacts not captured by carbon footprints** (e.g. additional renewable energy and chemicals consumption) and trade-offs.

THANK YOU FOR YOUR ATTENTION!

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AND...

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