Deliverable D7.3: Commercial opportunities for EU-India partnerships to exploit wastewater treatment, water re-use and resource recovery opportunities (RRR)

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Authors: Ivo Boonen (Aquafin), Marc Spiller (VITO), Sofie Van Ermen (VITO), Paul Campling (VITO)

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SUMMARY

Deliverable 7.3 aims to provide a comprehensive understanding of commercial opportunities for EU-India partnerships in wastewater treatment, water reuse, and resource recovery, focusing on specific case studies and potential business models.

The environmental and governance situation in India presents challenges such as water scarcity, pollution, climate change impacts, and complex water governance structures. Initiatives like Pavitra Ganga aim to address these challenges by promoting wastewater treatment and reuse. The Indian government supports water sector improvements through decentralization, regulatory measures, and programs like Namami Gange. Opportunities for businesses exist, with funding available from various sources including municipal bonds, grants, and loans from development banks. The India Europe Water Partnership offers avenues for accessing financial resources to implement water management measures, crucial for scaling up initiatives like Pavitra Ganga.

The Pavitra Ganga project aims to upscale innovations in wastewater treatment and resource recovery at an existing large-scale wastewater treatment plant (WWTP) in India, so we investigate how this can be done for the Jajmau STP at Kanpur. The implementation is divided into three stages:

1) Compliance with Present Effluent Standards: Upgrading existing aeration equipment to meet current standards.
2) Resource Recovery: Implementing sludge digestion, dewatering, and solar sludge drying to recover resources such as biogas and dried sludge for energy production.
3) Compliance with Future Effluent Standards and Reuse: Upgrading to meet future standards and increasing effluent reuse possibilities.

Based on Deliverable D7.2 and financial analysis, stage 2—sludge digestion with mechanical dewatering and drying—is found to be financially viable. This stage generates income through electricity and energy production. Additionally, income from stage 1, the aeration system upgrade, combined with stage 2, is sufficient to implement stage 3, even without considering the benefits of producing higher-standard water.

We take this further by discussing the opportunities for the exploitation of co-pelletization using wastewater treatment secondary sludge in India. Despite efforts to expand sewage treatment capacity, challenges remain in sewage sludge management, including its complex composition, pathogens, heavy metal accumulation, and high moisture content. To address these challenges, co-pelletization with biomass materials is an energy-efficient solution. We review technological aspects of co-pelletization, including sewage sludge composition, pre-treatment technologies such as dewatering and drying, and the pelletization process. We also discuss the technical and research challenges, such as varying sludge characteristics, moisture content, ash content, odour control, and nitrogen loss. The implementation challenges in India include market opportunities, sludge as a resource for a circular economy, and the potential for sludge incineration for energy and phosphorus recovery. Overall, co-pelletization presents a promising opportunity for sustainable waste management and renewable energy production in India.

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CHAPTER 1 INTRODUCTION

In Deliverable 7.1, a methodology was proposed and applied to identify the pathways to best valorise wastewater and other resources in the area of the Kanpur Nagar region. The roadmap was conceived with a 50-year time horizon, looking at centralized solution for the wastewater treatment services and a wide-scale strategic view into different resource recovery options. The roadmap concretely resulted in a proposal for the renovation of the Jajmau WWTP in harmony with a sustainable development of the existing markets and production pathways. The proposed scenario (called the "baseline" scenario) consisted of:

- A treatment system that produces ultra-filtered effluent water including removal of metals and recovery of chromium;
- Reuse of the effluent in industry (primarily) and secondarily in agriculture;
- Energy and heat recovery combined with agricultural residues and co-pelletisation with charcoal;
- Integration of septic material and other feasible organic streams for boosting anaerobic digestion at the full-scale site; and,
- Sludge thermal treatment by sun drying.

The aim of Deliverable 7.2 was then to provide recommendations concerning the appropriate investment and financing models, in respect to Pavitra Ganga technologies, to deliver the baseline scenario defined in the "Road map to exploit the wastewater treatment, water reuse and resource recovery opportunities for the Kanpur Nagar Region (Deliverable 7.1). This included an investigation of the technical feasibility and financial viability of the first steps of the baseline scenario implementation being:

- Upgrade of the biological treatment of the wastewater; and,
- Energy recovery of the sludge.

For Deliverable 7.3 the objective has been to assess the commercial opportunities for EU-India partnerships to exploit wastewater treatment, water re-use and resource recovery opportunities in India. During the project we have engaged with India Europe Water Partnership – which has already reported on some of the general commercial aspects of wastewater treatment and RRR, so we summarise this information and focus on the business case the investments needed to upgrade the biological treatment of the wastewater and promote energy recovery of the sludge at STP Jajmau, Kanpur, and explore the opportunities to deal with the secondary sewage sludge through co-pellitisation. Therefore, to fulfil the objective of Deliverable 7.3 we provide:

- an overview of the general opportunity assessments reported by the India Europe Water Partnership (Chapter 2);
- a potential business model for proposed investments to upgrade the biological treatment of wastewater and promote energy recovery of the sludge at STP Jajmau, Kanpur (Chapter 3 and Annexes);
- a review of the opportunities for secondary sewage sludge co-pelletisation, a key component of the Jajmau STP Roadmap (Chapter 4).

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CHAPTER 2 REVIEW OF COMMERCIAL OPPORTUNITIES TO EXPLOIT WASTEWATER TREATMENT, WATER RE-USE AND RESOURCE RECOVERY OPPORTUNITIES (RRR)

There are four important contextual points from the about the environmental and governance situation in India (EBTC, 2018) that can guide the opportunities to exploit wastewater treatment, water re-use and resource recovery and to kick-start actions to deal with them:

- Water Scarcity: 600 million people facing high to extreme stress of water (Government of India, 2018);
- Water Pollution: Approximately 70 % of the wastewater flows in the freshwater resources untreated, thus being one of the major sources of water pollution (Cronin et. al., 2014);
- Climate Change: Climate change has a heavy impact on the hydrologic cycle, including extreme floods and droughts (Mujumdar et. al., 2020);
- Water Governance: In India, water is being governed at three levels – at central, state and municipal level and is approached and represented by different governmental structures in each state - depending on the degree of water challenges of the state.

In Pavitra Ganga we position the exploitation of wastewater treatment and re-use by aiming to reduce the pollution of existing water resources and to secure future water resources supplies by promoting the re-use of treated wastewater, instead of freshwater for irrigation.

There are a number of Government initiatives in India and the India Europe Water Partnership (EBTC, 2018) discusses the role of the Central government and various initiatives influencing India's water sector. It highlights the decentralization of water management to states, with the Central government focusing on regulatory aspects and interstate river waters. National programs and funding offer opportunities for businesses, especially in projects like Namami Gange aimed at rejuvenating the Ganges. The National Mission for Clean Ganga emphasizes wastewater treatment restructuring and environmental technology verification. Additionally, the India Investment Grid portal showcases numerous water projects, mostly public, with a significant focus on PPP implementation. A forthcoming National Water Information Centre aims to provide sectoral data. The ease of doing business ranking of states complements project analysis, indicating states with conducive environments for investment.

The IEWP identifies the following avenues of support for accessing financial resources to implement measures. These avenues include:

- Synergies and Convergence: Aligning Central government and State schemes to optimize resources;
- Alternative Sources of Funding: Utilizing municipal bonds, accessing capital markets, and obtaining grants from State grants and central finance commission grants;
- Technology Demonstration Funds: Support from UN agencies, bilateral development agencies, and Water Partnerships for piloting studies and technology demonstration; and,
- Loans: Availing loans from multilateral/bilateral development banks like ADB, KFW, and World Bank.

This is important information for upscaling the outcomes of R&I projects such as Pavitra Ganga.

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CHAPTER 3 POTENTIAL BUSINESS MODEL FOR PROPOSED INVESTMENTS TO UPGRADE THE BIOLOGICAL TREATMENT OF WASTEWATER AND PROMOTE ENERGY RECOVERY OF THE SLUDGE AT THE STP JAJMAU, KANPUR

3.1. INTRODUCTION

One of the important aspects of our project has been to investigate how Pavitra Ganga wastewater treatment and resource recovery innovations can be upscaled to transform an existing large scale wastewater treatment plant (WWTP) in India, complying with the old effluent standards, into a plant which complies with the present and future standards including resource recovery, reduced energy consumption and CO_2 emissions.

Many plants in India comply with the old standards (Environmental Protection Rules 1986) where the main parameter is a BOD concentration of less than 100mg/l. Due to the publication of the Environmental (Protection) Amendment Rules 2017, the limit is lowered to 30mg/l since 2022. Also, court rulings exist that introduces nutrient removal standards in India. Many plants will thus have to be transformed to comply to the present and (probably) future standards, involving large investments. In this transition towards stricter standards, it will be important to find a pathway with a small number of lost investments for transitional standards without premature large investments in future standards. Meanwhile, recovery of resources (clean water, energy, nutrients) and reduction of the energy consumption and CO2 emissions has many economic benefits and results in more sustainable projects.

Every specific project will have its own preconditions. To make the whole transition more concrete, the WWTP of Jajmau (Kanpur) is used as an example. Although Jajmau has specific issues and not all data could be obtained, this case can be seen as a typical project in India. Based on Deliverable D7.2: "Investment and financing programme to exploit the wastewater treatment, water-reuse and resource recovery opportunities for a selected urban local body in Kanpur", the following investment strategy is selected for the WWTP at Jajmau:

Stage 1: Compliance to present effluent standards : The aeration system, in the existing aeration tanks, is replaced with a highly efficient fine bubble system with an increase oxygenation capacity. This will reduce the organic load in the effluent (BOD) and will reduce the energy consumption of the plant. By implementing this stage, the effluent quality will comply with the present effluent standard.

Stage 2: Resource recovery of the sludge: The produced sludge of the plant is digested in a local digestion plant and the sludge is dewatered. After dewatering, the sludge is dried on the existing sludge drying beds. The resulting dried sludge can be used as energy source in a power plant or cement oven. Based on the preliminary simulations in D7.2, the optimal solution will consist of:

- Gravity thickeners on the primary sludge
- Mechanical thickeners on the secondary sludge
- Thermophilic digestors
- Dewatering using centrifuges
- The dewatered sludge is dried on the existing sludge drying beds towards an average dry solids concentration of 80%

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Stage 3: Compliance to future effluent standards: It is assumed that in the (near) future nutrient removal will be required. Based on D7.2, the best solution in this case consists of:

- Increasing the sludge concentration in the existing aeration tank to 10g/l.
- Using SFD membranes to separate the clean water from the sludge mixture

The reasons to split the investment into 3 separated stages are:

- At this moment, no nutrient removal is required. This investment thus can be delayed. Although the SFD membranes work on lab and pilot scale, no large-scale installations are in operation. To make these membranes applicable, further developments in scaling up the equipment is needed – this is already being done by Xylem branded as Sanitaire Taron.
- Sludge digestion has (theoretically) a high potential because it would make the WWTP a net producer of electricity and generates a sludge with a net positive thermal energy. However, there is not much experience with sludge digestion in India and, at present, the digestion tests are not conclusive. Additional testing will be needed to guarantee a positive outcome of the large investment that is needed to implement this project.
- The present legislation already enforces a BOD limit of 30mg/l. This project is thus urgent. Replacing the existing aeration with a highly efficient aeration system is a straightforward project that does not need extensive research.

In the further analysis, we assume that the three stages can be separated by a 5-year interval. The final process after the 3 stages is illustrated in Figure 1.

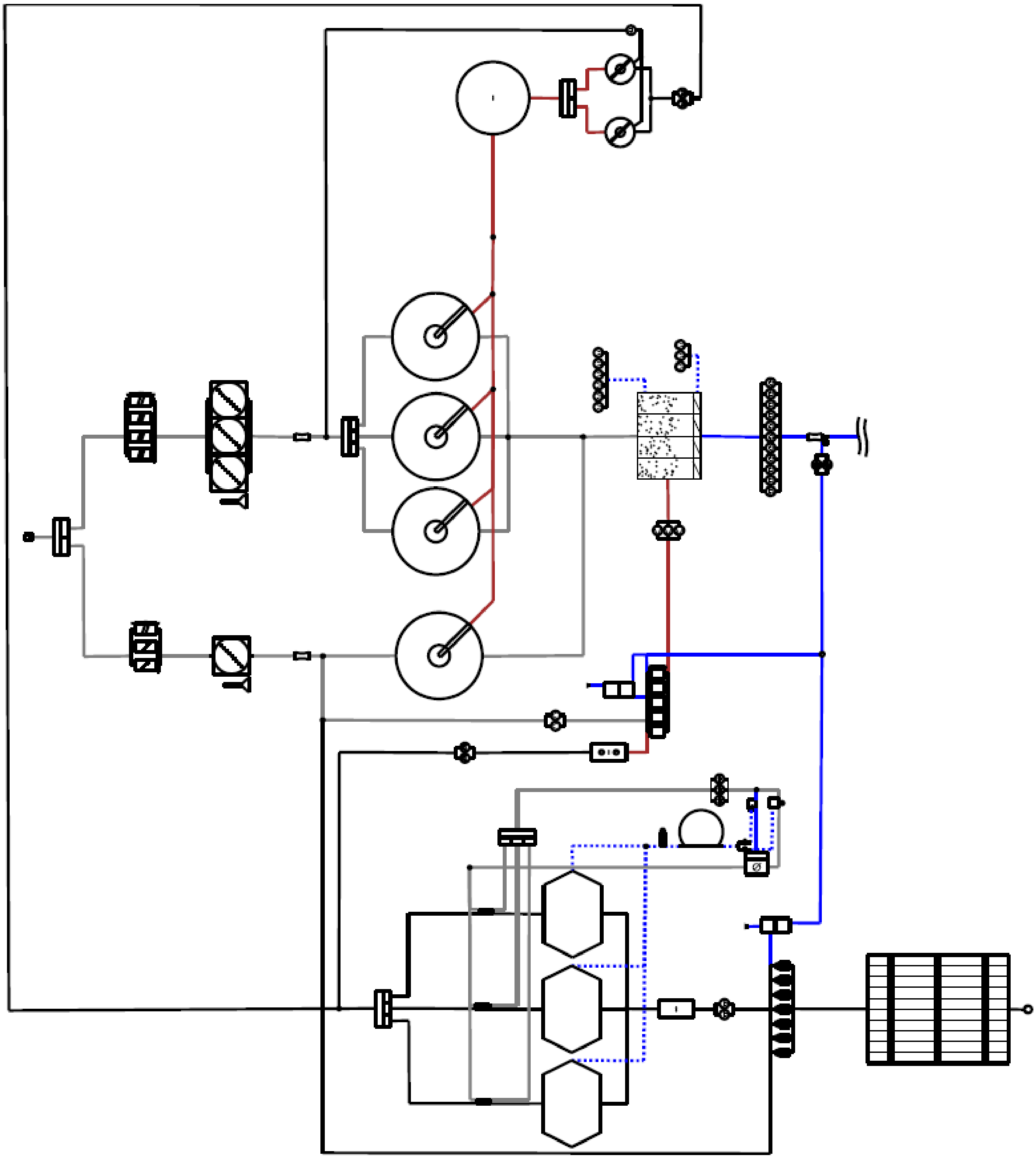

Figure 1: Schematic diagram representing the final process after completion of the 3 investment stages identified in the strategy to upgrade the wastewater treatment facility

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3.2. PROJECT COSTING

Because not all local costs (investment and operational) are known to us, the analysis will be done using European costs (Belgian costs in 2022). Operational costs only include energy costs, sludge disposal costs and chemical costs. It is assumed that, in the case of no upgrade, the existing aeration equipment must be replaced every 15years. This is estimated at 1,500kEUR. Based on D7.2, the following costs are estimated.

Stage	Description	Investment (kEUR)			Operational (kEUR/y)
		EM	Civil	Total	
0	Present	1,500	0	0	3,584
1	BOD removal	8,000	0	8,000	2,615
2	Digestion	17,500	11,000	28,500	-3,543
3	Nutrient removal	22,000	3,000	25,000	731

Table 1: Cost estimates

The economic benefit of stage 2 is the production of dried sludge that can be used as fuel. The long-term cost of lignite (brown coal) is about 0.1EUR/kg with a caloric value of 17.4MJ/kg. The caloric value of dried sludge (80%DS) is estimated at 11.5MJ/kg, giving the dried sludge a value of (0.1*11.5/17.4=) 0.066EUR/kg. With an estimated sludge production of 37,200T/y, this gives a benefit of 2,459kEUR/y.

3.3. FINANCIAL ANALYSIS

The financial analysis is done over a period of 30 years using a financing cost of 3% above inflation and a reinvestment of the electro-mechanical equipment after 15years. The viability of the project is valuated using the discounted cumulative cashflow of the difference between the project and the zero scenario (no upgrade). The calculations are summarised in attachment. The results are given in Table 2. The column "Years to positive" gives the number of years between the last project investment and the moment that a positive discounted cumulative cashflow is generated.

Scenario	Annex	Years to positive
Total project without economic benefits	1	-
Stage 1	2	7
Stage 1 + 2 without economic benefits	3	7
Stage 1 + 2 with economic benefits	4	4
Total project with economic benefits	5	3

Table 2: Results of the financial analysis

From the above, it is clear that Stage 2 is the generator of income. It generates a direct income of about 3.5MEUR/y and an indirect income of about 2.5MEUR/y. This income makes the total project economically viable. The benefits of producing cleaner water that can be used for re-use in industry or agriculture are not necessarily needed to make this a viable project.

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3.4. SUMMARY

One of the important aspects of our project has been to investigate how Pavitra Ganga wastewater treatment and resource recovery innovations can be upscaled to transform an existing large scale wastewater treatment plant (WWTP) in India, complying with the old effluent standards, into a plant which complies with the present and future standards including resource recovery, reduced energy consumption and CO_2 emissions.

Because some parts of the project need more research and/or development, the implementation is split into 3 stages:

1) Compliance to present effluent standards by upgrading the existing aeration equipment;
2) Resource recovery by implementing sludge digestion, dewatering and solar sludge drying; and,
3) Compliance to future effluent standards and increase the possibility of reuse of effluent

Based on Deliverable D7.2 and the financial analysis, it is found that sludge digestion with mechanical dewatering and drying using the existing sludge drying beds (stage 2) is a very viable project. This stage of the project generates income through:

- Electricity production from biogas
- Energy production form dried sludge

The upgrade of the aeration system (stage 1) is a viable part of the project. The income of stage 1 and 2 is enough to implement stage 3 even without considering the economic and/or ecological benefits of producing water with a higher standard.

CHAPTER 4 OPPORTUNITIES FOR THE EXPLOITATION OF CO-PELLITISATION USING WASTEWATER TREATMENT SECONDARY SLUDGE

India is home to 1.31 billion people and has been undergoing rapid urbanization over the past two decades. Strict requirements for wastewater treatment plant discharges were set by the national green tribunal in 2019 and were upheld by the Supreme Court of India in June 2021. Even before this decision, India has been building more than 800 STPs in the last six years in anticipation of tightening discharge limits. Nonetheless, according to a research report published by the Central Pollution Control Board (March 2021), India's sewage treatment capacity is only 18.6 % (with another 5.2 % capacity in development) and thus sewage treatment will likely continue to increase in the future (International Trade Administration, 2024). The increase in wastewater treatment is paired with a challenge of sewage sludge management. Sewage sludge is a complex mixture of organic matter, inorganic solids, and water (96-99%) that comes free as a by-product of the treatment of wastewater (Singh et al., 2020). It contains essential nutrients such as N and P for plant growth as well as carbon. Therefore, sewage sludge can be regarded as a fertilizers (Kumar et al., 2017). In India use as a fertiliser is currently the recommended implemented sludge management route (Cambi, 2021), while it is suggested that landfilling is the most common method currently (Singh et al., 2020). The management of sewage sludge is challenging as it contains pathogens (viruses, bacteria and parasitic invertebrates) as well as man-made chemicals from personal care products or medicines, it accumulates heavy metal in particular when industries discharge into the sewage treatment systems. These aspects pose concerns for the valorization of sewage sludge in agriculture. Indeed, in several countries, sewage sludge cannot be applied to land (BE, NL) even after hygenisation. Furthermore, raw sewage sludge has a high-water content, limiting transport options or demanding dewatering and/ or drying before transportation.

Given these challenges and limitations an energetic valorization of sludge can be an attractive option. Specifically, a previous deliverable (D7.1) developed a wastewater treatment transition roadmap proposing that wastewater sludge could be co-pelletized with charcoal and/ or agricultural residues and used to substitute fossil fuels (Figure XXX).

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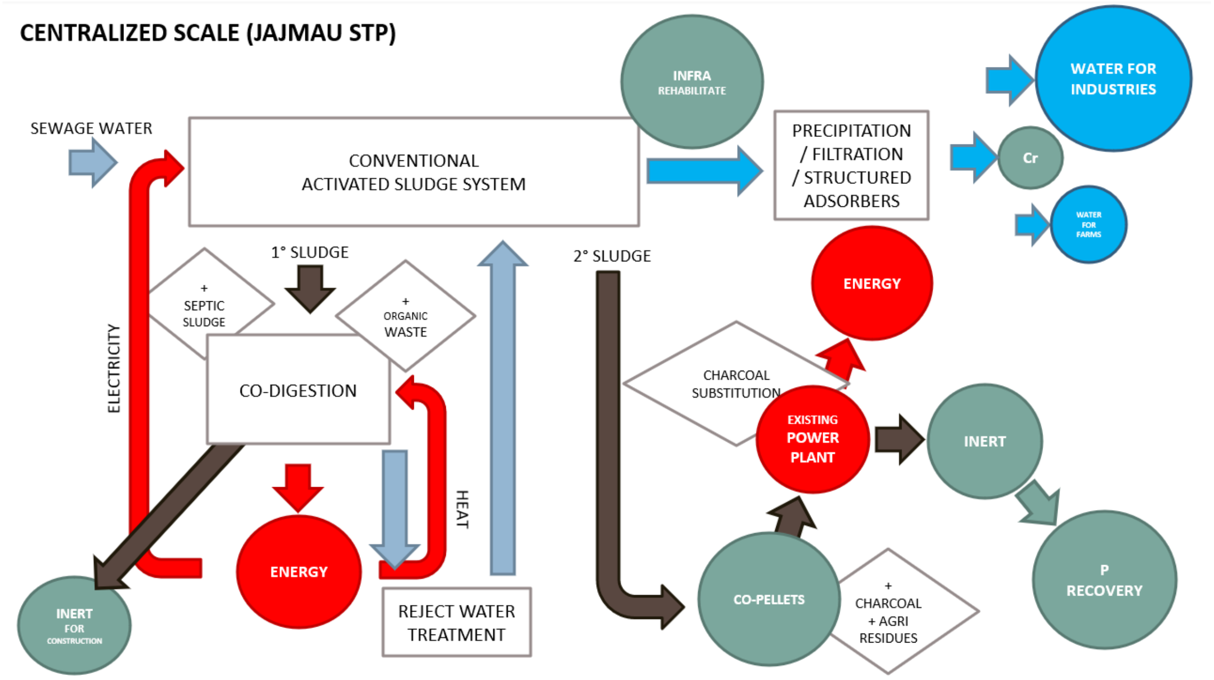

Figure 2: Suggested centralized solution. Squares refer to operational processes, circles to products, rhombus to external products added. The arrows represent the displacement of different materials: Dark Brown is sludge. Light brown is sludge water. Blue is water. Red/Green/Blue colors indicate energy/material/water pathway products.

Sewage sludge has indeed properties that can make is a suitable renewable energy source. The organic matter contained in sewage has an energic value of 16–20 MJ/kg DM (dry mass), but for digested sludge it drops to 6.3–15 MJ/kg DM (Yilmaz et al., 2018). Specifically for India a calorific value of 8–21 MJ/kg for sludge dry matter has been found (Singh et al., 2020). Singh et al. (2020) also estimated that the energetic potential for sewage sludge incineration in India to be up to ~15.3 × 10^5 MWh. Co-pelletization, a process that combines sludge with other biomass materials often from agricultural origin, has emerged as a promising alternative for valorizing this waste stream and producing renewable energy in the form of pellets. A key advantage of co-pelletisation is the enhancement of the fuel properties. Sewage sludge is typically high in moisture content and has a low energy density, making it difficult to burn directly. By co-pelletizing it with other biomass materials, the moisture content can be reduced and the energy density increased, making it a more viable fuel source. For developing countries comparable to India it was argued that pelletisation of sewage sludge can be an economically viable option. Duangjaiboon et al.(2021), for the case of Thailand, find that a high proportion of sewage sludge is optimal and a return-on-investment period of 5-3 years depending on the ratio between rice straw and sewage sludge. They further suggest that the chemical composition of sewage sludge has environmental advantages as the sulfur dioxide emissions will be reduced as a result of a lower S content than for coal. This is of particular relevance for India that has a share of more than 70% of coal in the energy mix (Ministry of Coal, 2024).

The objective of this section is to review the current technology for sewage sludge pelletisation and to outline key challenges for technology development in general and for implementation in India in particular.

4.1. TECHNOLOGICAL ASPECTS OF CO-PELLETISATION

4.1.1. COMPOSITION OF SEWAGE SLUDGE

According to the Best Available Technology assessment by the European Commission (the Joint Research Centre) the composition of sewage sludge varies according to many factors (Neuwahl et al., 2019), including:

- system connections, e.g., industrial inputs can increase heavy metal loads;
- coastal locations, e.g., for salt water inclusion;
- treatments carried out at the treatment works, e.g., crude screening only, anaerobic sludge digestion, aerobic sludge digestion, addition of treatment chemicals;
- weather/time of year, e.g. rainfall can dilute the sludge; and,
- The composition of sewage sludge varies greatly.

Indeed, as can be seen for the case studies investigated in this project for example the illegal discharge of industrial waste into the sewage system causes significant heavy metal pollution and increases COD. Typical composition ranges for dewatered communal and industrial sewage sludge are given below (Table 3)

Table 3: Average composition of dewatered communal sewage sludge and industrial sewage sludge

Component	Communal sewage sludge	Industrial sewage sludge
Dry solids (%)	10-45	
Organic material (% of dry solids)	45-85	
Metals (mg/kg of dry solids)		
Cr	20-77	170
Cu	200-600	1 800
Pb	100-700	40
Ni	15-50	170
Sb	1-5	< 10
Zn	500-1 500	280
As	5-70	< 10
Hg	0.5-4.6	1
Cd	1-5	< 1
Mo	4-20	

Sewage sludge also contains phosphorus generally in the range 1-2.5 % dry matter, depending on whether or not the sewage works operate phosphorus removal and on the pre-treatment. There is thus an opportunity for phosphorus recovery either upstream of sewage sludge incineration or from the incineration ashes.

Important factors to take into account when incinerating sewage sludge are (Neuwahl et al., 2019):

- whether the sludge is digested or not this will affect its heating value as pointed out above;

- the composition of the sludge as primary-, secondary-, digestate etc. again as this affects heating values;
- odour problems, especially during sludge feeding in the storage areas.

4.1.2. PRE-TREATMENT TECHNOLOGIES

Different types of pre-treatment are applied to sewage sludge. Some are specifically connected to the incineration properties of the material (in particular, processes for the reduction of the water content of the sludge), while others can have different purposes, including for the recovery of the resources contained in the raw sludge (e.g. biogas, phosphorous), and may have a more or less pronounced influence on the ensuing incineration process. Here the focus is on the methods for dewatering and drying before pelletization.

4.1.3. PHYSICAL DEWATERING

Mechanical drainage before incineration reduces the volume of the sludge mixture and increases the heat value. This is required for economical incineration and reduction of transport costs. Through mechanical dewatering of the sewage sludge. In the simplest form sludge dewater beds can be used. In decanters, centrifuges, belt filter presses and chamber filter presses, a dry solids (DS) level of between 10 % and 45 % can be achieved. The sludge is usually conditioned before the mechanical dewatering to improve its drainage. While there are various methods to achieve this (Figure 3), a common methods is to add organic polymeric flocculants (e.g. polyacrylamide) (Wei et al., 2018).

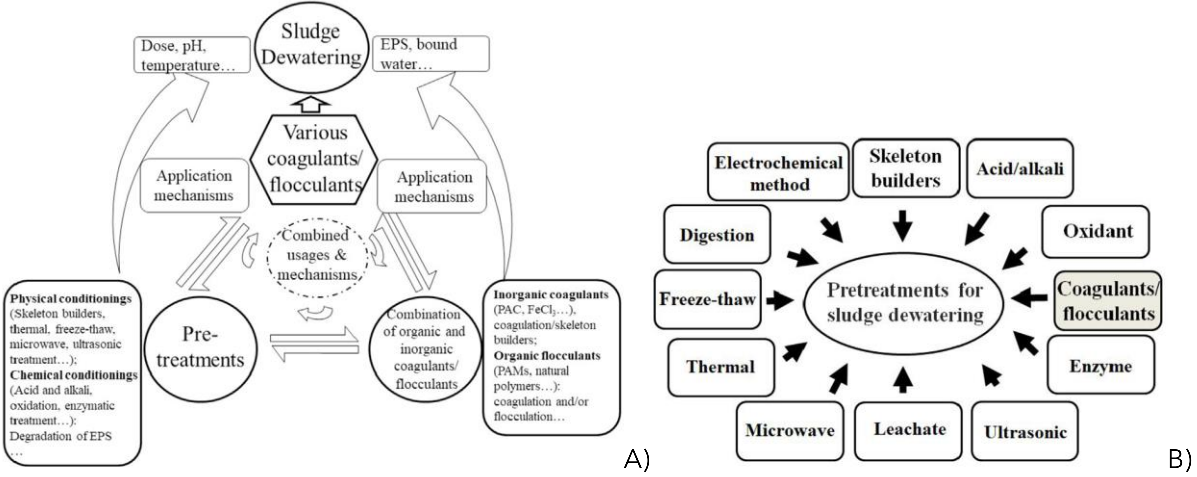

Figure 3: A) Schematic description on sludge dewatering using coagulation/flocculation. B) Various conditioning methods for sludge dewatering (Wei et al., 2018).

Figure 4: Sludge thickeners Line 1 Jajmau Standard Treatment Plant (STP)

Figure 5: Sludge dewatering Line 2

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4.1.4. DRYING

Often, the dewatered sludge is too wet for auto-thermal incineration and too wet for further processing in a pelletizer. Therefore further, thermal drying needs to be used to increase the heat value and reduce the volume of the sludge before the incineration furnace and further pelletizing. The following dryer configurations can be utilized (Neuwahl et al., 2019):

- disk dryer;
- drum dryer;
- fluidised bed dryer;
- belt dryer;
- thin film dryer/disk dryer;
- cold air dryer;
- thin film dryer;
- centrifugal dryer;
- solar dryer;
- combinations of different types.

Drying processes can be divided into two groups:

- partial drying, up to approximately 60–80 % dry solids;
- complete drying, up to approximately 80–90 % dry solids.

In the present project we observed the drying of sludge in drying beds in India. The realized DM content in the dried sludge is currently unknown. It is likely that the degradation of the biomass continues during these slow drying processes, resulting in a lowering of the calorific value. More advanced solar drying as mentioned above may be an interesting alternative to the open sludge drying bed (Bennamoun, 2012). It will speed up the drying process, possibly reduce biomass loss and reduce the space demand. By reducing space demand potential future drying capacity limitations can be increased.

Figure 6: Existing sludge drying beds at STP Jajmau, Kanpur

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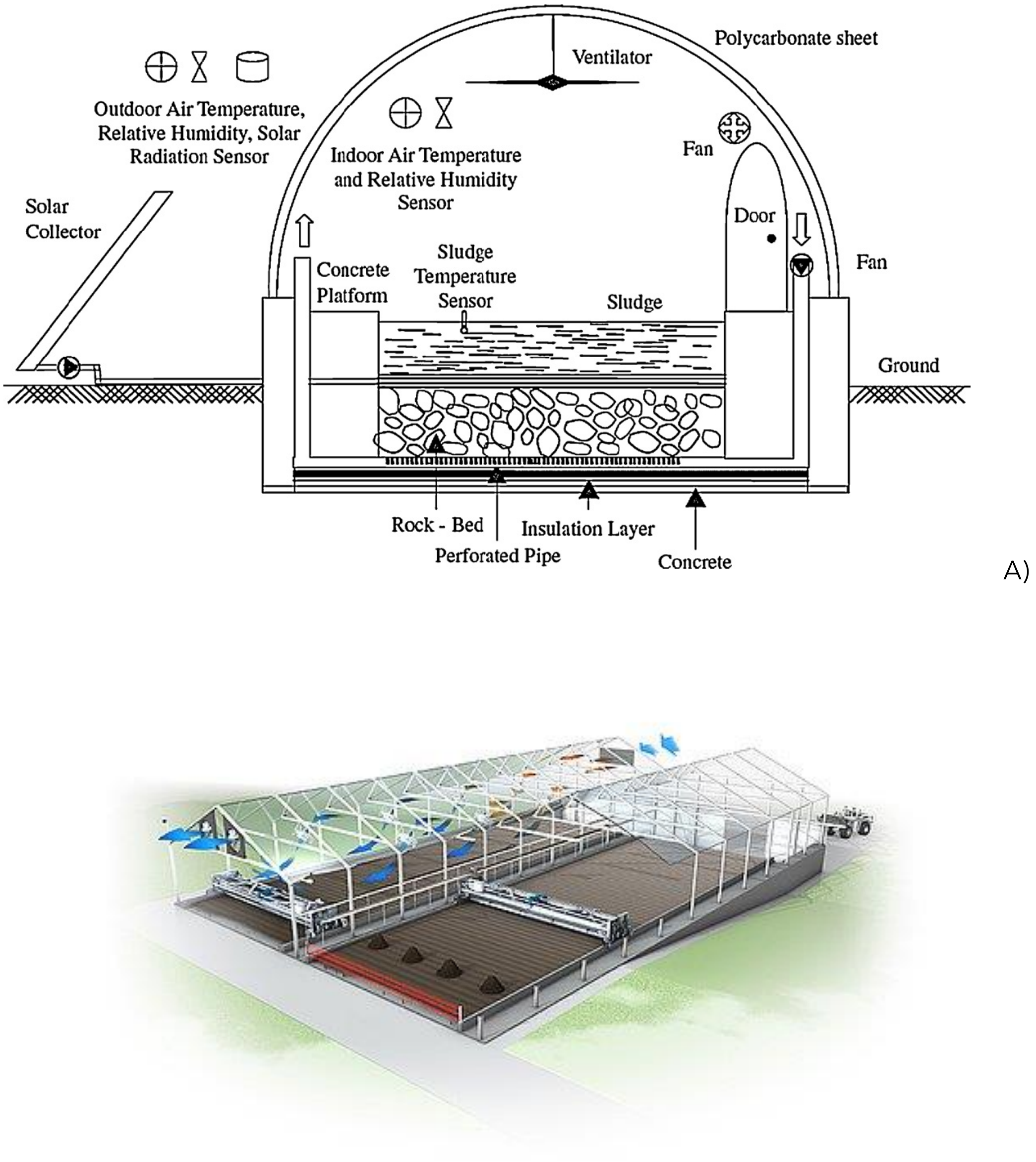

Figure 7: A) Example of a sludge drying installation (Bennamoun, 2012). Illustration of a commercial installation by (Huber Technology, 2024).

An alternative to drying is the in situ drying of sludge by incineration together with higher calorific waste. For auto-thermal incineration in sewage sludge mono-incineration plants, a 35 %dry solids content is sufficient. This can be achieved by mechanical dewatering and may not require thermal drying. The required dry solids content for auto-thermal incineration in each installation is, however, dependent on the composition of the sludge (energy content of the dry solids, largely related to the content of organic material) and the share of sludge that is co-combusted with other waste streams. Typical operating conditions are about 10 % drained sewage sludge with 20–30 % dry solids (Neuwahl et al., 2019).

4.1.5. PELLETISATION PROCESS

According to Kahl (Kahl, 2024) the pre-treated sewage sludge for pelletisation requires a solids content of 70 to 95%. This value of DM is also suggested for the pelletisation of fruit agricultural residuals (10-12% moisture content) (Cui et al., 2021) and sewage sludge (10-15% moisture content) (Jiang et al., 2014). Contrary to this Yilmaz et al. (2018) produced pellets from a sludge with a moisture content of 35-45% (55-45% dry matter) in the laboratory and dried them thereafter to a dry matter content of 90% in 1-3 days using solar energy. The underlying mechanism of pelleting makes use of the organic compounds, mainly comprising proteins and carbohydrates. The denaturation of protein and the gelatinization of carbohydrates in the sludge is thought to serve as a natural binder, which provides the strength of fiber grid in the pellet (Li et al., 2015). Indeed, (Jiang et al. (2014) concluded that good quality pellets cannot be produced at moisture content above 20%, because moisture trapped within the particles may prevent complete flattening and the release of natural binders from the particles due to the incompressibility of water. A design of a pelletiser can be seen in Figure 8.

Biomass size is important for a successful pelletization processes as it affects pellet hardness (small particles = higher hardness).Higher surface areas are relevant to facilitate binding properties (Jiang et al., 2014). Therefore, sewage sludge may have to be grinded before pelleting. The design of the Kahl sewage sludge pelleting plant therefore includes a pre-bin which is followed by a multiple screw (Kahl, 2024). The product is then mixed and fed to a flat die pellet mill, where it is processed by means of the pan grinder rollers and the die. Kahl (2024) claim that this system is particularly appropriate for sewage sludge, as it can be adapted without problems to varying organic contents.

Figure 8: Sewage sludge pelleting machine of Kahl (Kahl, 2024)

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4.2. TECHNICAL AND RESEARCH CHALLENGES OF THE CO-PELLETIZATION PROCESSES

While co-palletization holds significant promise as outlined in the introduction, it is not without its challenges, some of which are outlined below.

1. Varying sludge characteristics: Sludge composition and properties can vary significantly between wastewater treatment plants, necessitating a flexible and adaptable pelletization process.
2. Moisture content: Sludge's high moisture content can hinder pellet formation and combustion. Drying processes can be energy-intensive and add to the cost of co-pelletization. For example (Singh et al., 2020) found that most of the sludge in India after dewatering contains 60-70% moisture content. So, there would certainly be a requirement of additional energy for the removal of extra water to meet the requirement for incineration (total solids > 40%). Singh et al. (2020) estimate that the energy demand of water removal is about 3000 kJ/ kg water removed.
3. Ash content: Sludge ash can contain high concentrations of heavy metals, which pose environmental risks if not properly managed. Therefore, incineration of pelletization do not directly resolve this environmental problem. While these residuals can be land filled. Following our concept of resource recovery the essential macro nutrient P that accumulates in the sludge of up to 8% w/w should be recovered (Biswas et al., 2009). Acid leaching technologies applied to incineration ash are increasingly adopted to recover P and use it in agriculture (Biswas et al., 2009). This, however, requires mono-incinerators that only burn sewage sludge in order to maximize the recovery potential.
4. Odor control: Sludge drying and further processing to pellets can generate odorous compounds from sludge, necessitating effective odor control measures.
5. Nitrogen loss and emissions: Incineration in general leads to the loss of the essential macronutrient N to air. This means it is not directly available for resource recovery and for example use in agriculture. It further leads to NOx emissions to air that can cause health and environmental impacts. Advanced air treatment technologies such as Selective Catalytic Reduction (SCR) or DeNOx, are required to remove this reactive N. In principle this process entails the mixing of a NOx source with ammonia (or another agent) and allowed it to react at the surface of a catalyst to produce N_2 gas.

4.3. DISCUSSION: IMPLEMENTATION CHALLENGES IN INDIA

4.3.1. MARKET OPPORTUNITIES FOR CO-PELLETISATION IN INDIA

The current market price of biomass pellets in India is €0.17 to €0.21/kg (Jain *et al*., 2015). These pellets are mainly used for cooking applications in the commercial sector (Jain *et al*., 2015). A recently published paper evaluated the techno-economic feasibility of biomass pellets for power generation in India (Purohit and Vaibhav, 2018). The study infers that surplus biomass availability from the agricultural sector (123 Mt in 2010–11) alone is sufficient to substitute 25% of the current coal consumption in the power sector. Pelletized biomass can potentially produce 6% of India's total electricity in 2030/31 (Purohit and Vaibhav, 2018). Large amounts of agricultural residues are available especially in the Northern states such as Punjab, Haryana, and Uttar Pradesh.

The upscaling of the co-pelletization for a biomass power plant is a giant opportunity ahead for India: the associated carbon dioxide mitigation potential resulting from the substitution of coal is estimated

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at 205 Mt in 2030–31 if the entire biomass surplus is diverted to power generation (Purohit *and* Vaibhav, 2018). Additionally, such projects will generate employment for more than 5 million person-months in the construction of biomass power plants and over 200000 full-time employees in the operation and production of biomass pellets (Purohit and Vaibhav, 2018).

The capacity of an Indian WWTP (Jajmau STP in this specific case) to penetrate this market with the dried secondary sewage sludge depends on some crucial factors: sludge drying beds should efficiently operate and assure the necessary moisture requirement; the sewage sludge must still have sufficient caloric power after treatment for energetic exploitation, and therefore digested sludge might not be favourable; pellet production should happen on site, and close to the sludge drying beds. In fact, this process is becoming widespread in Germany, where more municipal WWTPs have already been equipped with compact containerized solutions. Considering that examples of co-pelletization of secondary sludge are already upscaled (Yilmaz et al., 2018) (Hossain and Haij Morni, 2020), this might turn into a very interesting end-route scenario for secondary sludge.

4.3.2. SLUDGE AS A RESOURCE FOR A CIRCULAR ECONOMY IN INDIA

As the Kanpur Nagar region is an area with a strong agricultural component, the problem of fertilizer supply is relevant to Pavitra Ganga. Plants require macronutrients and micronutrients for their growth and fertilizers are the source of these nutrients, which not only enhance the plant growth but also maintain soil fertility. The State of Uttar Pradesh uses 16621 kilotonnes of fertilsers per year (Usama and Monowar, 2018), which is the largest amount in India. Rice and wheat are the major crops which are consuming 37% and 24% of the total fertilizers consumed in India. Fertilizers should be used in a balanced manner through integrated management of nutrient involving the use of chemical fertilizers, biofertilizers, compost and vermicompost (Usama *and* Monowar, 2018). Balanced use of fertilizers reduces the harmful effects of chemical fertilizers on the environment and helps in making agriculture sustainable. Sewage water is an important source of nutrients. To date, many farmers are irrigating with raw sewage, a practice that poses severe risks to human health and requires a smarter approach to nutrients.

Currently, most of the fertilizer formation processes are based on crystallization or precipitation from the digester supernatant. The recovery rate of phosphorus from the liquid phase is lower (10–60% from wastewater treatment plant influent), than from sludge (35–70%) and from sludge ashes (70–98%) (Cardoso Chrispim *et al*., 2019). Phosphorous recovery from the ashes therefore allows the highest recovery but it is not applicable as long as there is no plan for sludge incineration. Sludge incineration in Kanpur Nagar region could become a favourable solution only in the case of a biomass-based power plant where secondary sludge could be conveyed, as advocated by Purohit *and* Vaibhav (2018). This option would allow to combine energy valorization from the dried sludge and phosphorous recovery from the ashes of Jajmau STP. Being a very ambitious project, it would require a strong financial and political support from all parties.

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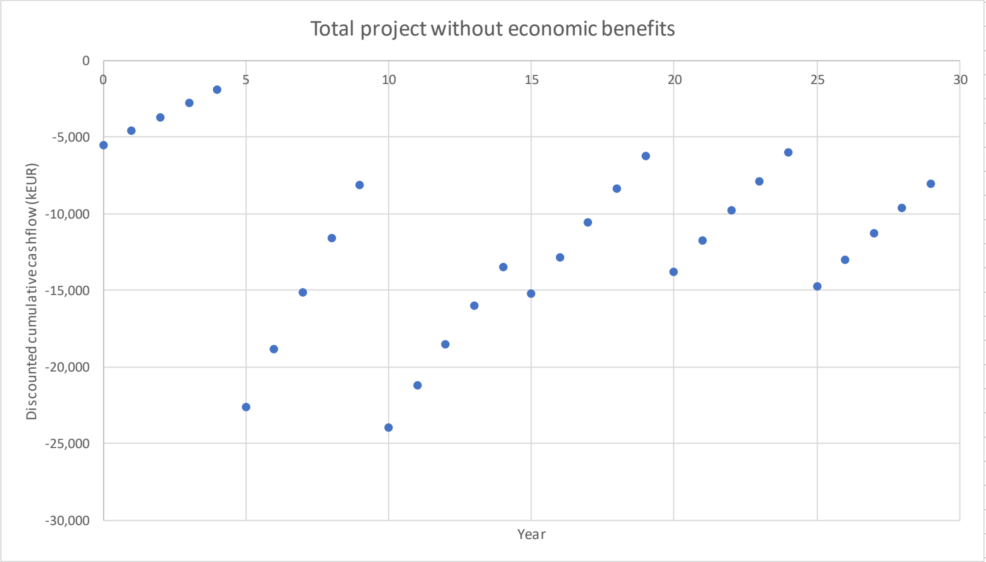
CHAPTER 6 ANNEXES

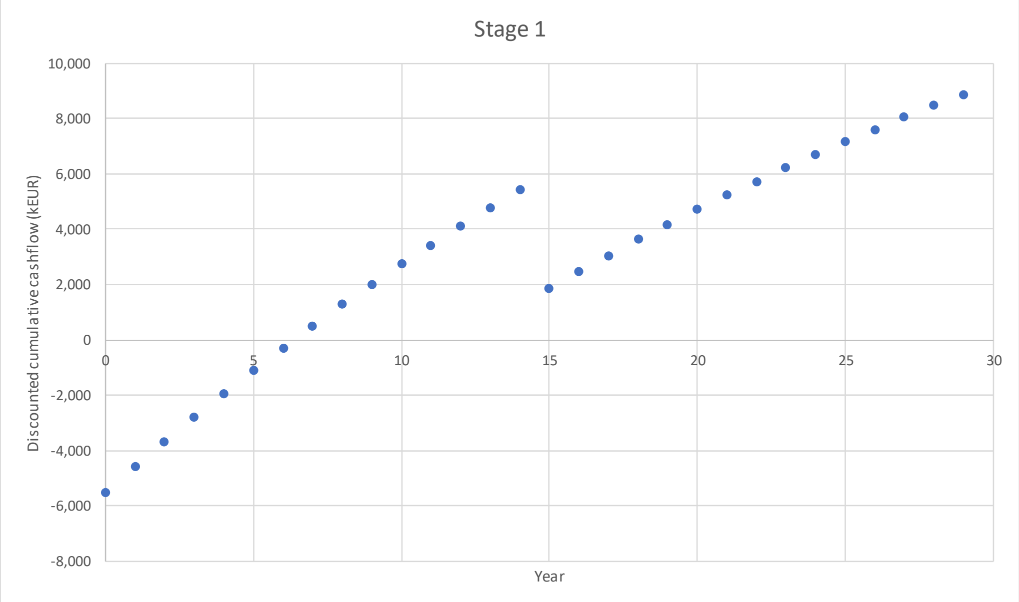
6.1. ANNEX 1: TOTAL PROJECT WITHOUT ECONOMIC BENEFITS

	Do nothing				Total Project					
Year	Invest	Operational	Cashflow		Invest	Operational	Cashflow	Dif	NPV	Cumulative
0	1,500	3,584	5,084		8,000	2,615	10,615	-5,531	-5,531	-5,531
1	0	3,584	3,584		0	2,615	2,615	969	941	-4,590
2	0	3,584	3,584		0	2,615	2,615	969	913	-3,677
3	0	3,584	3,584		0	2,615	2,615	969	887	-2,790
4	0	3,584	3,584		0	2,615	2,615	969	861	-1,929
5	0	3,584	3,584		28,500	-928	27,572	-23,988	-20,692	-22,621
6	0	3,584	3,584		0	-928	-928	4,512	3,779	-18,843
7	0	3,584	3,584		0	-928	-928	4,512	3,669	-15,174
8	0	3,584	3,584		0	-928	-928	4,512	3,562	-11,612
9	0	3,584	3,584		0	-928	-928	4,512	3,458	-8,154
10	0	3,584	3,584		25,000	-197	24,803	-21,219	-15,789	-23,943
11	0	3,584	3,584		0	-197	-197	3,781	2,731	-21,212
12	0	3,584	3,584		0	-197	-197	3,781	2,652	-18,560
13	0	3,584	3,584		0	-197	-197	3,781	2,575	-15,985
14	0	3,584	3,584		0	-197	-197	3,781	2,500	-13,485
15	1,500	3,584	5,084		8,000	-197	7,803	-2,719	-1,745	-15,231
16	0	3,584	3,584		0	-197	-197	3,781	2,356	-12,874
17	0	3,584	3,584		0	-197	-197	3,781	2,288	-10,587
18	0	3,584	3,584		0	-197	-197	3,781	2,221	-8,366
19	0	3,584	3,584		0	-197	-197	3,781	2,156	-6,210
20	0	3,584	3,584		17,500	-197	17,303	-13,719	-7,596	-13,805
21	0	3,584	3,584		0	-197	-197	3,781	2,032	-11,773
22	0	3,584	3,584		0	-197	-197	3,781	1,973	-9,800
23	0	3,584	3,584		0	-197	-197	3,781	1,916	-7,884
24	0	3,584	3,584		0	-197	-197	3,781	1,860	-6,024
25	0	3,584	3,584		22,000	-197	21,803	-18,219	-8,701	-14,725
26	0	3,584	3,584		0	-197	-197	3,781	1,753	-12,972
27	0	3,584	3,584		0	-197	-197	3,781	1,702	-11,270
28	0	3,584	3,584		0	-197	-197	3,781	1,653	-9,617
29	0	3,584	3,584		0	-197	-197	3,781	1,604	-8,013



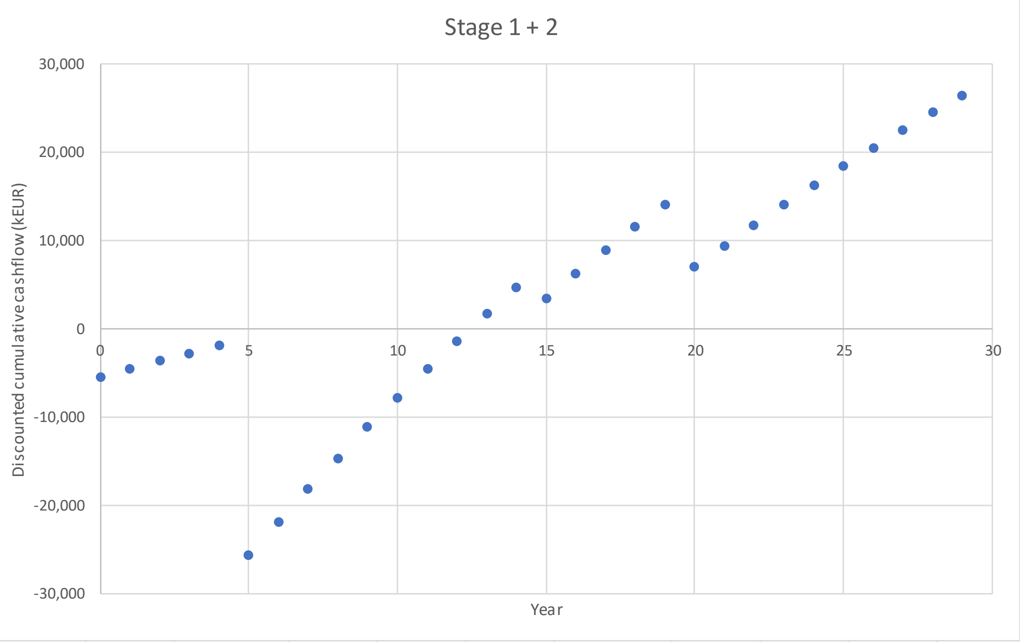
6.2. ANNEX 2: STAGE 1

	Do nothing				Stage 1					
Year	Invest	Operational	Cashflow		Invest	Operational	Cashflow	Dif	NPV	Cumulative
0	1500	3584	5084		8,000	2,615	10,615	-5,531	-5,531	-5,531
1	0	3584	3584		0	2,615	2,615	969	941	-4,590
2	0	3584	3584		0	2,615	2,615	969	913	-3,677
3	0	3584	3584		0	2,615	2,615	969	887	-2,790
4	0	3584	3584		0	2,615	2,615	969	861	-1,929
5	0	3584	3584		0	2,615	2,615	969	836	-1,093
6	0	3584	3584		0	2,615	2,615	969	812	-282
7	0	3584	3584		0	2,615	2,615	969	788	506
8	0	3584	3584		0	2,615	2,615	969	765	1,271
9	0	3584	3584		0	2,615	2,615	969	743	2,014
10	0	3584	3584		0	2,615	2,615	969	721	2,735
11	0	3584	3584		0	2,615	2,615	969	700	3,435
12	0	3584	3584		0	2,615	2,615	969	680	4,114
13	0	3584	3584		0	2,615	2,615	969	660	4,774
14	0	3584	3584		0	2,615	2,615	969	641	5,415
15	1500	3584	5084		8,000	2,615	10,615	-5,531	-3,550	1,865
16	0	3584	3584		0	2,615	2,615	969	604	2,469
17	0	3584	3584		0	2,615	2,615	969	586	3,055
18	0	3584	3584		0	2,615	2,615	969	569	3,624
19	0	3584	3584		0	2,615	2,615	969	553	4,177
20	0	3584	3584		0	2,615	2,615	969	537	4,713
21	0	3584	3584		0	2,615	2,615	969	521	5,234
22	0	3584	3584		0	2,615	2,615	969	506	5,740
23	0	3584	3584		0	2,615	2,615	969	491	6,231
24	0	3584	3584		0	2,615	2,615	969	477	6,707
25	0	3584	3584		0	2,615	2,615	969	463	7,170
26	0	3584	3584		0	2,615	2,615	969	449	7,620
27	0	3584	3584		0	2,615	2,615	969	436	8,056
28	0	3584	3584		0	2,615	2,615	969	424	8,479
29	0	3584	3584		0	2,615	2,615	969	411	8,891



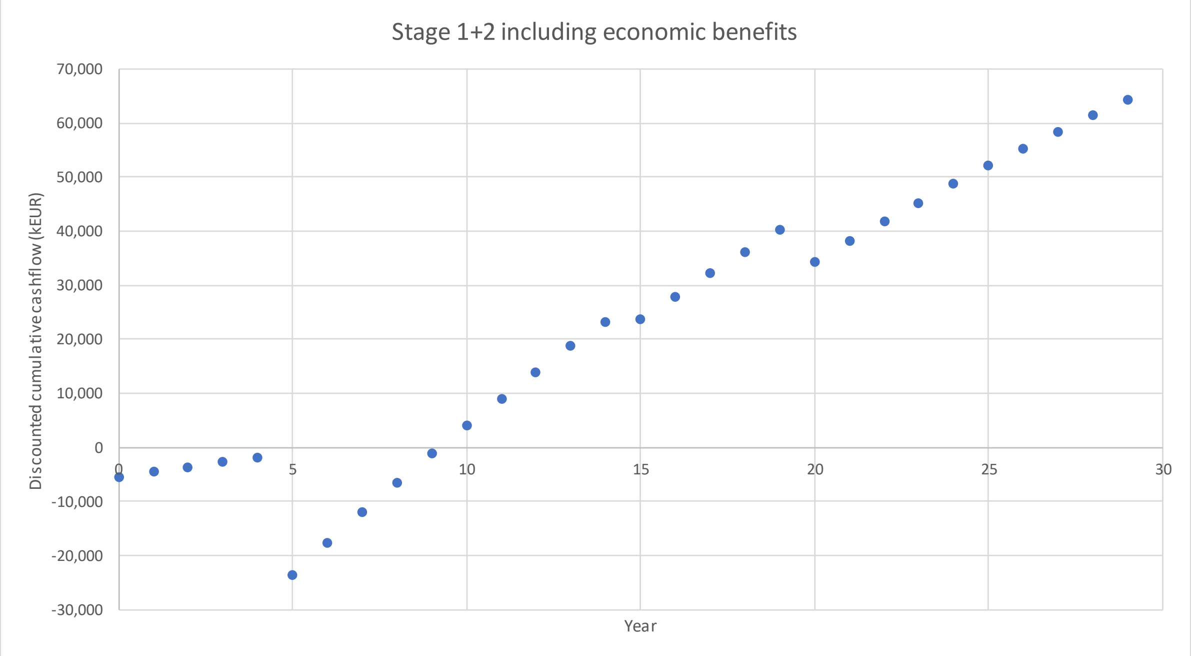
6.3. ANNEX 3: STAGE 1 +2

	Do nothing				Stage 1 + 2					
Year	Invest	Operational	Cashflow		Invest	Operational	Cashflow	Dif	NPV	Cumulative
0	1500	3584	5084		8,000	2,615	10,615	-5,531	-5,531	-5,531
1	0	3584	3584		0	2,615	2,615	969	941	-4,590
2	0	3584	3584		0	2,615	2,615	969	913	-3,677
3	0	3584	3584		0	2,615	2,615	969	887	-2,790
4	0	3584	3584		0	2,615	2,615	969	861	-1,929
5	0	3584	3584		28,500	2,615	31,115	-27,531	-23,748	-25,678
6	0	3584	3584		0	-928	-928	4,512	3,779	-21,899
7	0	3584	3584		0	-928	-928	4,512	3,669	-18,230
8	0	3584	3584		0	-928	-928	4,512	3,562	-14,668
9	0	3584	3584		0	-928	-928	4,512	3,458	-11,210
10	0	3584	3584		0	-928	-928	4,512	3,357	-7,853
11	0	3584	3584		0	-928	-928	4,512	3,260	-4,593
12	0	3584	3584		0	-928	-928	4,512	3,165	-1,429
13	0	3584	3584		0	-928	-928	4,512	3,072	1,644
14	0	3584	3584		0	-928	-928	4,512	2,983	4,627
15	1500	3584	5084		8,000	-928	7,072	-1,988	-1,276	3,351
16	0	3584	3584		0	-928	-928	4,512	2,812	6,162
17	0	3584	3584		0	-928	-928	4,512	2,730	8,892
18	0	3584	3584		0	-928	-928	4,512	2,650	11,542
19	0	3584	3584		0	-928	-928	4,512	2,573	14,116
20	0	3584	3584		17,500	-928	16,572	-12,988	-7,191	6,924
21	0	3584	3584		0	-928	-928	4,512	2,425	9,350
22	0	3584	3584		0	-928	-928	4,512	2,355	11,705
23	0	3584	3584		0	-928	-928	4,512	2,286	13,991
24	0	3584	3584		0	-928	-928	4,512	2,220	16,210
25	0	3584	3584		0	-928	-928	4,512	2,155	18,365
26	0	3584	3584		0	-928	-928	4,512	2,092	20,458
27	0	3584	3584		0	-928	-928	4,512	2,031	22,489
28	0	3584	3584		0	-928	-928	4,512	1,972	24,461
29	0	3584	3584		0	-928	-928	4,512	1,915	26,376



6.4. ANNEX 4: STAGE 1 + 2 WITH ECONOMIC BENEFITS

	Do nothing				Stage 1 + 2 with economic benefits						
Year	Invest	Operational	Cashflow		Invest	Operational	Economical	Cashflow	Dif	NPV	Cumulative
0	1500	3584	5084		8,000	2,615	0	10,615	-5,531	-5,531	-5,531
1	0	3584	3584		0	2,615	0	2,615	969	941	-4,590
2	0	3584	3584		0	2,615	0	2,615	969	913	-3,677
3	0	3584	3584		0	2,615	0	2,615	969	887	-2,790
4	0	3584	3584		0	2,615	0	2,615	969	861	-1,929
5	0	3584	3584		28,500	2,615	-2,459	28,656	-25,072	-21,628	-23,557
6	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,838	-17,719
7	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,668	-12,051
8	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,503	-6,549
9	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,342	-1,206
10	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,187	3,981
11	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,036	9,016
12	0	3584	3584		0	-928	-2,459	-3,387	6,971	4,889	13,905
13	0	3584	3584		0	-928	-2,459	-3,387	6,971	4,747	18,652
14	0	3584	3584		0	-928	-2,459	-3,387	6,971	4,608	23,260
15	1500	3584	5084		8,000	-928	-2,459	4,613	471	302	23,563
16	0	3584	3584		0	-928	-2,459	-3,387	6,971	4,344	27,906
17	0	3584	3584		0	-928	-2,459	-3,387	6,971	4,217	32,124
18	0	3584	3584		0	-928	-2,459	-3,387	6,971	4,095	36,218
19	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,975	40,193
20	0	3584	3584		17,500	-928	-2,459	14,113	-10,529	-5,830	34,364
21	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,747	38,111
22	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,638	41,749
23	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,532	45,281
24	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,429	48,710
25	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,329	52,039
26	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,232	55,271
27	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,138	58,409
28	0	3584	3584		0	-928	-2,459	-3,387	6,971	3,047	61,456
29	0	3584	3584		0	-928	-2,459	-3,387	6,971	2,958	64,414



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6.5. ANNEX 5: TOTAL PROJECT WITH ECONOMIC BENEFITS

	Do nothing				Project + income						
Year	Invest	Operational	Cashflow		Invest	Operational	Eco sludge	Cashflow	Dif	NPV	Cumulative
0	1500	3584	5084		8,000	2,615	0	10,615	-5,531	-5,531	-5,531
1	0	3584	3584		0	2,615	0	2,615	969	941	-4,590
2	0	3584	3584		0	2,615	0	2,615	969	913	-3,677
3	0	3584	3584		0	2,615	0	2,615	969	887	-2,790
4	0	3584	3584		0	2,615	0	2,615	969	861	-1,929
5	0	3584	3584		28,500	-928	-2,459	25,113	-21,529	-18,571	-20,501
6	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,838	-14,663
7	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,668	-8,995
8	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,503	-3,492
9	0	3584	3584		0	-928	-2,459	-3,387	6,971	5,342	1,850
10	0	3584	3584		25,000	-197	-2,459	22,344	-18,760	-13,959	-12,109
11	0	3584	3584		0	-197	-2,459	-2,656	6,240	4,508	-7,602
12	0	3584	3584		0	-197	-2,459	-2,656	6,240	4,376	-3,225
13	0	3584	3584		0	-197	-2,459	-2,656	6,240	4,249	1,023
14	0	3584	3584		0	-197	-2,459	-2,656	6,240	4,125	5,149
15	1500	3584	5084		8,000	-197	-2,459	5,344	-260	-167	4,981
16	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,888	8,870
17	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,775	12,645
18	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,665	16,310
19	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,558	19,868
20	0	3584	3584		17,500	-197	-2,459	14,844	-11,260	-6,235	13,634
21	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,354	16,988
22	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,256	20,244
23	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,162	23,406
24	0	3584	3584		0	-197	-2,459	-2,656	6,240	3,069	26,475
25	0	3584	3584		22,000	-197	-2,459	19,344	-15,760	-7,527	18,948
26	0	3584	3584		0	-197	-2,459	-2,656	6,240	2,893	21,841
27	0	3584	3584		0	-197	-2,459	-2,656	6,240	2,809	24,650
28	0	3584	3584		0	-197	-2,459	-2,656	6,240	2,727	27,377
29	0	3584	3584		0	-197	-2,459	-2,656	6,240	2,648	30,025