Friedrich-Alexander-Universität
Technische Fakultät

Retrofitting of an existing waste incineration plant – WASTE2X

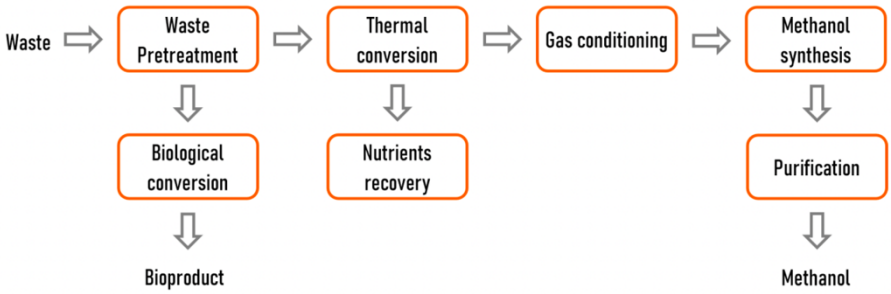
Executive Summary

CBI Project Course – 04/2024

Project Partner: Hitachi Zosen Inova

Objective

The recycling of waste is a crucial part of achieving a sustainable and global circular economy. Currently, around 25 million tons of residual waste are thermally recycled in Germany every year. In Germany, biowaste is currently partly composted for further use as fertilizer and compost (7.4 million tons/year) or used in biogas plants to generate energy (6.2 million tons/year).[1] To use the waste for more than just energy, an alternative was sought in collaboration with Hitachi Zosen Innova.[2] The task was the **retrofitting of an existing waste incineration plant** into a **WASTE2X production** with an input quantity of 100 t/h bio-municipal waste, targeting energy carrier materials like methanol. Additionally, a way of producing bioplastics from biowaste was developed and a special focus was placed on the recovery of nutrients like phosphorus.



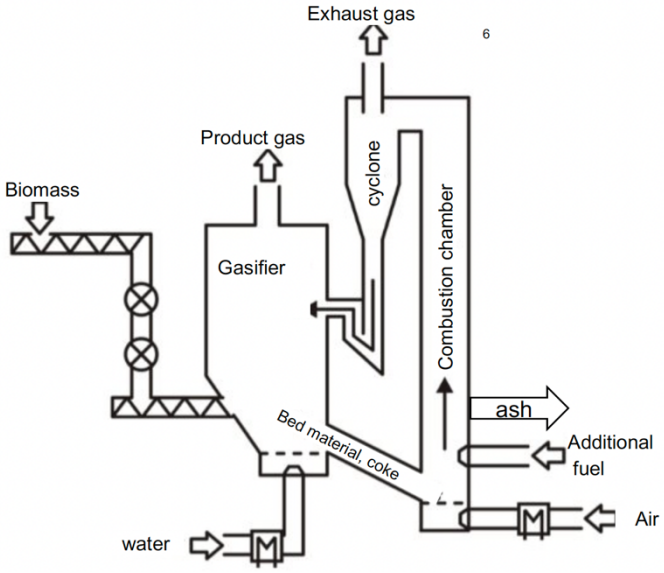
A **location for the plant** in Germany was chosen considering the infrastructure, taxes, subsides, availability of raw materials as well as availability and quality of labor. Since the project seeks to convert 100 t/h biological waste, which corresponds to 5.5% of Germany's total biowaste[3], the metropolitan area Rhine-Ruhr was selected. The Rhine-Ruhr-Area fits the requirements not only for sufficient supply of raw material, but also of a good infrastructural network via river, railways, and street. In addition, there will be a connection to the German hydrogen network and methanol processing industries are located nearby. Due to the retrofit and the usage of new substances like methanol, H_2S and hydrogen, **regulations** like the *Bundesimmissionsschutzgesetz (BImSchG)*, the *Technische Anleitung für die Reinhaltung der Luft (TA-Luft)*, the *Umweltverträglichkeitsprüfung (UVP)* and the *Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen (AwSV)* need to be considered. The total duration from planning to **commissioning** of the plant is estimated to approximately 8 years.

In the process of **waste pretreatment**, the incoming organic waste is purified by removing any contained and disturbing impurities. The incoming waste typically has an average moisture content of approx. 59 % and contains approximately 6 % impurities (plastics, sand, glass, stones, metals). The organic waste with a grain size of more

[1] Abfallwirtschaft in Deutschland 2023. Fakten, Daten, Grafiken, https://www.bmuv.de/fileadmin/Daten_BMU/Pools/Broschueren/abfallwirtschaft_2023_bf.pdf, (accessed 02.05.2024).
[2] https://www.hz-inova.com/ (accessed 02.05.2024).
[3] Bioabfälle, https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/bioabfaelle#bioabfalle-gute-qualitat-ist-voraussetzung-fur-eine-hochwertige-verwertung (accessed 02.05.2024).

than 160 mm is separated and the coarse fraction is subjected to manual sorting. The remaining fraction is then subjected to a pre-comminution step so that the entire waste stream has a particle size smaller than 160 mm. Afterwards, the organic waste stream undergoes mechanical drying in a screw press to reduce the moisture content to 40%. The organic waste is then sent to a second shredding step to reduce the particle size to less than 70 mm. The moisture content is then further reduced to 15% by a combined mechanical and thermal drying process in a drum dryer. Sand is removed in a vibrating sieve with a separation grain size of 3 mm. The magnetic metals are extracted by a ferrite overband magnet. The separation of the non-magnetic metals is realized by an eddy current separator. Finally, a separator based on near-infrared spectroscopy is used to separate plastics and inert materials such as stone and glass, which ensures the targeted removal of impurities. Finally, an **average of 55 t/h of cleaned biomass** is grinded to a **particle size of 5 mm** and remoistened to a **moisture content of 30%** for further processing in the thermal and biological conversion process.

The **gasification of the biomass** leads to a product gas with H_2, CO, CO2 and CH_4 as main components.[4] For this process step a fluidized bed reactor was chosen in the design of a **Güssing Gasifier**. This type of gasifier is characterized by its two fluidized beds.[5] One of them being the gasification section where steam is used as a fluidization medium, and the temperature is 800 °C. The other fluidized bed is the combustion chamber in which coke residue from the gasification and not converted biomass are burned with air at 900 °C.



The combustion reaction is used to heat up the bed material which is then circulated back into the gasification bed via a cyclone. The heat of the product gas as well as the exhaust gas from the combustion are used to preheat the fluidization media steam which enters the gasification chamber at 600 °C and air which is needed at 700 °C in the combustion chamber. The 52.2 t/h biomass entering the gasification chamber has a moisture content of 30%. During the heat up of the biomass, the moisture evaporates and helps with the fluidization of the bed. The resulting gas stream consists of 27.6 t/h product gas and 49.7 t/h steam of which 34 t/h are circulated back into the fluidized bed. The **product gas composition is 49 vol-% H_2, 18 vol-% CO, 25 vol-% CO_2 and 8 vol-% CH_4**. The gasification of

[4] Peter Treiber, Steam gasification of lignite and biomass with integrated syngas cleaning for decentralized SNG production, FAU, 2021.
[5] Sebastian Gellert, Thermochemische Herstellung von Wasserstoff aus Biomasse unter besonderer Berücksichtigung der Rohgasreformierung, TUHH, 2013, ISBN-13: 978-3954044511.

the thermal conversion process is simulated in Aspen Plus by a RYIELD reactor, which is followed by a RGIBBS reactor. For the combustion a simple separator is used, to separate the ash and unused carbon from the gas stream. The overall energy input from biomass is 142 MW and results in an energy value of 98 MW in the product gas, which means the cold gas efficiency of the process is at 0.69.

For the **biological conversion**, it was decided to focus on an alternative usage of waste, namely the production of the **biopolymer polyhydroxybutyrate** (PHB). PHB can be processed into bioplastic, which is completely biodegradable in nature and has similar properties as polypropylene.[6] For this process we selected the bacterium *Cupravidus Necator* as the PHB producing microorganism, due to its ability to transform diverse carbon sources into PHB and the high amount (>80%) of polymer it can accumulate intercellular. The upstream process includes the thermal hydrolysis of the pretreated organic waste to kill all unwanted microorganisms and break down complex into easier digestible molecules. Following the hydrolysis, the treated media is inoculated with *C. Necator*, which has been pre-cultured in an inoculum tank. From this point the bacteria culture proliferates 23 h at an oxygen saturation rate from > 30%. The main part is the following fermentation, where the PHB is produced intercellular, induced by modulating the oxygen saturation rate. For that, after the culture enrichment, the biomass is pumped in another fermenter, saturation rate is set to around 10% and the biomass is stirred for additional 72 h. In the downstream process the PHB rich biomass is separated from the broth via centrifugation. The cells are crushed and the released PHB is extracted from the residual biomass by adding butyl acetate. The PHB solved in butyl acetate is precipitated by adding the antisolvent hexane. 120 kg/h of pretreated organic waste can be biologically transformed into approximately 45 kg/h of PHB, 32 kg/h of water and 80 kg/h of CO_2.

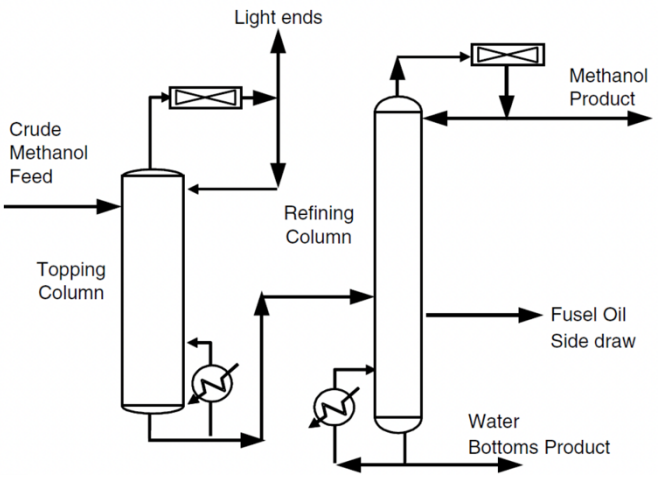
Impurities contained in the synthesis gas are removed by **gas conditioning** before it enters the reactor, to avoid potential problems like catalyst poisoning. The **impurities** in the syngas are namely: dust particles (0.3 ppm), HCl (4.1 ppm), Hg (0.02 ppm), COS (45 ppm), HCN (10 ppm) and H_2S (930 ppm). The process consists of five unit operations to clean the 43.3 t/h of gas leaving the gasification step. The gas first goes through an electrostatic precipitator to remove all the dust and solid particles achieving a separation of 99.3%.[7] After the electrostatic precipitator the gas stream is cooled to 30 °C in a condenser and the liquid water (14.5 t/h) is removed. Part of the water removed is used in the next step to absorb all the HCl as well as 83.5% of the Hg. This is done in a packed bed wet scrubber. 90% of the remaining Hg is separated in the following Hg removal step, which is a fixed bed containing 2 tons of adsorbent based on semi coke, leaving only **0.3 ppb of Hg** in the gas mixture. After this the syngas is compressed to 110 bar and cooled to 60 °C, condensing out 1.15 t/h of water, which is removed. The temperature is then increased

[6] A. Gęsicka, P. Oleskowicz-Popiel and M. Łężyk, Biotechnology Advances, 2021, 53, 107861.
[7] M. Achternbosch & U. Richers (1999), „Stoffströme und Inverstionskosten bei der Rauchgasreinigung von Abfallverbrennungsanlagen“ Forschungszentrum Karlsruhe GmbH.

to 220 °C and the process continues with a simultaneous hydrolysis of COS and HCN, this is done in a fixed bed reactor with a TiO_2-based catalyst achieving a conversion of 98%.[8] The gas is left with **0.9 ppm of COS** and **0.2 ppm of HCN** while the H_2S content is 974 ppm because it is produced during the COS hydrolysis. The gas is then heated to 270 °C for the final desulfurization, which is done in another fixed bed reactor with a ZnO-based sorbent called RVS-1, which reduces the **H_2S content to 0.1 ppm**. Finally, **27.6 t/h of clean synthesis gas** with a H_2 to CO molar ratio of 2.72 continue to the **methanol synthesis**. Methanol can be synthesized via CO or CO_2 hydrogenation according to the following reactions:

$$CO + 2H_2 \rightleftharpoons CH_3OH$$
$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

Both reactions are exothermic and volume-reducing, hence an elevated pressure at 110 bar is chosen for the synthesis. The established $CuO/ZnO/Al_2O_3$ catalyst prefers an optimal reaction temperature of 260 °C. Suitable for **isothermal operation** and efficient temperature control is the steam raising converter, a **multitubular reactor** (Lurgi reactor), cooled using boiling water, with 8000 tubes each with a diameter of 0.03675 m and a length of 12.2 m.[9] Based on the process layout with **heat recovery** and a two stage separator, simulated in Aspen Plus with a reactor design according to the Langmuir Hinshelwood-kinetics (RPLUG reactor), it was possible to generate **8436.95 kg/h bio-methanol**, with a purity of 79 mol% for the following purification step. The feed-stream composition leads to two main problems: The first one is the high amount of inert methane, that leads to a total purge of 17956 kg/h and a bigger reactor. That problem could be solved by an upstream methane removal, for example with catalytic reforming, which would reduce the purged gas by 26%. The relatively low hydrogen content is the second challenge. Additionally purchased **green hydrogen** could be the solution in the future, resulting in a higher product stream and less purge, but then currently uneconomic operation of the plant. The purification process is simulated in Aspen Plus with two RADFRAC columns. The product stream of the methanol synthesis was simplified to a two-component mixture of only water and methanol. The get the first input data (number of staged, feed stage, distillation to feed ratio and reflux ratio) for the RADFRAC column the DSTWU



[8] D. Chiche und J.-M. Schweitzer, „Investigation of competitive COS and HCN hydrolysis reactions upon an industrial catalyst: Langmuir-Hinshelwood kinetics modeling", Applied Catalysis B: Environmental, Bd. 205, S. 189–200, Mai 2017, doi: 10.1016/j.apcatb.2016.12.002.
[9] W. L. Luyben, Ind. Eng. Chem. Res., 2010, 49, 6150.

column was used. To meet the desired purities of the product streams design specs were used in the RADFRAC and resulted in the ideal reflux to feed ratio as well as the ideal reflux ratio.

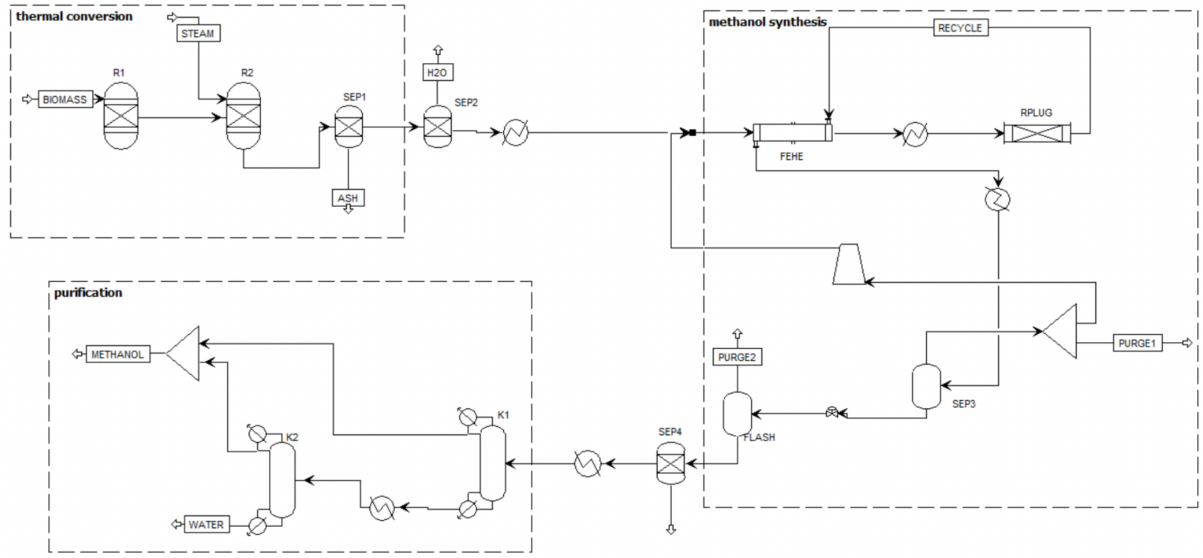
The **nutrients** contained in the biomass (mainly P compounds) are removed by a **thermochemical process** known as AscDec® developed by Outotec.[10] The core methodology involves feeding hot ash into a rotary kiln, where it is combined with preheated sodium carbonate and treated at a temperature of 900°C. The rotary kiln serves the purpose of mixing and enabling chemical reactions between phosphates and sodium carbonate (Na_2CO_3), resulting in the formation of a phosphate compound called rhenanite ($CaNaPO_4$). The reducing atmosphere within the reactor facilitates the evaporation of heavy metals and the synthesis of $CaNaPO_4$. The heating of the kiln is accomplished directly by using exhaust gas from the thermal conversion process, which is appropriately heated by a natural gas burner. After the kiln, the process gas undergoes cooling in a quench utilizing fresh air and water, followed by the removal of dust particles, particularly heavy metals, in an electrostatic precipitator. The exhaust gas is then employed in a bulk heat exchanger to preheat sodium carbonate before being recirculated for flue gas cleaning within the thermal conversion system. The product exits the kiln and is directed to a screw cooler equipped with a cooling circuit, then stored in a silo. The ash, which contains the **bioavailable phosphate compound $CaNaPO_4$**, can be utilized as a soil additive or fertilizer, thereby effectively recycling phosphorus, and contributing to sustainable nutrient management practices.

For flows below 1000 m3/h, **oscillating displacement pumps** are chosen, and for flows above 1000 m3/h, **centrifugal pumps** are selected. For compressing gas flows, **piston compressors** are mainly used because they are impermeable and protected against overpressure and cavitation. An exception is the compressor in the gas conditioning unit, which compresses the synthesis gas from 1 bar to 110 bar. For this purpose, a **three-stage turbo compressor** is used, driven by a single shaft, the energy is obtained through a turbine driven by hot steam from other processes. This is particularly suitable because high volume flows and pressures are required, and high energy consumption can be mitigated by energy coupling with other processes via steam stream. Overall, the entire plant requires 14 pumps and 7 compressors. With an assumed efficiency of $\eta = 0.9$ for all pumps and compressors, the total energy consumption is thus 7.54 MW. For the **design of the pipes**, stainless steel 1.4301 X 5 CrNi 18-20 is used, with a safety factor of 2 calculated for higher stability. This material is particularly suitable for transporting hydrogen and other similar substances, up to the pressure of 486 bar and is therefore corrosion resistant.

The overall external **heating duty** was 35.0 MW whereas the external **cooling duty** was 78.1 MW. In addition, there was an **electrical energy** requirement of 12.4 MW altogether. The waste pretreatment process was identified as the largest consumer of external energy with a heating duty of 21.8 MW to dehumidify the waste. The second largest

[10] Ludwig Hermann, Outotec modular energy and phosphorus recovery process, Outotec, 2019.

energy consumer was the conditioning process with a total energy requirement of 19 MW, consisting of 9.3 MW heating duty and 9.7 MW electrical energy. The needed temperature levels were all above ambient temperature, so no chillers were required. The high energy input into the overall system resulted in **large process heat flows**, which offered potential for further utilization. For this reason, a **pinch analysis** was used to reduce the external heat requirement and thus make the best possible use of the heat generated. As a result, 6.6 MW of heat and 48.8 MW of cooling would have to be purchased for the overall process. However, these values can only be regarded as the theoretical ideal case. According to the calculations, 16.5 MW could be saved with **heat integration**. An efficiency factor was defined using the calorific value of the methanol product in relation to the calorific value of the biomass, the overall heat requirement, and the electrical energy requirement. This efficiency factor could be increased from 41% to 47% by connecting hot and cold streams.



Due to the complexity of the overall process, a deeper understanding of the individual sub-processes and their interaction is necessary for **automation**. The resulting findings led, for example, to the installation of additional storage containers. Examples of parameters to be controlled are the familiar variables of pressure, temperature, and flow rate. However, fill levels, agitator speeds, pH values and oxygen saturations must also be constantly monitored and regulated, especially in biological processes. For this reason, many **sensor-actuator** connections have been planned in all process steps, which can function according to one of two principles. Feedback control is a system in which the controller and system form a closed control loop. The measured signal is compared with the desired behavior and the controller dynamically corrects the system input. The feedforward control operates the system in a predefined manner without measuring the output or reacting to any changes that occur. The controllers, which serve to ensure stable and smooth operation of the system, were finally drawn in a Piping and Instrumentation Diagram (P&ID).

A **life cycle assessment** was carried out to enable the evaluation of the environmental impacts of the production of methanol. For this process, a **"cradle to gate" analysis** was performed, which only considers the processes inside the factory and transport to the plant. So, the use phase and disposal phase of the product were excluded. The end-of-life cycle scenarios of methanol were not included in the calculation, but they were considered in the life cycle assessment as they are also important key factors for a more sustainable process. The life cycle inventory analysis is the most essential stage of the life cycle assessment, which calculates the flows of the process in the software OpenLCA with the database Ecoinvent. After the calculation the data was classified in six different impact categories such as the climate change, water depletion, fossil depletion, human toxicity, particulate matter formation and terrestrial ecotoxicity. To get an estimation of the values calculated, the impact of the retrofitted process was compared to the regular incineration of biomass. The **retrofitted process outperformed the regular incineration** in every category except the fossil depletion, this is because the nutrition treatment needs a high amount of natural gas. The better performance can be mostly attributed to good waste treatment and selling of most byproducts.

For the **cost calculation** several aspects were considered. Investment was determined by researching the prices for different pieces of equipment directly from suppliers as far as possible. Based on these costs, adjacent investment costs for heat exchangers, electronic equipment and pipes were determined by factors and added to the equipment costs. Infrastructure, assembly & commissioning costs as well as costs for measurement & control technology were then determined with a factor based on the total equipment costs. This comes to a **total investment of 382.9 Mio. €** not including any engineering costs for planning. The **operating costs** including chemicals, water & wastewater, electricity, steam, heat, CO_2-tax, maintenance, disposal and the depreciation of equipment and infrastructure are **78.5 Mio. €/a**. Operating costs were then adjusted for 2.2% inflation and calculated for the next 50 years. The depreciation of equipment is accounted for after 15 years which leads to a decrease in cost. **Labor costs are 6.95 Mio. €** in the first year and the total labor cost adjusted for 1.5% wage rise per year. This leads to **total operation costs of 85.45 Mio. €/a** in the first year. The required loan for the initial investment was taken slightly above the value for investment at 385 Mio. €. An interest rate of 4.5% was assumed. The interest on this loan was then calculated for a payback period of 10 years assuming linearity of payments and therefore equal amounts for each year. The revenue including methanol, heat, and waste disposal (money gotten for accepting the initial waste) are 86.6 Mio €/a. With all these values a Profit & Loss analysis was performed, and it shows that the plant reaches **amortization after 27 years**. To make the plant profitable, the methanol price would have to rise by 20% to avoid any losses. The price would have to rise even further to make any profit and therefore be able to even pay back the loan. Other possibilities of achieving profitability would be to decrease running costs by increasing energy efficiency, lowering labor costs, or receiving a lower interest rate on the loan.

Imprint

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