

# INNOVATIVE GASIFICATION TECHNOLOGY FOR THE CIRCULAR ECONOMY

## INOVATIVNA TEHNOLOGIJA UPLINJANJA ZA KROŽNO GOSPODARSTVO

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**Keywords:** Gasification, carbonaceous, waste, tars, syngas, catalyst, circular economy, carbon, methanol

### **Abstract**

This article presents a novel gasification technology process in the context of achieving carbon neutrality by establishing a sustainable circulation of carbonaceous materials with a focus on the production of virgin materials from various kinds of waste. The technology can alleviate the key limitations of existing gasification systems, which are the production and management of residue tars. The innovative technology process re-utilizes tars within the reaction itself, enabling an endless cycle of carbon. It also ensures high flexibility for efficiently handling heterogenic waste materials.

### **Povzetek**

Članek predstavlja nov tehnološki postopek uplinjanja v okviru doseganja ogljikove nevtralnosti z vzpostavitev trajnostnega kroženja ogljikovih materialov s fokusom na proizvodnji izvornih surovin iz različnih vrst odpadkov. Tehnologija lahko reši ključne omejitve obstoječih sistemov uplinjanja, to je proizvodnja in upravljanje ostankov katrana. Inovativni tehnološki postopek uporabi katrane v sami reakciji, kar omogoča neskončno kroženje ogljika. Zagotavlja tudi visoko prilagodljivost za učinkovito ravnanje s heterogenimi odpadnimi materiali.

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## 1 INTRODUCTION

Talking about global warming is talking about carbon management, which should be simple: the release of carbon into the atmosphere should be reduced as much as possible. For example:

- avoiding the use of C for energy production;
- avoiding biodegradation (which is also a cause of GHG emissions);
- the use of biomass, as optimal and efficient circulation of GHG is possible only via biomass;
- all C from carbonaceous wastes and residues should be prioritized for the production of new virgin raw hydrocarbons;

With the existing technological solutions, a circular economy cannot be established. The transformation of carbon from residues to new virgin materials should be the basis of any programme. Existing methods for recycling carbonaceous materials can assure only limited cycles, after which the recycled products end up as waste in incineration plants, or, as is the case for the EU, in the landfills of southern continents, as well as (of course) in the oceans:



**Figure 1: The 5 Gyres**

The term “recycling” should mean an endless circulation of materials, as is the case with metals. The treatment of hydrocarbons as we know it today is in reality only extending the life cycle of products, which contributes to the reduction of fossil hydrocarbon consumption; however, the material flow balance is inexorable in the end: all inputs will sooner or later become outputs. This fact calls for an appropriate and better technological solution with the possibility of processing heterogeneous carbonaceous waste and residue materials into new virgin materials. Chemical recycling based on the gasification process is one of them.

Solving the major problem of the gasification process through an innovative approach, a technological solution of producing new virgin materials from any kind of waste or residues is now available. According to Directive 2010/75/EU on industrial emissions (IED), the gasification technology presented in this paper may be treated as “End of Waste” technology, as the prescribed technical conditions are met. According to the R3 process (recycling), syngas is considered a new raw material. Besides the application of such syngas as a technical gas or energy source, its major importance is in acting as the first process phase in the synthesis

## **2 GASIFICATION PROCESS**

The gasification process of solid carbonaceous materials is an old and very well-known technology, [1], which has once again become very attractive. It relies on the partial oxidation of hydrocarbons, by which the greater part of the material is converted into a combustible product gas. Such product gas is useful for various purposes, such as combustion in furnaces for thermal applications, or internal combustion engines and turbines to produce electricity. The most attractive application of the product gas is as synthesis gas for chemical synthesis to produce new raw materials used in the chemistry or energy industries. With this, a perfect carbon cycle (100% recycling) can be achieved, resulting in completely new products similar to those that could be produced from fossil sources.

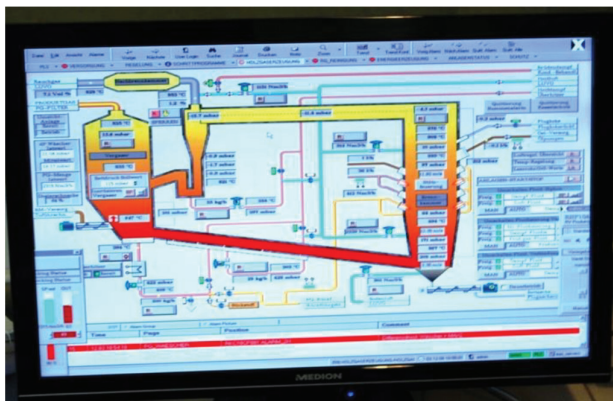


**Figure 2:** *Gasification tower Güssing, Austria*

The project aimed to develop a technology that is sufficiently flexible and would allow the use of all types of poor-quality biomass, such as logging residues, residues of primary processing of wood and other kinds of used wood. At the first verification of state-of-the-art technology, several basic technical obstacles that were not sufficiently solved appeared. The essence of the problem is best illustrated by R.W.R. Zwart's report, [2]:

Gasification of biomass results in a producer gas containing numerous contaminants like dust and tar. Although concentrations could be relatively low depending on the feedstock used and the type of gasifier applied, at least some of these contaminants have to be destructed or removed upstream the final application of the producer gas, whether it is a boiler, gas engine or turbine, fuel cell or synthetic application. Hence, gas cleaning is inevitable in general, whether it is on tar components or non-tar components.

Still not many gasifiers are operating commercially on biomass feedstock, in particular when not taking into account those gasification systems (co-)firing the product straight into boilers. The need for gas cleaning, and in particular tar removal technology, for CHP or synthesis purposes is still the Achilles heel of biomass gasification and gas cleaning. Standard technology has proven to be insufficient for tar destruction or removal and has led to years of (still ongoing) R&D on thermal and catalytic tar cracking as well as (advanced) scrubbing technologies. For the moment, the latter ones seem to have made the biggest progress, with operating biomass-based CHP plants at e.g. among others Harboøre and Güssing, and water as well as organic liquid (RME, oil) based technologies being commercially available.



**Figure 3:** The computer scheme of Güssing gasifier in operation, Austria

A step by step approach could be considered in which technology is scaled up gradually. There has been a tendency to construct large (demonstration) facilities hoping that these are operated successfully and due to scale are commercially attractive as well. The risks are high though, as solving unexpected issues will require enormous budgets. The risk that such a plant becomes mothballed instead of a commercial success has been proven to be relevant. Examples of this are the 180 ton per day Battelle gasification plant in Burlington, USA, and the 8 MWel ARBRE combined-cycle plant in Eggborough, UK.

Tars are still considered to be the major bottleneck or even stumbling blocks in the application of biomass gasification. This holds for fluidized as well as updraft fixed bed-based gasification performed at temperatures well below 1000°C, as tar contents in the raw gas can be up to several tens of g/Nm<sup>3</sup>. A description of tars and the main associated issues are included in the appendices. The cleaning from these organic species down to values that are acceptable for different downstream processes is of crucial importance for successful implementation of biomass gasification technology. Tar reduction measures can be classified in three main categories, being:

- i. *tar cracking and reforming (thermal or catalyst),*
- ii. *mechanical tar removal and*
- iii. *physical tar removal (emphasis added).*

Many sophisticated technical solutions have been developed to solve the tar problem. However, most (if not all) solutions go at the expense of process flexibility, which should be the most important advantage of gasification technology. The purpose of gasification should be the

ability to process all challenging materials, such as worthless biomass (wet or contaminated with dust), or any kind of municipal and industrial waste. The use of high quality dry and dustless wood chips or even pellets for gasification is not in line with sustainability criteria and waste hierarchy. Losing upstream flexibility does not aid in avoiding losing downstream flexibility. An example of this is the Güssing CHP plant: the use of dustless wood chips for gasification did not prevent the need for a sophisticated filtering system, which led to high operational costs. The plant was not profitable without subsidies; hence production was halted in 2016, [3].

### 3 A NEW APPROACH

A new approach to the tar problem has led to successful results with many benefits: using tars as a necessary element in the process eliminates the need for tar removal – more tars results in a better process. The developed technological solution is based on the selective catalytic conversion of complex hydrocarbons into CO and H<sub>2</sub>, supported by the Catalytic Partial Oxidation (CPOX) process. The system considers tars to be a reactant, and by increasing tar concentration in the product gas, the efficiency of the CPOX process also increases. Such catalyst reactors are well known in the petrochemical industry, where they are used for cracking long and heavy hydrocarbons into short hydrocarbon chains.

The partial oxidation process taking place in the reactor differs from thermal cracking. The best example of this type of reaction is the decomposition of methane, CH<sub>4</sub>:

- Example A, full oxidation:
 
$$\text{CH}_4 + 2 \text{O}_2 = \text{CO}_2 + 2 \text{H}_2\text{O} \text{ (803 kJ/mole)}$$
- Example B, partial oxidation occurring at thermal cracking:
 
$$\text{CH}_4 + 0.5 \text{O}_2 = 0.25 \text{CO}_2 + 0.5 \text{H}_2\text{O} + 0.75 \text{CH}_4 \text{ (201 kJ/0.25 mole)}$$
- Example C, partial oxidation in CPOX:
 
$$\text{CH}_4 + 0.5 \text{O}_2 = \text{CO} + 2 \text{H}_2 \text{ (36 kJ/mole)}$$

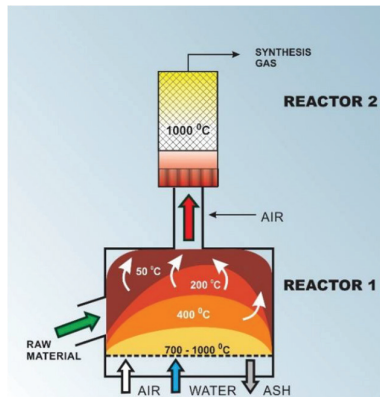
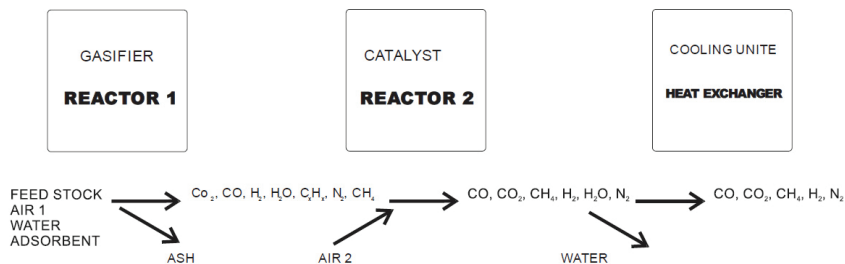


Figure 4: Schematic representation of the device

In CPOX, the exothermic reaction is taking place inside the reactor. Partial oxidation releases significantly less heat than full oxidation, but still enough to get the catalyst up to working temperature. Another advantage of the CPOX is its compactness, as the residence time ranges from 0.14 to 0.08 sec, while the residence time in full oxidation systems can reach up to 10 s.

In order to reach higher tar concentrations in the product gas, heterogeneous and poor-quality gasification materials may be used, with less drying and sieving (to remove dust). The quality of the material used depends on the type of gasifier. For basic CPOX testing, a specially designed multi-fuel updraft gasifier was used, which can accept all kinds of heterogeneous carbonaceous materials, except for very fine dust or explosives. It can operate on sawdust, all kinds of waste, sludge, coal, charcoal, plastic, wood chips and agricultural residues. The gasifier produces product gas with up to 20% tar content, which is optimal for the CPOX catalyst system.

Gasification takes place in two reactors. In the first reactor, the inorganic and organic compounds are separated. Inorganic compounds leave the system in the form of ash, while the organic part flows in a gaseous phase to the second reactor – the catalyst. After the cracking process, the tar-free synthesis gas is cooled, and water is extracted. If waste materials are used as feedstock, an adsorbent is added to remove S and Cl compounds from hydrocarbons. The separated S and Cl are deposited into ash and removed from the process.



**Figure 5:** Process operating scheme

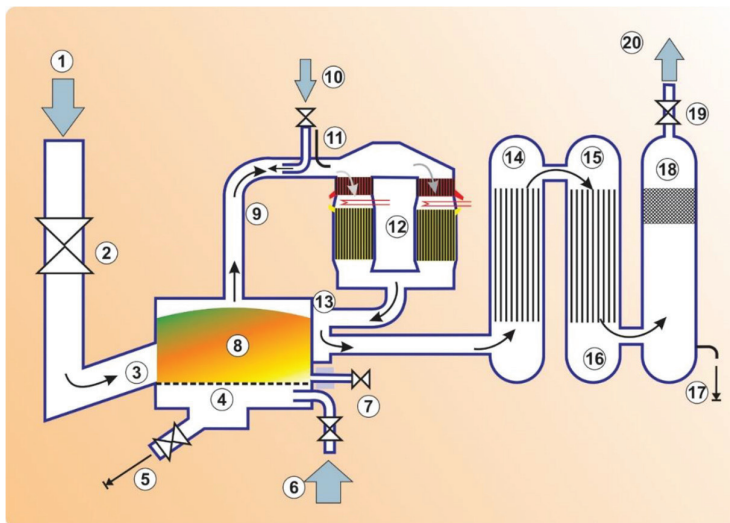
Based on tests on fixed-bed downdraft gasifiers, the prototype gasification line was designed with a new thrusting stream updraft gasifier, which delivers tar rich product gas to the CPOX reactor. Testing at the TRL6 level (System Adequacy Validated in Simulated Environment) lasted from 2015 until 2017. Significant optimization of technology has been achieved. Biomass was primarily used as feedstock for gasification in this period. In 2017, tests on municipal waste were carried out as well. Compared to biomass, mixed wastes 19 12 12 (mix of light and heavy fractions) yielded more optimal results.



**Figure 6:** Prototype gasifier with 600 kW<sub>th</sub> input power

General specifications of the testing device are as follows:

- Grid: 0.7 m<sup>2</sup>
- Input power: 700 kW<sup>th</sup>
- Gasification material consumption: 150–200 kg/h
- Oxidant: air
- Synthesis gas production: 650 Nm<sup>3</sup>/h
- Outputs: Ash: 1 – 40 kg/h,  
Condensate water: 77 kg/h,
- Composition of synthesis gas: CO: 28.6 %,  
CO<sub>2</sub>: 5.8 %,  
CH<sub>4</sub>: 2.1%,  
O<sub>2</sub>: 1.7%,  
H<sub>2</sub>: 20.1 %,  
N<sub>2</sub>: 41,7 %;  
HHV: 7.0 MJ/Nm<sup>3</sup>



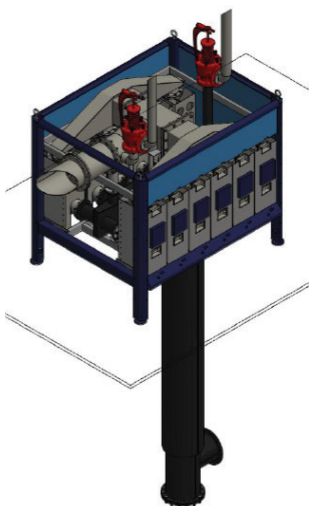
1	Gasification material input	11	Starting gas inlet
2	Cell barrier	12	Catalyst
3	Inlet transportation system	13	Heat exchanger 1 (gas/gasifier)
4	Grid	14	Heat exchanger 2 (gas/air)
5	Ash output system	15	Heat exchanger 3 (gas/water)
6	Air and water inlet	16	Condensate water collector
7	Ignition system	17	Condensate water outlet
8	Gasifier	18	Demister
9	Product gas outlet	19	Main process valve
10	Air inlet for CPOX	20	Synthesis gas outlet

**Figure 7:** Technological line composition

In 2015 and 2016, the CPOX 2400 catalyst system was developed for the Ruše CHP project as an independent unit, which was installed on the gasification line. The gasifier used was an Ankur gasifier with an input capacity of 3.000 kW<sup>th</sup>. The design of the CPOX 2400 was modular, so that it could be easily adjusted for different gas flows. One standard reactor element can process up to 200 Nm<sup>3</sup>/h of product gas. For the Ruše CHP, a system with 12 catalyst units was developed.

CPOX 2400 has an air supply via a rotary vane compressor to assure an independent reaction air inlet. CPOX 2400 can operate in over-pressure or under-pressure mode. The catalyst itself presents a pressure resistance of 20–50 mbar. CPOX 2400 is equipped with a heat exchanger. The product gas is mixed with the oxidant (air) as it enters the reactor. It enters the reactor at 400 °C, reaching up to 800/900 °C in the reactor zone, then dropping to 500 °C in the collector. After exiting the reactor, it passes through the heat exchanger, where it is used to heat the input air, and the temperature drops under 400 °C.





**Figure 8:** CPOX 2400 catalyst device

## 4 WASTE CARBONACEOUS MATERIALS AS FEEDSTOCK FOR GASIFICATION

Gasification is a slow thermochemical process in which materials are heated to 600 °C, which is the temperature at which the majority of hydrocarbons break down. The process is generally determined by the amount of C and H (as well as other contaminants) added to the process, while the structure of the molecules in which the elements are arranged is not of importance. In the case of using waste as the feedstock, the fraction of Cl and S should also be determined. Limitations are presented only by clean materials in the shape of dust, or rapidly combustible materials which must be diluted. Liquid hydrocarbons must be mixed with a solid carrier, such as sawdust or a heavy fraction of waste.

### **Technical conditions for gasification materials preparation:**

- material should be heterogeneous;
- material should be wet;
- density must be 200 kg/m<sup>3</sup> (mix of light + heavy fraction);
- material should be crushed to G50 – G70;
- metals and minerals must be removed as much as possible;
- dust or moisture removal not needed;
- removal of materials with S and Cl elements not needed (according to S and Cl content, the appropriate amount of adsorbent is added);
- separation of fractions by waste type not needed.

**Main parameters of the innovative gasification technology:**

- gasification efficiency: 80% of energy from input materials is converted into chemical energy of syngas;
- outputs consist of inert ash without organic carbon and condensate water;
- no tars, water or particles are present in the syngas;
- according to technical standards from Directive 2010/75/EU, syngas has the same or better purity as natural gas and is classified as a new raw material, even if waste is used as feedstock;
- syngas may be used as technical gas, as energy source or as a feedstock for chemical synthesis of new virgin products (such are synthetic methane, methanol, or FT products);

According to article 42/1 of the Directive 2010/75/EU on industrial emissions (IED), the conditions for a classification as “End of Waste” technology is assured. The implementation procedure of the above statutory provision is determined by the non-paper document prepared by the EU Commission [4]. According to the aforementioned document, the following list of combustible wastes will be tested in the gasification process:

• **Non-hazardous combustible wastes:** 02 01 02, 02 01 03, 02 01 04, 02 01 07, 02 01 09, 02 02 02, 02 02 03, 02 03 01, 02 03 03, 02 03 04, 02 03 05, 02 05 01, 02 05 02, 02 06 01, 02 07 02, 02 07 03, 02 07 04, 03 01 01, 03 01 05, 03 01 99, 03 02 99, 03 03 01, 03 03 02, 03 03 05, 03 03 07, 03 03 08, 03 03 10, 04 01 08, 04 01 09, 04 02 09, 04 02 10, 04 02 21, 04 02 22, 05 01 10, 05 01 13, 05 01 17, 07 01 12, 07 02 12, 07 02 13, 07 02 15, 07 02 17, 07 03 12, 08 01 12, 08 01 14, 08 04 10, 08 04 12, 09 01 07, 09 01 08, 10 01 25, 12 01 05, 15 01 01, 15 01 02, 15 01 03, 15 01 05, 15 01 06, 15 01 09, 15 02 03, 16 01 03, 16 01 19, 16 03 06, 17 02 01, 17 02 03, 17 03 02, 18 01 04, 18 01 07, 18 01 09, 18 02 03, 18 02 06, 18 02 08, 19 02 03, 19 02 06, 19 02 10, 19 03 05, 19 03 07, 19 05 01, 19 05 02, 19 06 04, 19 06 06, 19 08 01, 19 08 05, 19 08 09, 19 08 12, 19 08 14, 19 09 04, 19 09 05, 19 11 06, 19 12 01, 19 12 04, 19 12 07, 19 12 08, 19 12 10, 19 12 12, 20 01 01, 20 01 08, 20 01 10, 20 01 11, 20 01 25, 20 01 28, 20 01 30, 20 01 32, 20 01 38, 20 01 39, 20 01 40, 20 01 41, 20 03 01, 20 03 02 and 20 03 07;

• **Hazardous combustible wastes:** 02 01 08\*, 03 01 04\*, 04 02 14\*, 05 01 09\*, 07 01 11\*, 07 02 11\*, 07 02 14\*, 07 02 16\*, 07 03 11\*, 08 01 11\*, 08 01 13\*, 08 04 09\*, 08 04 11\*, 15 01 10\*, 15 02 02\*, 16 03 05\*, 17 02 04\*, 17 03 01\*, 17 09 02\*, 17 09 03\*, 18 01 03\*, 18 01 06\*, 18 01 08\*, 18 02 02\*, 18 02 05\*, 18 02 07\*, 19 02 05\*, 19 02 08\*, 19 02 09\*, 19 03 04\*, 19 03 06\*, 19 08 10\*, 19 08 11\*, 19 08 13\*, 19 11 05\*, 19 12 06\*, 19 12 11\*, 20 01 26\*, 20 01 27\*, 20 01 29\*, 20 01 31\* and 20 01 37\*;

The need for the heterogeneousness of gasification materials leads to a much simpler waste preparation process, compared to today’s separation methods into fractions or even separate waste types. A new and simpler system of waste treatment could be implemented, employing cheaper methods, leading to a much more effective transformation of carbonaceous materials into new virgin materials. Landfilling of useless wastes and GHG emissions will decrease significantly, and a large part of fossil carbon can be replaced with carbon circulation in a true recycling cycle.

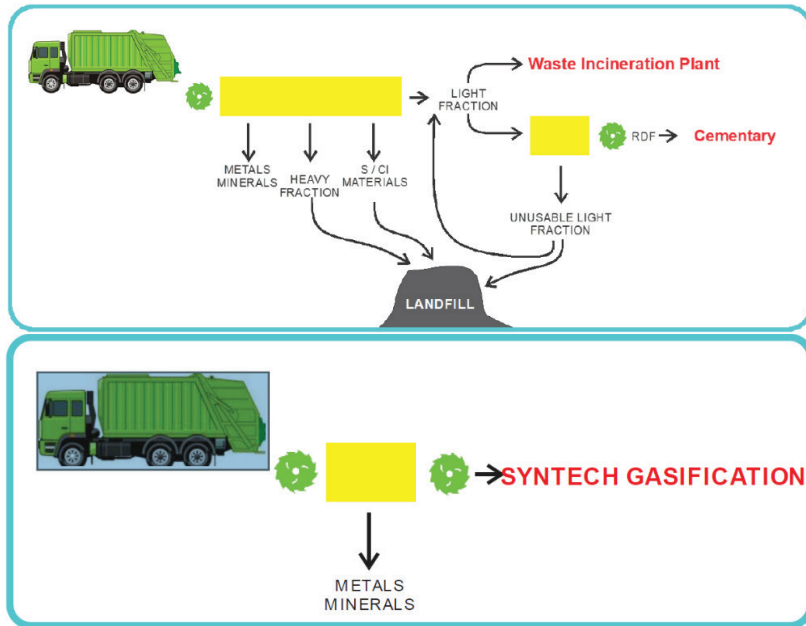
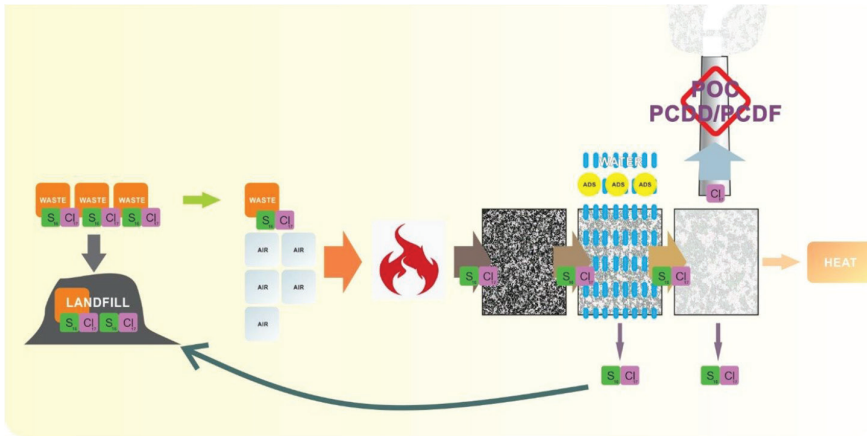


Figure 9: Present waste management versus SYNTECH solution

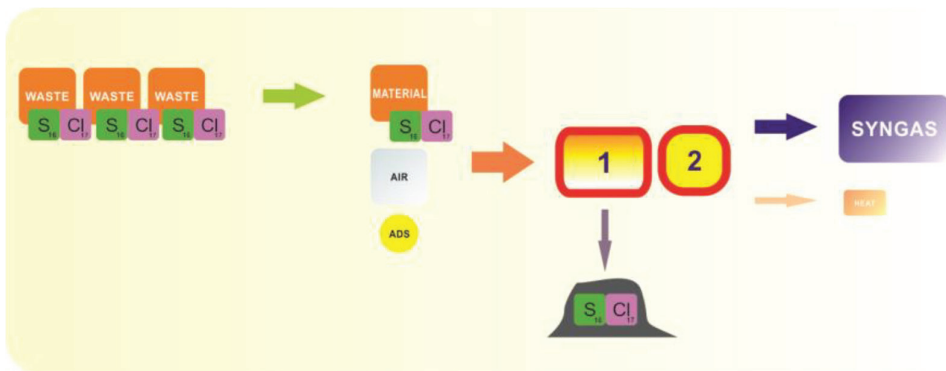
## 5 INCINERATION VS GASIFICATION

Comparing incineration and SYNTECH gasification technology shows significant differences between the two concepts. Combustion is a quick thermochemical process in which a forced air intake is usually used. If combustion is too fast, a part of fuel does not oxidize fully. If the temperature is too low, toxic tar compounds are formed. With stronger airflow, more ash is lifted into the flue gas. However, the main problem is the presence of S and Cl elements, which form aggressive compounds that damage processing equipment, and also cause the formation of toxic compounds due to the so-called de novo formation of PCDDs and PCDFs, [5]. Therefore, incineration has to include very efficient filtering systems, and the process conditions must be managed with great precision and caution.



**Figure 10:** Process scheme of the incineration plant

Before entering the incineration line, materials with S and Cl elements must be excluded from the waste as much as possible. Because of that, many hydrocarbon materials end up in landfills unexploited. Nevertheless, a 1% presence of S and Cl cannot be avoided. For incineration, roughly one part of waste and five parts of air are combined to release heat. After flue gases pass through a heat exchanger, the cleaning process of flue gas consumes large amounts of energy, water, and adsorbents, causing additional hazardous waste.



**Figure 11:** Process scheme of novel gasification

Waste preparation for SYNTECH gasification is much simpler because there is no need for separation of materials with S and Cl elements. For gasification, one part of gasification material and one part of air (if air is used as an oxidant) are mixed in the thermochemical process, which produces lower gas flow compared to the incineration process. Because gasification is a slow process, the reaction between the adsorbent and S and Cl elements can take place in the first step of gasification, producing inert S and Cl compounds, which are removed with ash. In the end, 80% of energy from the input material converts into syngas energy and 10% into useful heat energy. The gasification process causes much fewer waste materials for landfill disposal and no releases into air (practically all gas components in syngas can be separated and used as technical gasses).

Comparing process efficiency, releases from the process, production safety, and costs efficiency between incineration and gasification, the facts are in favour of the gasification process. Comparison of a small incineration facility, [6], and SYNTECH gasification system shows the following:

	Measure	SYNTECH	Incineration
Gasification material	t/year	30,000.00	30,000.00
<b>Investment costs</b>	<b>EUR</b>	<b>15,000.000</b>	<b>19,500.000</b>
Electrical power	MW	4.80	0.80
Thermal power	MW	8.80	9.00
Electricity production	MWh	38,400.00	6,400.00
Heat production	MWh 1/2 year	35,200.00	36,000.00
<b>Efficiency</b>	<b>% acc. to input</b>	<b>47%</b>	<b>27%</b>
Adsorbent consumption	t/year	1,880.00	
Ash	t/year	6,360.00	
Condensate water	t/year	14,448.00	
Selling of electricity	50 EUR/MWh	€1,920,000	€320,000
Selling of heat energy	10 EUR/t	€352,000	€360,000
Waste incomes	85 EUR/t	€2,550,000	€2,550,000
<b>TOTAL INCOME</b>		<b>€4,822,000</b>	<b>€3,230,000</b>

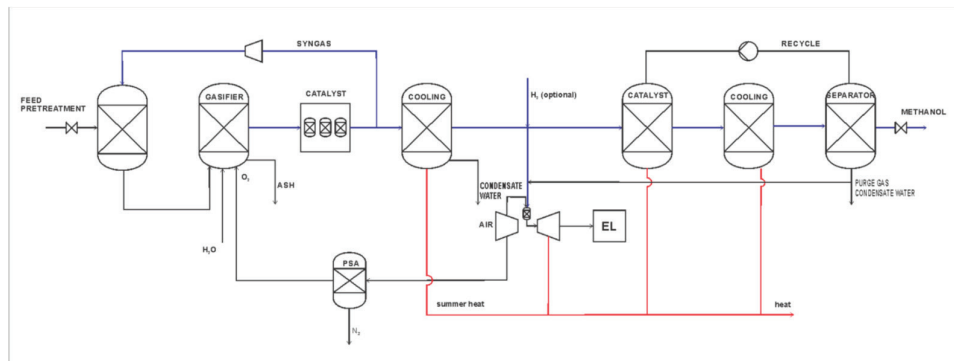
**Table 1:** Comparison of operational parameters between conventional incineration and gasification

## 6 SYNTHETIC METHANOL PRODUCTION STUDY

Energy exploitation of syngas is economically the least attractive option, especially if biomass in the form of dry wood chips is used. The production of synthetic hydrogen or methane is more attractive, but even if alternative fuels such as biomass residues or wastes are used, the production cost is still higher than the price of fossil natural gas. With the production of synthetic methanol, the gasification of biomass residues and wastes becomes profitable without subsidy on the product side. Synthetic methanol also has an important advantage: it is in liquid form, so it is easy and safe to handle and store. With synthetic methanol production, the circulation of carbon materials is closed, as a wide range of different virgin hydrocarbons can be produced, as predicted by the methanol economy.

A pilot project study for synthetic methanol production in a small-scale facility, [7], predicts an annual consumption of 140,000 t of alternative gasification material, of that 40,000 t of solid waste of various origin and 100,000 t of biomass restudies. The energy value of gasification

materials is 560,000 MWh. The input power of the high-pressure gasification line is 80 MW<sup>th</sup>. In 7,000 operational hours per year, 154,000 t of clean syngas is produced from which 67,000 t of methanol is synthesized. A 6 MW electricity power station is installed for the line's consumption (engines or gas turbine).



**Figure 12:** Process diagram of synthetic methanol production

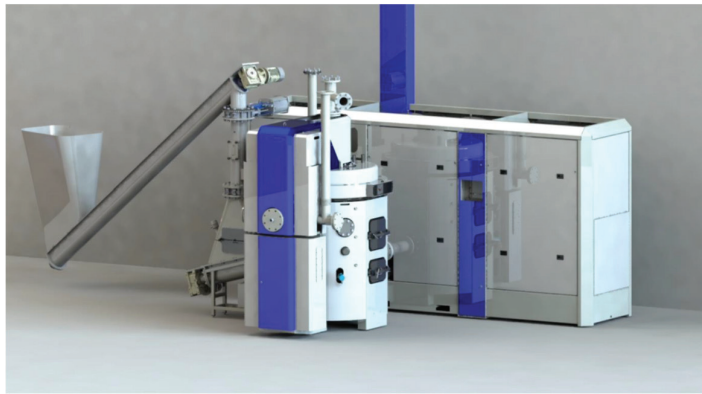
Total investment costs should be €97.5 million or €1,223.75 EUR per 1 kW<sup>input</sup>, which are, according to ECN's economic study, very competitive costs, [8]. The annual revenue is €28 million, with total production costs of €13 million. The entire plant can operate with 30 staff. The amortization period is 20 years. If ROI is set at seven years, the product price (raw synthesis methanol) should be €354.62/t.

Despite the favourable economic picture, some benefit from the CO<sub>2</sub> emission market should be included in the synthesis methanol price: 1 t of synthetic methanol from carbonaceous materials from sustainable sources results in a 1.62 t CO<sub>2</sub> emissions reduction;

#### Pilot project specifications:

- Input material:
  - Various waste materials: 40,000 t/year
  - Biomass residues: 100,000 t/year
- Nominal power of gasification device: 80 MW<sup>th</sup>;
- Input capacity: 20 t of raw material/h
- Synthetic methanol production: 67,000 t/year
- Heat energy production: 67,000 MWh/year
- Energy consumption for operation: 44,800 MWh/year
- Adsorbent consumption: 2,520 t/year
- Process outputs:
  - Inorganic ash: 18,000 t/year
  - Condensate water: 67,000 t/year
- Process CO<sub>2</sub> emissions: 186,057 t/year
- Investment costs: €97,900,000
  - Gasification technology: €32,000,000
  - Oxygen plant: €6,800,000
  - Methanol synthesis: €40,600,000
  - Electrical energy production: €6,000,000
  - Waste preparation equipment: €5,000,000

- Location and buildings: €3,000,000
- Engineering and documentation: €4,500,000
- Price for acquiring waste: €85.00/t
- Biomass price: €74.55/t
- Planned synthetic methanol price: €350/Sm<sup>3</sup>
- Heat price: €10 /MWh
- Number of job positions: 30
- Duration of the project: 20 years
- Average annual revenue: €27,000,000
- Average annual expenses: €13,500,000
- Amortization: €4,800,000



**Figure 13:** Demonstration gasifier T2-800 with input power of 800 kW<sup>th</sup>

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