FTI Initiative Energy Model Region

Publishable final report

Programme control:

Climate and Energy Fund

Programme management:

The Austrian Research Promotion Agency (FFG)

Final Report

created on

30/06/2025

Project title: TCP_to_Industry

Project number: 880745

Call	3rd Call FTI Initiative Energy Model Region
Project Starting Date	01/02/2024
Project Ending Date	31/01/2025
Total duration of project (in months)	48 Months
Project holder (Institution)	Chair of Energy Network Technology, Montanuniversität Leoben
Contact person	Univ.-Prof. Dipl.-Ing. Dr.techn. Thomas Kienberger
Postal address	Franz-Josef-Straße 18, 8700 Leoben
Telephone	+43 3842 402 5400
Fax	
E-mail	evt@unileoben.ac.at
Website	https://www.evt-unileoben.at/de/

TCP_to_Industry

Thermal Cracking Process for Energy Recovery to Industry

Authors:

Julia Vopava-Wrienz, Ahmad Fayyaz Bakhsh, Alexander Cont, Benjamin Engelhart, Thomas Kienberger (Montanuniversität Leoben)

Christine Öhlinger (OÖ Energiesparverband)

Jürgen Secklehner, Anton Secklehner (seccon GmbH)

Christoph Resl (WSA - Waste Service GmbH)

Table of content

List of Figures

List of Tables

1 Introduction

To achieve national and international climate targets, global CO_2 emissions must be significantly reduced. In Austria, more than two-thirds of all CO_2 emissions are currently generated by the energy supply and consumption across various economic sectors, including industry, residential buildings, and transportation [1]. About one-third of the total Austrian primary energy consumption (approx. 140 TWh/a) is caused by industry [2]. Consequently, reducing industrial primary energy consumption is a key priority in the transition to a climate-neutral economy. One of the most promising approaches to achieve this is the application of advanced process integration methods, such as exergy analysis, which allow for a more efficient and targeted use of energy.

Within this context, the industrial heating sector plays a central role, as approximately 90% of heat generation worldwide was still based on fossil energy sources in 2018 [3] Decarbonization of this sector can be effectively driven by three main strategies: improving process efficiency, integrating renewable energy sources, and utilizing waste heat. Although waste heat is already being reused in some industrial processes or district heating networks, a substantial amount remains unused due to technical, infrastructural or spatial restrictions. This may occur, for example, because the internal reuse potential has been exhausted or there are no suitable consumers nearby. Unlocking this unused waste heat potential could therefore play a major role in reducing both energy consumption and CO_2 emissions in the industrial sector.

Additionally, circular economic approaches offer the potential for reducing both the use of primary energy and the associated emissions. By processing recyclable materials, primary raw materials as well as primary energy can be saved if more energy is required to extract primary raw materials than to process secondary raw materials. Recyclable materials are processed using mechanical, chemical or thermal processes. Mechanical processes usually deliver products with a poor degree of purity, whereas chemical and thermal processes are energy-intensive and increase the process costs and emissions generated. Ideally, waste heat can be used for thermal processes. [4]

This is where the “TCP_to_Industry” research project comes in. In addition to the practical testing of seccon GmbH's patented process, the research project focuses on the development of a comprehensive energy model. The patent submitted by seccon for a “Process for recovering recyclable materials from recycling materials” describes a thermo-chemical process in which waste is thermally processed. The thermo-chemical process takes place in a rotary kiln. The heat required for this is obtained from a nearby industrial production plant that generates waste heat. This is intended to guarantee cost- and emission-efficient processing of recyclable materials using waste heat, which would otherwise remain unused. [5]

<u>The project pursues three main objectives:</u>

1. Integration and operation of a novel thermo-chemical process based on the patent of seccon GmbH on a laboratory scale (small-scale demonstrator, SSD) and investigation of the scale-up to a large-scale demonstrator (LSD)

2. Energy system modelling and optimization of the thermo-chemical process as well as the integration concept under various technical and economic boundary conditions to determine optimal operating strategies and improve overall energy efficiency
3. Systemic and techno-economic assessment including the quantification of potential savings in energy consumption, CO_2 emissions and transport efforts

The technical implementation focuses on the SSD, whose operation is based on various waste fractions such as coffee capsules, printed circuit boards, biomass and fibre composites. Based on the operating experience gained in the pilot plant, a detailed energy model was developed that depicts the pyrolysis process and determines the optimum operating point in terms of exergy - considering technical boundary conditions such as waste heat availability, energy requirements for material processing and product purity.

A key outcome of the project is the development of a systemic energy model that covers both the technical configuration and the operational restrictions of the SSD. This model is used to analyse various operating scenarios in which, among other things, the influence of different seasons, energy prices and process conditions on the energy consumption and economic efficiency of the process is investigated. By combining real process data, techno-economic modelling and scenario-based optimization, significant potential for increasing energy efficiency, lowering operating costs and reducing CO_2 emissions was demonstrated.

The methods and findings developed in the project enable a transferable exergetic integration strategy. This means that the thermo-chemical process can be efficiently transferred from the small-scale demonstrator to large-scale demonstrator and integrated into industrial energy systems. The project thus makes an important contribution to the sustainable scaling of the technology.

2 Challenges in recycling composite materials and low-grade waste streams

There are several techniques as state-of-the-art methods for recycling composite materials and low-grade waste streams. In the following section, 3 more used techniques will be explained. Moreover, microwave-assisted pyrolysis, which is still in the first steps and not industrialized yet, will be explained as well.

2.1 Thermal utilisation of organic waste streams

Thermal utilization of organic waste streams is known for the controlled combustion of organic materials, such as biomass, plastics, food waste, and the resin matrices in composite materials like carbon fibre-reinforced polymers and glass fibre-reinforced polymers to recover energy in the form of heat, which can be reused in the process or for external applications. [6] This method transforms waste into a valuable resource, particularly to fulfil all requirements (e.g., legal requirements, burn abilities, fineness, etc) of various industries and significantly reducing reliance on fossil fuels. A notable technique within thermal utilization is fluidized-bed combustion, where waste is burned in a suspended bed of particles (e.g., sand or ash) fluidized by an upward flow of air, ensuring efficient combustion, uniform temperature distribution, and effective heat recovery, especially for recovering fibres from composites like fibre-reinforced polymers and glass fibre-reinforced polymers. [7]

In general, there are two pathways to thermally utilize waste: typical incineration (e.g., municipal waste), which mainly serves disposal purposes and where the heat is directly used or converted to electricity, and co-incineration (e.g., cement industry), which fulfils different tasks like substitution of raw materials. In Austria, the disposal of the 4.45 million tonnes of municipal waste from households breaks down as follows: 43% thermal utilisation, 27% biological treatment, 27% material recovery and 3% treatment of problematic substances (e.g. batteries). The latter three pathways also involve high shares of thermal utilization resulting overall in about 87% for the residual and bulky waste being thermally utilised. [8]

Various industries such as the cement industry, brick industry, iron and steel production, chemical industry, power plants or concrete plants are customers for the utilisation of waste as fuels [8,9]. According to Lorber et al. [10], in the past, substitute fuels in Austrian co-incineration are mainly used for fluidised-bed plants and cement plants. In contrast to that, in Germany special substitute fuel plants, cement plants, coal power stations and industries with high heat or steam requirements, like the paper industry, are the main application pathways [11]. In recent years, in Austria, substitute fuels, such as solid recovered fuel (SRF), refuse-derived fuel (RDF), biomass, and sewage sludge, are predominantly used in cement plants, achieving thermal substitution rates of up to 80–100%, and in fluidised-bed plants for waste-to-energy, with additional applications in other industrial and dedicated incineration facilities such as paper and pulp industry, chemical industry, steel industry, power generation, etc. to support decarbonization and circular economy goals. [12–16]

Depending on the process, different types of waste might be used. The Austrian cement industry, for instance, uses them for several purposes. The main purpose is the utilisation as substitute fuels (e.g. plastic waste, waste oil, old tires). Thereby a positive side-effect is, that ashes of the substitute fuels can reduce the use of raw material (mainly $CaCO_3$). Another purpose can be the direct substitution of raw materials (e.g. slag, building rubble instead of $CaCO_3$). In 2018 about 81 % (3 122 GWh) of the thermal use of energy of Austrian cement production were gained by substitute fuels [17,18]. In Austria, the brick industry mainly uses substitute raw materials like sawdust, oilseeds or waste of the pulp- and paper industry whereas the building materials industry uses different sort of ashes (e.g. fly ash), recycled building materials or moulds [19].

Germany also utilises its waste in thermal processes. The Umweltbundesamt (UBA) [20] states that the average efficiency for the utilization of municipal waste in all incineration plants is about 50%. All 68 incineration plants have a combined capacity of 19.8 million tonnes municipal waste per year. Furthermore, Germany also runs about 30 substitute fuel plants with a capacity of 4.7 t/a of substitute fuels and therefore enables the reduction of conventional fuels. Similar to Austria, in 2014, the German cement industry achieved substitution rates of up to 75% [21].

When talking about incineration, it is necessary to distinguish between mono-incineration and co-incineration because the latter requires a higher quality and homogeneity of waste as well as the consideration of lower emission limits [4]. If the process's purpose is disposal, waste can directly be fed from the bunker into the combustion chamber of grate firing systems and rotary kilns. For the use of waste fuels within fluidised beds, crushed or grinded waste is necessary [22]. For co-incineration in power plants different methods are available. One of them is pyrolysis. Another often applied method is to utilise substitute fuels by means of a circulating fluidised bed boiler. The concrete industry mainly uses rotary kilns, some also use gasification units, installed up-stream [21]. Co-incineration in the steel industry might be realised by blowing the material into the blast furnace or with a primary gasification and blow in reduction gas [23]. Deeper insight to firing technologies is given in [4], [22] or [23].

All incineration processes generate useful heat but also residues like ashes and unusable waste heat, which causes efficiency losses. For instance, more than 28% of the energy-input of Austrian's cement production remains as unusable waste heat [24]. According to [25], overall energetic efficiencies of only maximum 70% are achieved by German cement plants, while substitute fuel plants show even lower overall efficiencies of about 50%, depending on the produced form of energy (e.g. steam, electrical energy). The lowest overall efficiencies are obtained by waste-incineration plants (below 40%), although rates up to 80% can be achieved if the only output is steam instead of electricity [26]. Recent developments in this area, including fluidized-bed combustion, increased the efficiency, although it is limited to specific materials. To be more specific, catalysts like CuO can reduce processing time and energy use, enhancing heat recovery, while better control of fluidized-bed combustion conditions helps to recover the tensile strength of carbon fibres, which is of actual importance for most of its target industries. [27]

Beside unusable waste heat, waste incineration results in different residues such as metals, sulphur, or chlorides. The share of solids to be reused as construction materials or even be recycled (e.g. metal), is significant [28]. For example, 1.2 million tonnes of waste-incineration residues in Austria in 2017 were used to substitute 140 000 t of raw materials for cement production [19].

2.2 Thermal cracking processes of organic waste streams

Organic waste stream thermal cracking is the thermal breakdown of materials to yield useful gases, liquids, and solids, in an oxygen-free or oxygen-starved state. The feed materials can include organic materials, including plastics, rubber, biomass, and resin matrices in composite materials, such as glass fibre-reinforced polymers and carbon fibre-reinforced polymers. Unlike in thermal utilization, where combustion is utilized to recover energy in form of heat, thermal cracking utilizes chemical conversion-based processes like pyrolysis and gasification, which tend to recycle heat produced in the process for maintaining the endothermic reaction or for outside uses. Organic matter breakdown with minimal oxygen or other reactive components is known as pyrolysis and represents a key process in thermal cracking [4]. Several raw materials can be treated in pyrolysis reactors using different types of pyrolysis, i.e., fast, catalytic fast, medium, slow, and vacuum [29].

The German Umweltbundesamt [30] states that mainly medium to slow pyrolysis processes along medium to high temperatures (350–900 °C) are used for the thermal utilisation of waste. They also highlight advantages of pyrolysis compared to incineration like the efficient use of pyrolysis residues, such as oils or ashes, and lower emissions. Another big benefit of pyrolysis compared to incineration is, that no dioxins are formed. The challenge within pyrolysis, although, lies in making it economically viable because current technologies are still more expensive than incineration technologies [4,29,31]. One prominent subtype of pyrolysis is microwave-assisted pyrolysis (MAP), which heats waste using microwave energy to achieve faster processing times and lower energy consumption. Although MAP is still in the early testing stages and not yet prepared for widespread use, it is especially effective at recovering fibres from composites like CFRP and GFRP.

Pyrolysis is an endothermic process in which materials are decomposed by phase transformations and chemical reactions in an oxygen-poor atmosphere. The end products of pyrolysis include pyrolysis gas from non-condensable gases, pyrolysis oil, and carbon-rich residues. Temperatures between 350 and 500 °C favour the formation of pyrolysis oil. As temperatures continue to rise, the molecules of the solid and liquid residues are broken down into smaller components that enter the gas phase. The yield of pyrolysis products from a wide variety of starting materials can be optimized by changing the process conditions. Low temperatures and slow heating rates increase the yield of solids. Higher temperatures, slower heating rates, and longer gas residence times lead to an increased amount of pyrolysis gas. The production of liquid pyrolysis products is favoured by medium temperatures, fast heating rates, and short gas residence times. [32] Table 1 summarizes the more detailed process information on typical products obtained by different pyrolysis methods. The percentage distribution of yields can also be approximately applied to the materials investigated in this work.

Table 1: Typical product yields in the conversion of biomass [33]

Process	Temperature [°C]	Heating rates [°C/s]	Solid phase [%]	Liquid phase[%]	Gaseous phase[%]
Fast Pyrolysis	600 - 800	10 - 200	12	75	13
Slow Pyrolysis	300 - 500	< 1	35	30	35
Gasification	650 - 1200	1 - 100	10	5	85

There are several types of pyrolysis studied by researchers in recent years. Hasan et al [34]. studied the energy recovery from municipal waste by using pyrolysis technology. Their review compared the reactor type used for the pyrolysis of different components. They showed that there are plenty of reactor types that can be used for each municipality, such as fixed bed, fluidized bed, hybrid, auger and microwave, etc. The selection of a reactor depends on the type of municipal solid waste and the required temperature of the used reactor. Figure 1 illustrates six different types of pyrolysis reactors that are commonly discussed in the literature, highlighting their technical design and process flow.

Zhou et al. [35] and Satiada et al. [36] also discuss state of the art technologies and remark, similarly to [31], that pyrolysis can be part of combustion-melting systems, stand-alone concepts or preliminary procedures (e.g. ConTherm Technology). In combustion-melting systems, both, pyrolysis gas and coke are burnt above the ash-melting temperature, causing a liquid slag to be removed at the bottom of the reactor. Sometimes metals are also separated within these technologies. The Siemens Schwel-Brenn Technology, is only one example for such systems, which aim for a complete conversion of waste to energy. Stand-alone technologies, like Destrugas oder Pyreg, mainly focus on the use of pyrolysis gas in burning chambers or steam generators and do not further convert pyrolysis coke and ash [30,31]. Extensive information on pyrolysis technologies used in pilot, demonstration and industrial plants can be found in [30] and [31].

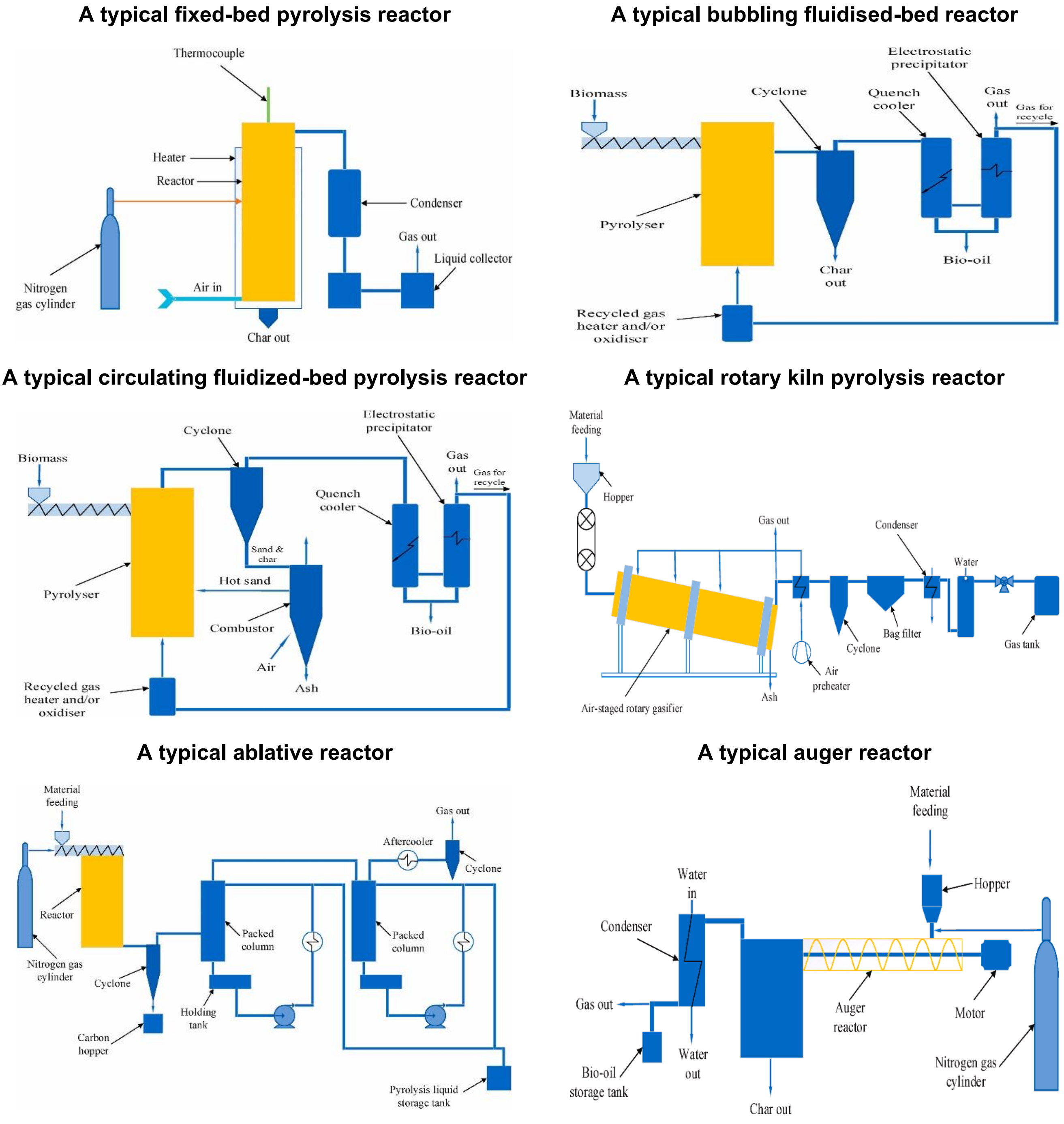

Figure 1 Different types of reactors in pyrolysis [34]

Regardless of all pyrolysis technologies mentioned so far, good quality of the raw material (particularly any material which includes organic carbon) is decisive for its economic success [29,30].

After appropriate processing, the pyrolysis gas can be processed into syngas, which is used in engines, turbines, or industrial combustion plants. Compared to biotechnologically produced biogas, pyrolysis gas has a lower methane content. Pyrolysis oil can be used in diesel engines and decentralized power generation systems, as well as in large power plants as a substitute for heating oil. Despite its potential, liquid pyrolysis products are still underutilized in industry due to challenges such as their limited fuel quality, high viscosity and corrosiveness, and low stability and sustainability. Pyrolysis also produces between 10 and 35% solid carbon-rich residues, which, depending on their composition, can be used in various industrial applications, such as fuel for boilers. When selecting biomass for pyrolysis, certain requirements must be met to ensure maximum process efficiency. The following factors have a significant influence on the pyrolysis yield: [33]

- **Moisture content (MC):** A distinction is made between inherent and external moisture. Inherent moisture refers to the moisture content of the biomass, which is not affected by atmospheric conditions, in contrast to external moisture, which depends on external influences such as the weather. A high moisture content promotes the pyrolysis process, but the efficiency of pyrolysis is impaired because additional energy is required to evaporate the water.
- **Calorific value (B):** The calorific value describes the maximum amount of energy that can be released during the complete combustion of a fuel, including the latent heat generated by the condensation of water vapor from the fuel and the combustion gases. The higher the calorific value, the faster the pyrolysis process.
- **Fraction of fixed carbon (FC) and volatile matter (VM):** The content of volatile matter in a solid fuel refers to the proportion that is released as gas when heated. The bound carbon content comprises the mass of the fuel remaining after the release of the volatile components, minus ash and moisture. Both factors influence the rate of ignition and the subsequent gasification or oxidation of the fuel. Elemental analysis, which includes the contents of oxygen (O), hydrogen (H), carbon (C), nitrogen (N), and sulphur (S), shows that a higher oxygen content compared to the carbon content reduces the heat of combustion of the fuel, as the energy yield is lower due to the higher oxygen content. A high content of volatile components and carbon, combined with a low oxygen content, is desired.
- **Ash content:** When a fuel derived from biomass decomposes through thermochemical or biochemical processes, a solid residue is produced, which is called ash. The ash content of the biomass significantly influences the overall cost of energy conversion; accordingly, the ash content should be as low as possible.
- **Alkali metal content:** Since a high alkali metal content promotes the formation of slag, a low alkali metal content is desirable.
- **Cellulose/lignin ratio:** Cellulose decomposes at lower temperatures than lignin. Therefore, the total conversion of the carbonaceous plant mass is higher with high cellulose content than with plants with a higher lignin content. A high cellulose content and a low lignin content are therefore advantageous.

The content of cellulose, hemicellulose, and lignin in the biomass composition significantly influences the pyrolysis properties [37,38]. The yield of the liquid pyrolysis product increases with increasing cellulose content of the biomass. The amount of pyrolysis gas depends strongly on the hemicellulose content, while the proportion of solid residues in the pyrolysis products is predominantly determined by the lignin content. [33] The degradation of hemicellulose occurs in the temperature range of 220–315 °C, while cellulose is decomposed between 300–400 °C. Lignin, on the other hand, is degraded over a wider temperature range of 160–900 °C. The thermal decomposition of cellulose, hemicellulose, and lignin produces a gas mixture whose composition consists primarily of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), and light hydrocarbons. Pyrolysis generates syngas and oils that can produced into chemical feedstock, such as olefins to produce plastic, and refined to sustainable jet fuel. Unlike combustion, pyrolysis causes less emission, while enabling resource recovery. [39–41]

A high proportion of hemicellulose in the biomass contributes to a higher CO_2 concentration, while a high proportion of cellulose promotes the formation of carbon monoxide. To increase the release of hydrogen and methane, the reactor temperature should be above 800 °C. Hydrogen is mainly formed by the condensation of aromatic compounds or the alkyl aromatization reaction during pyrolysis at temperatures above 500 °C. [32]

The influence of biomass particle size on the pyrolysis and gasification products shows that smaller particles (0.15 to 0.5 mm) lead to a higher concentration of gaseous products because their larger specific surface area per unit mass improves heat and mass transfer. This more efficient exchange promotes the reaction rate and increases the gas yield while decreasing the formation of solid residues. In contrast, the use of larger particles (1 to 5 mm) leads to a higher temperature gradient within the particles, thus keeping the temperature inside lower than at the surface. This favours the formation of solids while decreasing the gas fraction. Furthermore, the thermal decomposition of larger particles contributes to the emission of methane, ethylene (C_2H_4), and carbon monoxide. Furthermore, the heat of combustion is highest for particles 3 to 5 mm in size, indicating a more intense reaction. [33]

2.3 Secondary raw material processing

Secondary raw materials form a key component of the raw material base for many industry sectors. By secondary raw materials, the consumption of primary raw materials is significantly reduced, which in most cases are non-renewable. This technique equally replaces and facilitates technological processes in the production of various materials, resulting in a reduction in energy and material demand for products [42].

Thermal integration secondary raw material processing is the use of heat to separate organic materials from composite waste streams, such as the resin matrices of carbon fibre-reinforced polymers, glass fibre-reinforced polymers, and homogeneous polymer waste, followed by sorting and post-treatment to recover valuable materials for re-use. It is the combination of thermal separation processes, often derived from thermal cracking processes such as pyrolysis, with mechanical and chemical processing, while recycling heat produced in separation to enhance efficiency and sustainability.

A challenge in recycling processes is the large number of composite materials. As these materials include various material mixes as well as mechanically and chemically interlocked compounds, a separation into homogenous fractions can be complex. Therefore, mostly mechanical methods are used. Common methods for separation into fractions after crushing are classifying by particle size or separating by electrical, magnetic or density properties. Depending on the materials in the mix, other methods could be used additionally. Following the separation-step, contaminations of the valuable substances, e.g. with organic matter, need to be addressed. Failing to refine the materials will reduce the value of the waste materials. For reuse as secondary raw material, it is necessary to further improve the chemical purity. To achieve this, post-treatment is often required. This post-treatment can include rerunning some mechanical separation steps, which might improve chemical purity. Other methods, e.g. chemical separation or carbonisation are also used. These methods usually require substantial effort like additional energy input. Additionally, a loss of valuable waste material often is inherent, following abrasion of insufficient separation of contaminations. [43] More recent advances have raised the effectiveness and efficiency of the processing of secondary raw materials. For example, chemical post-processing with hot NaOH after thermal separation can achieve up to a 75% recovery of the strength of carbon fibre-reinforced polymers, and recovered fibres are more adequate for reapplication in new composites [27]. Besides, there have also been developments to utilize the heat generated in the step of separation to a greater extent, reducing the cost of energy and enhancing sustainability [44]. Despite these benefits, the process faces vulnerability to contamination, loss of quality during sorting, and limited applicability in some plastics due to thermal degradation [27]. Environmental problems, such as thermal separation emissions, and economic problems, such as energy costs being too high for post-treatment, need to be addressed to make this process more viable for commercial application [45].

Table 2: Summarized factors of different types of state-of-the-art methods for recycling composite materials and low-grade waste str

Method	Core Process	Application	Advantages	Disadvantages	The latest improvement	Ref
Thermal Utilization	Controlled combustion to recover energy	For mixed waste with high calorific value, Food packaging	Energy recovery	High emission, and limited material recovery	Catalysts like CuO reduce processing time and energy use, enhancing heat recovery. Fluidized bed combustion (more heat efficiency and less NOx emission)	[46,47]
Thermal Cracking	Breaking down waste with heat (Pyrolysis and gasification)	Polymers, rubber, biomass	Valuable chemical recovery, and handles mixed waste, lower emission	Complex product streams, cost	Microwave-assisted Pyrolysis, and catalytic pyrolysis using novel zeolite catalysts, flash pyrolysis techniques that make the system able to reach 800°C temperatures in seconds (treatment of hazardous materials), and combined pyrolysis-gasification	[7,48–51]
Secondary Raw Material Processing	Thermal separation (pyrolysis followed by Mechanical sorting and processing	Clean, and homogeneous waste streams	Low energy input, and direct material recovery, high applicability in wide ranges of materials, but limited for thermosets	Highs sensitivity to contamination, quality degradation	Chemical purification to remove contaminations of recycled materials, AI-powered sorting systems with 99.9% accuracy for complex waste streams. Chemical purification to remove contamination of recycled streams.	[52–54]

3 Technical Implementation and operation of the novel thermo-chemical process

As part of the project, a comprehensive concept was developed for the integration and operation of the innovative thermochemical process based on the seccon GmbH patent for the recovery of recyclable materials from waste streams. The concept was successfully implemented in a technical Lab and validated under real operating conditions. The key element of the concept, the small-scale demonstrator (SSD), serves as a modular pilot plant for the recovery of high-quality materials from recyclable materials, in particular aluminium coffee capsules. The aim is to establish a scalable process for sustainable material recycling and emission reduction.

3.1 Overall technical concept and main components of the system

The technical concept has a modular structure and consists of several coordinated functional areas. The modular components can be adapted to different input materials and process conditions without complex modifications. In practice, this should make it easy to switch between different waste streams such as coffee capsules (made of plastic and aluminium), printed circuit boards, tinplate or beverage cans. To prepare the input material for thermo-chemical processing, two industrial shredders are installed to ensure that the material is coarsely shredded. A feed unit with dosing box enables controlled material feeding. A coarse screen and a drum screen are available for fractionation according to grain size. An optional metal separator (FE/NE) can be integrated to remove coarse metal parts or battery residues before the thermo-chemical process. The central processing unit is an electrically heated rotary kiln, also called small-scale demonstrator, with a process volume of 400 litres. The system measures 5 000 mm in length, 1 200 mm in width and 2 500 mm in height. Eight separately controllable heating zones enable precise control of the temperature profile in the range of 50-950 °C. A specially configured screw conveyor ensures continuous and uniform feeding. To comply with Technical Instructions on Air Quality Control (German: Technische Anleitung zur Reinhaltung der Luft) and European environmental standards, the process gases are collected after thermo-chemical treatment via an optimized exhaust air system and fed into the post-combustion process. This oxidizes organic residues from the process gases. In addition, emissions (CO, NO_x, VOC) are continuously monitored via external measuring points and sensors in the control system. In addition, after thermochemical processing, the output materials are separated using screening systems and air classification. Post-cleaning systems (e.g. electrostatic separation, washing, drying) have been installed for certain fractions (e.g. aluminium, plastic).

Furthermore, the technical lab is equipped with a central control system to monitor and optimize the technical concept and the thermochemical process. The integration of numerous sensors (temperature, humidity, throughput, energy consumption) enables precise process control and the continuous recording of all operating data.

3.2 Use Case: coffee capsules

The focus lay on the processing of coffee capsules with the aim of achieving output streams that are as pure as possible, in particular pure aluminium or pure plastic by removing coatings and organic residues as well as recovering the coffee grounds for possible reuse.

After commissioning the plant, systematic test series were carried out to determine a suitable process setup. The focus lay on determining the optimum process parameters and identifying the factors influencing the output purity. The process temperature, the residence time in the rotary kiln and the moisture content of the material proved to be particularly critical. A two-stage treatment process was developed to react to the high moisture content in the input material. In the first phase, the coffee capsules are dried in the rotary kiln. In the second phase, the actual thermo-chemical treatment takes place in the rotary kiln. Despite the double thermal processing, the overall energy consumption was reduced, as the residence time in the second process step was shortened and the temperature could be controlled more precisely. This had a positive effect on the purity of the separated fractions.

Other quality-determining factors were the degree of comminution of the input materials, the exact temperature control during processing, the selection of suitable screen cuts and the effectiveness of the mechanical post-cleaning. In order to improve this, the plant technology was continuously developed further. For example, a non-ferrous separator was integrated to remove impurities such as batteries at an early stage. A second shredder improves the homogeneity of the material flow prior to thermo-chemical processing. Furthermore, the exhaust air technology was optimized by installing a cyclone and an additional fan. The conveyor technology was also revised, including by adapting the screen sections, using an infeed conveyor belt and integrating an internal buffer container. To increase the separation quality in the post-treatment, a non-ferrous separator was used, which effectively separates aluminium, plastics and organic components.

3.3 Scalability and Exploitation

The technical concept and the modular design of the existing pilot plant have proven to be future proof over the course of the project. The SSD is currently operated in a single-shift system with a throughput of 3 to 5 tonnes aluminium coffee capsules per week. In the medium term, the aim is to achieve an annual capacity of up to 250 tonnes. The pilot plant is not only used for ongoing operations, but increasingly as a research and development centre on which the concept is continuously developed and prepared for stable, long-term operation. The focus here is on the complete digitalisation of all process modules, the further development of an effective post-cleaning concept for contaminated plastics and a planned stress test in continuous operation over several days.

At the same time, preparations are being made for scaling up to an industrial scale. The operating experience gained from the SSD forms the basis for the planning of large-scale demonstrator. Initial preliminary studies for new sites in Austria and Central Europe are already well advanced. A possible start of construction is realistic for 2026 or 2027, subject to official approvals. Until then, the existing pilot plant will continue to serve as a test environment for optimising processes and interfaces.

A promising approach to industrial integration can be seen in the cement industry. A central component of the integration concept is the utilisation of the waste heat produced in the cement plant. This can be used directly to supply energy to the thermo-chemical processes, which significantly reduces the additional demand for primary energy. The thermal coupling of both systems therefore not only enables ecological synergies but also makes a significant contribution to the efficiency and cost-effectiveness of the overall approach.

In the long term, the aim is to implement regionally distributed plants with an annual capacity of up to 30,000 tonnes. Depending on the location, these should be able to process different waste streams. Specialisation in certain material groups - such as aluminium capsules, beverage cans or printed circuit boards - is likely. However, the flexible process management means that several materials can also be processed at one site, for example in alternating operation adapted to seasonal energy requirements. The technical concept follows a ‘thermo-mix’ approach: a specific process window is defined for each material, which can be customised based on the research results.

The development of suitable recycling paths for the output fractions is also progressing. The aluminium contained in the capsules is being recycled and remelted in Austria. Based on successful laboratory tests, the first industrial trials are planned for 2025, in which new aluminium capsules are to be produced from it. Innovative recycling solutions have also been developed for the organic residues produced, in particular coffee grounds. For example, a high-quality soil conditioner is produced from this, a biodegradable oil binder is about to be launched on the market and initial tests to produce a bio-based furniture material are underway. As in the technical concept (chapter 3.1), the SSD (rotary kiln) is also the key element in the energy system model.

4 Energy system modelling and optimisation

The following chapter presents the overall energy system model, which is used to systematically determine an exergetic optimized integration concept for the novel thermo-chemical process. The aim is to determine the optimum operating point of the overall system, considering defined framework conditions such as available waste heat potential, specific energy requirements for material processing and the required output quality. The structure of the overall model developed, the input parameters used, and the selected calculation scenarios are explained below. In each of these scenarios, a conventional operating mode and a cost-optimized control approach are compared by simulation. Finally, the simulation results are discussed.

4.1 Methods

To develop the energy system model, the system boundaries and requirements were first defined to identify relevant input and output streams as well as key parameters. The model focuses on the novel thermo-chemical processing of secondary raw materials, which is operated with industrial waste heat. This thermo-chemical process is a pyrolysis process carried out in a rotary kiln. An essential aspect of the modelling approach was to consider the chemical reactions that take place during the thermo-chemical processing of the secondary raw materials as accurately as possible. At the same time, particular attention was paid to the optimal use of the energy sources electricity, waste heat and gas, with a focus on the substitution of fossil gas. As a result, a comprehensive overall energy system model was developed, based on three main components as shown in Figure 2: (1) Aspen Plus model, (2) interface and neural network, (3) optimization model.

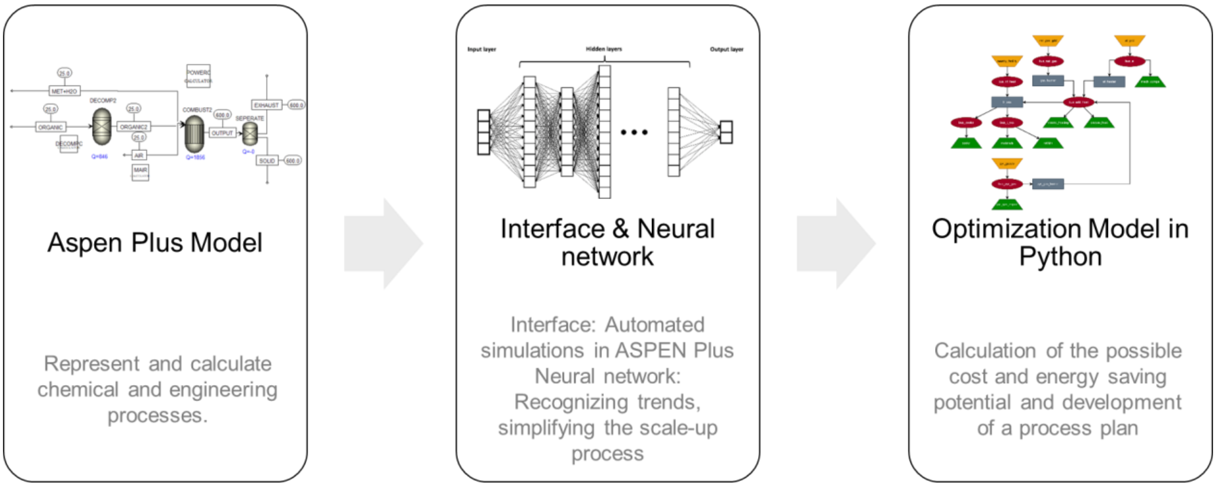

Figure 2: Overview overall energy system model

Each of these three components serves a specific function within the overall energy system model and comes with distinct goals and implementation requirements. Table 3 provides an overview of the respective **goal(s)** and **requirement(s)** for each component.

Table 3: Goal(s) and Requirement(s) of the respective main component

	Goal(s)	Requirement(s)
Aspen Plus Model	Representation and calculation of the thermo-chemical process	Consideration of chemical and engineering processes and reactions
Interface & Neural Network	• Identification of Trends between operating points • Development of characteristic fields • Provide the necessary input data for the optimization model	• Execute simulations • Reinitialize simulations • Access input and output values • Adjust input and output values • Development of a neural network that is trained on time-series data to predict output conditions of the thermo-chemical process
Optimization Model	Development of an optimized process plan to identify cost and energy savings	• Development of a generic model • Handling multiple temperature levels and different materials • Minimal use of electricity and fossil gas

To accurately simulate the thermo-chemical processing of secondary raw materials, particularly the pyrolysis process in a rotary kiln, the process was modelled using Aspen Plus. The aim was to represent the pyrolysis process and the associated chemical reactions in sufficient detail to assess the quality and composition of the resulting solid residues and pyrolysis gas. Aspen Plus was chosen because it enables the consideration of both chemical reactions and process engineering aspects, which is essential for realistically representing the energy and mass flows involved. The developed process model includes three main components and can be seen in Figure 3:

- Ryield Reactor (DECOMP): This reactor decomposes organic components through pyrolysis, with the yield determining the ratio of reactants to products.
- Rgibbs Reactor (COMBUST): Here, the organic products further react with metal and air.
- Separator (SEPARATE): This component separates liquids and gases from solids.

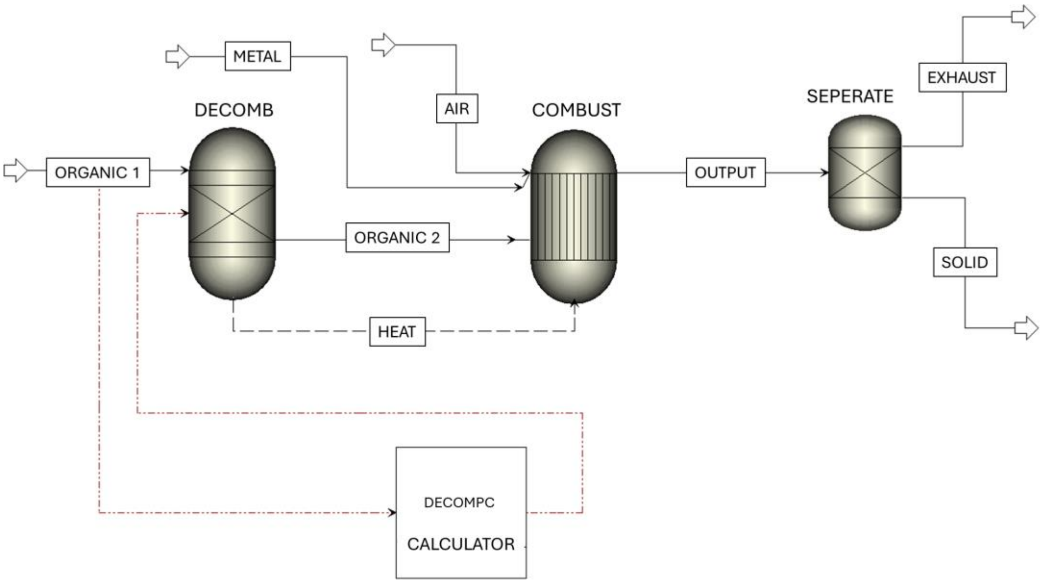

Figure 3: ASPEN Plus model of the pyrolysis process

Since ASPEN Plus represents individual operating points but cannot compute time series or optimization, and any change in input parameters or boundary conditions must be made directly in the software, the next step was to develop an interface between ASPEN Plus and an output using Python combined with a neural network. This interface enables the automated execution of time series calculations. In this process, different operating points or points in time are transferred to the Python code, each of which starts a separate simulation in ASPEN Plus. The results of the individual simulations are then combined and processed into a time-resolved overall visualisation. In this way, dynamic processes can be analysed and evaluated in detail over defined periods of time. This interface has several requirements:

- **Execute simulations**: Python enables the control of the ASPEN Plus model to start simulations directly.
- **Reinitialize simulations**: This helps with model adjustments or restarting the program to ensure all parameters are correctly set.
- **Access input and output values**: Python can be used to read and access the model's input and output variables.
- **Adjust input and output values**: The values can be dynamically modified via the Python interface to simulate different scenarios or make optimizations.

The model’s flexible control and adjustments allow for easy identification of trends between operating points and the development of Characteristic fields. The output values are displayed as CSV files (tables), see Figure 4, or graphically, see Figure 5.

input (tempVals)	TEMP-EX (°C)	PRES-EX (bar)	MASS_FLOW_MX-EX (kg/hr)	ENTHALPY-EX (J/kmol)	DENSITY-EX (kg/m^3)	...
-15	314,473008	1	140,619238	-158360753	0,287326583	
-10	317,746608	1	140,619238	-158249017	0,285734777	
-5	321,043737	1	140,619238	-158136389	0,28414926	
0	324,36405	1	140,619238	-158022879	0,282570277	
5	327,707201	1	140,619238	-157908497	0,280998065	
10	331,07285	1	140,619238	-157793253	0,279432847	
15	334,460659	1	140,619238	-157677156	0,277874834	
20	337,870294	1	140,619238	-157560215	0,276324228	
25	341,301414	1	140,619238	-157442440	0,274781223	
30	344,753687	1	140,619238	-157323841	0,273246	
35	348,226785	1	140,619238	-157204426	0,27171873	
40	351,720382	1	140,619238	-157084205	0,270199574	

Figure 4: Example of dataset from CSV file

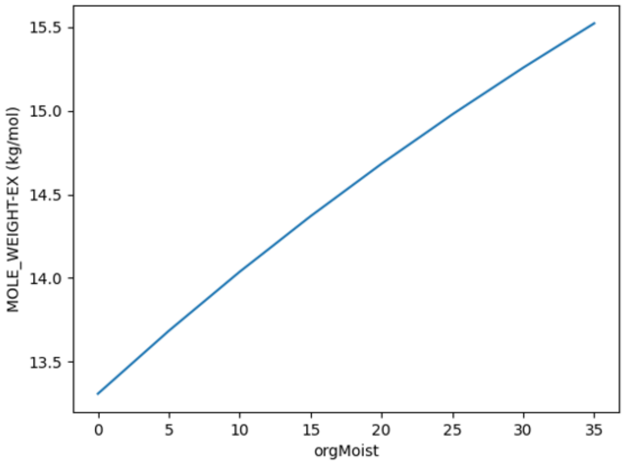

Figure 5: Example of relationship between input (moisture levels) and output (molar mass)

To further expand the model's capabilities, a neural network was integrated into the interface. The aim of the neural network is to predict the initial conditions of the rotary kiln and to provide input data for the subsequent optimization model, even for operating points that are not calculated directly by Aspen Plus. A Long Short-Term Memory (LSTM) recurrent neural network was selected and trained using the time series data obtained from the simulations. The LSTM model can recognize temporal patterns and relationships between process variables, which enables a faster and more flexible evaluation of system performance.

With the integration of the neural network and interface, it is now possible to provide the optimization model with the necessary input parameters and boundary conditions derived from the pyrolysis process. This optimization model represents the final component of the overall energy system model. Its primary objective is to determine an optimal process configuration that minimizes energy consumption and costs while maximizing the use of available waste heat. For this purpose, a generic exergy-based optimization model was developed using the Python library OEMOF (Open Energy MOdelling Framework). The model allows for the simulation of different energy supply scenarios, enabling the identification of operation strategies that reduce dependence on electricity and fossil gas, improve resource efficiency, and support the cost-effective and sustainable operation of the overall system.

The main objective of the optimization model is to ensure maximum flexibility for different use cases: this includes processing different types of material at one site, handling multiple temperature levels and integrating site-specific waste heat sources. Furthermore, the model aims to minimize the use of electricity and fossil gas while making the best possible use of available thermal energy, especially in the form of industrial waste heat. It also considers material-specific requirements such as the temperature level required for pyrolysis, the specific energy requirement per kilogram of input, the calorific value of the resulting pyrolysis gas and the potential revenue from the sale of the recovered materials.

The optimization model, see Figure 6, consists of multiple components (buses, transformers, sources and sinks), linked together with energy flows (black arrows), and constraints, which describe the behaviour of the energy system. The model is divided into four sections, each describing a specific part of the energy system:

- **Thermal management** (blue section in Figure 6): This section focuses on "process gas" and "temperature management". It includes the injection of the process gas via the "nearby_facility" (typically waste heat from a nearby industrial plant), the "cooler" component for cooling the process gas temperature, and the "heat_out" component representing unused energy and losses. Additionally, this section features sinks for the processed "materials" and for the rotary kiln's energy demand, referred to as "rotKiln" as well as transformers and buses for each temperature level, described as “tr_xxx” and “bus_t_xxx” respectively. These two types of components (with their corresponding constraints) are needed to describe the thermal behaviour of the plant, considering temperature change over time. Without these, OEMOF would not be able to include temperature changes in the simulations. This modular solution effectively addresses the "temperature problem" and represents a novel application of OEMOF, allowing for accurate simulation of time-dependent heat transitions.
- **Pyrolysis gas handling** (purple section in Figure 6): This section describes the handling of the pyrolysis gases, resulting from the processed materials. The pyrolysis gases “pyr_gases” can either be sold to an external buyer (“pyr_gas_export”), reused in a burner (“pyr_gas_burner”) in the process itself or itself or delivered to the nearby production plant, from which the waste heat is obtained. Depending on various input parameters, the optimizer decides which of the two purposes is most suitable in each point of time.
- **Supplementary heating** (red section in Figure 6): This section handles the additional heat required to increase the process temperature. The additional heat can be obtained by the pyrolysis gas burner (as described above), a natural gas burner (“nat_gas_burner”) and an electric heater (“el_heater”). If too much heat is available, it can be fed into a district heating system (“district_heating”) or released into the atmosphere without further use (“excess_heat”).
- **Mechanical energy needs** (green section in Figure 6): This section describes the use of electrical energy for mechanical purposes. This energy is used, for example, for the rotational energy of the rotary kiln and for pumps or compressors to transport the

process gas. The use of mechanical energy depends on various factors such as material and gas flow and is calculated during optimization.

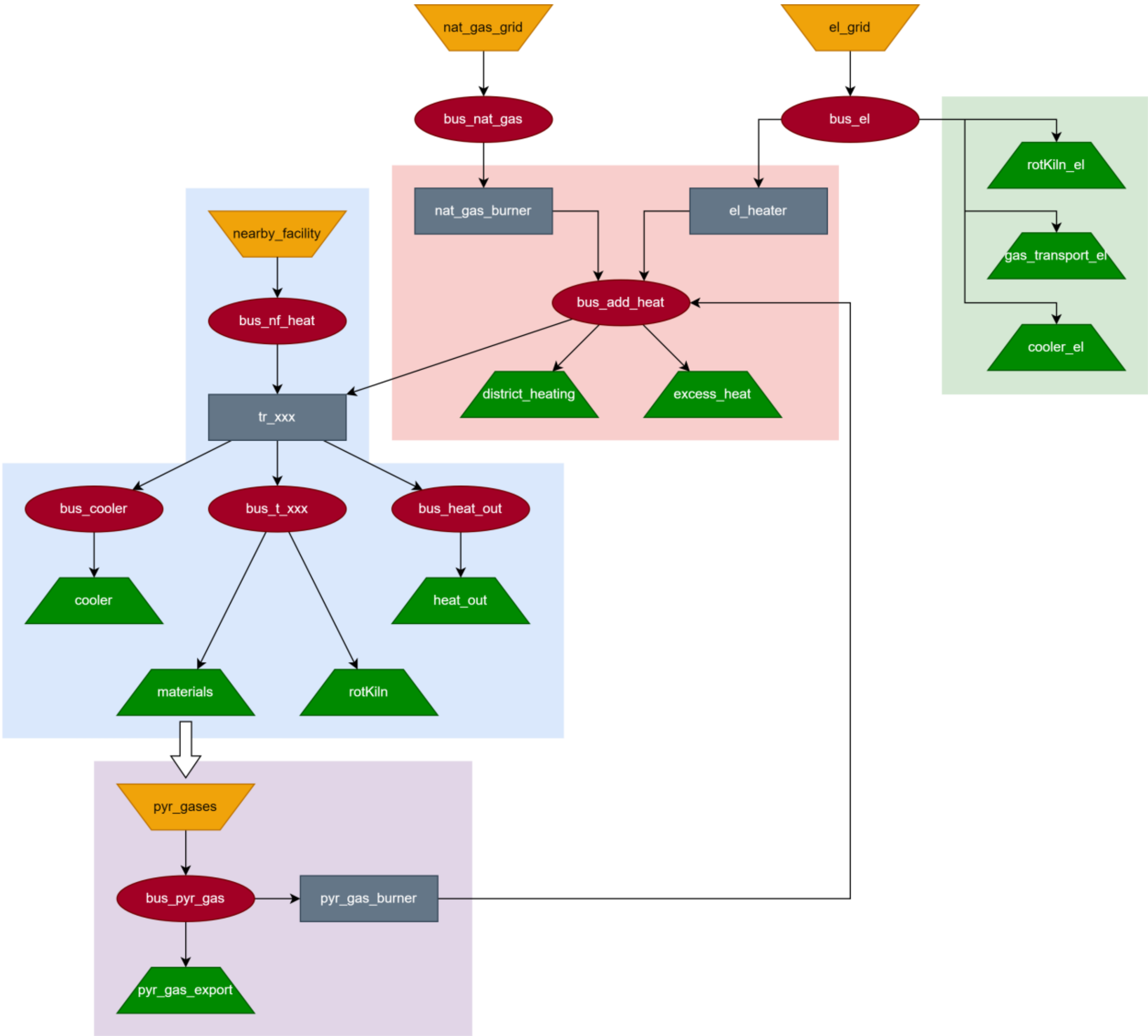

Figure 6: Optimization Model in Python based on OEMOF

The generic structure of the model allows for simulation of different plant sizes and scenarios without structural modification, making it highly adaptable for future applications. Moreover, the integration of Aspen Plus output with this optimization model enables scenario-based evaluation of system performance, helping identify the most energy- and cost-efficient configurations.

4.2 Szenario Definition

Four scenarios are analysed to identify potential energy and cost savings: the first refers to the existing SSD, while the other three scenarios relate to a LSD to be built in the future. Specifically, these are the following scenarios: the pilot plant (SSD), the large-scale plant in summer operation (LSD - summer), the large-scale plant in winter operation (LSD - winter) and the large-scale plant during a maintenance phase without hot gas supply from a nearby plant or a thermal process (LSD - maintenance).

In each of these scenarios, four recyclable materials are treated using pyrolysis to separate valuable materials from contaminants such as organic coatings. The materials considered are coffee capsules, printed circuit boards, biomass and fibre composites. The most important material parameters are shown Table 4. The optimization model remains unchanged in all scenarios; differences only arise due to varying settings and input parameters that are passed to the model. To ensure that the use of waste heat as hot gas is preferred, it is assumed that the waste heat is initially available free of charge.

Table 4: Material parameters for scenarios including references

Parameter	Unit	Coffee capsules	Printed circuit boards	Bio mass	Fiber compo sites	Ref.
Required process temperature	K	773	773	1073	973	[55–58]
Specific pyrolysis energy	$\frac{kWh}{kg(\text{Inputmasse})}$	0,625	5,469	2,39	0,778	[55–57,59]
Specific calorific value of the pyrolysis gas produced	$\frac{kWh}{kg(\text{Inputmasse})}$	0,499	0,664	3,75	0,56	[55–57,59]
Specific revenue of the pyrolysed material	$\frac{€}{kg(\text{pyrolysiertes Material})}$	0,26[1]	1,4[1]	0,105	1,0	[60,61]

For the pilot plant (SSD), the first calendar week of April 2025 is simulated, corresponding to moderate ambient temperatures. The setup at Seccon's technical lab does not include a hot gas supply from a nearby plant or a thermal process, so all process heat must be provided using natural gas and electricity. The process gas used (inert gas or ambient air) is at ambient temperature and must be heated, e.g. via electric heating, to the required process temperature

[1] Specified by project partner Seccon GmbH

before being fed into the rotary kiln. Additionally, no district heat feed-in or sale of the resulting pyrolysis gas is possible. Electricity and gas supply is assumed to be unlimited by assigning nominal values of one terawatt. The working schedule consists of six days per week, with twelve working hours per day. Each waste fraction must be processed for at least 60 minutes before switching to another material is allowed. A total of 18 tonnes of waste are processed over the examined week.

Three scenarios are being investigated for the future LSD. In contrast to the pilot plant, this plant runs continuously, i.e. seven days a week and 24 hours a day. Optimization is carried out for each calendar month in 30-minute steps. The LSD is linked to a nearby plant or thermal process from which hot gas can be obtained. The material may be changed every four hours at the earliest. For comparability of the scenarios, a constant material mass of 1,500 tons is assumed in all three cases. The first large-scale plant scenario (LSD - Summer) relates to July. The other two scenarios (LSD - Winter and LSD - Maintenance) relate to January to analyse seasonal differences in ambient temperature and energy costs. In the summer and winter scenarios, the connected plant or thermal process is active so that hot gas with a randomly generated temperature distribution of around 600 °C is available. The resulting pyrolysis gas can be sold and fed back into the thermal process. In the maintenance scenario, on the other hand, the nearby plant or thermal process is out of operation. Therefore, no hot gas is available, and the process gas is at ambient temperature, as in the pilot plant. The sale of the pyrolysis gas is also excluded in this scenario. The main input parameters for the four simulation scenarios are summarized in Table 5.

Table 5: Main input parameters for the four simulation scenarios

Parameter	Unit	SSD	LSD – Summer	LSD – Winter	LSD – Maintenance	Ref.
District heating	[-]	no	yes	yes	yes	Seccon[2]
Process gas temperature	[°C]	Ambient temperature	Random (ca. 600 °C)	Random (ca. 600 °C)	Ambient temperature	[61]
Pyrolysis gas sales	[-]	no	yes	yes	no	Seccon[2]
Hot gas limitation	[kW]	none	8 000	8 000	none	Seccon[2]
Mass flow limitation	[kg/h]	500	4 000	4 000	4 000	Seccon[2]
Process heat limitation	[kW]	2 000	17 000	17 000	17 000	[62,63]
Material lead time	[min]	30	60	60	60	[64–66]
Working hours	[-]	6:00 bis 18:00 Uhr	continuous	continuous	continuous	Seccon[2]
Working days	[-]	Monday to Saturday	continuous	continuous	continuous	Seccon[2]
Minimum time until material change	[h]	1	4	4	4	-
Coffee capsules	[kg]	8 000	800 000	800 000	800 000	-
Printed circuit boards	[kg]	2 000	100 000	100 000	100 000	-
Biomass	[kg]	5 000	350 000	350 000	350 000	-
Fiber composites	[kg]	3 000	250 000	250 000	250 000	-

4.3 Results

To assess the performance of the developed optimization model and to identify potentials for energy and cost savings, four distinct scenarios are analysed. Two simulations are carried out for each of the four scenarios, as described in Section 4.2. In the first simulation, referred to as PP (process plan), the material usage is specified according to a fixed process plan, while only the energy usage is optimized. In the second simulation, referred to as OPT (optimized material usage), a comprehensive optimization of both energy and material use is carried out

[2] Specified by project partner Seccon GmbH

with the aim of minimizing operating costs. The underlying input data, such as cost profiles, remain constant across all simulations. The available material quantities are identical in both simulation approaches. In the variant with a fixed process plan, the entire material is processed, whereas in the optimized variant, partial processing is permitted depending on economic boundary conditions. This enables the optimizer to identify and selectively exclude economically unfavourable materials.

Table 6 summarizes the pyrolyzed material quantities for each scenario according to the simulation with a predefined process plan (PP) and for the simulation with optimized material usage (OPT). In the scenarios without available waste heat (Scenario SSD and Scenario LSD – Maintenance), not all stored materials are pyrolyzed under the optimized simulation. This suggests that the optimizer can identify uneconomical material types and avoids their processing under unfavourable conditions. Since waste heat was assumed to be available free of charge in the evaluated scenarios, even economically marginal materials can be processed profitably in Scenario LSD – Summer and Scenario LSD – Winter.

Table 6: Pyrolyzed material quantities for each scenario according to process plan (PP) and with optimization (OPT)

scenario	**SSD**		**LSD – Summer**		**LSD – Winter**		**LSD – Maintenance**	
	PP	**OPT**	**PP**	**OPT**	**PP**	**OPT**	**PP**	**OPT**
Coffee capsules	8	8	800	800	800	800	800	800
Printed circuit boards	2	2	100	100	100	100	100	100
Biomass	5	2	350	350	350	350	350	0
Fiber composites	3	3	250	250	250	250	250	250
Total	18	15	1500	1500	1500	1500	1500	1150

As illustrated in Table 7, a comparison between Scenario LSD – Summer and Scenario LSD – Winter shows that approximately 200 MWh more energy is required in winter to process the same amount of material. This can be attributed to the lower ambient temperatures in winter, which increase the proportion of non-usable waste heat in the overall energy consumption. When comparing total energy consumption between Scenario LSD – Winter and Scenario LSD – Maintenance, a reduction in energy input of approximately 500 MWh (around 10%) is observed. This comparison refers to the simulations with a predefined process plan (PP), since a direct comparison of the results with optimized material usage (OPT) is impeded by the absence of biomass in Scenario LSD – Maintenance. The lower energy input in this case can be explained by the fact that in LSD – Winter, energy is extracted from the system via the "cooler" component to reduce the hot gas to the required process temperature. In LSD – Maintenance, by contrast, the process gas is already at ambient temperature and does not require cooling at any point in time.

Table 7: Overview results – Comparison of results according to process plan (PP) and with optimization (OPT)

scenario	Total amount of energy PP	Total amount of energy OPT	Total energy savings	Profit increase potential		Specific profit increase
	[MWh]	[MWh]	[%]	[€]	[%]	[€/kg]
SSD	68	52	23.54	400	6.26	0.0250
LSD – Summer	5 163	5 158	0.08	3 125	0.46	0.0021
LSD – Winter	5 349	5 341	0.14	2 726	0.39	0.0018
LSD – Maintenance	4 815	2 980	38.10	51 936	13.17	0.0400

A comparison of the costs and revenues between Scenario LSD – Summer and Scenario LSD – Winter reveals that, despite identical material quantities, the profit increase in the winter months is approximately €400 lower. This can be attributed to higher electricity prices during winter, which in turn increase electricity-related operating costs and thus reduce overall profitability. To enable a more meaningful comparison of the profit improvement potentials across all scenarios, absolute profit values must be translated into relative indicators. For this purpose, a specific profit increase in euros per kilogram of processed material is calculated, see Table 7. A comparison of the specific profit increase values across all scenarios shows that the optimizer identifies particularly high profit potentials if no waste heat is available from a nearby plant (scenario Maintenance). In scenarios in which such heat integration is possible (scenario LSD - summer and scenario LSD) winter - the specific profit increase remains low at around 0.002 €/kg. However, the effects of optimization become much clearer if the entire process energy has to be sourced externally, as in the LSD - Maintenance scenario. In this case, a significantly higher specific profit increase of around 0.04 €/kg is achieved, which underlines the importance of waste heat integration for economic efficiency.

Overall, the optimizer plays a key role in economic process control by identifying waste fractions that are not economically viable under given boundary conditions. In practice, these fractions could be excluded from processing, improving both cost-efficiency and resource use in large-scale implementation.

5 Systemic and Techno-economic Assessment

In the following section, the Systemic and Techno-Economic Assessment is presented with the aim of comprehensively evaluating the ecological and economic potential of the thermo-chemical processing of waste streams. The study focuses on identifying possible energy savings using industrial waste heat, analysing the reduction of transport distances, and quantifying the resulting CO_2 savings. In addition, a techno-economic assessment is carried out to analyse the economic viability of the concept under various framework conditions. The chapter is divided into two central sections: Firstly, the underlying methodology is explained, followed by an analysis of the results obtained.

5.1 Methods

To estimate the possible energy and CO_2 savings by substituting primary energy with industrial waste heat, the theoretically available waste heat potential of relevant industrial sectors was analysed. The focus here is particularly on the temperature level of the waste heat flows, as only waste heat with a sufficiently high temperature can be used directly in the analysed thermo-chemical process for processing secondary raw materials. The aim of the analysis is to identify those industrial sectors whose waste heat potential is sufficient in terms of quantity and temperature to cover the energy requirements of the process.

The analysis of theoretical waste heat potentials in industrial sectors is based on a top-down approach that relies on the systematic evaluation of industrial energy flows. This specifically considers those waste heat flows that are discharged via waste gases (e.g. flue gas, steam, air) and wastewater (e.g. cooling water) and are therefore potentially usable waste heat. However, other losses such as radiation or friction losses are not included. The calculations are based on the European Union's energy data for 2022, provided by EuroStat [67]. This data includes the energy consumption and the use of energy sources (e.g. natural gas, oil, electricity) in industry, divided into industrial sectors. In addition, statistical data from Statistics Austria and findings from the ‘Waste Heat Register Styria’ study [68] were used to systematically classify and quantify the waste heat potential in Austria and the EU. The evaluation of the theoretical waste heat potential is based on three factors: the energy input per source, the proportion of losses in these processes and the temperature level of these losses (low, medium or high temperature). If there are several loss values for an energy source, a weighted average is used to correctly reflect their realistic significance. The aim is to use this methodology to identify those industrial sectors whose waste heat potential in the corresponding temperature range is sufficient to integrate the thermo-chemical process for processing secondary raw materials.

A central element of the study is the ecological and economic evaluation of transport logistics. For this purpose, an analysis was carried out regarding the quantities of residual materials generated for selected waste streams. Therefore, the predicted total quantity was distributed among the individual federal states in proportion to the number of inhabitants. In addition, existing landfill sites and available recovery and recycling capacities in Austria were analysed. In practice, it is often the case that only a few centralised recycling plants are available for certain material flows. One example is the collection and recycling of aluminium coffee capsules, which are collected nationwide and transported centrally to the only corresponding plant in Tyrol at present. Two scenarios are therefore compared: a centralised scenario with a single processing plant and a decentralised scenario in which existing industrial plants with sufficient waste heat potential are used as potential sites for processing waste streams. Technical framework conditions such as space or integration requirements for the thermal-chemical process in existing industrial complexes are not considered in this potential analysis. The aim of this comparison is to quantify the possible savings potential in terms of tank to wheel energy consumption and CO_2 emissions using several decentralised locations - based on the new thermo-chemical processing of secondary raw materials.

For the analysis of transport logistics, the transport routes are evaluated using the Ecological Transport Information Tool World (ETW), which creates detailed emission and environmental balances for goods transportation. This tool enables the detailed modelling and evaluation of transport chains, considering numerous parameters such as route, vehicle type, engine emissions, load, empty runs and means of transport. ETW enables not only the representation of individual deliveries, but also the comparison of several transportation strategies in terms of their environmental impact. The quantities to be transported are allocated based on the total volume per secondary raw material and in proportion to the number of inhabitants per federal state. Specific quantities are estimated for three material fractions: coffee capsules, printed circuit boards and glass fibre composites (e.g. rotor blades from wind turbines). The analysis of transport routes focuses on the pathways from regional waste collection centres to the respective processing plant. In most cases, the starting points are located in the provincial capitals; however, for Lower and Upper Austria, the largest-capacity collection centres were selected instead. The routes for the different materials as well as the initial and decentralized scenarios are visualized in the form of maps.

As part of the quantitative evaluation of CO_2 reductions, the thermal-chemical processing of secondary raw materials in the rotary kiln is analysed in detail. The aim of the analysis is to quantify the potential savings that can be achieved by substituting natural gas with lower-emission energy sources. To this end, conventional operation with natural gas and hybrid operation are analysed in more detail. While in natural gas operation the entire energy requirement is covered exclusively by fossil natural gas, hybrid operation combines various, lower-emission energy sources. These include industrial waste heat and recovered pyrolysis gas, which is generated during the thermos-chemical process itself. Depending on the scenario, either natural gas or electrical energy is also used, resulting in two variants of hybrid operation: gas-based and electricity-based hybrid operation. The CO_2 emissions are determined for all operating modes and then compared. Furthermore, the calculations are carried out on a site-specific basis for selected processing plants in accordance with the decentralized scenario, considering the respective aggregated material quantities and associated transport routes. In addition, the material-specific CO_2 emissions from the pyrolysis process are analysed, with a focus on the emissions that arise directly during thermal-chemical processing in the rotary kiln. Emissions that occur during the subsequent utilisation of the pyrolysis gas produced are not considered in this analysis. This means that only those emissions that are released directly during the thermo-chemical processing are included in the life cycle assessment. Another aspect of the analysis is the evaluation of the environmental impact of using industrial waste heat. Allocated CO_2 emissions from upstream cement production are also considered if the waste heat comes from this industry. In this way, a realistic view of the overall emissions balance is obtained.

Finally, the techno-economic assessment compares different potential processing plants based on a defined cost structure that includes investment, operating, transportation and depreciation costs. The aim is both to evaluate the economic efficiency of the different sites and to quantify the potential cost benefits of changing the energy source - for example from pure natural gas operation to operation with waste heat, pyrolysis gas or electricity. The analysis considers key influencing factors such as energy costs and revenues from the sale of recycled secondary materials. Static investment indicators such as amortization period and profitability are also used to evaluate the long-term profitability. These enable a well-founded assessment of the economic efficiency and sustainability of the respective operating models.

5.2 Results

5.2.1 Theoretical waste heat potential

The identified waste heat potential in the most important industrial sectors of the 27 European member states is shown in Figure 7. The evaluation shows that the chemical industry, the non-metallic materials sector, which includes the production of cement, glass, ceramics and lime, the paper industry and the food and tobacco industries provide the highest waste heat potential. The temperature distribution of the waste heat is also shown in this figure. Here, the temperatures are divided into a low temperature range (LT), medium temperature range (MT) and high temperature range (HT). Although the chemical industry has a high waste heat potential, no waste heat with temperatures above 300 °C is available. In contrast, the non-metallic materials sector offers a high potential of 63 TWh for the temperature range above 300 °C. The food industry is also able to provide significant amounts of waste heat at temperatures above 300 °C. The mining and raw materials extraction and textile and leather industries have the lowest waste heat potential. In addition, the figure illustrates the percentage share of waste heat in the energy input of the respective sectors, whereby these shares are represented by the percentages shown next to the bars. Despite the high waste heat potential of the non-metallic materials sector, the share of usable waste heat in energy input is only 21.5%. This ratio is particularly pronounced in the food and tobacco industry, the construction industry, the iron and steel industry, vehicle manufacturing and the textile industry.

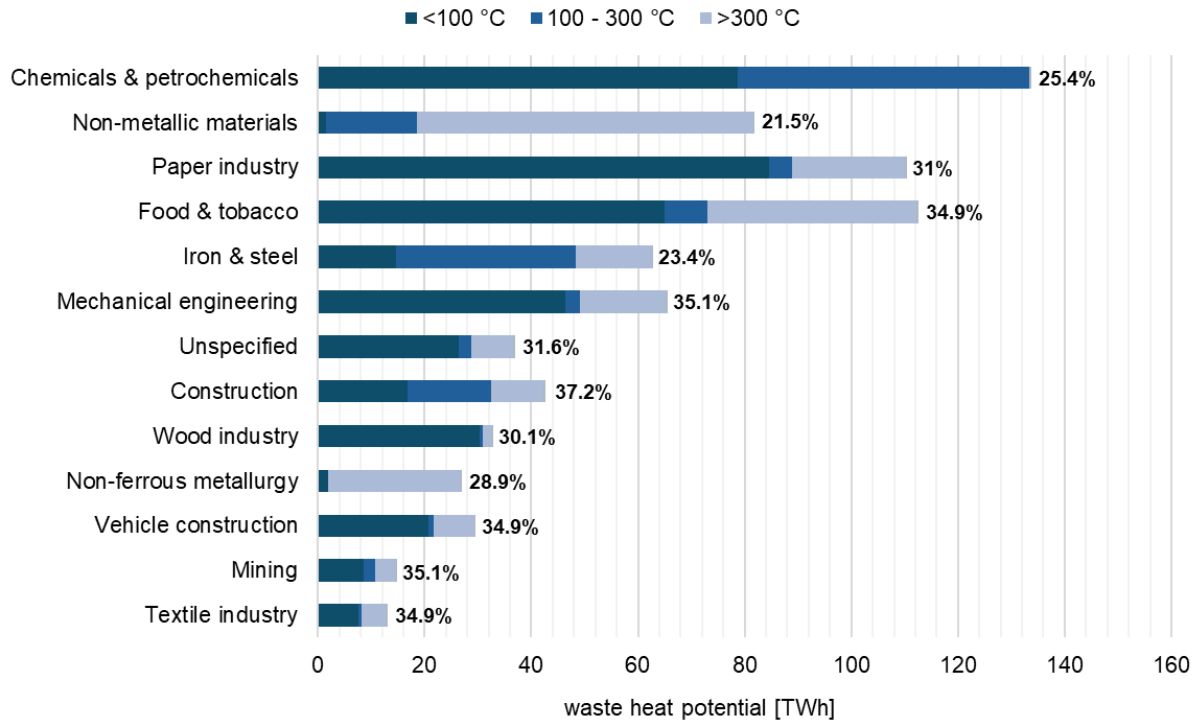

Figure 7: Theoretical waste heat potential of the European industrial sectors

Figure 8 illustrates the theoretical waste heat potential of the Austrian industrial sectors. The paper industry, the production of non-metallic materials and the iron and steel industry have the greatest waste heat potential with a significant proportion in the high-temperature range. This sector is crucial for the thermo-chemical treatment and processing of materials, particularly for the removal of by-products and impurities. The non-metallic materials sector guarantees a theoretical waste heat potential of 2.2 TWh, of which 2.0 TWh is contained in the high-temperature range of waste gas and wastewater flows. Accordingly, this sector is of particular interest for the provision of waste heat for the thermos-chemical process under investigation. The shares of the theoretical waste heat potential in energy consumption in the various sectors in Austria shown in Figure 8 are largely in line with the percentages for European industry. In the non-metallic materials sector, the share of waste heat in total energy consumption falls slightly to 19.7%. The textile industry has the lowest theoretical waste heat potential, with the ratio of waste heat potential to energy input at 34.7%.

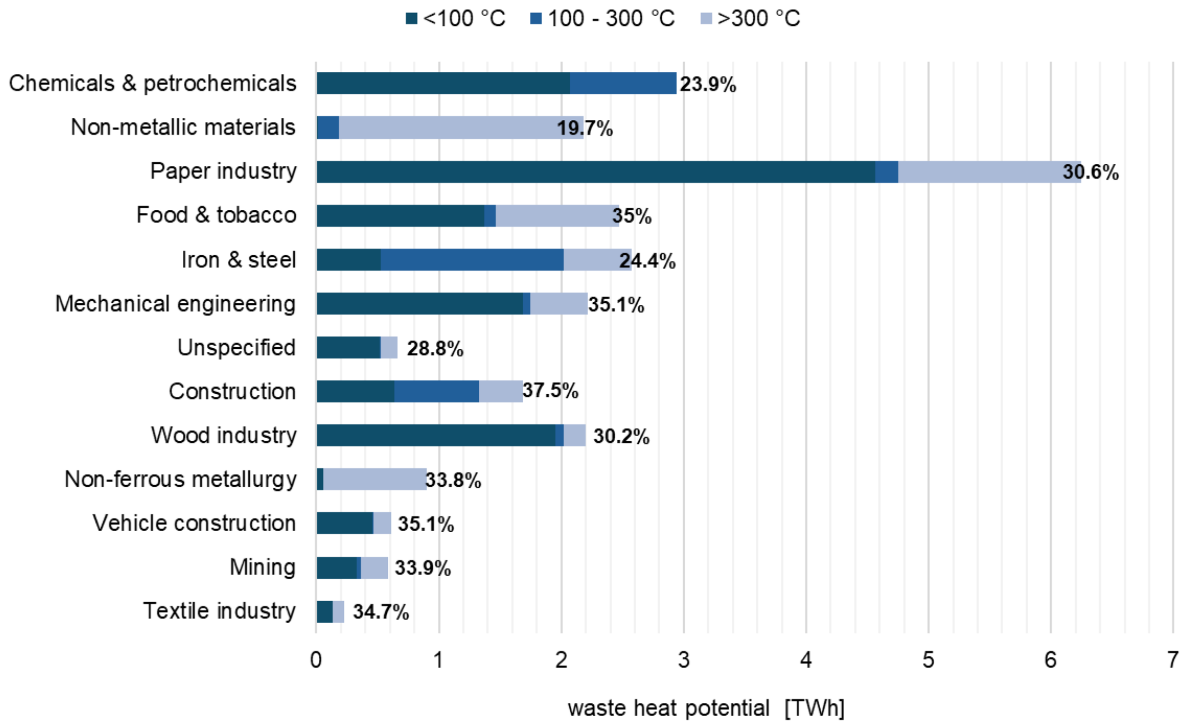

Figure 8: Theoretical waste heat potential of the Austrian industrial sectors

Based on the waste heat potentials identified, industrial sectors and subsequently industrial plants were identified as potential locations for the integration of the technology developed in the project. This identification was also important for the quantification of reduced transportation efforts.

5.2.2 Reduced transportation efforts

Three specific waste streams were selected to analyse the thermo-chemical process and the associated potential for recycling secondary raw materials: Aluminium coffee capsules, printed circuit boards from electronic scrap and glass fibre reinforced plastics from the deconstruction of wind turbines. The selection is based on their relevance in terms of recyclability, availability and material quality. The corresponding forecast waste volumes per federal state and material are shown in Table 8.

The evaluation of coffee capsule quantities is based exclusively on the quantities collected via a newly introduced collection system. According to Altstoff Recycling Austria (ARA), a total of 122.33 tonnes of coffee capsules were collected within six months in the pilot regions of Upper Austria, Krems-Land and Schwechat. [69] Extrapolating this data to the population of Austria results in an annual collection potential of around 1 500 tonnes.

The quantities of printed circuit boards are analysed based on the volume of electronic waste in Austria. According to the Waste Management Plan 2023, around 140,000 tonnes of electronic waste were generated in 2020, including small and large appliances, IT and telecommunications equipment and other fractions. With an average recycling rate of around 82%, this results in a recyclable potential of around 114,000 tonnes.

The quantities of printed circuit boards (PCB) are analysed based on the volume of electronic waste in Austria. According to the Waste Management Plan 2023, around 140 000 tonnes of electronic waste was generated in 2020, including small and large appliances, heat exchangers, display screen equipment, IT and telecommunications equipment and lamps. With an average recycling rate of around 82%, this results in a recycling potential of around 114 000 tonnes of electronic waste. Given an estimated PCB share of 4% [70], this results in a total quantity of 4 560 tonnes of PCBs in 2020. It is assumed that the recycling plant in question processes 15% of the total volume of printed circuit boards in Austria, resulting in an assumed volume of around 700 tonnes.

The quantities of glass fibre reinforced plastic are predicted based on the expected waste quantities from the deconstruction of wind turbines. For this purpose, the average forecast quantity for Germany over the next five years [71] is used and translated into the installed wind power capacity in Austria. This results in an annual waste volume of around 900 tonnes of rotor blades in Austria that cannot be resold or otherwise recycled.

Table 8:Transport quantity per federal state and material

Federal state	Inhabitants [Mio.]	Aluminium coffee capsules [t]	Circuit boards [t]	glass fibre reinforced plastic [t]
Lower Austria	1.72	282	132	169
Vienna	2.01	329	153	197
Burgenland	0.30	49	23	30
Styria	1.27	208	97	125
Upper Austria	1.53	251	117	150
Carinthia	0.57	93	44	56
Salzburg	0.57	94	44	56
Tyrol	0.78	127	59	76
Vorarlberg	0.41	67	31	40
Austria	**9.16**	**1 500**	**700**	**900**

The waste collection centres (WCC) of the federal state capitals serve as starting points for the calculation of the transport routes - both in the centralised and decentralised scenarios. The federal states of Lower Austria and Upper Austria are an exception: here, the largest waste collection centres with the highest capacity were used as starting points to ensure a realistic representation of the actual material flows. The main difference between the two scenarios lies in the location of the recycling plants. In the central scenario, aluminium coffee capsules are transported to Tyrol (see Figure 9), where the only specialised processing plant is currently located. It is assumed that printed circuit boards are treated in an existing electronic scrap recycling plant in Lower Austria (see Figure 10). As there is currently no suitable processing plant for rotor blades from disused wind turbines in Austria, these are not included in the analysis of transport-related energy consumption and CO_2 emissions. In contrast, the new decentralised scenario shown in Figure 11 takes a different approach: the materials are processed in three regionally distributed plants in Austria.

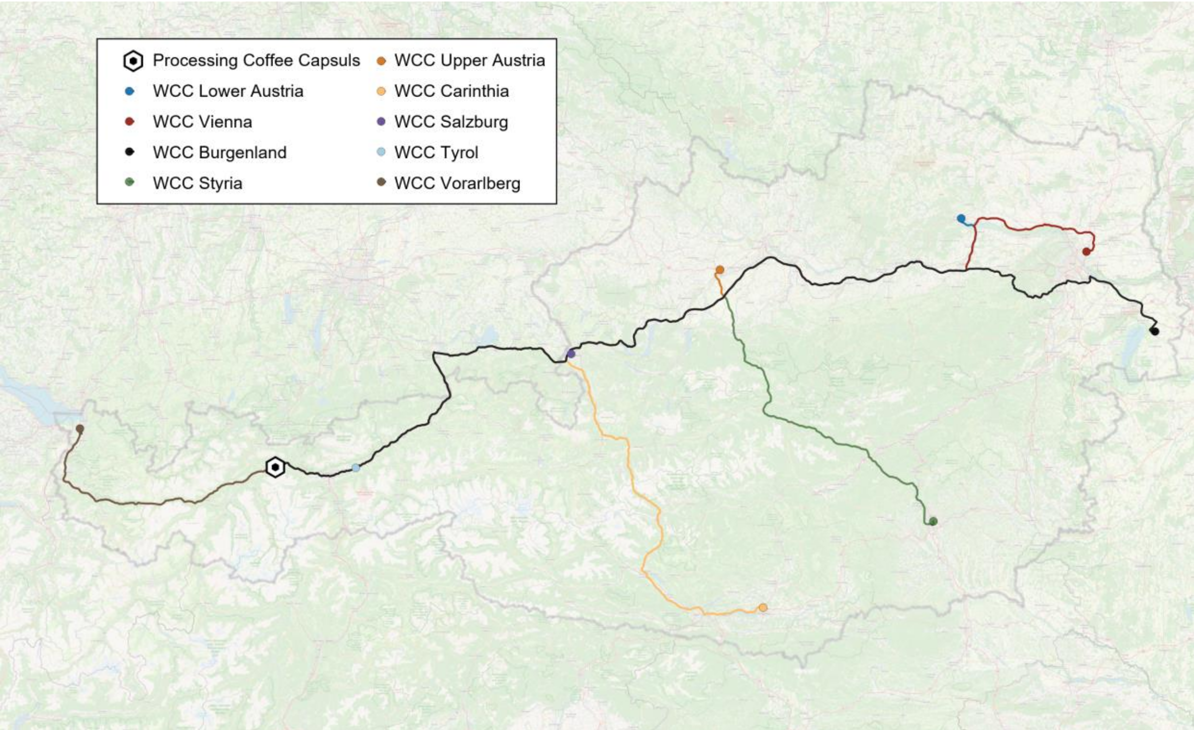

Figure 9: Centralised scenario of the coffee capsule transport

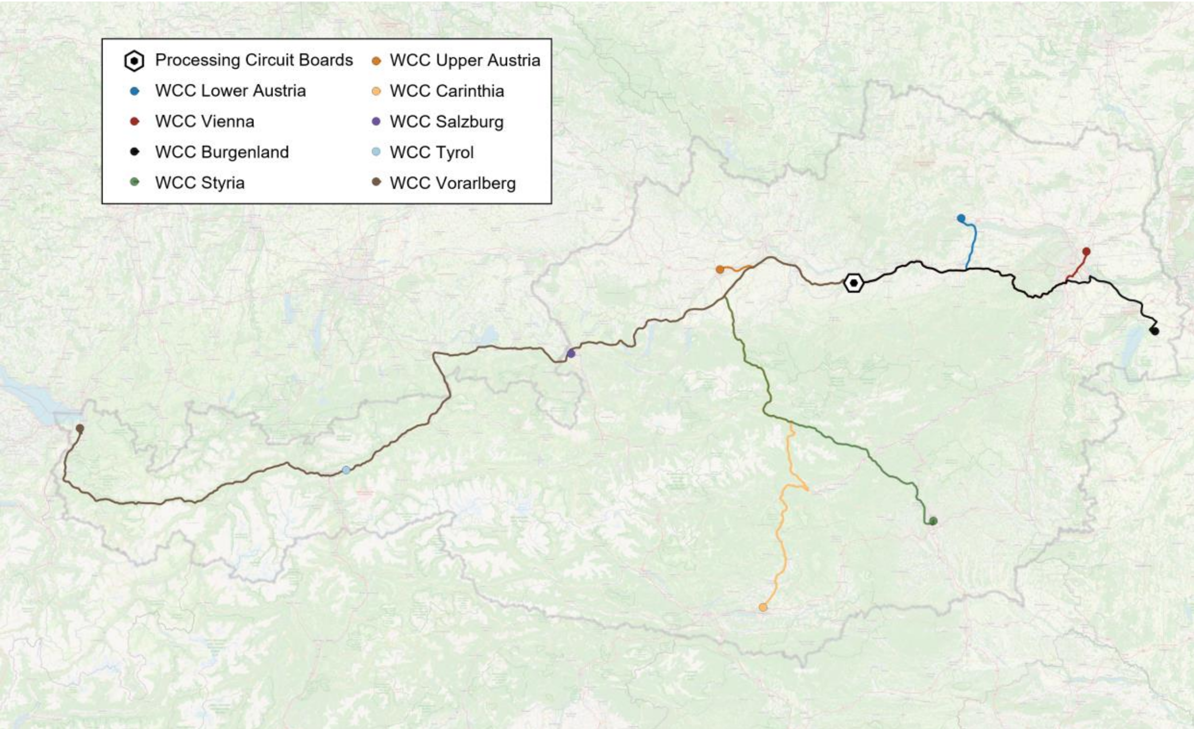

Figure 10: Centralised scenario of the printed circuit boards

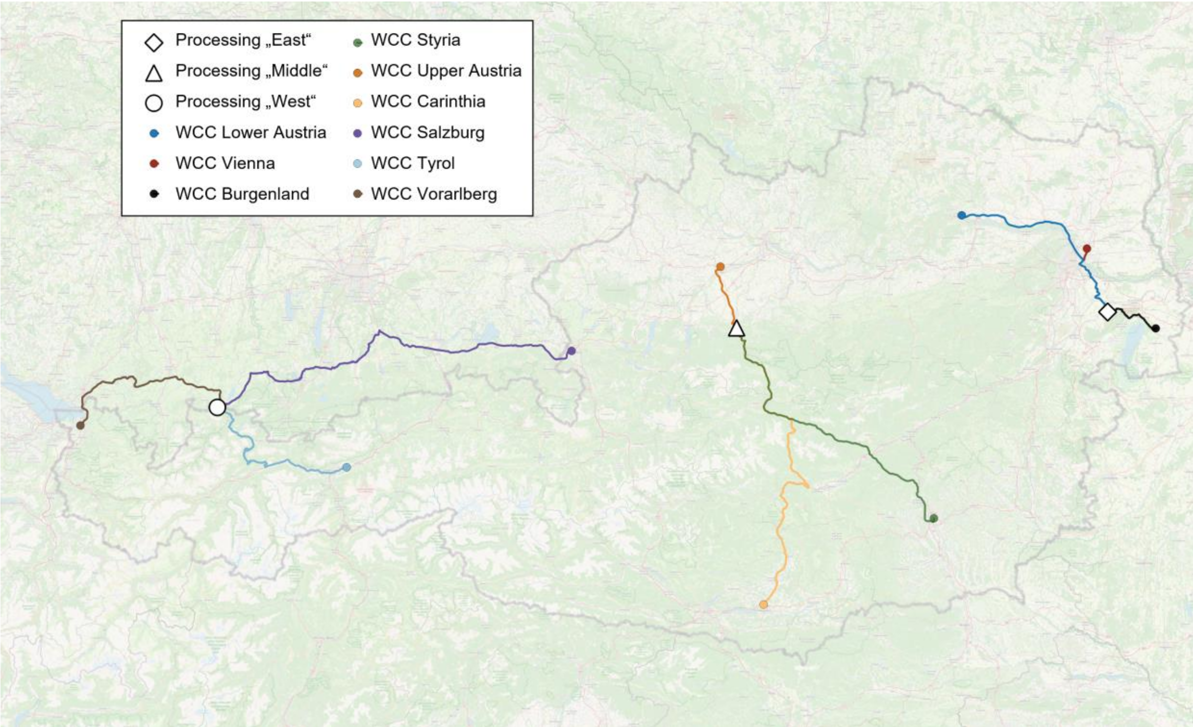

Figure 11: Decentralised scenario of the transport network

The possible savings potential in terms of tank to wheel energy consumption and CO_2 emissions for the comparison of the scenarios is explained below using the example of coffee capsules.

Figure 12 illustrates the tank-to-wheel energy consumption of the coffee capsules for all transport routes of the two scenarios. The differences in the various transport routes between the centralised (Figure 9) and decentralised (Figure 11) scenarios become clear. With the exception of Salzburg and Tyrol, there is a significant decrease in energy consumption. In Salzburg, energy consumption remains almost constant, while in Tyrol there is an increase in energy consumption. Overall, the result is positive for Austria, as the decentralised location leads to a 75% reduction in energy consumption.

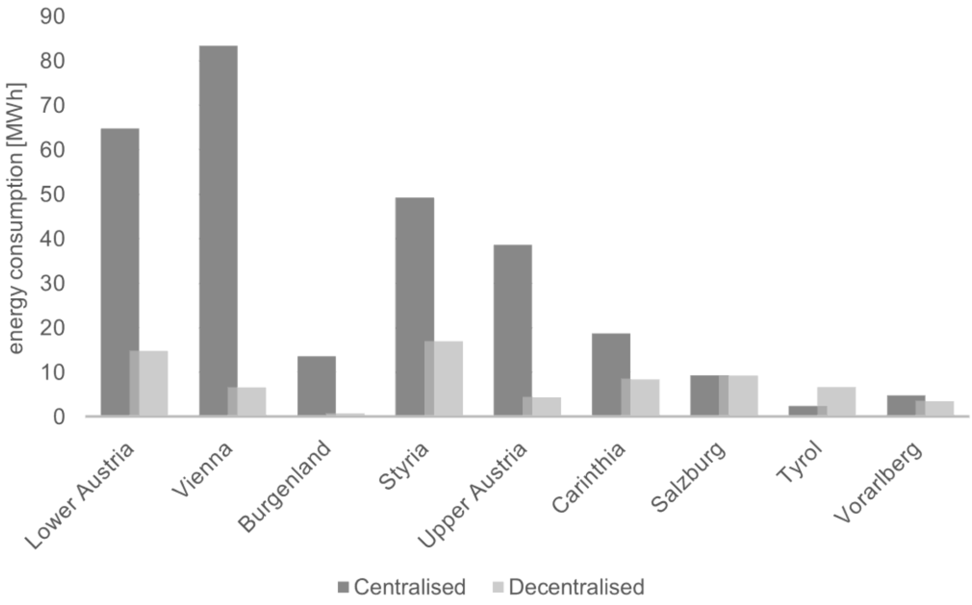

Figure 12: Comparison of the energy consumption for centralised and decentralised processing of coffee capsules

Figure 13 shows the comparison of the CO_2 emission savings potential of the two scenarios for the transport of coffee capsules. Due to the long distances and high transport volumes, the transport routes from Lower Austria, Vienna and Styria cause the most CO_2 emissions, but at the same time they also offer great savings potential. The largest percentage reduction in emissions (94%) can be achieved by the transport route in Burgenland. Apart from the transport route in Salzburg, which shows no change, the savings in Vorarlberg are the lowest at just 27%. The newly designed optimization scenario can reduce CO_2 emissions during the transport of coffee capsules by 75%.

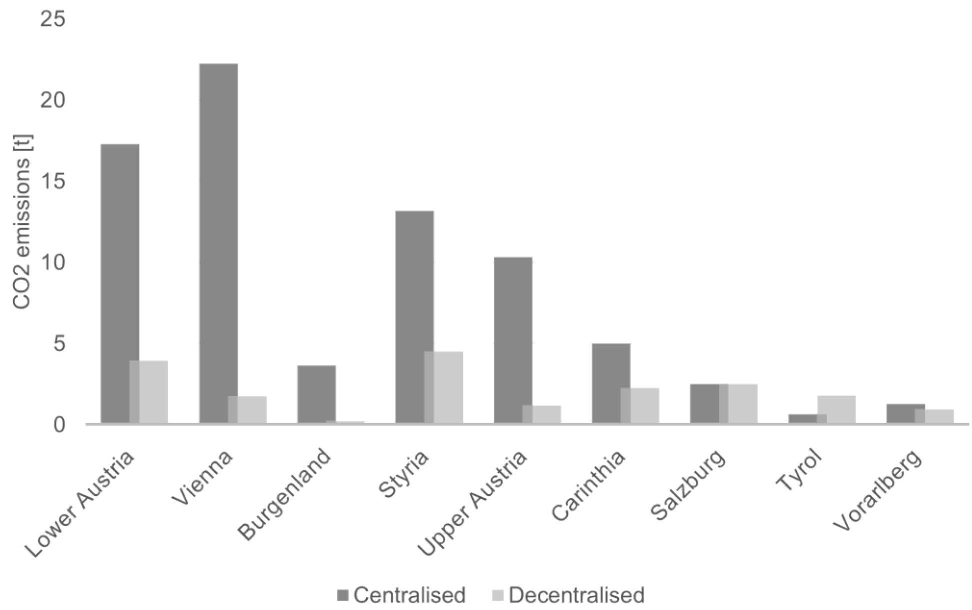

Figure 13: Comparison of the CO_2 emissions for centralised and decentralised processing of coffee capsules

5.2.3 CO_2 emission reduction potential

The resulting total emissions of the three processing plants analysed are illustrated in Figure 14 under the three operating scenarios: pure natural gas operation, gas-based hybrid operation and electricity-based hybrid operation. This clearly shows that natural gas operation alone is associated with the highest emissions. By using waste heat and pyrolysis gas in gas-based hybrid operation, CO_2 emissions can be reduced by up to 62% across all plants. Electricity-based hybrid operation even leads to a reduction of 74% compared to conventional operation. As all three plants use the same proportion of alternative energy sources in hybrid operation, the relative savings are similar in all cases. The absolute emission values, on the other hand, differ due to the different processing quantities of the respective materials, as the energy requirement - and thus also the CO_2 emissions - increases directly with the throughput.

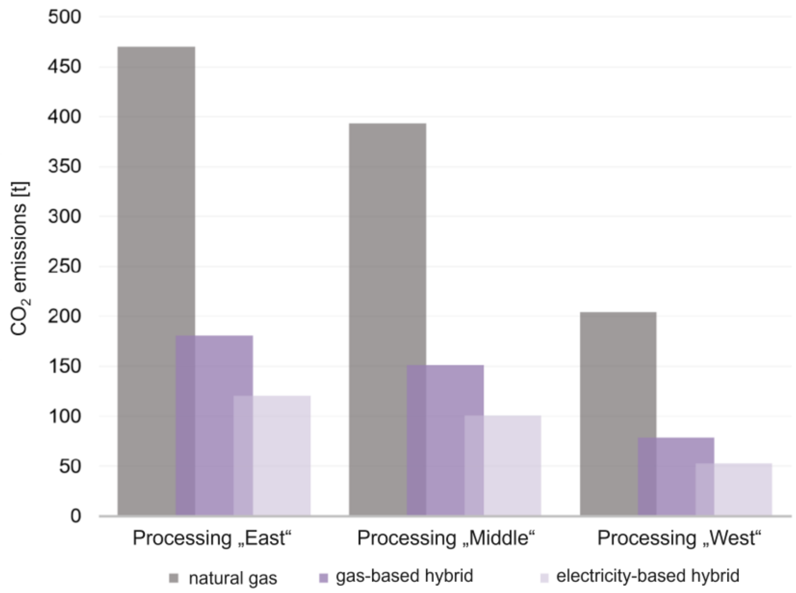

Figure 14: CO_2 emission reduction potential

5.2.4 Techno- economic assessment

The results of the techno-economic evaluation show that a decline in plant utilisation leads to both an increase in the amortisation period and a reduction in profitability. Despite these generally negative effects, however, the overall result is positive.

Figure 14 compares the cost savings, the potential for increasing profits and the amortisation period for the two operating modes, gas-based hybrid operation and electricity-based hybrid operation. As can be seen in the figure, the change in energy source at the processing plant east takes the greatest contribution to reducing overall costs. The integration of waste heat and pyrolysis gas into the process and the reduced transport routes are therefore a key factor in optimising the plant's costs. Although an increase in plant size leads to an increase in investment and operating costs, it also enables an increase in revenue. The analysis makes it clear that investments in larger processing plants make economic sense if the additional revenue exceeds the additional costs. Revenues are primarily generated from the sale of the secondary materials obtained, the market value of which is largely determined by current raw material prices. Accordingly, fluctuations on the raw materials markets can have a considerable impact on the profitability of the plants. The trend in energy prices - especially for natural gas and electricity - also plays a key role in profitability. Substituting fossil fuels with more climate-friendly and self-sufficient energy sources such as industrial waste heat or pyrolysis gas not only reduces operating costs but also reduces dependence on imports. This helps to increase security of supply and promote a more sustainable energy supply. Continuous market monitoring is therefore essential to make sound economic decisions and adapt planning flexibly.

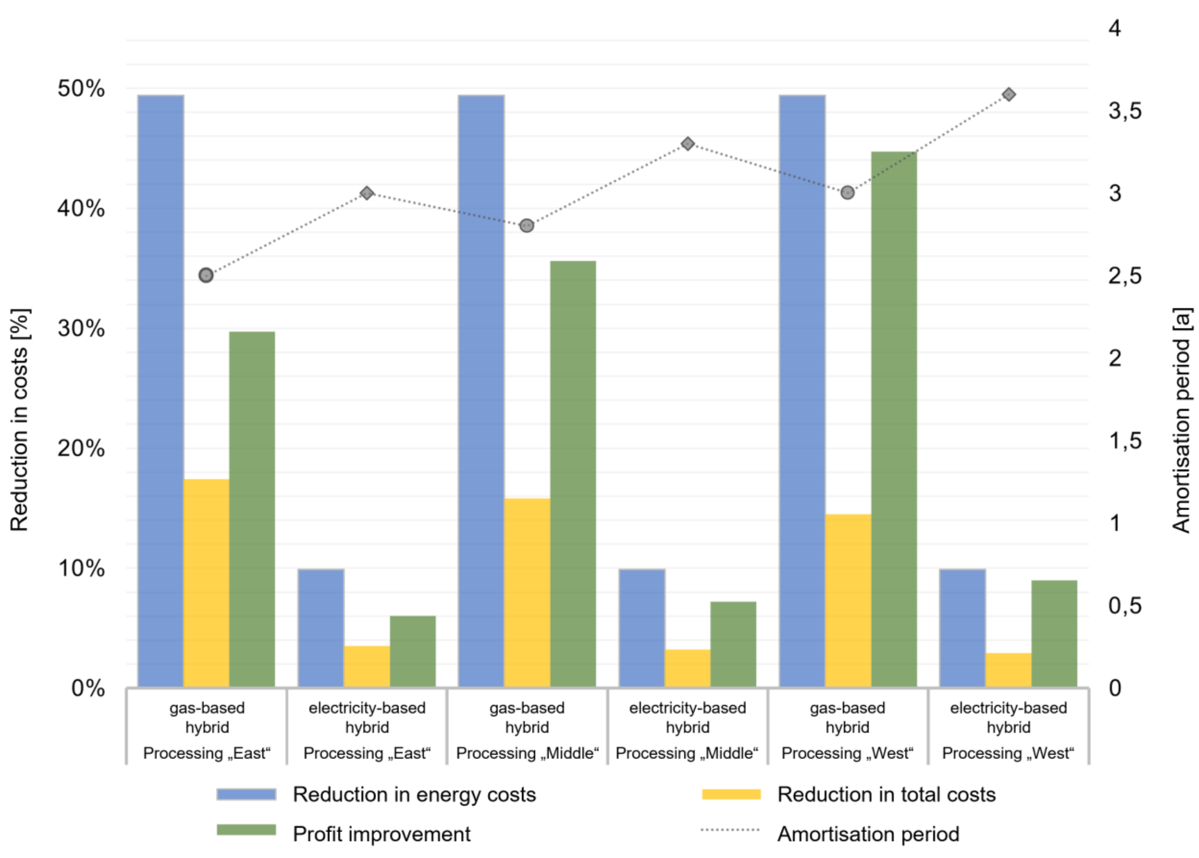

Figure 15: Cost savings and profit improvement potential as well as amortisation period

6 Conclusion and Outlook

The aim of the TCP_to_Industry project was the development, technical implementation and systemic evaluation of a novel thermochemical process for processing secondary raw materials. The focus was on the integration of a small-scale demonstrator (SSD) in a technical lab and the derivation of a scalable concept for large-scale industrial use (large-scale demonstrator, LSD) with the integration of industrial waste heat. The focus of the technical implementation and operation of the SSD in the technical lab was on the efficient processing of post-consumer aluminium coffee capsules. However, during the design phase, care was taken to ensure that the technology would also be suitable for other material fractions such as beverage cans, printed circuit boards or glass fibre-reinforced composite materials in the future to enable high-quality recovery of secondary raw materials. A modular concept was therefore developed which, in addition to the SSD, also includes pre- and post-processing of the materials.

While the SSD is currently operated electrically in the technical centre, industrial waste heat is primarily to be used to operate the rotary kiln on an industrial scale. To support this goal, a comprehensive energy system model was developed based on both real operating data from the technical lab and simulation-based model calculations. This ensured that both empirically validated process parameters and theoretically optimised operating scenarios were included in the integration concept of future systems.

The overall energy system model developed, consisting of an Aspen Plus process model, a Python interface with neural network and an optimisation model, enabled a simulation-based evaluation of dynamic operating points and varying operating conditions. The time-resolved simulations provided insights into optimal process management, particularly under fluctuating load profiles. Energy- and cost-efficient operating strategies were identified based on various supply scenarios, which serve as a basis for the design of future large-scale plants.

Both transport routes and potential CO_2 savings were systematically analysed in the techno-economic analysis. The analysis shows that hybrid plant operation using industrial waste heat, recovered pyrolysis gas and electrical energy can enable a reduction in process-related CO_2 emissions of up to 74% compared to purely natural gas-based operation. In addition, the decentralisation of the processing infrastructure - particularly due to the closeness to the sources of the waste streams - leads to a significant reduction of up to 75% in energy consumption in transport logistics for aluminium coffee capsules. The economic assessment shows that investments are economically viable even for medium-sized plants, provided that suitable locations with usable waste heat potential are available and stable sales markets exist for the recovered secondary raw materials.

In the future, the existing pilot plant in the technical lab is to be further expanded as a reference and development centre. At the same time, several large-scale follow-up projects are being prepared in Austria and Central Europe - particularly in the cement, brick and biomass industries. The plan for these large-scale plants is to operate the thermo-chemical process primarily by using industrial waste heat. If the locally available waste heat potential is not sufficient in terms of temperature level or energy quantity, supplementary, sustainable supply concepts are planned - such as the use of high-temperature heat pumps or additional firing with pyrolysis gas generated in the process. The technical, energetic and systemic principles developed in the project thus make a substantial contribution to the decarbonisation of industrial processes and the implementation of a resource-conserving circular economy.

7 References

[1] Anderl M, Friedrich A, Haider S, Kriech M, Lampert C, Moosmann L et al. Austria's National Inventory Report 2017: Submission under the United Nations Framework - Convention on climate Change and under the Kyoto Protocol.

[2] Sejkora C, Kühberger L, Radner F, Trattner A, Kienberger T. Exergy as Criteria for Efficient Energy Systems—A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential. Energies 2020;13(4):843. https://doi.org/10.3390/en13040843.

[3] International Energy Agency. Renewables 2019: Analysis and forecasts to 2024. [June 26, 2025]; Available from: https://www.iea.org/reports/renewables-2019.

[4] Martens H, Goldmann D. Recyclingtechnik: Fachbuch für Lehre und Praxis. 2nd ed. Wiesbaden: Springer Fachmedien Wiesbaden; 2016.

[5] Secklehner J. Verfahren zur Rückgewinnung von Wertstoffen aus Recycling-Objekten(AT 520225 A2 2019-02-15); 2017.

[6] De B, Bera M, Bhattacharjee D, Ray BC, Mukherjee S. A comprehensive review on fiber-reinforced polymer composites: Raw materials to applications, recycling, and waste management. Progress in Materials Science 2024;146:101326. https://doi.org/10.1016/j.pmatsci.2024.101326.

[7] Kwong KY, Marek EJ. Combustion of Biomass in Fluidized Beds: A Review of Key Phenomena and Future Perspectives. Energy Fuels 2021;35(20):16303–34. https://doi.org/10.1021/acs.energyfuels.1c01947.

[8] Bundesministerium Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasserwirtschaft. Die Bestandsaufnahme der Abfallwirtschaft in Österreich Statusbericht 2025; 2025.

[9] Grech H. Mitverbrennung von Abfällen und Reststoffen in industriellen Feuerungsanlagen. Wien: Umweltbundesamt; 2000.

[10] Lorber KE, Sarc R, Pomberger R. Österreichische Erfahrungen zum Einsatz verschiedener Abfälle als Ersatzbrennstoffe (EBS) und mögliche Anwendungsprobleme 2011.

[11] Mauschitz G. Emissionen aus Anlagen der österreichischen Zementindustrie: Berichtsjahr 2019. Wien; 2020.

[12] Tihin GL, Mo KH, Onn CC, Ong HC, Taufiq-Yap YH, Lee HV. Overview of municipal solid wastes-derived refuse-derived fuels for cement co-processing. Alexandria Engineering Journal 2023;84:153–74. https://doi.org/10.1016/j.aej.2023.10.043.

[13] Rahnama Mobarakeh M, Kienberger T. Climate neutrality strategies for energy-intensive industries: An Austrian case study. Cleaner Engineering and Technology 2022;10:100545. https://doi.org/10.1016/j.clet.2022.100545.

[14] Viczek SA, Aldrian A, Pomberger R, Sarc R. Determination of the material-recyclable share of SRF during co-processing in the cement industry. Resources, Conservation and Recycling 2020;156:104696. https://doi.org/10.1016/j.resconrec.2020.104696.

[15] Kim J, Sovacool BK, Bazilian M, Griffiths S, Lee J, Yang M et al. Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science 2022;89:102565. https://doi.org/10.1016/j.erss.2022.102565.
[16] Smart. - Simple.: Energy from clearing sludge. [June 26, 2025]; Available from: https://smartcity.wien.gv.at/en/approach/smart-city-made-simple/energy-from-clearing-sludge/.
[17] Mauschitz G. Emissionen aus Anlagen der österreichischen Zementindustrie: Berichtsjahr 2018. Wien; 2019.
[18] Berger Helmut. Energieeffi zienz der österreichischen Zementindustrie.
[19] Bundesministerium für Nachhaltigkeit und Tourismus. Die Bestandsaufnahme der Abfallwirtschaft in Österreich: Statusbericht 2019. Wien; 2019.
[20] Umweltbundesamt. Thermische Behandlung. [March 17, 2020]; Available from: https://www.umweltbundesamt.de/themen/abfall-ressourcen/entsorgung/thermische-behandlung#thermische-abfallbehandlung.
[21] Cleaner Production Germany. Thermische Nutzung von Abfallstoffen durch industrielle Mitverbrennung; 2015.
[22] Stubenvoll J, Böhmer S, Szednyj I. State of the Art for Waste Incineration Plants. Wien; 2002.
[23] Rapf M, Thomanetz E. Co-incineration of residues – principles and practical examples in Germany. Unpublished; 2016.
[24] Vereinigung der Österreichischen Zementindustrie. Energieeffizienz der österreichischen Zementindustrie.
[25] CUTEC Institut. Studie: Differenzierung der energetischen Verwertung am Kriterium der Energieeffizienz. Clausthal-Zellerfeld; 2016.
[26] Vodegel S, Davidovic M, Ludewig A. Differenzierung der energetischen Verwertung am Kriterium der Energieeffizienz. In: Energie aus Abfall: Band 15; 2018, p. 761–768.
[27] Krauklis AE, Karl CW, Gagani AI, Jørgensen JK. Composite Material Recycling Technology—State-of-the-Art and Sustainable Development for the 2020s. J. Compos. Sci. 2021;5(1):28. https://doi.org/10.3390/jcs5010028.
[28] Papynov EK, Shapkin NP. Organic waste utilization by means of thermal cracking. Theor Found Chem Eng 2009;43(5):842–5. https://doi.org/10.1134/S0040579509050406.
[29] Czajczyńska D, Anguilano L, Ghazal H, Krzyżyńska R, Reynolds AJ, Spencer N et al. Potential of pyrolysis processes in the waste management sector. Thermal Science and Engineering Progress 2017;3:171–97. https://doi.org/10.1016/j.tsep.2017.06.003.
[30] Quicker P, Neuerburg F, Noël Y, Huras A, Eyssen RG, Seifert H et al. Sachstand zu den alternativen Verfahren für die thermische Entsorgung von Abfällen; 2017.
[31] Chen D, Yin L, Wang H, He P. Pyrolysis technologies for municipal solid waste: a review. Waste Manag 2014;34(12):2466–86. https://doi.org/10.1016/j.wasman.2014.08.004.

[32] Glushkov DO, Nyashina GS, Anand R, Strizhak PA. Composition of gas produced from the direct combustion and pyrolysis of biomass. Process Safety and Environmental Protection 2021;156:43–56. https://doi.org/10.1016/j.psep.2021.09.039.
[33] Glushkov D, Nyashina G, Shvets A, Pereira A, Ramanathan A. Current Status of the Pyrolysis and Gasification Mechanism of Biomass. Energies 2021;14(22):7541. https://doi.org/10.3390/en14227541.
[34] Hasan MM, Rasul MG, Khan M, Ashwath N, Jahirul MI. Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments. Renewable and Sustainable Energy Reviews 2021;145:111073. https://doi.org/10.1016/j.rser.2021.111073.
[35] Zhou T, Zhang W, Shen Y, Luo S, Ren D. Progress in the change of ash melting behavior and slagging characteristics of co-gasification of biomass and coal: A review. Journal of the Energy Institute 2023;111:101414. https://doi.org/10.1016/j.joei.2023.101414.
[36] Satiada MA, Calderon A. Comparative analysis of existing waste-to-energy reference plants for municipal solid waste. Cleaner Environmental Systems 2021;3:100063. https://doi.org/10.1016/j.cesys.2021.100063.
[37] Chen D, Cen K, Zhuang X, Gan Z, Zhou J, Zhang Y et al. Insight into biomass pyrolysis mechanism based on cellulose, hemicellulose, and lignin: Evolution of volatiles and kinetics, elucidation of reaction pathways, and characterization of gas, biochar and bio-oil. Combustion and Flame 2022;242:112142. https://doi.org/10.1016/j.combustflame.2022.112142.
[38] Zhong D, Zeng K, Li J, Qiu Y, Flamant G, Nzihou A et al. Characteristics and evolution of heavy components in bio-oil from the pyrolysis of cellulose, hemicellulose and lignin. Renewable and Sustainable Energy Reviews 2022;157:111989. https://doi.org/10.1016/j.rser.2021.111989.
[39] Emmanouilidou E, Mitkidou S, Agapiou A, Kokkinos NC. Solid waste biomass as a potential feedstock for producing sustainable aviation fuel: A systematic review. Renewable Energy 2023;206:897–907. https://doi.org/10.1016/j.renene.2023.02.113.
[40] Chang SH. Plastic waste as pyrolysis feedstock for plastic oil production: A review. Sci Total Environ 2023;877:162719. https://doi.org/10.1016/j.scitotenv.2023.162719.
[41] Shah HH, Amin M, Iqbal A, Nadeem I, Kalin M, Soomar AM et al. A review on gasification and pyrolysis of waste plastics. Front. Chem. 2022;10:960894. https://doi.org/10.3389/fchem.2022.960894.
[42] Baranek S, Cerny V, Drochytka R, Meszarosova L, Melichar J. Electrically conductive composite materials with incorporated waste and secondary raw materials. Sci Rep 2023;13(1):9023. https://doi.org/10.1038/s41598-023-36287-x.
[43] Schubert H. Handbuch der Mechanischen Verfahrenstechnik. Hoboken: John Wiley & Sons; 2012.
[44] Oliveux G, Dandy LO, Leeke GA. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. Progress in Materials Science 2015;72:61–99. https://doi.org/10.1016/j.pmatsci.2015.01.004.

[45] Asmatulu E, Twomey J, Overcash M. Recycling of fiber-reinforced composites and direct structural composite recycling concept. Journal of Composite Materials 2014;48(5):593–608. https://doi.org/10.1177/0021998313476325.
[46] Brunner PH, Rechberger H. Waste to energy--key element for sustainable waste management. Waste Manag 2015;37:3–12. https://doi.org/10.1016/j.wasman.2014.02.003.
[47] Packiyadhas P, Sivaperumal SK, Murugesan S. A comprehensive review of food waste: composition, current management, thermal treatment, valorization into bioproducts and sustainable development goals linkages. J Mater Cycles Waste Manag 2025;27(2):777–95. https://doi.org/10.1007/s10163-024-02153-9.
[48] Meng F, McKechnie J, Turner TA, Pickering SJ. Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Composites Part A: Applied Science and Manufacturing 2017;100:206–14. https://doi.org/10.1016/j.compositesa.2017.05.008.
[49] Miandad R, Barakat MA, Aburiazaiza AS, Rehan M, Nizami AS. Catalytic pyrolysis of plastic waste: A review. Process Safety and Environmental Protection 2016;102:822–38. https://doi.org/10.1016/j.psep.2016.06.022.
[50] Yang Y, Zhou T, Cheng M, Xie M, Shi N, Liu T et al. Recent advances in organic waste pyrolysis and gasification in a CO2 environment to value-added products. Journal of Environmental Management 2024;356:120666. https://doi.org/10.1016/j.jenvman.2024.120666.
[51] Giorgini L, Benelli T, Brancolini G, Mazzocchetti L. Recycling of carbon fiber reinforced composite waste to close their life cycle in a cradle-to-cradle approach. Current Opinion in Green and Sustainable Chemistry 2020;26:100368. https://doi.org/10.1016/j.cogsc.2020.100368.
[52] Lapkovskis V, Mironovs V, Kasperovich A, Myadelets V, Goljandin D. Crumb Rubber as a Secondary Raw Material from Waste Rubber: A Short Review of End-Of-Life Mechanical Processing Methods. Recycling 2020;5(4):32. https://doi.org/10.3390/recycling5040032.
[53] Boelens P, Pereira L, Tumakov K, Da Assuncao Godinho JR, Da Silva Tochtrop CG, Gupta S et al. A workflow to assess the recoverability of secondary raw materials via physical separation. Waste Manag 2025;193:561–70. https://doi.org/10.1016/j.wasman.2024.12.040.
[54] Lucas Pereira. Mineralogy and microfabric as foundation for a new particle-based modelling approach for industrial mineral separation: Unpublished; 2022.
[55] Cao Y, Wang Y, Riley JT, Pan W-P. A Novel Biomass Air Gasification Process for Producing Tar-Free Higher Heating Value Fuel Gas. Fuel Processing Technology 2006;87(4). https://doi.org/10.1016/j.fuproc.2005.10.003.
[56] Guo X, Qin FGF, Yang X, Jiang R. Study on Low-Temperature Pyrolysis of Large-Size Printed Circuit Boards. Journal of Analytical and Applied Pyrolysis 2014;105. https://doi.org/10.1016/j.jaap.2013.10.014.

[57] Li X, Strezov V, Kan T. Energy Recovery Potential Analysis of Spent Coffee Grounds Pyrolysis Products. Journal of Analytical and Applied Pyrolysis 2014;110. https://doi.org/10.1016/j.jaap.2014.08.012.
[58] Wong K, Rudd C, Pickering S, Liu X. Composites Recycling Solutions for the Aviation Industry. Science China Technological Sciences 2017;60(9). https://doi.org/10.1007/s11431-016-9028-7.
[59] Song YS, Youn JR, Gutowski TG. Life Cycle Energy Analysis of Fiber-Reinforced Composites. Composites Part A: Applied Science and Manufacturing 2009;40(8). https://doi.org/10.1016/j.compositesa.2009.05.020.
[60] Shehab E, Meiirbekov A, Amantayeva A, Tokbolat S. Cost Modelling for Recycling Fiber-Reinforced Composites: State-of-the-Art and Future Research. Polymers 2022;15(1). https://doi.org/10.3390/polym15010150.
[61] Vochozka M, Maroušková A, Váchal J, Straková J. Biochar Pricing Hampers Biochar Farming. Clean Technologies and Environmental Policy 2016;18(4). https://doi.org/10.1007/s10098-016-1113-3.
[62] Kantorek M, Jesionek K, Polesek-Karczewska S, Ziółkowski P, Stajnke M, Badur J. Thermal Utilization of Meat-and-Bone Meal Using the Rotary Kiln Pyrolyzer and the Fluidized Bed Boiler: The Performance of Pilot-Scale Installation. Renewable Energy 2021;164. https://doi.org/10.1016/j.renene.2020.10.124.
[63] Zhang M, Vogelbacher M, Hagenmeyer V, Aleksandrov K, Gehrmann H-J, Matthes J. 3-D Refuse-Derived Fuel Particle Tracking-by-Detection Using a Plenoptic Camera System. IEEE Transactions on Instrumentation and Measurement 2022;71. https://doi.org/10.1109/TIM.2022.3217858.
[64] Pichler M, Haddadi B, Jordan C, Norouzi H, Harasek M. Influence of Particle Residence Time Distribution on the Biomass Pyrolysis in a Rotary Kiln. Journal of Analytical and Applied Pyrolysis 2021;158. https://doi.org/10.1016/j.jaap.2021.105171.
[65] Liu XY, Specht E. Mean Residence Time and Hold-Up of Solids in Rotary Kilns. Chemical Engineering Science 2006;61(15). https://doi.org/10.1016/j.ces.2006.03.054.
[66] Benanti E, Freda C, Lorefice V, Braccio G, Sharma V. Simulation of Olive Pits Pyrolysis in a Rotary Kiln Plant. Therm sci 2011;15(1). https://doi.org/10.2298/TSCI090901073B.
[67] eurostat. Database. [June 26, 2025]; Available from: https://ec.europa.eu/eurostat/databrowser/explore/all/all_themes.
[68] Gruber-Glatzl W, Krainz R, Fluch J, Mauthner F, Hammer A, Lachner E et al. Öffentlicher Kurzbericht des Projekts Abwärmekatatster III Steiermark; 2021.
[69] Altstoff Recycling Austria AG. Bilanz des Recyclingprojekts des Österreichischen Kaffee- und Teeverbands und der ARA; Available from: https://www.ara.at/news/bilanz-des-recyclingprojekts-des-oesterreichischen-kaffee-und-teeverbands-und-der-ara.
[70] Chatterjee S. Sustainable Electronic Waste Management and Recycling Process.
[71] Umweltbundesamt (ed.). Entwicklung von Rückbau- und Recyclingstandards für Rotorblätter: Aufbereitung von Rotorblättern; 2022.

8 Contact details

Project manager	Chair of Energy Network Technology, Montanuniversität Leoben Thomas Kienberger Franz-Josef-Straße 18, 8700 Leoben +43 3842 402 5400 evt@unileoben.ac.at https://www.evt-unileoben.at
Project partners	OÖ Energiesparverband Christine Öhlinger Landstraße 45, 4020 Linz +43 732 7720 14861 Christine.oehlinger@esv.or.at www.energiesparverband.at
	seccon GmbH Jürgen Secklehner Halsgraben 10, 4644 Scharnstein office@seccon.co.at http://www.seccon.co.at/
	WSA - Waste Service GmbH Christoph Resl Habersdorferstraße 21, 8230 Hartberg +43 332 66368-25 Christoph.Resl@wsa.co.at https://www.wsa.co.at/