Waste Management 176 (2024) 105–116

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Pyrolysis of mixed engineering plastics: Economic challenges for automotive plastic waste

Christoph Stallkamp [a,*], Malte Hennig [b], Rebekka Volk [a], Dieter Stapf [b], Frank Schultmann [a]

[a] Karlsruhe Institute of Technology (KIT), Institute for Industrial Production (IIP), Karlsruhe, Germany

[b] Karlsruhe Institute of Technology (KIT), Institute for Technical Chemistry (ITC), Karlsruhe, Germany

ARTICLE INFO

Keywords:
Industrial ecology
Chemical recycling
Circular economy
Economic assessment
Pyrolysis
Mixed engineering plastic waste

ABSTRACT

Chemical recycling of complex plastic waste via pyrolysis can reduce fossil resource dependence of the plastics value chain and greenhouse gas emissions. However, economic viability is crucial for its implementation, especially considering challenging waste streams with high shares of engineering plastics that have lower pyrolysis product quality than standard thermoplastics waste. Thus, this study conducts a techno-economic assessment determining the profitability factors of pyrolysis plants for automotive plastic waste in Germany including different plant capacities and calculating cost-covering minimum sales prices for the resulting pyrolysis oil. Main findings are that due to economies of scale, the cost-covering minimum sales prices vary between 1182 €/Mg pyrolysis oil (3750 Mg input/year) and 418 €/Mg pyrolysis oil (100,000 Mg input/year). The pyrolysis technology employed must be robust and scalable to realize these economies of scale. Large plant capacities face challenges such as feedstock availability at reasonable costs, constant feedstock quality, and pyrolysis oil quality, affecting pyrolysis oil pricing. Due to the limited yield and quality of pyrolysis oil produced from these technically demanding feedstocks, policy implications are that additional revenue streams such as gate fees or subsidies that are essential to ensure a positive business case are necessary. Depending on the assessed plant capacity, additional revenues between 720 and 59 €/Mg pyrolysis oil should be realized to be competitive with the price of the reference product heavy fuel oil. Otherwise, the environmental potential of this technology cannot be exploited.

1. Introduction

Global plastic production reached 367 million metric tons in 2020 (Plastics Europe, 2022) and contributed 3.4 % of global greenhouse gas emissions (GHG) in 2019 (OECD, 2022). Current production primarily relies on fossil carbon sources (EMAF, 2016), resulting in 88 % of the GHG emissions of the plastic value chain being accounted for by plastic production and conversion (OECD, 2022), while 12 % of GHG emissions result from end-of-life (EoL) waste management (OECD, 2022). Globally, the incineration of plastic waste contributes 5 % to the total life cycle emissions (Vanderreydt et al., 2021). With the forecast of a further increase in plastic production (IEA, 2018), the pressure to implement strategies to reduce the life cycle emissions of plastics is increasing.

Several strategies can be employed when focusing on the fossil decarbonization of the plastic life cycle. The electrification of the production process focuses on the electrical provision of required process energy (Schiffer and Manthiram, 2017; Cabernard et al., 2021), while biomass can be used to supply the carbon raw material needed (Zheng and Suh, 2019; Meys et al., 2021). Circular economy strategies, including improved recycling, aim to maintain carbon in the industrial cycle and reutilize the carbon in production processes (Zheng and Suh, 2019; Meys et al., 2021). However, recycling of engineering plastics such as from the automotive sector is particularly challenging due to mineral fillers, diverse additives and flame-retardants. In this study, we focus on a novel defossilization approach of the plastic's EoL through enhancing engineering plastic recycling. Enhanced plastic recycling could reduce the need for fossil resources and energy demand in plastic production and limit greenhouse gas emissions in production and EoL (Agora Industry, 2022; IPCC, 2022). Since this is a challenge and a novel technology, policy implications are important to foster R&D and economic feasibility.

In Europe, the current EoL management of post-consumer plastic waste is dominated by energy recovery (42 %), while 23 % of the waste is still landfilled, and only 35 % is recycled (Plastics Europe, 2022).

* Corresponding author.
E-mail address: christoph.stallkamp@gmail.com (C. Stallkamp).

https://doi.org/10.1016/j.wasman.2024.01.035
Received 18 September 2023; Received in revised form 31 December 2023; Accepted 18 January 2024
Available online 26 January 2024

These numbers emphasize the need to strengthen recycling and support a circular economy, especially since post-consumer plastic waste landfills are prohibited under the EU Waste Framework Directive 2008/98/EC and EU Landfill Directive 1999/31/EC. The EU Circular Economy Action Plan also underlines the EU's ambitions towards a circular economy, improving the recyclability of products and creating circular value recovery models (Schempp & Hirsch, 2020).

Chemical recycling technologies like pyrolysis are being explored to recover additional circular value by recovering waste materials that cannot be recovered otherwise (Schempp & Hirsch, 2020). In pyrolysis, plastic waste decomposes in an inert atmosphere at elevated temperatures, resulting in solid, liquid, and gaseous products (Dogu et al., 2021). Liquid products have the potential to replace fossil hydrocarbon feedstock in petrochemistry to produce high-value chemicals, closing the carbon cycle (Lechleitner et al., 2020). Since the produced platform chemicals can be used for many different production processes and are not necessarily used for the production of plastics, pyrolysis is an open-loop recycling technology (Nicholson et al., 2022).

Pyrolysis is complementary to mechanical recycling and is designed for recycling waste streams that previously could not be recycled. Multiple studies highlight the environmental benefits of pyrolysis[1] compared to energy recovery and landfilling of plastic waste unsuitable for mechanical recycling (Jeswani et al., 2021; Meys et al., 2020; Schwarz et al., 2021; Stallkamp et al., 2023). Combining different recycling technologies can result in high recycling rates and low environmental impacts (Volk et al., 2021).

However, chemical recycling via pyrolysis must be economically feasible to realize these environmental advantages. Kulas et al. (2023) economically assess the recycling of mixed polyolefin waste through pyrolysis and calculate the minimum sales price of pyrolysis oil with naphtha-like quality. The price of secondary naphtha is slightly higher than that of primary naphtha and the sensitivity analysis shows the influence of waste plastics feedstock costs, pyrolysis gas sales, operating capacity, and waste disposal costs on the financial outcome. Other studies assess the economics of plastic waste recycling via pyrolysis for mixed plastic waste (MPW). Westerhout et al. (1998) evaluate different reactor types in a concept screening to identify the reactor design with the highest financial returns. Sahu et al. (2014) simulate a catalytic fluidized bed reactor to analyze its economic performance in producing fuel from MPW. Fivga and Dimitriou (2018) assess the economics of a fluidized bed reactor using an ASPEN simulation model. Jiang et al. (2020) evaluate the economics of a molten salt pyrolysis plant with MPW feedstock employing an ASPEN simulation model with an internal rate of return (IRR) of 33 %. Larrain et al. (2020) determined that a plant capacity between 70,000 and 115,000 Mg input/a is required to economically operate a pyrolysis plant in Belgium, depending on the product mix. Riedewald et al. (2021) assess the economic performance of a pyrolysis plant employing the PlastPyro process handling MPW in Belgium. They outline that a plant with 40,000 Mg input/a capacity is economically viable, with higher throughputs increasing the financial returns. Yadav et al. (2023) discuss the economic and environmental performance of a catalytic fast pyrolysis facility that converts 240 metric tons/day of MPW with a high polyolefin content. When producing naphtha, the minimum sales price of secondary naphtha is around 4-fold higher than virgin naphtha. A conducted sensitivity analysis highlights the impact of feedstock cost, co-product sales prices, capital cost for product separations, and operating costs as key cost drivers.

Current economic assessments of plastic pyrolysis primarily focus on plastic waste with a high polyolefin content. However, when considering the synergy between mechanical and chemical plastic recycling (Volk et al., 2021) as well as increasing recovery rates for standard thermoplastics in sorting (Antonopoulos et al., 2021; Lim et al., 2022), it becomes evident that the material suitable for chemical recycling will primarily consist of plastic waste that cannot undergo mechanical recycling. Accordingly, these waste streams will contain significantly smaller amounts of polyolefins and higher shares of engineering plastics, e.g., polyamides, polycarbonates, or composites of reinforced standard thermoplastics. We provide a more comprehensive overview of engineering plastics in Section 2.1.1. Due to the different technical challenges of handling such complex feedstocks (Arena & Ardolino, 2022), a more detailed analysis of the pyrolysis is needed to identify economic challenges. Automotive plastic waste (APW) is an example of a demanding waste stream usually incinerated (Cossu & Lai, 2015; Mehlhart et al., 2018). While other waste streams with high proportions of engineering plastics may show different behavior in pyrolysis, the key challenges and requirements for an economically feasible recycling process will be similar. Thus, the APW case can provide valuable insights into business cases for other complex waste streams, such as automotive shredder residues (ASR) or waste electronics and electric equipment (WEEE).

Stallkamp et al. (2023) show that chemical recycling of APW is associated with a lower carbon footprint than energy recovery and can potentially contribute to closing the carbon cycle. This study conducts a techno-economic assessment (TEA) to determine the economic challenges and minimum sales prices of pyrolysis oil from engineering plastics that cover production costs for the different plant capacities. The TEA is based on the case study of the pyrolysis of APW from workshops in Germany.

The paper is organized as follows: Section 2 describes materials and methods for the pyrolysis process and the techno-economic assessment. Section 3 covers the results split into CAPEX, OPEX, scale-up, and sensitivity analysis. This is followed by a discussion (Section 4) and conclusion (Section 5).

2. Materials and methods

This section describes the assessed pyrolysis process and its implementation in a screw reactor plant design. Feedstock and products, as well as mass and energy balances, are established. A techno-economic assessment can be used to assess novel technologies in intermediate technology readiness levels and to determine capital (CAPEX) and operational expenditures (OPEX) (Van Dael et al., 2015). The TEA calculations were performed in MS Excel.

2.1. Pyrolysis process

The twin-screw reactor assessed in this study was derived from the single-screw plastic pyrolysis reactor described by Zeller et al. (2021) and Tomasi Morgano et al. (2015). The product recovery section was adapted based on the product recovery of the biomass-to-liquid (BtL) pyrolysis plant described by Trippe et al. (2010). Using a similar reactor concept and reaction conditions in the assessment as used in pilot-scale APW pyrolysis experiments, we assume that the mass and energy balance reported by Stallkamp et al. (2023) can be transferred to the process layout assessed here (Fig. 1). This assumption is discussed in Section 2.1.3. For validation, pilot-scale experiments need to be conducted in the industrial set-up.

In the delivery and pre-treatment module, the feedstock is conditioned by reducing the particle size and removing metals before being stored to ensure the plant's supply (Trippe et al., 2010). For the pyrolysis, feedstock and quartz sand are fed into the twin-screw reactor (Trippe et al., 2010). The sand is used for improved heat transfer within the electrically heated pyrolysis reactor, providing the temperature of 450 °C required for pyrolysis (Zeller et al., 2021). The feedstock decomposes into pyrolysis vapors that are extracted from the reactor, filtered, and fed to a condensation module for product recovery (Zeller et al., 2021). Sand and pyrolysis residue are discharged from the reactor and separated in a vibration sieve (Trippe et al., 2010). The sand is sent back to the reactor while pyrolysis residues are discharged.

[1] when including the avoided burdens of primary plastic production

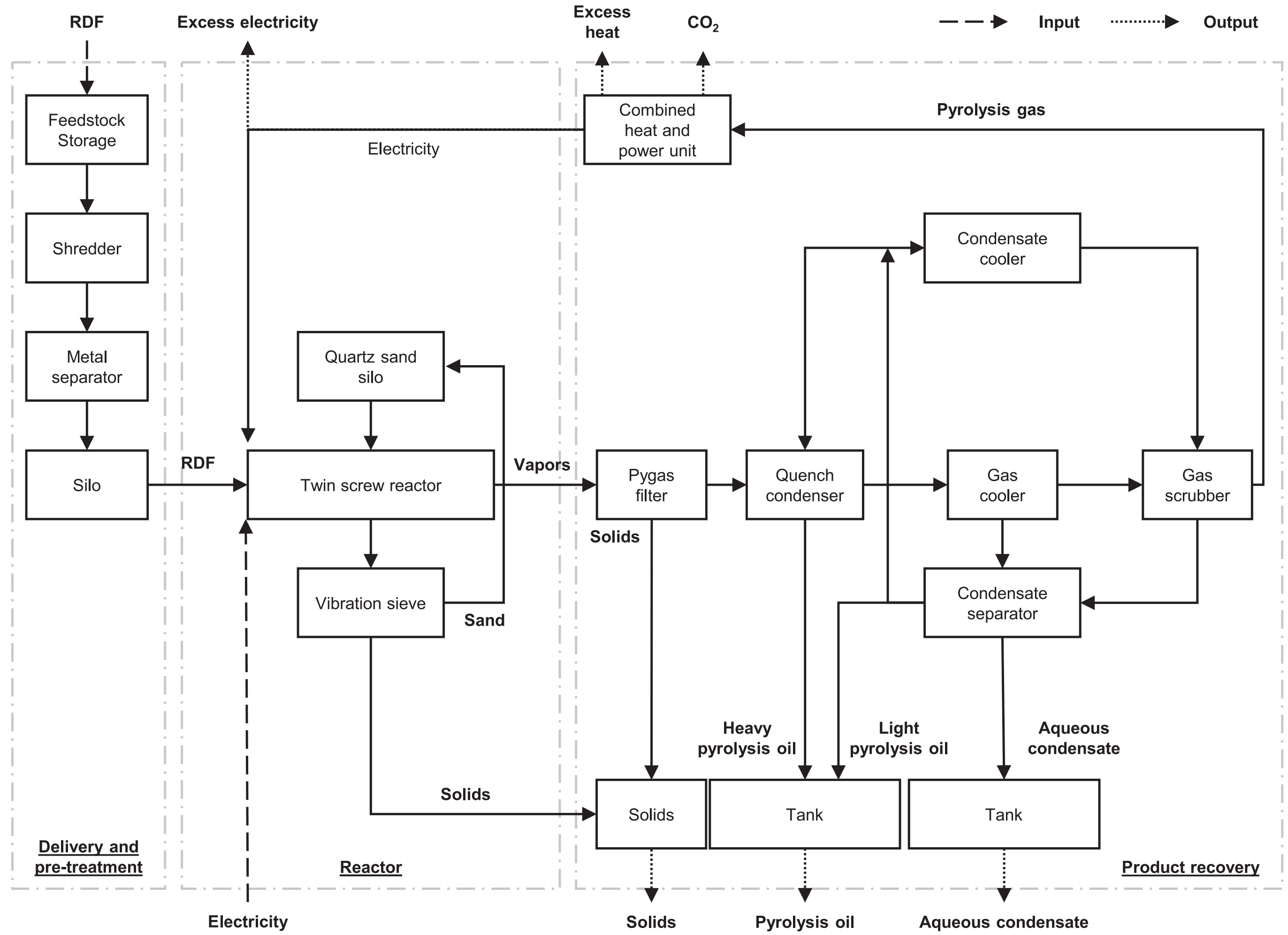


Fig. 1. Pyrolysis plant design with three modules: (1) delivery and pre-treatment, (2) reactor, and (3) product recovery (adapted from Trippe et al., 2010). Dashed lines indicate inputs into the system, and dotted lines imply system outputs associated with costs or payments.

The pyrolysis oil recovered from the condensation is the desired main product of the pyrolysis process and is collected in a tank. Non-condensed gases and vapors are cooled in a gas cooler and purified in a gas scrubber (Trippe et al., 2010). Lighter condensing fractions and water are separated and collected in tanks. Parts of the light condensates are used in the quench condenser and the gas scrubber to recover the pyrolysis condensates (Trippe et al., 2010). The aqueous condensate is collected for disposal via co-incineration. The remaining incondensable pyrolysis gas is incinerated in a gas engine with heat recovery (combined heat and power unit (CHPU)) to generate electricity and heat. The generated heat is sold, e.g., to a district heating network. The generated electricity is used to provide the electrical energy demand of the plant. Surplus electricity exceeding the plant's demand is sold to the grid operator. If electricity production is insufficient, additional electricity is sourced from the grid.

2.1.1. Feedstock in Germany

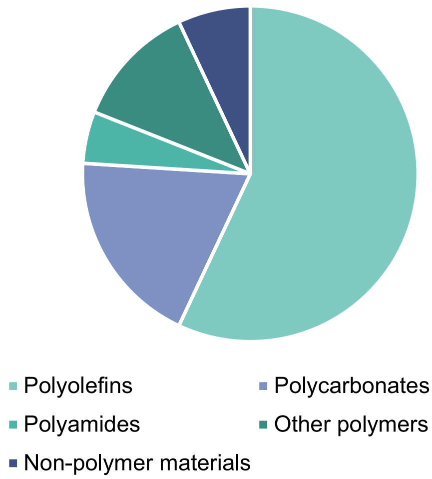
Engineering plastics comprise a wide range of different polymers, including polyamides (e.g., PA6, PA66, PA12), polycarbonates (PC), polyoxymethylene/polyacetal (POM), composites of reinforced standard thermoplastics (e.g., by glass fiber reinforcement or addition of talc to polypropylene), plastic alloys (e.g., PC/ABS), and specialty plastics (e.g., Polyether ether ketone, PEEK) in addition to their modifications by use of flame retardants, pigments, and coatings (Crawford and Martin, 2020; American Chemistry Council, 2020). APW from workshops is an example of plastic waste streams with high shares of engineering plastics. APW is used primarily for energy recovery in Germany (Stallkamp et al., 2023); therefore, this study assumes that the feedstock competes with energy recovery.

In Germany, the waste treatment of APW from workshops starts with its collection and transport to refuse-derived fuel (RDF) production. Metals are separated and sent to established recycling processes, while all other materials are processed to RDF (Stallkamp et al., 2023). Stallkamp et al. (2023) provide a characterization of an RDF from APW of a premium car manufacturer in Germany. Fig. 2 shows the composition of the APW sample and its elemental composition based on Stallkamp et al. (2023) used in this assessment. Fig. S-1 in the supporting information (SI) shows a picture of the non-shredded feedstock.

APW can originate from two sources: (1) treatment of end-of-life (EoL) vehicles and (2) repair jobs in workshops during the use phase of a vehicle. While no specific data exist for the latter, a conservative estimate of the waste volume of APW can be derived based on the annual number of EoL vehicles treated. The German Environmental Agency (Umweltbundesamt) states that around 3 kg of plastic parts are dismantled from an EoL vehicle in Germany (UBA, 2022). With approximately 460,000 EoL vehicles in 2019 (UBA, 2022), this results in an APW volume of 1380 Mg/a. According to Wilts et al. (2016), this amount can increase by six if dismantling large plastic components becomes part of automobiles' EoL treatment processes, resulting in 8280 Mg for 2019.

The available feedstock increases when considering mixed plastic waste fractions separated from automotive shredder residues (ASR).

a)



b)

Element	[wt-%]
C	53.6
H	6.8
N	4.0
S	0.1
Cl	1.5
F[1] in ppm	-
Br[1] in ppm	-
Ash (incl. metals)	21.8
O[2]	12.2
NCV[3,4] [MJ/kg]	26.3

[1] Neglected in elemental balances
[2] Calculated as difference to 100%
[3] Calculated value based on elemental composition
[4] Adopted to a metal-free feedstock / RDF

Fig. 2. APW with a) sample composition and b) elemental composition, ash content, and calculated net calorific value (NCV) (Stallkamp et al., 2023).

These mixed plastic fractions have shown similar behavior in pyrolysis regarding mass and energy balances like APW (Zeller et al., 2021). Based on the ASR waste volume of 2019 and assuming the implementation of a post-shredder technology (ARN, 2016), an additional amount of 1622 Mg/a of APW could be made available. Accounting for process losses at the RDF producer (Stallkamp et al., 2023), the total ASR-based feedstock volume is just below 10,000 Mg for 2019 in Germany.

The pyrolysis plant obtains the feedstock from RDF producers. The prices vary between −60€ and +30€/Mg, depending on the RDF quality (EU-Recycling, 2019). Therefore, gate fees for treating or purchasing waste as a raw material are conceivable. Since the RDF from APW is a high-calorific feedstock from commercial waste, we assume the feedstock is purchased for 15 €/Mg. Since the prices are acceptance prices and we assume the same logistical effort as with the delivery to energy recovery facilities, we do not consider any diseconomies of supply. We analyze the impact of a fluctuation in the feedstock price in the sensitivity analysis.

2.1.2. Pyrolysis oil and other process products

Pyrolysis oil is the main product of the recycling process. The obtainable price for the oil depends on various factors, such as the oil's quality and current market dynamics (Tullo, 2022). The elemental composition of the heavy pyrolysis oil shows a significant share of oxygen (6.6 %) as well as nitrogen (1.17 %), sulfur (0.08 %), and a chlorine content of 0.05 % (cf. Table 1). Nitrogen, sulfur, and chlorine content are similar to marine fuels (World Fuel Services, 2017), while oxygen usually cannot be found in fossil fuels. However, since the possible prices also depend on the demand for pyrolysis oil and other market dynamics and reference prices are not available, we do not assume a fixed price for the pyrolysis oil but calculate the minimum sales price to cover the costs of the pyrolysis plant.

The pyrolysis gas is used in a CHPU to generate electricity and heat. Depending on the amount of electricity generated, the energy demand of the pyrolysis plant can be covered. Excess electricity can be fed to the grid (0.03 €/MJ; (Fraunhofer ISE, 2023)). If additional electricity is needed, it is supplied from the grid (0.06 €/MJ; (Bundesnetzagentur, 2022)). Excess heat is provided to a district heating network. In 2021, Germany's average price for district heating was 0.02 €/MJ (AGFW, 2022). The by-products aqueous condensate and solid residues have to be disposed of and are treated by co-incineration in waste incineration associated with costs of 150 €/Mg (EUWID, 2023).

Table 1
Pyrolysis oil characterization regarding mean elemental composition, water content, and calculated NCV (calculated from Stallkamp et al., 2023).

Elemental composition	
C [wt.-%]	80.4
H [wt.-%]	11.7
N [wt.-%]	1.2
S [wt.-%]	0.09
Cl [ppm]	500
F [ppm]	< 60
Br [ppm]	< 60
O[1] [wt.-%]	6.56
Water content [wt.-%]	0.85
Net calorific value[2] [MJ/kg]	38.4

[1] Calculated as difference to 100 %, including oxygen bound in form of water.
[2] Calculated value based on elemental composition.

2.1.3. Transferability of mass and energy balances from pilot-scale experiments

Hennig et al. (2022) and Stallkamp et al. (2023) performed experiments with APW from car workshops. Regarding the transferability of these pilot-scale experimental results, there are three aspects to be considered: (1) the choice of technology for the scaled-up process, (2) the similarity of reaction conditions, and (3) the representativeness of the pilot-scale experiments. As APW contains a high amount of non-polymeric, non-volatile matter, the reactor concept must tolerate large amounts of solids in the system (cf. Fig. 2). Since sand is used for improved heat transfer, the screw reactor concept can process feedstocks with high amounts of solid residue. On the downside, the feedstock transport by the screw limits the maximum capacity of the scaled-up reactor to approximately 500 kg/h feedstock due to mechanical restraints. The pilot-scale reactor used for the experiments was designed to allow continuous operation with similar reaction conditions as in an industrial-sized unit regarding mass and heat transfer, particle size, and gas and solids residence time. By conducting five experiment runs with a sample size of 5 kg each, the material heterogeneity present in the feedstock even after thorough comminution and mixing was captured. Therefore, we assume that overall, the experimental results from the pilot-scale are transferable to the scaled-up version due to the comparable technology employed, similar reaction conditions present, and sample representativity of pilot-scale experiments. Nevertheless, we conduct a sensitivity analysis considering energy demand and plant availability, among others, to account for possible differences between pilot-scale experiments and an industrial-sized plant and aging effects over the years (cf. Section 3.4).

2.1.4. Mass and energy balances

Following the considerations regarding the transferability of experimental data from pilot-scale to industrial scale, the mass and energy flow for the pyrolysis of RDF from APW are adopted from Stallkamp et al. (2023) and are presented in Table 2. Stallkamp et al. (2023) measured the specific heat demand for pyrolysis at 6.3 % of RDF's initial net calorific value, resulting in an electricity demand of 1578 MJ/Mg input. The product composition is 49 % pyrolysis oil, 20 % pyrolysis gas, and 31 % pyrolysis residues for co-incineration in a waste incineration plant.

The recovered energy from pyrolysis gas incineration depends on the CHPU's efficiency. With an increasing baseload, the electrical efficiency of the CHPU increases while the combined electrical and thermal efficiency drops slightly (cf. Table S-1, S1) (EPA, 2015). Therefore, the amount of recovered electricity and heat depends on the size of the pyrolysis plant. Table 2 shows the energy recovery for a plant with an input capacity of 3750 Mg/a. CO_2 emission fees must be paid for the CO_2 emissions associated with incinerating the pyrolysis gas.

2.2. TEA assumptions

2.2.1. Equipment and infrastructure investment

The equipment and infrastructure (E&I) investment for the pyrolysis plant is calculated based on the plant design and a list of equipment needed, following the capacity estimate approach for all standard mechanical and process engineering components (Humphreys, 2005). The components' investment is scaled based on the capacity and component-specific cost-capacity factors (cf. Eq. (1)).

$$I_2 = I_1 \times \left(\frac{C_2}{C_1}\right)^x \quad (1)$$

I_2: Investment for scaled capacity 2
I_1: Investment for baseline capacity 1
C_2: Scaled capacity 2
C_1: Baseline capacity 1
x: Component-specific cost-capacity factor

However, reactors like the twin-screw reactor have mechanical limitations that do not allow limitless scaling. Due to the reactor filling level and screw design, a maximum reactor capacity of 0.5 Mg/h is assumed. This capacity corresponds to the reactor installed in the BtL plant (IKFT, 2018) and a current commercial pyrolysis plant construction (KIT Technology, 2021). For higher throughputs, it is assumed that additional reactors must be operated following a numbering-up approach. Scaling single reactors following the capacity estimate approach (cf. Eq. (1)) is possible. It is assumed that a maximum of four reactors are connected to one product recovery unit[2] to reduce the complexity of the plant design.

All used component prices were adapted to 2021, accounting for inflation using the ProcessNet Chemical Plant Index Germany (PCD) (DECHEMA & VDI, 2022). Based on Dysert et al. (2016) and Towler & Sinnott (2012) and the chosen capacity estimate approach, the conducted study is classified as a project screening or feasibility study (class 4). For this level, the classification matrix for estimating costs in the process industry assumes an accuracy interval for the investment between −30 % and +50 % (Dysert et al., 2016; Towler & Sinnott, 2012).

2.2.2. Capital expenditures (CAPEX)

The CAPEX is based on the required E&I investment and calculated using an equipment factor method. Following Peters et al. (2003), the CAPEX are computed by applying defined percentages of the E&I investment (cf. Table 3). To calculate the CAPEX, we assume a brownfield setting to enable the integration of product streams into existing production or district heating networks.

2.2.3. Operational expenditures (OPEX)

The OPEX is separated into fixed and variable OPEX. The fixed OPEX is independent of the amount of feedstock handled and is based on the size and capacity of the plant. They include personnel costs, maintenance, yearly insurance, and general plant overhead calculated based on percentages of the E&I investment (cf. Table 3) (Larrain et al., 2020). Personnel costs depend on the wages paid and are not influenced by the investment. The plant's capacity determines the number of workers needed. The fixed OPEX also includes depreciation and costs for financing the plant.

The variable OPEX depends on the amount of feedstock handled and is calculated based on the process flows and mass and energy balances. Here, material and energy streams are associated with costs, and the OPEX can be calculated by multiplying these cost rates (cf. Table 3) with the actual streams within the plant.

2.2.4. Scale-Up

Four different capacity classes are assessed, starting at a pilot-scale plant's input capacity of 3750 Mg/a, i.e., one reactor unit (KIT Technology, 2021). Other assessed plant capacities are 25,000 and 50,000 Mg input/a, that are similar to existing operated pyrolysis plants (Quantafuel, 2023). The 100,000 Mg input/a capacity is in the same range as currently planned pyrolysis plants (Quantafuel, 2023). All plants are operated 7500 h/a, resulting in an uptime of 85 % and allowing for inspections.

The plant concept is scaled up based on the baseline cost estimation for the pilot-scale plant. The numbering-up approach for the reactor and the product recovery module is combined with gradual scaling and specific cost-capacity factors for individual equipment (section 2.2.1).

3. Results

3.1. E&I investment and CAPEX

The E&I investment of the pyrolysis plant is calculated as described in Section 2.2. The investment (cf. Table S-2, S1) and CAPEX (cf. Table S-3, S1) of all assessed capacities are provided in S1. Here, the E&I investment and CAPEX for the pilot-scale plant with an input capacity of 3750 Mg/a are presented.

The land investment results in 167,000 €. The delivery and pretreatment module of the plant includes crane systems for unloading, conveyor belts, metal separators, and a shredder. In total, it is associated with an estimated investment of 518,000 €. One twin-screw reactor is operated. Reactor, vibration sieves, and sand cycle components add up

Table 2
Mass and energy balance for APW pyrolysis and coupled energy recovery from pyrolysis by-products (based on Stallkamp et al., 2023).

Input		Output	
Item	Quantity	Item	Quantity
Pyrolysis			
RDF (Mg)	1	Pyrolysis oil (Mg)	0.49
		Pyrolysis gas (Mg)	0.20
Electricity demand (MJ)	1578	Pyrolysis residues (Mg)	0.31
Energy recovery from pyrolysis gas			
Pyrolysis gas (Mg)	0.20	Electricity[1] (MJ)	1103
		Heat[2] (MJ)	1907
		CO_2 (Mg)	0.17

[1] Electrical efficiency varies between 27 % and 42 % depending on the size of the CHPU (EPA, 2015); values are presented for an input capacity of 3750 Mg/a.
[2] Thermal efficiency varies between 35 % and 53 % depending on the size of the CHPU (EPA, 2015); values are presented for an input capacity of 3750 Mg/a.

[2] Excluding the CHP unit.

Table 3
Assumptions and parameters for the techno-economic assessment of the pyrolysis plant.

Technical parameters		
Yield pyrolysis oil	49 %	(Stallkamp et al., 2023)
Pyrolysis gas	20 %	(Stallkamp et al., 2023)
Aqueous condensate	2 %	(Stallkamp et al., 2023)
Pyrolysis residues	29 %	(Stallkamp et al., 2023)
Electrical energy demand pyrolysis plant	6 % of the feedstock's net calorific value	(Stallkamp et al., 2023)
Net calorific value of feedstock	26.3 MJ/kg	(Stallkamp et al., 2023)
Net calorific value of pyrolysis oil	38.4 MJ/kg	(Stallkamp et al., 2023)
Net calorific value of pyrolysis gas	19.4 MJ/kg	(Stallkamp et al., 2023)
Net calorific value of pyrolysis residues	12.0 MJ/kg	(Stallkamp et al., 2023)
Operational parameters		
Operating time	7500 h/a	Assumption
Shifts	3 per day	n/a
Financial parameters		
Reference year	2021	n/a
Method of financing	Bank loan	Assumption
Calculation interest rate	8 %	(Peters et al., 2003)
Operating life	20 years	(German Federal Ministry of Finance, 1995)
CAPEX (specified as % of E&I investment)		
Equipment installation	39 %	(Peters et al., 2003)
Instrumentation and controls (installed)	26 %	(Peters et al., 2003)
Piping (installed)	31 %	(Peters et al., 2003)
Electrical system (installed)	10 %	(Peters et al., 2003)
Buildings (including services)	29 %	(Peters et al., 2003)
Yard improvements	12 %	(Peters et al., 2003)
Service facilities (installed)	55 %	(Peters et al., 2003)
Engineering and supervision	32 %	(Peters et al., 2003)
Construction expenses	34 %	(Peters et al., 2003)
Project Management	20 %	(Peters et al., 2003)
Legal expenses	4 %	(Peters et al., 2003)
Contractor's fee	19 %	(Peters et al., 2003)
Contingency	37 %	(Peters et al., 2003)
Working capital	75 %	(Peters et al., 2003)
OPEX		
Labor expenses*		
Plant operators	55,000 €/a	(Riedewald et al., 2021)
Yard team & maintenance	59,000 €/a	(Riedewald et al., 2021)
Management & engineering	70,000 €/a	(Riedewald et al., 2021)
Maintenance	4 % of E&I investment	(Larrain et al., 2020)
Yearly insurance	2 % of E&I investment	(Larrain et al., 2020)
General plant overhead[1]	65 % of labor and maintenance	(Riedewald et al., 2021)
Disposal of solid residues	150 €/Mg output	(EUWID, 2023)
Disposal of aqueous condensate	150 €/Mg output	(EUWID, 2023)
Costs of electricity from the grid	0.06 €/MJ	(Bundesnetzagentur, 2022)
Price for electricity sold	0.03 €/MJ	(Fraunhofer ISE, 2023)
Price for heat sold	0.02 €/MJ	(AGFW, 2022)
CO_2 emission fees	53 €/Mg	(EU ETS, 2022)
Feedstock costs	15 €/Mg	(EU-Recycling, 2019)

*: The number of workers in each job description depends on the plant's capacity; compare S1, Table S-5 for the personal breakdown.

[1] Include human resources, research and development, information technology, finance, and legal (Larrain et al., 2020).

to an investment of 569,000 €. For the product recovery module, an investment of 657,000 € is needed. This includes cleaning steps for the pyrolysis gas and vapors, condensation steps, the separation of condensates, and the CHPU. In total, the E&I investment results in 1,910,000€.

The CAPEX are calculated based on the E&I investment using the percentages in Table 3 (Peters et al., 2003) and results in 9,993,000 € (cf. Table S-3). CAPEX and the composition of the investment for different plant sizes are presented in Section 3.3.

3.2. OPEX

The OPEX for all capacities are summarized in S1 (cf. Table S-4). Here, the OPEX for the pilot-scale plant are presented. Fixed OPEX depend on the capacity and the total investment for the pyrolysis plant. Based on the parameters shown in Table 3, maintenance results in 76,000 €, insurance amounts to 29,000 €, and general plant overhead results in 384,000 €. Personnel costs are calculated based on the plant's staffing (cf. Table S-5) and associated wages, resulting in 515,000 € per year.

Annualization is used to calculate the cost of capital (Smith, 2016). A period's non-periodic and periodic payments are transformed into regular periodic payments (annuity). It reflects the interest and repayment of capital. The annuity of the investment-linked payments corresponds to the cost of capital, resulting from multiplying the fixed capital investment and the annuity factor (Eq. (2)). Direct and indirect plant costs add to the fixed capital investment (Table S-3, S1). The annuity factor depends on the lifetime of the plant and the interest rate (Eq. (3)).

$$C_{capital} = \text{Fixed capital investment} \times f_A \quad (2)$$

$$f_A = \frac{(1+i)^n \times i}{(1+i)^n - 1} \quad (3)$$

$C_{capital}$: Cost of capital
f_A: Annuity factor
i: interest rate
n: the lifetime of the plant

This study assumes an interest rate of 8 % (Peters et al., 2003) and a plant lifetime of 20 years (German Federal Ministry of Finance, 1995). This results in an annuity factor of 0.10 and cost of capital of 872,000 €/a for the investment. Additional capital costs for the working capital result from the multiplication with the calculation interest rate and sum up to 115,000 €/a.

The variable OPEX include CO_2 emission fees, feedstock costs, electricity costs, and disposal costs for aqueous condensate and solid residues. Payments for generated heat and electricity[3] are shown separately. Table S-4 (S1) provides an overview of the costs and payments associated with each item. The total gross OPEX result in 2,358,000 € if full capacity is utilized, corresponding to 629 €/Mg feedstock input. Including the payments from the by-products, the net OPEX result is 2,198,000 €, corresponding to 586 €/Mg feedstock input.

3.3. Scale-up

The investments and CAPEX of each plant capacity are summarized in Fig. 3. Comparing the total CAPEX of the pilot-scale plant with the

[3] The returns from excess electricity are a theoretical construct, since no excess electricity is harvested in any of the considered configurations. This case only occurs with the parameter variation.

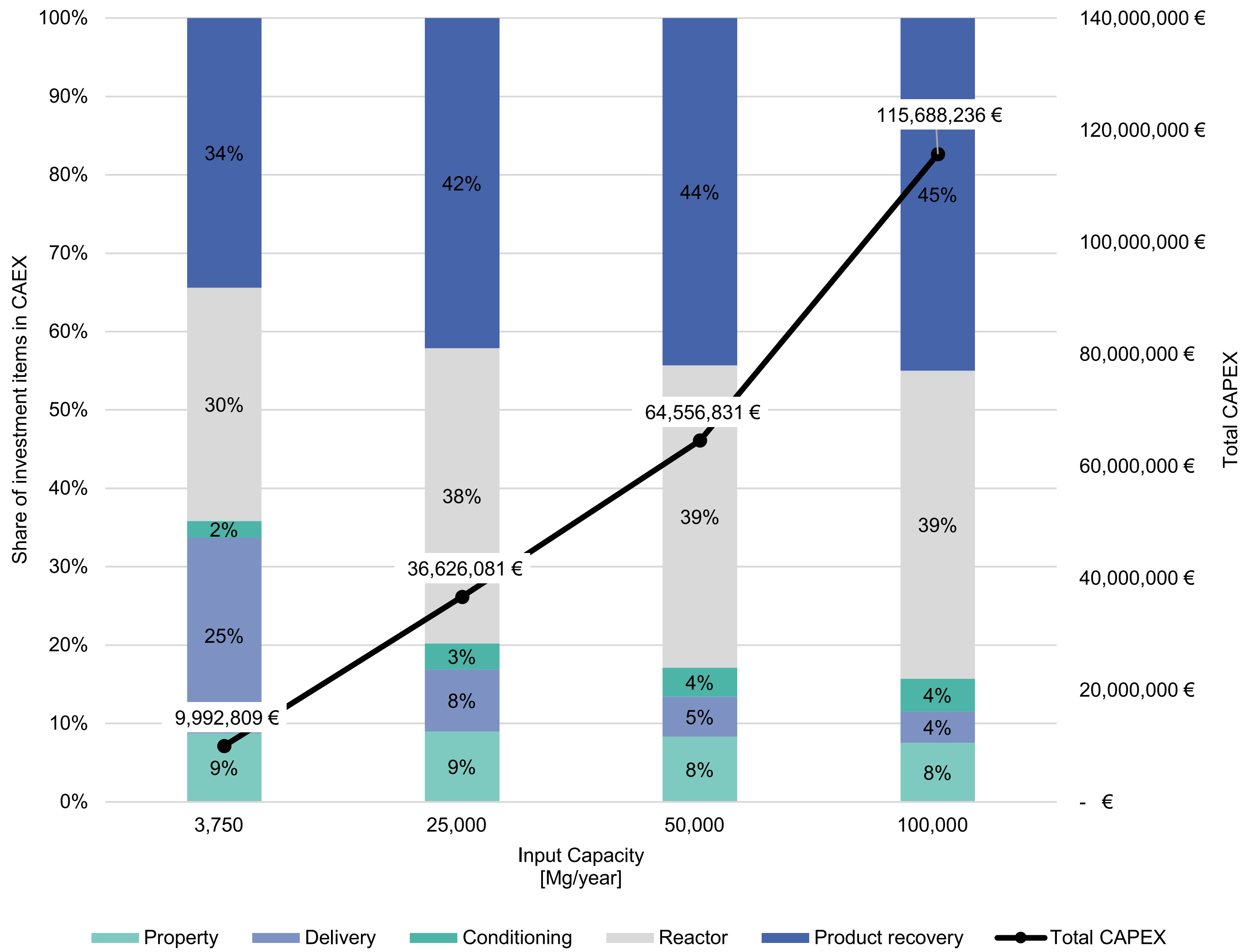


Fig. 3. Investment composition and total CAPEX of different capacity classes of a pyrolysis plant for APW.

plant with 100,000 Mg input/a, a 37-fold increase in capacity results roughly in a 12-fold increase in CAPEX. In particular, it can be seen that the importance of the reactor and product recovery modules for the investment, i.e., both modules, characterized by the numbering up approach, increase with increasing plant capacity. The influence of delivery and preparation of the feedstock decreases. In summary, the total CAPEX increases disproportionately with a capacity increase due to the established economies of scale in process engineering (Turton et al., 2008).

Fig. 4 also shows the economies of scale in decreasing OPEX with increasing plant capacity. The net OPEX include the payments from excess heat and electricity. They fall from 586 €/Mg input for the pilot-scale plant to 207 €/Mg input for a plant with an input capacity of 100,000 Mg. The plant financing and the working capital dominate the OPEX. The financing costs are attributed to the OPEX as they incur when the plant is operated (Peters et al., 2003). With increasing capacity, the impact of personnel and general plant overhead costs decreases. In contrast, the disposal costs for the solid residues and feedstock costs increase.

The minimum sales price for pyrolysis oil (cf. Fig. 4) is calculated by allocating the OPEX to the output quantity of pyrolysis oil. A cost-covering minimum sales price of 1182 €/Mg pyrolysis oil is calculated for the pilot scale plant. With increasing plant capacity and oil production, minimum sales prices decrease as relative costs fall due to economies of scale (section 3.1). For a plant input capacity of 100,000 Mg, the cost-covering minimum sales price drops to 418 €/Mg pyrolysis oil.

For a potential business case, the economic assessment shows that higher plant capacities reduce the minimum sales price, enabling a more economical operation. The primary drivers of the OPEX include plant financing and working capital. By achieving technical advancements and enabling scaling instead of adding extra modules, it is possible to lower required investments for the reactor and product recovery unit, thus decreasing CAPEX and financing expenses. This enhances the appeal of the business case.

3.4. Sensitivity analysis

A sensitivity analysis is conducted to identify the impact of single parameters on the minimum sales price of pyrolysis oil and, therefore, a potential business case and economic challenges for the pyrolysis of APW. For this purpose, the investment, full load hours, maintenance costs, yearly insurance costs, general plant overhead, the feedstock price, CO_2 emission fees, electricity price, heat price, and electricity demand of the plant are varied individually in five steps from/to ±20 %. The analysis is conducted for an APW pyrolysis plant with an input capacity of 50,000 Mg/a, since realizing such capacities is plausible and comparable plant capacities are already in operation (Quantafuel, 2023). The results are shown in Fig. 5.

The minimum sales price of pyrolysis oil varies most with the full

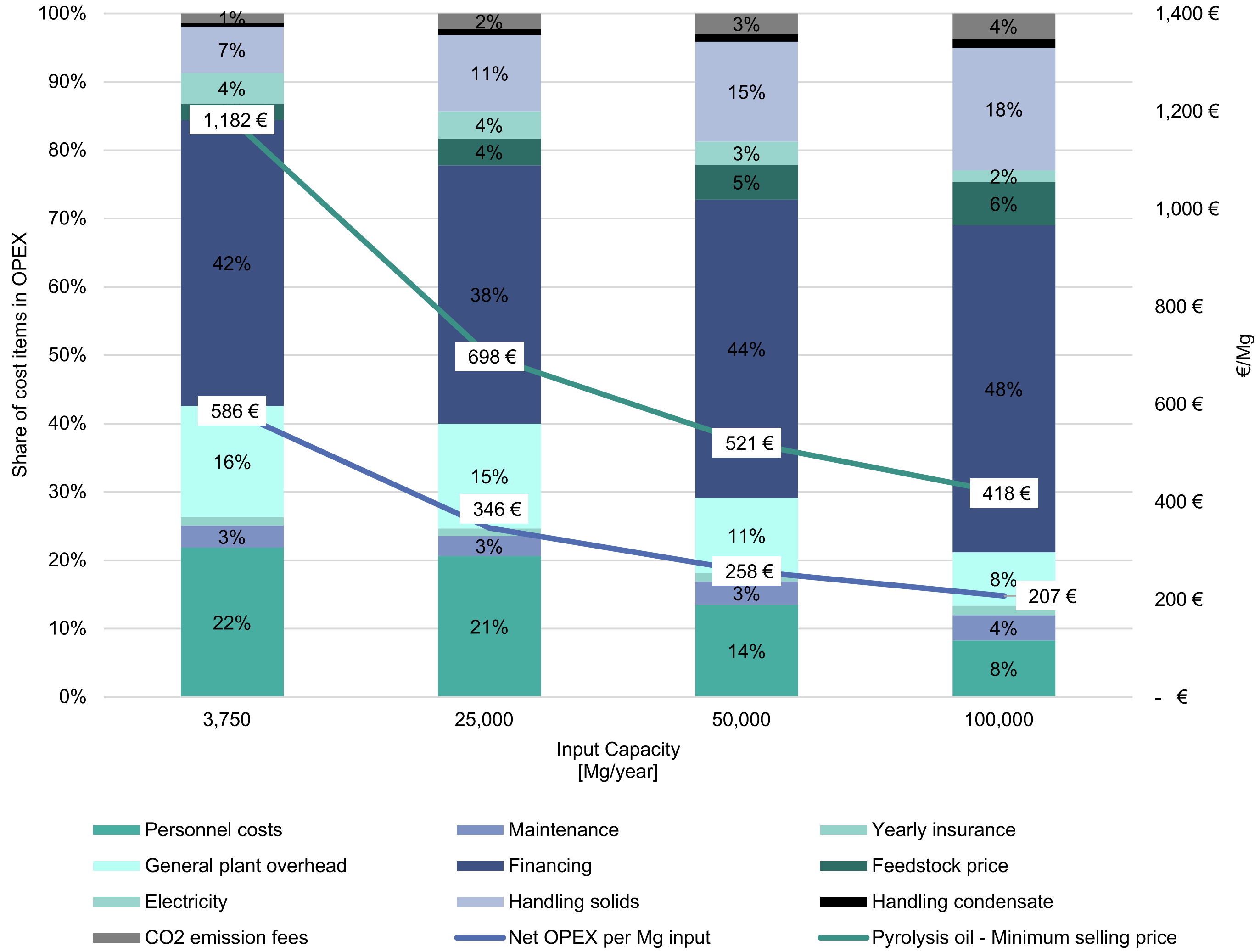


Fig. 4. OPEX composition and total net OPEX per Mg input for different scales of a pyrolysis plant for APW. The minimum sales price for pyrolysis oil is calculated by dividing the OPEX by the pyrolysis oil output.

load hours of the plant. A 20 % decrease in utilization results in a 17 % increase in the minimum sales price. The full load hours are only reduced but not extended beyond the maximal capacity of the plant. The impact of the full load hours demonstrates that feedstock supply for full plant utilization should be ensured to be economically viable. At the same time, robust plant operation is imperative to an economical business case to prevent downtimes beyond planned maintenance.

The calculated investment has an impact of ±11 %, supporting the argumentation of needed technical developments to scale the reactor and product recovery module. This would allow a reduction of the required investment and associated financing costs.

The plant's electricity demand unsymmetrically impacts the minimum sales price. This results from either available excess electricity that can be sold or the need to buy additional electricity. An increase in the electricity demand by 20 % results in a rise in the minimum sales price of 10 %, while a 20 % decrease results in an 8 % decrease in the minimum sales price.

All other assessed parameters have an impact of below ±5 % and are therefore not further described. Qualitative influences on the business case are addressed in the discussion (cf. Section 4).

4. Discussion and limitations

The TEA shows economies of scale when planning pyrolysis plants for technically challenging plastic waste streams. For the business case, this has the consequence that large plant capacities should be realized to reduce the output-related OPEX and thus the cost-covering minimum sales price for the pyrolysis oil. However, there are challenges when realizing these large-scale plants:

(1) Regarding the available feedstock, the analysis for Germany (cf. Section 2.1.1) shows that APW occurs only in small quantities that are not sufficient for the supply of larger pyrolysis plants. Accordingly, the amount and availability of suitable waste should be increased by importing waste from surrounding European countries or by including other waste streams with similar properties that can be co-processed. Importing additional waste would lead to higher transport costs and more complex logistics, increasing the currently assumed feedstock prices and resulting in a higher cost-covering minimum sales price. When co-processing different plastic waste streams, the overall waste composition could change the pyrolysis mass and energy balances. Thus, additional experiments should be carried out to validate the business case with a mixed feedstock, even though Zeller et al. (2021) demonstrated the robustness of the assessed reactor technology regarding different feedstocks. Co-processing various plastic waste streams can also potentially optimize the feedstock concerning yield or oil quality.

(2) The feedstock quality must also be addressed. The composition of the RDF from APW significantly affects product yield (Roosen

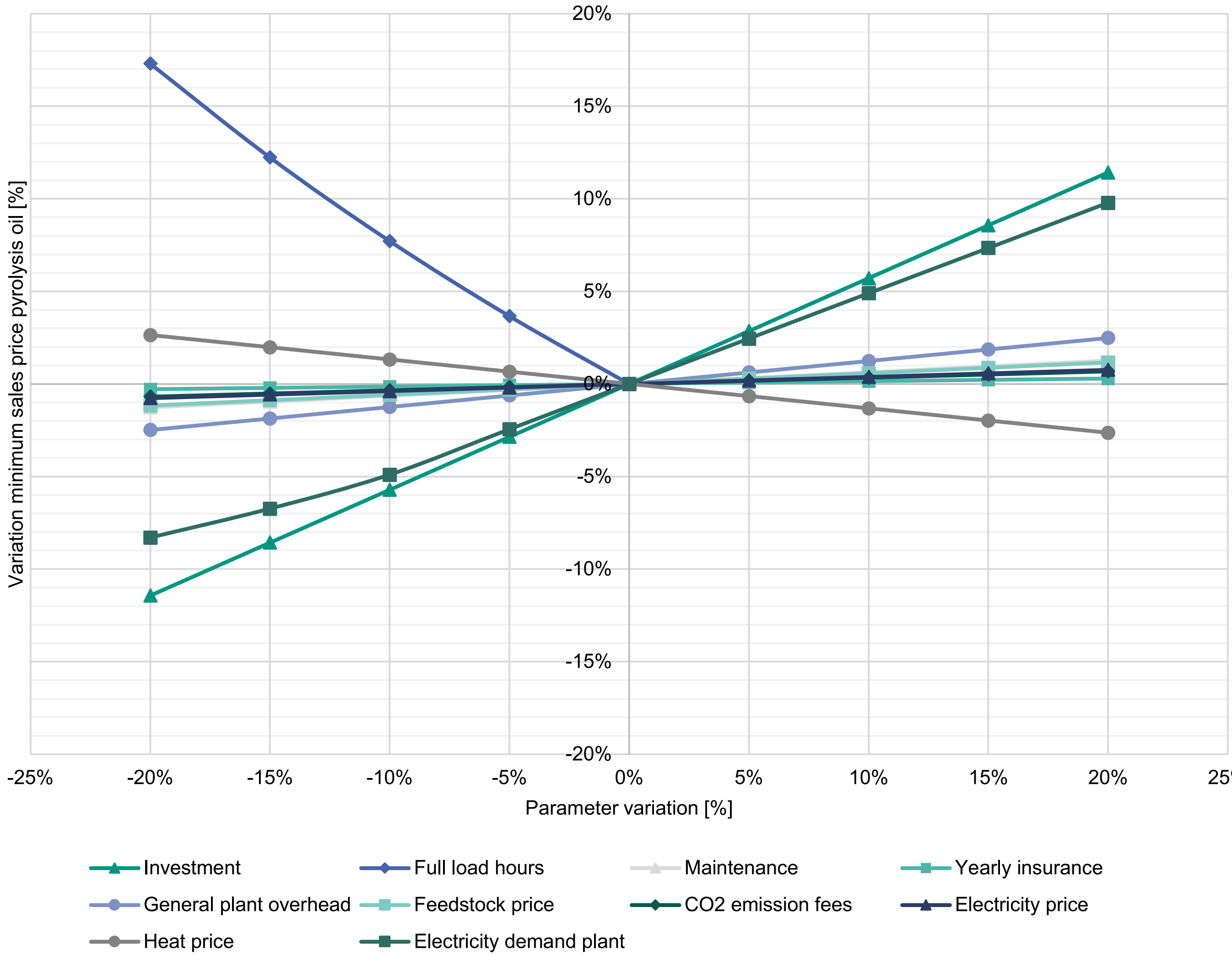


Fig. 5. Sensitivity analysis with a parameter variation of ± 20 % and its impact on the minimum sales price of pyrolysis oil. The sensitivity analysis is conducted for the plant configuration with an input capacity of 50,000 Mg/a.

et al., 2020) and product quality. While pyrolysis oil yield directly reflects the amount of product available, the quality of the oil will determine the product's sales price (Tullo, 2022). Accordingly, additional efforts in feedstock conditioning by the RDF manufacturer, e.g., through improved sorting, could enhance feedstock quality and, thus, the overall business case.

(3) Focusing on the pyrolysis oil quality and the obtainable sales price, this TEA does not assume a sales price for pyrolysis oil due to scarcity of data. Instead, the cost-covering minimum sales price is calculated to reduce uncertainty in the results/statements. The elemental composition of the pyrolysis oil shows some similarity to marine fuel (cf. Section 2.1.2). Therefore, a potential reference product is US residual fuel oil, with an average price of 462 €/Mg in 2021 (EIA, 2022). The prices increased towards the end of 2021 and the beginning of 2022 (EIA, 2022). Assuming this price can be obtained for the produced pyrolysis oil, plants with input capacities greater than 70,000 Mg/a achieve cost covering minimum sales prices lower than that, indicating an economical operation. This economically viable plant capacity can be lowered if the quality of the pyrolysis oil increases and higher prices can be achieved.

Due to these technical and economic challenges, the currently achievable technical capacities are not financially sustainable, leading to a scenario where small plants would necessitate gate fees, subsidies, or a kind of CO_2 certificate credit for avoided emissions to ensure their economic viability during operation. Plants with an input capacity of 3750, 25,000, and 50,000 Mg/a require additional payments of 720 €/Mg, 236 €/Mg, or 59 €/Mg to lower the minimum sales price to the average price level of the reference product. Currently, no respective subsidy programs are known to the authors.

Assuming that upcoming legislation requires the recycling of APW and other challenging plastic waste streams, gate fees depending on the quality of the waste are imaginable to generate the additional payments needed. If the waste is of an inferior composition, resulting in a lower-quality pyrolysis oil, the payments have to be even higher. If waste has a composition enabling the production of high-quality pyrolysis oil, then the plant operator could buy the feedstock. This ensures that the pyrolysis plant is profitable regardless of the feedstock quality. At the same time, there is an economic incentive in the waste collection and recycling chain to generate high-quality waste that can be further recycled.

The conducted TEA clearly shows the challenges of a business case for the pyrolysis of APW, representing demanding waste streams with engineering plastics. These challenges align with those recognized by the European Joint Research Centre (JRC et al., 2023). The TEA also shows which investments are needed for pyrolysis plants of different capacities and how these are distributed among the parts of the plant.

Technological advances in reactors and product recovery units would allow for scaling and avoid the numbering-up approach. This could result in lower investment, reduced CAPEX, and lower financing costs.

There are limitations to the study regarding technology, geographical scope, and maturity of the assessment:

(1) The results are limited to the employed reactor technology and the process layout outlined in Fig. 1. Additionally, the assessments are currently based on experiments conducted on pilot-scale reactors. Scaling up to a commercial scale can impact the mass and energy balances and, thus, in particular, the plant's electricity demand, which significantly affects the assessment. Experiments should be carried out on larger reactors and demonstration plants to confirm mass and energy balances on an industrial scale.
(2) The results are also limited to the assessed plastic waste stream of APW from workshops in Germany. This waste stream is an example of a demanding waste stream containing high proportions of engineering plastics. Other waste streams may show different behavior in pyrolysis depending on the waste composition.
(3) The assessment is also conducted for a German case study, assuming the German waste composition and other parameters. In other regions, however, these might differ, e.g., with lower personnel costs, lower energy costs, or more favorable investment conditions.
(4) Due to the maturity of the assessed plant, a deviation from the calculated investment is possible (cf. Section 2.2.1). However, the accuracy of the TEA is high compared to other studies. Other studies (Fivga & Dimitriou, 2018; Jiang et al., 2020; Sahu et al., 2014; Westerhout et al., 1998) mainly use the less precise factored cost estimation method. This study combines the factored cost estimation method with a numbering-up approach for critical parts of the pyrolysis plant, such as the reactor or the product recovery module. Therefore, a more accurate estimate is possible as technical limitations in the components' capacity are considered.

Despite these limitations, this TEA is both innovative and essential, as existing TEAs of pyrolysis facilities for plastic recycling evaluate diverse plant configurations, technologies, feedstocks, and other variables that cannot be directly applied to the specific case under investigation. No studies are known to the authors that performed a TEA for pyrolysis of engineering plastics where the results could be directly compared.

5. Conclusions and outlook

Chemical recycling via pyrolysis can complement the current mechanical recycling of plastics and thus provide a recycling alternative to the incineration of demanding non-recycled waste streams. Recent studies show the environmental advantages of pyrolyzing mixed engineering plastics from automobiles compared to energy recovery and landfilling (e.g., JRC et al., 2023). However, pyrolysis also needs to be economically viable to succeed.

The conducted economic assessments of the pyrolysis plants highlight the challenges for a business case of APW pyrolysis in Germany: Feedstock availability, feedstock quality, and the quality of the pyrolysis oil. Due to these challenges, the currently achievable technical capacities are not financially sustainable, resulting in policy implications like gate fees, subsidies, or CO_2 certificate credit for avoided emissions to ensure the economic viability of pyrolysis plant operation. In future work, the effect of such incentives on the whole waste treatment sector should be examined carefully to avoid unwanted consequences on other waste treatment options.

However, the TEA also establishes the economies of scale of the pyrolysis plants, concluding that capacities greater than 70,000 Mg/a achieve cost covering minimum sales prices lower than the assumed price of the reference product US residual fuel oil. The conducted sensitivity analysis points out that the needed investment and the full load hours significantly influence the minimum sales price, so technical developments scaling the reactor and product recovery module could reduce the required investment and associated financing costs.

The impact of the full load hours outlines the central challenges of a robust pyrolysis process, feedstock availability, and the need for a consistent operation to achieve a positive business case. The waste feedstock quality must be ensured as it directly impacts the pyrolysis oil quality and, therefore, the obtainable price for the oil.

Future research can address these availability and quality challenges by combining various plastic waste streams, generating an optimized pyrolysis feedstock, and conducting experiments to establish mass and energy balances. Also, additional upgrading steps for the pyrolysis oil, like hydroprocessing, should be assessed. With the further development of pyrolysis oil upgrading, future research can improve product quality and value. Future research should also investigate the cost of a pilot or demonstrator plant to verify our assumptions and calculations, as this study is a theoretical analysis. More accurate cost estimations should be conducted based on detailed project implementation and commissioning plans. This makes it possible to examine how the improvement in oil quality affects the economics of pyrolysis and how it relates to the size of the pyrolysis plants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was carried out within the research project “Leuchtturm Kreislaufwirtschaft – Schwerpunkt Chemisches Recycling”, funded by the “THINKTANK Industrial Resource Strategies”. It is financed by the Ministry of the Environment, Climate Protection, and the Energy Sector of the state of Baden-Württemberg, Germany and industry partners. Furthermore, funding by the AUDI AG provided through its project “PlasticLoop – Circular Economy for mixed plastic fractions from the automotive industry” is gratefully acknowledged.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.01.035.

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