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Closing the Loop between Plastic Waste Management and Energy Cogeneration: An Innovative Design for a Flexible Pyrolysis Small-Scale Unit

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Abstract: This study proposes a simplified unit that can be employed in an industrial facility for the utilization of its own abundant plastic waste, primarily from discarded packaging, to achieve full or partial energy autonomy. By converting this waste into synthetic pyrolysis oil equivalent to 91,500 L, the industry can power a combined heat and power generation unit. The proposed unit was designed with a focus on maintaining high temperatures efficiently while minimizing oxygen exposure to protect the integrity of hydrocarbons until they transform into new compounds. Pyrolysis stands as a foundational procedure, paving the way for subsequent thermochemical transformations such as combustion and gasification. This study delves into the factors affecting pyrolysis and presents analytically the mathematical formulations and relevant calculations in order to effectively design and apply a real-life system. On this basis, fuels from plastic waste can be produced, suitable for utilization in typical equipment meant to produce heat, estimated for six months' operation and 800 MWh of electricity. This study enhances the transition towards a more circular and resource-efficient economy with technologies that unlock the latent energy contained within the discarded matter. Additionally, it demonstrates the feasibility of a moderate investment in a co-generation system for industries utilizing 568 tonnes of plastic waste per year. The design and accurate calculations of this study highlight the theoretical potential of this technology, promoting environmental sustainability and resource conservation.

Keywords: industrial; hydrocarbons; waste-to-energy; energy recovery; circular economy; resources management



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1. Introduction

During the last decades, there has been a rise in the manufacturing and consumption of plastics on a global scale, leading to a substantial increase in plastic waste. Although various measures have been taken to address this issue, a significant amount of waste remains prevalent in the form of large and small plastic pieces that gather in both land and sea environments. Large plastic debris contributes greatly to river pollution and worsens problems such as flooding while also harming the diversity of plant and animal life. Tiny pieces of plastic known as microplastics measure less than 5 mm in diameter. Stem from a variety of sources, such as the breakdown of plastic items and the inclusion of exfoliating beads in beauty products such as cosmetics and skincare items [1]. These harmful pollutants are now widespread in both freshwater and marine settings. It is predicted that by the year 2040 the amount of waste in our environments could triple, resulting in up to 37 million tons of plastic being introduced into our oceans annually [2]. While recycling presents a solution by collecting and reprocessing waste, it is concerning that the rate at which recycling is currently being carried out remains significantly low. Out of the 7 billion tons of waste produced worldwide, only 10 percent has been recycled so far. With plastic

manufacturing projected to hit 1100 million tons by the year 2050, it is evident that efficient actions are urgently required to tackle this worsening issue [2].

Although recycling is often seen as a way to handle waste and lessen its environmental effects, it does come with obstacles. It is common for recycling methods to demand energy, manpower, and materials, which in turn can harm the environment. Moreover, the financial viability of recycling may be restricted when addressing mixtures of plastics. On the other hand, broader waste management techniques such as pyrolysis are showing potential as solutions to this issue [3]. The process of pyrolysis and other methods, such as liquefaction and gasification, can transform waste into items such as fuels and chemicals while also generating energy in the process [4]. This type of chemical change does not lessen the amount of waste in landfills and oceans but also reduces environmental impact and yields high material recovery rates. By combining these technologies, it is possible to promote a circular economy approach and improve the lifespan of plastic products. In addition to that, the progress in techniques for chemical recycling has increased the effectiveness of these methods. They are being widely adopted globally through pyrolysis initiatives in Asia, Australia, and America, which show a rise in consciousness and the opportunity to reclaim energy from waste [5,6].

Pyrolysis and plastic waste management are becoming increasingly acknowledged as processes to be incorporated into sustainable waste management. Uzosike et al. (2023) [1] studied the mechanical recycling of solid plastic waste on a small-scale level. Vasileiadou & Tsiopstias (2023) [2] analyzed thermochemical and kinetic parameters of plastic waste combustion, while Rathi et al. (2023) [3] elucidated different methods for the thermochemical conversion of plastic waste. Despite the recent advances in the scientific literature, implementation mainly depends on a centralized framework that typically involves significant investments in large facilities and a well-coordinated waste collection system [7]. A process that can be expensive and environmentally unsustainable [8]. Centralized waste management systems often require the transportation of waste to processing facilities, leading to complexities and higher carbon emissions. Additionally, the requirement for an amount of money to construct and sustain these facilities restricts the acceptance of pyrolysis in areas that lack efficient waste collection infrastructure. Despite the benefits of pyrolysis in managing waste, the current centralized approach poses challenges to expanding operations and ensuring environmental viability, especially when contrasted with decentralized waste, to energy systems that could offer cost savings and lessen ecological footprints [9].

While there has been a lot of study on large-scale plastic waste-to-energy (WtE) conversion systems and other WtE solutions for waste management, there seems to be a notable lack in creating compact modular units for industrial use. These smaller-scale systems show promise in enabling businesses to harness their waste to power their operations while also sharing electricity with the grid and earning extra income with the help of beneficial government regulations such as net metering [10]. Despite global legislative support for small-scale energy producers such as bioenergy production from waste materials, there is a lack of exploration into industry-specific solutions for managing plastic waste effectively and making a second round of profit out of them [11].

The purpose of this study is to present a hypothetical scenario in which the proposed unit transforms plastic waste into energy while maximizing the utilization of heat produced during the procedure. In contrast to techniques in which the fuel derived from pyrolysis is exclusively burned for heating purposes, this inventive system harnesses the engine-generated heat during power generation to fulfill the heating requirements of the main industrial building. By cooling the engine and providing surplus heat concurrently, it advocates for the idea of energy circularity [12]. Industries with abundant plastic waste, such as plastic film production or plastic manufacturing plants, are particularly well-suited for this model, offering them an opportunity to become more sustainable and economically viable by integrating waste management, energy generation, and grid contribution into their operations [13].

2. Results

2.1. Related Cost Analysis and Techno-Economic Assessment

Following the description of the equipment, the technical specifications, and the design requirements and calculations, the CAPEX of the equipment is presented in Table 1.

Table 1. Technical and economic characteristics of electromechanical equipment.

Electromechanical Equipment	Power (kW)	Weight (kg)	Cost (Euros)
Feeding and shredding of plastic waste	2.2	250 + 32	2500
Feed screw for crushed material in the warehouse	1.1	174 + 23	1600
Daily storage Silo		1500	4500
Raw material feed screw to the reactor	1.1	44 + 20	800
Pyrolysis reactor	2.2	800 + 23	8500
Gas supply in tank		30 + 630	2400
Fractional cooling of gases	0.1	400	5000
Synthetic oil transfer pump to the tank	0.1	2	100
Pyrolysis fuel tank		1000	2500
Water-cooled diesel engine		725 + 160	13,000
Power generator		600 + 85	6000
Electrical power and control panel		100	2000
Water circulator for radiator	0.2	20	400
Piping and wiring		300	2700
Lighting	0.5		1000
Total	7.5	6832	53,000

The cost of acquiring the equipment is 53,000 Euros, while the installation costs are assumed to be 10% of the acquisition cost. Unforeseen expenses are also considered around 3% $\cong$ 1700 Euros. Thus, the total installation cost of the investment is estimated approximately to be 60,000 Euros. The market research was conducted based on supplier pricing data from the industry.

2.1.1. Raw Material Cost

The estimated energy content of the synthetic oil produced is 80% of that of diesel, which translates to 33.8 MJ/kg. To fuel the engine, 32 kg/h (1053 MJ/h divided by 33.8 MJ/kg) of synthetic oil is needed. Assuming that around 45% of the plastic feed transforms into a liquid distillate, 71 kg/h of plastic waste input is required. The total amount of raw material per year is 568,000 kg (based on 8000 h of unit operation per year). For the 250 working days a year, on a daily basis, 2.3 tonnes/day.

In case the industry is unable to supply the necessary amount of material for the pyrolysis unit, importing plastic waste from municipal waste streams can be under consideration. Notably, plastic waste may sometimes be acquired at a negative cost, suggesting that the industry could potentially profit from processing municipal plastic waste. However, it is important to consider transportation expenses, which are significant [14,15]. These costs amount to approximately 80 Euros for every 8000 kg load, equivalent to 10 Euros/tonne. Including loading and unloading costs, the total acquisition cost of plastic waste could reach approximately 40 Euros/tonne. This analysis reflects the direct correlation of waste management along with transportation. Thus, the total annual cost of the raw materials is estimated to be 22,270 Euros.

2.1.2. Energy Cost

The energy cost is determined by the power of the equipment and the duration of operation. The power of the machines for preparing and converting plastic waste into usable fuel is added to 7.5 kW. The operating time of this equipment depends on the amount of raw material being processed. Table 2 presents the parameters for the calculation of the energy cost of the proposed unit with the electricity typical cost of 0.05 Euros/kWh.

Table 2. Operational cost of the proposed unit.

Raw Material Parameters	Units
Amount of raw material to be processed per year	568.000 kg
Daily quantity of raw material to be processed	2.300 kg/day
Operating days for processing	250 days
Hours of operation based on 4 h per day	988 h
Required energy in kWh	7410/yr
Electricity cost with a price of 0.05 Euros/kWh	370 Euros

2.1.3. Environmental Equivalent

Economic factors are intertwined with both public health and environmental protection, i.e., the environmental benefit from rationalizing waste management while simultaneously decarbonizing the industry should be underlined. More specifically, before evaluating the financial benefits of the CHP unit, it is crucial to first assess its environmental impact. According to the previous calculation of synthetic fuel for the annual electricity production of 800 MWh_{el} and the 95 MWh_{th} in the cogeneration unit, a minimum of 568 tonnes of plastic waste will be processed. With the capacity of the cogeneration facility of 100 kW_{el} and 100 kW_{th} described, 568 tonnes of plastic can be utilized as energy from waste. If this were not the case, the value chain would include fossil fuels with the environmental impact of the refined 76.170 kg of diesel (Table 3).

Table 3. Equivalent amount of diesel fuel.

Energy Needs	Units
Annual energy needs of the industry	895 MWh
Plastic waste	568 tonnes/year
Equivalent amount of diesel with $H_u = 11.75$ kWh/kg	76.170 kg
Equivalent volume amount of diesel	91.440 L

2.1.4. Energy Equivalent Cost

The generated electricity can be promoted to the grid by net metering, providing an income for the industrial facility [15,16]. For example, the electricity generated by renewable energy sources according to Greek law can be sold to the energy market at a very competitive price of 90 Euros/MWh. In case the energy is sold to the grid with net metering, the profit can be $800 \text{ MWh} \times 90 \text{ Euros/MWh} = 72,000$ Euros per year. Synthetic oil produced from plastic waste is replacing heating oil with a sale price of 1.28 Euros/L, as of current market values. The price of heating oil is 1.28 Euros/L (1.54 Euros/kg with $\rho = 8169 \text{ N/m}^3$). The savings from heating are 12,423 Euros ($1.28 \text{ Euros/L} \times (95 \text{ MWh}_{th} / 11.75 \text{ kWh/kg} / 0.833 \text{ kg})$). On this basis, approximately 84,000 Euros per year savings in expenses are provided.

The initial raw material acquisition cost of 40 Euros/tonne might deter investment. Nevertheless, if local municipalities leverage their existing waste management infrastructure or if private waste collection companies are incentivized to deliver their waste to the facility, the acquisition cost could be reduced to approximately 20 Euros/tonne. This significant reduction would markedly enhance the investment's appeal.

3. Materials and Methods

3.1. Theoretical Background

3.1.1. Pyrolysis Outcome—Products

Hydrocarbon reactions in the absence of oxygen trigger the process known as pyrolysis. This intricate phenomenon results in the transformation of substances into three forms, each with unique properties and potential applications [17]. It is crucial that in hydrocarbon reactions, a certain stoichiometry must be applied due to the fact that total oxidation can lead to a totally different outcome [18]. This balance is measured by the index λ ,

where $\lambda = 1$ signifies the amount of oxygen needed for complete oxidation. If there is an excess of oxygen during this process, represented by an index ($\lambda > 1$), combustion takes place. This situation is common in processes that aim to maximize energy release by oxidizing the material. On the other hand, gasification happens when there is a shortage of oxygen with an index ($\lambda < 1$) allowing for partial oxidation of the material and producing a syngas containing hydrogen, carbon monoxide, and sometimes small amounts of carbon dioxide and methane. In the case that there is no oxygen, with an index ($\lambda = 0$), it signifies pyrolysis [19]. This condition enables the breakdown of substances at temperatures in a controlled environment, resulting in the creation of solids (char or ash), liquids (pyrolysis oil), and gas products (non-condensable gases). By eliminating oxygen, it prevents the material from burning, thereby preserving the energy content in the gases and liquids produced. Pyrolysis is essential for converting plastics into a range of chemical products and fuels. The distinction based on oxygen levels shows how thermochemical processes can be versatile in achieving energy and material recovery [20].

- (1) Gases: The gas generated during pyrolysis primarily consists of carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), methane (CH₄), and several other gases depending on the material used [21].
- (2) Liquids: These liquids are dense, oily fractions containing hydrocarbons such as alkanes, alkenes, aromatics, and various oxygenated compounds, depending on the type of plastic used. This diverse mixture presents an opportunity for converting it into liquid fuel with similar properties as common fossil liquid fuels [19].
- (3) Solids: Regarding the leftover residue from pyrolysis, it mainly comprises carbon (C) and inert materials that remain unchanged throughout the conversion process. This residue exemplifies how effectively matter decomposes into its components.

In the case of plastic pyrolysis, the material is subjected to heating at atmospheric or higher pressure. As the temperature rises, a sequence of processes is taking place:

- (1) At temperatures under 100 °C, volatile compounds evaporate and substances sensitive to heat break down.
- (2) As the temperature rises and approaches 100 °C, the rate of moisture evaporation within the material increases significantly. Materials that are hydrated and trapped within crystalline structures are released at higher temperatures [19]. This stage consumes a considerable amount of energy because of the latent enthalpy of the liquid components, which keeps the temperature stable until the process is finished. Additionally, components within plastics, such as plasticizers, some additives, and waxes, may begin to melt, decompose, or volatilize, many of which do so at temperatures both below and above 100 °C, depending on the specific material [22].
- (3) Between temperatures of 100 °C and 500 °C, many organic components of plastic break down. For instance, polyethylene and polypropylene, commonly used in plastic products, decompose at temperatures between 300 °C and 500 °C, leading to the production of hydrocarbons such as alkenes and alkanes. Additives and stabilizers within the plastics may volatilize or decompose, contributing to the formation of gases and liquids. The remaining non-volatile materials tend to be rich in carbon, forming char or ash as the material becomes “charred” [22].
- (4) At temperatures between 200–300 °C, if oxygen is not completely removed, the carbon residue is possible to self-ignite depending on its material content, resulting in a highly exothermic reaction, often without a visible flame. As combustion initiates, the temperature increases, causing the residue to glow and emit CO₂ and CO. At this stage, elements such as sulfur (S), chlorine (Cl), and others present in plastics undergo oxidation and volatilization [21].

Understanding the importance of the lack of oxygen is crucial in pyrolysis, as it occurs at temperatures surpassing the self-ignition points of the substances produced [21].

3.1.2. Slow-Paced Pyrolysis (Traditional)

Slow-paced or traditional pyrolysis, a method used to convert biomass into coal and charcoal for industrial and household purposes, is considered one of the oldest ways to transform biomass into fuel. Charcoal, known for its low moisture and high carbon content, has historically played a role in industrial processes. Its ability to reach temperatures easily has made it a valuable resource in metal-working industries such as iron casting and steel forging. This process involves stacking wood with space between the pieces for initial partial burning. The stack is then covered with soil to limit oxygen, allowing only a small amount of air inlet for controlled wood burning. Once lit, the stack slowly burns over days in an oxygen-depleted environment, leading to material carbonization [19]. After this deliberate process is complete, the soil covering is removed to reveal the charcoal ready for packaging and use.

In modern times, the principles of pyrolysis that were historically applied to biomass are now being utilized in the pyrolysis of plastic materials, although the objectives and outcomes differ. Slow-paced pyrolysis of plastics operates under similar foundational principles of heating in an oxygen-depleted environment. Such as biomass pyrolysis, plastic pyrolysis requires precise control of oxygen levels to prevent combustion and ensure the breakdown of materials into useful products. However, instead of producing charcoal, plastic pyrolysis yields a mixture of char, liquid hydrocarbons (pyrolysis oil), and non-condensable gases [17].

Both processes rely on temperature control and the absence of oxygen to drive material decomposition. In plastic pyrolysis, the heating of plastics at lower temperatures (around 400 °C) and at slow rates maximizes the production of char and liquid fuels, just as slow biomass pyrolysis maximizes the yield of solid charcoal [19]. The similarity in controlling oxygen and temperature in these processes shows how pyrolysis, although rooted in ancient techniques for biomass, can be adapted to address modern challenges such as plastic waste recycling.

3.1.3. Conventional Pyrolysis

The process of conventional pyrolysis occurs within a short timeframe, typically a few minutes. Historically applied to biomass, primarily for the production of charcoal, conventional pyrolysis has now been adapted to plastics for the breakdown of polymers into valuable products. In the traditional method, biomass (mainly wood) is heated to temperatures around 500 °C. For plastic pyrolysis, similar temperatures are used, though the focus shifts from producing charcoal to generating liquid hydrocarbons (pyrolysis oil), non-condensable gases, and solid residues (char) [19].

In the pyrolysis of plastics, secondary chemical reactions—similar to those that occur in biomass—take place as the components in vapor form continue to react. However, unlike biomass pyrolysis, where the final product is charcoal, in plastic pyrolysis, these secondary reactions help convert long-chain polymers into shorter hydrocarbon chains, which are then collected as valuable liquid fuels or gases. The gases produced in the process, such as hydrogen and methane, are often recycled to power the pyrolysis system, demonstrating a self-sustaining feature of the method, much like in biomass pyrolysis [23].

The conventional method involves filling the pyrolysis reactor with plastic feedstock, ensuring the chamber is sealed, processing the material, and removing the end products. In cases where the reactor is exposed to atmospheric air, there is a risk of partial combustion due to the high temperatures and the reactive nature of the plastic components. To initiate the process, an external heat source such as natural gas or electricity is used to raise the reactor's temperature. Once operational, the system can maintain heat by utilizing the gases produced during pyrolysis, much like the self-sustaining biomass pyrolysis process [24].

As the plastic polymers break down, they release short-chain hydrocarbons in gas form. These gases are directed from the reactor to help maintain the temperature and support the pyrolysis process, enhancing overall energy efficiency. In plastic pyrolysis, just as in traditional biomass pyrolysis, careful control is necessary to prevent combustion

when the materials are exposed to air. The process is completed within minutes to a few hours, classifying it as conventional pyrolysis and distinguishing it from slow pyrolysis, which operates over a longer time.

Once cooled, the solid residues (char) and liquid hydrocarbons produced during the process are ready for further refinement or direct use in various industrial applications. This method, while mirroring traditional biomass pyrolysis in terms of duration and basic methodology, showcases modern technical enhancements through the use of specialized reactors and a strategic approach to plastic waste management.

The conventional method includes the steps of filling the pyrolysis furnace with biomass, securing the closure, processing, and removing the finished product. In case the upper part is exposed to atmospheric air, usually it partially ignites because of the hot materials and their oxidation. The whole process is completed in a few minutes to hours, classifying it as convention pyrolysis, being distinct from the slow-paced. An external flammable substance such as gas is utilized to raise the temperature inside the furnace. Once the furnace door is securely shut, alternative flammable sources, such as biomass, can maintain the temperature [24].

As the hydrocarbons break down, they release short-chain gases, which are biomass vapors. The hydrocarbon gases or biomass vapors produced are then directed from the furnace to help maintain the temperature and support the combustion process to continue smoothly and more energy efficiently. In case the charcoal catches fire upon contact with air, it is put out gently using a mist of water. Once it cools down, the charcoal is considered ready to be packaged and distributed to the market. This method, mirroring traditional pyrolysis in both its duration and methodology, distinguishes itself through the technical enhancement involving the deployment of specialized equipment and a strategic approach to time management.

3.1.4. Fast-Paced Pyrolysis

In fast-paced pyrolysis, the temperature rise rate of the material reaches 1000 °C/s, optimizing synthetic oil production techniques. This approach drastically reduces the time needed to heat biomass for decomposition to a minimum length of time of 0.1 s to 0.5 s. Consequently, the process generates a range of products, around 60–70% pyrolysis oils, 15–25% char, and 10–15% non-condensable gases [22]. The gases produced are often used as fuel for the pyrolysis burner, making the process partially self-sustaining. During the breakdown of materials, in pyrolysis processes the substances are transformed into components such as gases and liquids, similar to the process of refining crude oil into various fractions [25]. At the refining stage, gases are cooled down at specific temperatures through distillation, allowing them to condense at varying rates based on their hydrocarbon composition. The liquefaction temperature of the materials in the gas phase is different for each group of hydrocarbons. These fractional temperatures can be used to produce similar matter from different hydrocarbon-rich feedstocks as well [26].

High-speed pyrolysis shows potential in tackling issues linked to waste materials such as vehicle tires and plastics, containing hydrocarbon-based matter. This focused method of pyrolysis not only is a waste management method but also results in valuable outcomes, such as liquid fuels (gasoline and oil), solid materials (coal), and recyclable metals [27]. As a result, the pyrolysis of waste is seen as an efficient approach, potentially sparking new circular economic ventures and employment opportunities that prioritize environmental conservation and public health. For example, materials such as hydrocarbons in solid, liquid, or gaseous form and steel (the reinforcement of the tire) can be recovered by pyrolysis from the waste of car tires. These components can be converted into 45–55% fuels, 10–15% steel wire, 30–35% pure carbon powder, and 8–10% gas fuel. The exact proportions of products vary depending on the setup and desired outcomes [28]. This process addresses the challenge of managing alternative hydrocarbon feedstock, such as plastics, and also brings economic advantages by generating alternative fuels beyond petroleum-based products [29].

The energy needed is partially self-powered. While an external fuel source such as biomass is used for the heating of the materials once decomposition begins, the resulting gaseous by-products, such as CH_4 , are captured and reintroduced into the burner. This practice reduces dependency on fuel sources by recycling energy within the pyrolysis process.

High-speed pyrolysis has shown an enhancement in the quality of the synthetic oil yielded compared to that produced by conventional pyrolysis. At a reaction temperature of $474\text{ }^\circ\text{C}$, 40.93 wt % (Weight Percentage) of the biomass was converted to synthetic oil with a Gross Calorific Value (GCV) energy content of 16.92 MJ/kg and a water content of 28.02 wt %. By reducing the water content, the synthetic oil can be used commercially as diesel fuel in engines, as its properties comply easily with the EN590 standard [30]. Table 4 categorizes the 3 types of pyrolysis described above by process parameters.

Table 4. Pyrolysis categorized by their process parameters.

Type	Time	Thermal Pace	Temperature	Main Outcome
Slow-paced	Hours-days	Slow	$400\text{ }^\circ\text{C}$	Solid
Conventional	5–30 min	$20\text{--}100\text{ }^\circ\text{C}/\text{min}$	$500\text{--}800\text{ }^\circ\text{C}$	Solid, Liquid, Gas
Fast-paced	0.5–5 s	$1000\text{ }^\circ\text{C}/\text{s}$	$900\text{--}1050\text{ }^\circ\text{C}$	Liquid

3.2. Scenario Definition

This study proposes an innovative design for a flexible pyrolysis small-scale unit. In this hypothetical scenario, the unit is assumed to be adopted by a small-medium industry (assuming $50 \times 12\text{ m} = 600\text{ m}^2$ of production facilities and offices of 100 m^2). In the framework of the defined application scenario, the industrial facility is utilizing its own abundant plastic waste, primarily from discarded packaging, to achieve full or partial energy autonomy. Examples of such industries are small- to medium-sized plants and other enterprises that dispose of plastic packages. Typical small-scale industries hold an area of approximately 250 m^2 while large-scale industries can hold up to 1200 m^2 [31]. By converting this plastic waste into synthetic pyrolysis oil, the industry can power a combined heat and power (CHP) generation unit. This fast-paced pyrolysis unit comprises a water-cooled diesel electric generator with a total output of 200 kW, 100 kW electric, and 100 kW thermal, thus effectively harnessing waste for energy.

The cogeneration unit will utilize the produced waste, which is assumed to be plastic. A typical material synthesis of the plastic by-products is depicted in Table 5.

Table 5. Characteristics of polymerized materials from typical plastic wastes for the defined scenario analysis [32–35].

Main Types of Plastic Wastes	Density ρ (kg/m^3)	Heat Capacity ($\text{kJ}/\text{kg } ^\circ\text{C}$)	Calorific Value (MJ/kg)	Share of Processed Waste (%)
Polyethylene HDPE	940	1.9	46	25%
Polyethylene MDPE	930	2.3	45	10%
Polyethylene LDPE	920	2.1	44	20%
Poly lactide	1300	1.8	20	5%
Polypropylene	900	1.8	46	15%
Polystyrene	1060	1.2	40	10%
Polyethylene terephthalate (PET)	1380	1.0	22	15%

Plastic waste will be processed into synthetic oil through pyrolysis to power a conventional water-cooled diesel electric generator, contributing both to the electrical needs and heating through the utilization of waste heat from the engine. The generator: (i) operates at 100 kW, (ii) enables connection to the low-voltage network, (iii) consumes 29.9 L/h or 24.9 kg/h of diesel (specific weight $\rho = 833\text{ kg}/\text{m}^3$, net calorific value, $H_u = 42.3\text{ MJ}/\text{kg}$),

and produces an hourly energy output of 1053 MJ/h. Annually, 8000 operational hours are allocated for the cogeneration unit, of which 760 h are for maintenance and repair of the diesel engine.

The typical scenario adopted in the framework of this analysis assumes the electric energy generated for the network is calculated as $8000 \text{ h} \times 100 \text{ kWh}$, totaling $800 \text{ MWh}_{\text{el}}$. Additionally, using discharged thermal energy for heating over six months (mid-October to mid-April), for 8 h daily at full power 66% of the time, the required thermal energy is computed as $100 \text{ kW} \times 8 \text{ h} \times 0.66 \times 6 \times 3,095,040 \text{ kWh}$, or $95 \text{ MWh}_{\text{th}}$. The thermal energy coming from the cooling of the diesel engine of $95 \text{ MWh}_{\text{th}}$ is called to replace fossil diesel with an energy content of 11.75 kWh/kg , which, with a combustion efficiency of 0.85, would save 9512 kg of heating oil per year.

3.3. Technical Specifications and Design Requirements

The cogeneration unit for the utilization of plastic waste is shown in Figure 1. In addition to the electromechanical equipment, the unit also includes adequate pipelines and wiring that facilitate the energy distribution to the grid and the thermal energy to be circulated into the industrial facility.

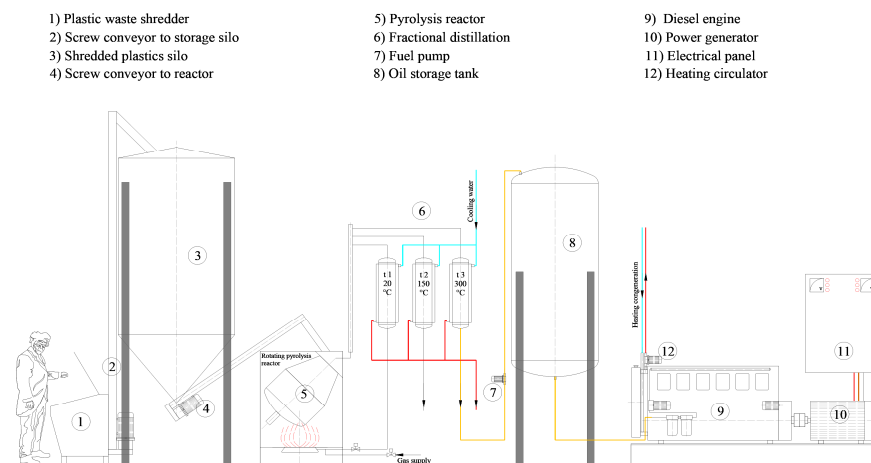


Figure 1. Layout of the cogeneration unit utilizing plastic waste pyrolysis and electric power generator. The cyan corresponds to cold water, the red to hot water, and yellow to pyrolysis oil.

3.3.1. Feeder of Raw Material and Shredder of Plastic Waste

Plastic waste is manually loaded into a shredder, equipped with a safety cover. A disc vertical conveyor driven by a 3-kW motor conveys the raw material into silo storage. For a 24 h continuous operation in order $24 \text{ h} \times 200 \text{ kW} = 4800 \text{ kWh}$ to be produced (due to 80% fuel efficiency of the 6000 kWh or 21,600 MJ required). It is estimated that approximately 675 kg of plastic waste, with an 80% energy recovery from its 40,000 kJ/kg potential, is necessary. A shredder, with a throughput of 500 kg/h, efficiently processes enough material for 24 to 48 h within 1–2 h daily. This equipment is about to have a weight of 250 kg and to be powered by a 2.2 kW engine.

3.3.2. Feed Screw of Crushed Raw Material in the Warehouse

The screw conveyor moves the shredded plastic to the pyrolysis reactor at 500 kg/h or 1000 L/h. Calculating these rates per second provides the exact volume and weight of waste advanced for storage in Equation (1) [36]:

$$\text{Raw material} = \frac{L}{s} = \frac{1000}{3600} = 0.28 \text{ L/s} \Rightarrow 0.00028 \text{ m}^3/\text{s} \quad (1)$$

$$m = p \times Q = 1000 \text{ kg} \times 0.00028 \text{ m}^3/\text{s} = 0.28 \text{ kg/s} \quad (2)$$

where

m: Mass flow rate (kg/s)

p: Density of the material (kg/m³)

p = 1000 kg/m³ taken average density of different plastics

Q: Volume flow rate (m³/s)

An Archimedean-type screw conveyor is selected with an external diameter $D = 0.08$ m, a shaft diameter $d = 0.027$ m, and a pitch equal to the external diameter. The amount transferred is calculated by Equation (3) [28,36]:

$$K_{conveyor} = \frac{D \cdot \pi (D^2 - d^2) \cdot \eta}{4} = \frac{0.8 \cdot 3.14 (0.8^2 - 0.27^2) \cdot 0.75}{4} = 0.27 \text{ L/rotation} \quad (3)$$

The symbols that are used for the calculation of the feed screw are listed in Table 6.

Table 6. Symbols used for the calculations of the feed screw of crushed raw material.

Symbols
K: Amount transferred by the screw conveyor (L/rotation)
D: External diameter of the screw conveyor (m)
d: Shaft diameter of the screw conveyor (m)
π : Mathematical constant, approximately
η : Efficiency of the conveyor, $\eta = 0.75$

The screw conveyor (accounting for material slippage and incomplete filling with a coefficient of 0.75), transports plastic to the pyrolysis reactor at adjusted rates of approximately 0.28 kg/s and 0.28 L/s, dealing with a 4-m elevation difference. The torque applied to the screw is calculated by Equation (4) [37]. Table 7 lists the symbols used on the calculations for the screw conveyor [37]. Table 8 presents the related specification for the unit under consideration.

$$M = F \times r \quad (4)$$

Table 7. List of symbols for the screw conveyor.

Symbols
M: Torque applied to the screw (N·m)
F: Force exerted on the screw (N)
r: Radius of the screw (m), $r = D/2 = 0.05$ m
D: Diameter of the screw (m)
L: Length of the screw (m), $L = 4$ m
P_1 : Pressure from the walls of the screw's shell (N/m ²)
P_2 : Pressure from the elevation difference (N/m ²)
P: Total pressure applied to the screw (N/m ²)
N: Power of the electric motor
ω : Angular velocity
n: Rotational speed
ρ : Density of plastic waste (kg/m ³)
g: Gravitational acceleration (m/s ²)
h: Elevation difference (m)
μ : Coefficient of friction between plastic and steel
V: Volume of Cylindrical Silo (m ³)
Wk: Weight of the screw (kg)

Table 8. Feed screw (of crushed raw material in the warehouse) specifications and design requirements.

Technical Specifications	Values
Torque	$M = 206 \text{ N·m}$
Rotational speed	$n = 40 \text{ rpm}$

Table 8. Cont.

Technical Specifications	Values
Angular velocity	$\omega = 3.14 \times n/30 = 4.18 \text{ rad/s}$
Power of the electric motor	$N = M \times \omega/\eta = 206 \times 4.18/0.75 = 1076 \text{ W} \sim 1.1 \text{ kW}$
Screw, dimensions	0.0762 m pipe in diameter with a weight of 8.47 kg/m and a length of 4 m
Shaft of the screw, dimensions	0.086 m pipe in diameter with a weight of 1.58 kg/m and a length of 4 m
Weight of the screw	$W_s = 4 \times (8.47 + 0.8 + 1.58) \times 4 = 174 \text{ kg}$

3.3.3. Daily Storage Silo

The shredded plastics are stored in a silo-type warehouse for easy management. Table 9 summarizes the calculated design requirements and specifications for the adopted silo.

Table 9. Silo specifications design requirements.

Design Requirements	Values
1 h operation of the pyrolysis reactor	675 kg/24 h = 28.2 kg/h $\cong$ 30 kg/h of waste are required
Daily supply	720 kg of plastic waste need to be shredded and stored.
8 h daily operation	90 kg/h
40 h weekly operation	$720 \text{ kg} \times 7 \text{ days}/40 \text{ h} = 126 \text{ kg/h}$
Operation of the cogeneration for 24 h and 48 h requires	720 kg and 1440 kg, respectively
In an 8 h period	1440 kg/8 h = 180 kg/h of waste will be shredded and stored
Volume of shredded materials, in the shape of ~5 mm side cubes *	$1.25 \times 10^{-7} \text{ m}^3$
Weight of one cube	$125 \times 10^{-6} \text{ kg}$
Storage required for 24 h	$(720 \times 2)/1000 \text{ kg/m}^3 = 1.44 \text{ m}^3$
Cylindrical silo will be 1.59 m in diameter and 2 m in height and volume	$V = \pi \times D^2 \cdot h/4 = 3.14 \times 1.592 \times 4/4 = 4 \text{ m}^3$

* In a pile, these cubes act like spheres, creating a situation where the material occupies a volume ratio of about $6/\pi$, or 1.91 times more than the cube's own volume. This means that essentially twice the volume is needed for the material's storage.

3.3.4. Feed Screw of Crushed Raw Material to the Reactor

Another screw conveyor delivers the plastic materials into the pyrolysis reactor at a rate of 180 kg/h by weight or 180 L/h by volume. Calculating these rates per second provides the exact volume and weight Equation (5) [12,36].

$$\text{Raw material} = \frac{L}{s} = \frac{180}{3600} = 0.05 \text{ L/s} \Rightarrow 0.0005 \text{ m}^3/\text{s} \quad (5)$$

$$m = p \times Q = 1000 \text{ kg} \times 0.0005 \text{ m}^3/\text{s} = 0.05 \text{ kg/s} \quad (6)$$

An Archimedean screw conveyor is chosen with an outer diameter of $D = 0.088 \text{ m}$, a shaft with a diameter of $d = 0.027 \text{ m}$, and a pitch equal to the outer diameter so as to transport the volume of material calculated by Equation (7) [36].

$$K_{\text{screw}} = \frac{D \cdot \pi (D^2 - d^2) \cdot \eta}{4} = \frac{0.8 \cdot 3.14 (0.8^2 - 0.27^2) \cdot 0.75}{4} = 0.27 \text{ L/rotation} \quad (7)$$

Table 10 includes the design requirements calculated with the use of Equation (4) for the feed screw of crushed raw material to the reactor.

Table 10. Feed screw (of crushed raw material to the reactor) specifics for the proposed unit.

Technical Specifications	Values
Radius	$r = D/2 = 0.04 \text{ m}$
Length	$L = 2 \text{ m}$
density of plastic waste	$\rho = 1000 \text{ kg/m}^3$
Height = 1 m	$H = 1 \text{ m}$
Pressure on the walls of the screw's shell	$P_1 = 250 \text{ N/m}^2$
Pressure from the elevation difference	$P_2 = 10,000 \text{ N/m}^2$
Total pressure	$P = 10,250 \text{ N/m}^2$
Torque	$M = 105 \text{ N}\cdot\text{m}$
Rotational speed	$n = 50 \text{ rpm}$
Angular velocity	$\omega = 3.14 \times n/30 = 5.23 \text{ rad/s}$
Coefficient for material slippage and incomplete filling	$\eta = 0.75$
Power of the electric motor	$N = 998 \text{ W} \sim 1.1 \text{ kW}$
Screw pipe	0.08 m pipe in diameter with a weight of 8.47 kg/m and a length of 2 m
Screw shaft	0.02 m pipe with a weight of 1.58 kg/m and a length of 2 m
Weight of the screw	$W_k = 2 \times (8.47 + 0.8 + 1.58) \times 2 = 44 \text{ kg}$

3.3.5. Pyrolysis Reactor

Pyrolysis reactors for plastic waste vary between fixed or moving chambers and batch or continuous flow modes. A rotating chamber with continuous flow is selected, ensuring effective mixing and even heating. The reactor is designed for daily input and able to process loads up to 1440 kg over weekends. Typically operates at 150 kg/h, processing 750 kg in 5 h.

Thermal energy requirements for decomposing plastic waste are calculated using several exothermic reactions. However, to simplify the procedure, the total heat is estimated using Equation (6) [38].

$$Q = m \times C \times \Delta T \quad (8)$$

is used to calculate the amount of heat energy transferred. In this equation:

Q represents the heat energy (in kJ/h),

m is the mass flow rate of the material (150 kg/h),

C is the specific heat capacity of the material (2.4 kJ/kg°C).

ΔT is the temperature difference, which is the difference between the vaporization temperature (470 °C) and the ambient temperature (20 °C).

Using these values, the energy required for the decomposition process is calculated to be 162,000 kJ/h. This represents 26% of the total energy content of the waste material, which has an energy content of 6,225,000 kJ/h.

The reactor has a thermal power output of 45 kWth and processes material at a rate of 0.042 kg/h. The material spends 0.33 h inside the reactor, requiring a minimum volume of 100 L to accommodate the process.

Given the estimated dimensions of the reactor, with a diameter of 0.5 m and a height of 0.6 m, the calculated volume is over 120 L, which exceeds the minimum required volume of 100 L.

3.3.6. Gas Supply for Initiation

A gaseous source such as biogas or propane/butane is necessary to initiate the reactor and the selected fast-paced pyrolysis process. A 3000 L gas tank weighing 630 kg provides the required gas. The process commences by lighting up the burner in the reactor. The gases produced during pyrolysis are then cooled at different temperatures. Some of the gases will condense into diesel and gasoline substances, while gases that do not liquefy at these temperatures are fed back into the gas supply system to support the reactor's combustion. The gas supply system is equipped with a pressure gauge to keep track of gas

levels from the pyrolysis process. When the pressure is sufficient, the gas valve from the pyrolysis process opens; otherwise, only the gas from the tank is utilized.

3.3.7. Fractional Cooling of Pyrolysis Gases

The gas from the pyrolysis process in the reactor travels through pipes to the coolers, where it is liquefied. The pyrolysis gas, after its decomposition in the pyrolysis reactor, consists of H_2 and C. The chemical elements “recombine” into new chemical compounds. The cooling of the gas, which takes place at the appropriate temperatures in the coolers, also contributes to this re-composition.

3.3.8. Synthetic Oil Transfer Pump to Tank

The yielded oil from the condensers will be a minimum of 32 kg/h or 38 L/h. The synthetic oil should be stored in the synthetic oil tank for later use in the diesel engine. The maximum height of the oil tank is taken to be 5 m. The pump that will transport the synthetic oil will be positive displacement, geared with a flow rate of ~50 L/h and an operating pressure of $5 \text{ m} \times 850 \text{ kg/m}^3 = 0.5 \text{ kg/cm}^2$. The power of the synthetic oil pump is $N = Q \times P/\eta = 5 \times (50 \times 10^{-3}/3600) \times (0.5 \times 105)/0.5$ (10 W), and its feed pipe is taken with a diameter of 0.013 m.

3.3.9. Pyrolysis Fuel Tank

The diesel engine requires, for each hour of operation, a quantity of synthetic oil $B = 32 \text{ kg/h}$, and thus for 24 h of operation, 768 kg of synthetic oil are required. The synthetic oil daily consumption tank with the specific weight of $\rho = 0.8336 \text{ N/m}^3$ and a safety margin of 50% should have a volume of $768 \times 1.5/0.8336 = 1355 \text{ L} \sim 1.5 \text{ m}^3$. A cylindrical tank with a diameter of 0.95 m and a length of 2 m has a volume of $V = 0.952 \times 3.14 \times 0.5/4 = 1.4 \text{ m}^3$ without the bottom part. With an elliptical bottom and all tank materials made of 0.003 mm thick sheet steel, the tank weight is $(0.95 \times 3.14 \times 2 + 1 \times 2) \times 0.003 \times 7850 \times 1.5 = 280 \text{ kg}$.

Synthetic oil storage for 48 h (Saturday & Sunday) will require $32 \text{ kg/h} \times 48 \text{ h} = 1536 \text{ kg}$ synthetic oil, or in volume with a 50% increment will be $1536 \times 1.5/0.85 = 2.710 \text{ L}$ (3000 L synthetic oil tank).

The construction of the cylindrical tank with a diameter of 0.95 m and a length of 4 m has a volume of $V = p \times D^2 \times h/4 = 2.83 \text{ m}^3$ without the bottom and with an elliptical bottom, and all tank materials are made of 0.003 m thick sheet steel. The tank weighs $(0.95 \times 3.14 \times 4 + 1 \times 2) \times 0.003 \times 7850 \times 1.5 = 492 \text{ kg}$.

For convenience, typical 3000 L tanks are selected, with a total weight of $492 \times 2 = 984 \sim 1000 \text{ kg}$, which will offer a 90-h autonomy.

3.3.10. Water-Cooled Diesel Engine

The assembly of the power-generating pair consists of a water-cooled diesel engine and an electric generator. The characteristics of the diesel engine of the assembly are presented in Table 11.

Table 11. Technical specifications of a typical branded diesel engine.

Characteristic	Value	Units
Rpm	1500	rpm
Number and arrangement of cylinders	6 in Series	
Cylinders volume	7	Lit
Engine air inlet type	TURBO	
Fuel consumption at full load	29.9	L/h
Fuel consumption at full load	24.9	kg/h
Fuel consumption at full load	221	gr/kVAh
Engine combustion/cooling air	8.1/228.6	m^3/min
Engine power	136.9	kW
Engine weight	725	kg

3.3.11. Electrical Generator

The electric generator provides 100 kW of power. The electric generator rotates at $n = 1500$ rpm with a rotational speed $\omega = \pi \times n/30 = 157$ rad/s. Thus, the torque applied to the electric generator must be greater than $M = N/\omega = 108,000/157 = 688$ N·m. The generator is synchronous three-phase with voltage $U = 400$ V, frequency 50 Hz, power factor = 0.8, and current $I = N/(\sqrt{3} \times V_{\pi} \times \cos\phi) = 108,000/(1.73 \times 400 \times 0.8) = 195$ A [39].

In addition, the electrical panel needed consists of three parts:

- (1) Electrical supply for the equipment.
- (2) Automation control for the equipment.
- (3) Supply of the excess electricity to the grid by net metering.

3.3.12. Water Circulator for Radiator

The thermal power that the CHP unit is going to produce is 100 kW. This power is intended for the radiators, which operate at temperatures of 90 °C (hot water enters the radiator) and 70 °C (water exits the radiator). The supply of the heat carrier (the hot water for the radiators) m is [40]:

$$m = \frac{Q}{c \times \Delta T} = \frac{100 \text{ kW}}{\frac{4.19 \text{ kJ}}{\text{kg}} \text{K} \times 20^\circ \text{C}} = 1.2 \frac{\text{kg}}{\text{s}} \Rightarrow 0.0012 \text{ m}^3/\text{s} = 4.3 \text{ m}^3/\text{h} \quad (9)$$

where

Q : heat flux = 100 kW, c (heat capacity of the material—in this case, water) = 4.19 kJ/kgK.

The diameter of the circulator tube is determined by Equation (10) [40].

$$Q = \pi \times D^2 \times V/4 \quad (10)$$

and thus $D = 0.05$ m.

The pressure of the pump depends on its network, and therefore it cannot be calculated at this stage. It is estimated that the pressure will be $P = 98.063$ Pa or 10 water column meters (mWC) = $\sim 1 \times 10^5$ N/m².

Thus, the power of the pump will be $N = Q \times P/\eta = 0.0012 \times 1 \times 10^5/0.65 = 185$ W [41].

3.3.13. Piping and Wiring

Piping and wiring depend on the placement of the equipment and cannot be determined without specific data. A typical estimation of 2700 euros is adopted in the defined study scenario.

4. Discussion

The proposed unit produces 800 MW_{el} and 95 MWh_{th} using discharged thermal energy for heating over six months (mid-October to mid-April) for 8 h daily at full power, 66% of the time from plastic waste. It is estimated that approximately 675 kg of plastic waste, with an 80% energy recovery from its 40,000 kJ/kg potential, is necessary. Furthermore, the thermal energy coming from the cooling of the diesel engine of 95 MWh_{th} is called to replace fossil diesel with an energy content of 11.75 kWh/kg, which, with a combustion efficiency of 0.85, would save 9512 kg of heating oil per year. Additionally, the total cost of the equipment is 53,000 Euros, while the electricity cost for the operation of the unit is 370 Euros.

With an initial investment of approximately 60,000 Euros, this pilot unit showcases notable efficiency by operating for 8000 h annually, utilizing 568 tonnes of synthetic oil. This output is equivalent to the energy content of 91,500 lt of diesel derived from fossil fuels. The generated electricity not only fulfills but also exceeds the operational demands of a typical small-scale industry, allowing the surplus energy to be fed back into the power grid. This contribution creates an additional revenue stream, augmenting the system's economic appeal alongside its environmental benefits, such as reducing waste

and leveraging renewable energy sources. Moreover, the system innovatively integrates the thermal energy produced during electricity generation into the industrial facility's operations, optimizing energy utilization and further reducing the carbon footprint.

The presented technical specification and design requirements of the WtE technological option can address simultaneously two fundamental issues: processing non-reusable and non-recyclable streams of plastic waste and producing significant amounts of energy included in the corresponding supply chain to satisfy the growing needs in regions over the world. In response to the increasing concern about waste environmental-related issues, the waste sector must switch to "intelligent" in its supply chain to consider its effect in terms of environmental deterioration and climate change and adopt initiatives to reduce this effect [34].

As industries move toward decarbonization, this approach presents a profitable and sustainable path forward. Its cost-effectiveness and efficiency make it an appealing option for the industrial sector. However, smaller enterprises may be more receptive and agile in adopting new technologies and directions, positioning them as pioneers in embracing this innovative energy solution. In essence, utilizing this technology to regenerate energy is a possible solution to the urgent problem of managing plastic waste by transforming it into valuable fuel, leveraging the chemical properties of plastics similar to biomass. This method is definitely seen as an eco-solution, as it helps with waste management and supports a carbon-neutral industry future. Transforming waste products into fuels through recycling signifies a move towards using natural resources in a more sustainable and effective way.

5. Conclusions

Summarizing the material presented, this analysis demonstrates the feasibility and financial advantages of utilizing plastic waste pyrolysis to produce synthetic oil for powering diesel engines. This strategy focuses on generating both electricity and heat that requires a moderate investment and utilizes conventional power generation methods. It is particularly beneficial for businesses with access to waste of plastic materials and thermal energy needs. This system not only fulfills the heating requirements in cold seasons but also provides additional benefits by utilizing electricity and selling it to the grid, making it an attractive choice for industries that generate amounts of plastic waste.

It is considered important that future research on pyrolysis from plastic waste should become niche-specific and focus on creating small-scale pyrolysis units that are adaptable and versatile for local enterprises and communities. These units have the potential to offer an approach to managing waste, especially in regions with limited recycling facilities. In addition, community approval is considered essential for the implementation of technology. The promotion of the economic advantages of pyrolysis could lead to increased support as communities realize the benefits of both reducing plastic waste and producing renewable energy. In addition, the necessity of regulating plastic waste management and defining suitable WtE processes (incineration, pyrolysis, etc.) for each type of waste stream becomes imperative, as does the consideration of various parameters (stakeholders, technological maturity, etc.) [42,43]. It is worth noting that in many countries, including the EU, such installations are given the status of waste incineration and specific legal regulations related to this classification.

Ensuring that pyrolysis is framed as a complementary stage to recycling will be essential for regulatory approval, highlighting its role in the waste management hierarchy, thus supporting the development of legislation that promotes pyrolysis as a sustainable alternative for managing non-recyclable plastics and enhancing recycling efforts without undermining them.

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Abbreviations

As	Arsenic
CAPEX	Capital Expenditure
CH ₄	Methane
CHP	Combined Heat and Power
Cl	Chlorine
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
GCV	Gross Calorific Value
kW	Kilowatt
kWh	Kilowatt hour
MJ	Megajoule
MW _{el}	Megawatt electrical
MW _{th}	Megawatt thermal
NO ₂	Nitrogen dioxide
N ₂ O ₂	Dinitrogen dioxide
WtE	Waste-to-energy

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