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Environmental Impact of Plastic Recycling in Terms of Energy Consumption: A Comparison of Japan's Mechanical and Chemical Recycling Technologies

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Abstract: In Japan, mechanical plastic recycling has been widely practiced. In recent years, the chemical recycling method has been gaining interest, especially due to its high-quality products similar to virgin materials. Understanding the environmental impact of both methods from the energy consumption standpoint is crucial so that attempts to preserve plastic resources can be based in the most energy-sustainable way. This research aims to determine the environmental impact of mechanical recycling and two types of chemical recycling technologies (coke oven and gasification) by analyzing their energy usage and environmental loads. The results relating to the electricity consumption and water usage show that mechanical recycling results in a 17% share of global warming potential (GWP), coke oven 51%, and gasification 32%. Although mechanical recycling results in a lower GWP, chemical recycling yields highly valuable products and byproducts that can be reused in its processes, such as steam and industrial water, reducing the overall environmental load. These recovered materials are also potentially useful for other industrial processes in an industrial symbiosis ecosystem.

Keywords: municipal plastic waste; recycling technologies; energy use; environmental impact assessment



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1. Introduction

Single-use plastic products have burgeoned recently due to the COVID-19 pandemic outbreak at the end of 2019 [1]. People also became increasingly concerned about health and hygiene. A 2021 exploratory study observing 202 households from 41 countries found a 50% increase in food packaging and a 35% increase in single-use bags in households' plastic waste [2]. The Japanese statistical agency reported that the total amount of plastic waste in Japan (municipal and industrial) was 8.24 million tons in 2021 [3]. Of these, 35% was polyethylene (PE), which accounts for the largest share, followed by polypropylene (PP) (23%), and 'other resins', with 22% of the total share. As the types of plastic waste in the 'others resin' category need to be specified, it becomes challenging to treat.

At the same time, new challenges have emerged in the recycling process since the pandemic, such as hygiene and sanitary concerns for the staff collecting and sorting plastic waste [4]. An increase in plastic consumption would increase the demand for chemical products and ultimately impact the expansion of oil and natural gas exploitation and production. As the chemical industries that produce plastic rely heavily on oil [5], it is not an exaggeration to claim that it would exacerbate the scarcity of fossil fuels. There is a consensus that energy conservation leads to sustainable development for society.

The 'waste management act' was enacted in Japan to set the standard for sorting and recycling methods in 1991 [6]. Japan also released the 'Basic Recycling Act' in 2000, containing guidelines on the reduce, reuse, recycle (3R) concept for efficient waste management, including the sorted collection and recycling of containers and packaging. However, the focus has predominantly been given to treating polyethylene terephthalate (PET). Plastic

container packaging other than PET has yet to be well developed in the country, despite being over two decades since the introduction of the law [7]. A year after the China plastic ban in 2018, the Japanese Ministry of the Environment released the “resource circulation strategy for plastics”. The strategy declared a national goal of reaching a 60% recycling rate of plastics by 2030 and a 100% recycling rate by 2035 [8,9].

The 2019 report from the plastic waste management institute in Japan [3] shows that Japan annually produces 8,240,000 tons of plastic waste (municipal and industrial). The waste ratio from the municipality and the industry is relatively equal [9,10]. Of the total amount of plastic waste produced, 1,770,000 tons is treated with mechanical recycling (MR) and 290,000 tons with chemical recycling (CR) [11]. The remaining 5,100,000 tons are treated using thermal recycling (TR) for energy recovery. Among the plastic waste treated with TR, 2,080,000 tons are used for fuel utilization, 2,520,000 tons in incineration to generate electricity, and 500,000 tons in incineration for heating [11]. It is evident that despite the government’s precautions only to use TR as an emergency route [7], it continues to be utilized at a greater rate to treat plastic waste than the MR and CR routes.

Thermal recycling should be used sparingly, as burning plastic results in harmful pollutants such as dioxin. Furthermore, the loss of plastic materials in the value chain cannot be considered a circular technology [12,13]. Other than the obvious environmental concerns, it has now become necessary for countries to join the transition toward the circular economy to remain competitive [14]. Japan is well aware of this, and as part of its efforts, the government issued the circular economy vision in 2020 [15–17]. Under this vision, the plastic industries in Japan now hold the key responsibility to choose and adopt circular economy strategies to improve their competitiveness [14]. The prioritization of MR and CR is also in line with the “waste management hierarchy pyramid” created by the European Union (EU) waste prevention and management to ensure the efficient use of energy [18]. The pyramid suggests that ‘prevention’ should take precedence over ‘preparation for reuse’ and that waste should be prevented before it can be prepared for reuse. It also advocates reusing products directly, with minimal processes and energy usage. Recycling is at the third priority level in the hierarchy, which treats waste as a valuable resource for future production. Energy recovery is the second lowest priority, and disposal without a reliable harness is the lowest priority.

Recycling technologies are a valuable link to the prospect of society’s sustainable development, as they play a major role in creating the circular economy. It can also provide opportunities to reduce energy consumption and greenhouse gas (GHG) emissions. On the other hand, energy recovery technologies may supplement most waste management methods because they enable electricity and heat generation with byproducts, resulting in a lower environmental load than the final choice disposal. Although less preferable in material preservation [12], energy recovery from plastic waste for a self-use approach is direct recycling at lower energy inputs for sorting and pretreatment. While emissions are difficult to manage in such an approach, utilizing carbon capture technologies can reduce unfavorable effects [8].

Previous studies have analyzed and compared the environmental impact performances of MR and CR for plastic packaging waste, commonly using the life-cycle assessment methodology [19–21]. While these studies indicated the limited performance of CR against MR in terms of technology maturity and research, particularly comparing the different CR technologies in Japan, [22] suggested that CR has many new potentials, including better efficiency and higher quality products. Furthermore, the study suggested that the potential can be achieved by building a better recycling system and environment where the connection between postconsumption and recycling plants is more established. With the promised benefits of CR performance in a suitable system, the question is whether the energy demand of CR technology would be worth higher-value products.

Additionally, an evaluation of the use of recycling for a circular economy in the real world can only be completed with an energy-use analysis, as such information is necessary to make an informed decision [12]. In this study, we assess the environmental impact of

the following three technologies: (1) MR, (2) coke oven, and (3) gasification in association with their energy consumption. Coke oven and gasification technologies belong to the CR category. The environmental impact assessment in this study aims to reveal the different relevance of energy and resource requirements with the environmental performances of recycling the same plastic waste input.

2. Literature Review

2.1. *Plastic Recycling Contribution to the Creation of a Circular Economy and Energy Security in Japan*

A dense population, high per-capita energy consumption, and a small land area characterize Japan. With such characteristics, it is challenging for countries to deploy solar and wind farms on a large scale, such as countries with large land areas and dispersedly populated countries in Europe and Africa [23,24]. On the other hand, the country is faced with high energy insecurity [25] due to the lack of conventional energy resources such as coal, oil, and gas [24]. Japan also bears a reputation as the fifth largest greenhouse gas (GHG) emitter in the world [26], approximately 42% of which is from the electricity system [24,27]. Since the 2011 nuclear accident, many nuclear plants have been shut down, and the country has become very reliant on energy imports [26]. Approximately 93% of its current energy use is supplied from other countries [25].

Intuitively, Japan should rely on domestic renewable energy resources to reduce its energy import dependency [24,27]. However, there needs to be more interest in renewable energy as a source of electricity [28]. This situation is exacerbated by insufficient knowledge regarding Japan's susceptibility to energy poverty [29], insufficient awareness of energy-saving benefits by the industry [30], and top-down decision-making in electricity and electricity pricing [31]. On the other hand, Japanese economic expansion and financial development will continue to raise the energy demand, exacerbate energy insecurity [25], and cause larger GHG emissions from power plants [32].

In October 2020, Japan declared its long-term goal of reducing GHG emissions to net zero by 2050 [27,33]. Reducing the dependency on external energy sources can be initiated by moving toward a more circular economy. The circular economy is a restorative and regenerative economy by design and aims to keep product components and materials at their highest utility and value [34]. One way to measure a circular economy in the recycling industry is by calculating the ratio between the value of recycled material and its value before entering the recycling plant [34]. To establish a circular economy, the French circular economy project proposed three dimensions (environment, social, economic) and seven areas of circular economic actions (sustainable procurement, eco-design, industrial symbiosis, functional economy, responsible consumption, extension of service life, effective management of materials and end of life products) [34,35].

As environmental policies can influence energy-reducing choices that lead to emission mitigation targets [30], in this study, we aim to provide information for decision-makers about the role of plastic recycling in contributing to the realization of the circular economy and energy independence through the preservation of the value of recycled plastic material and industrial symbiosis. It is estimated that, of the seven billion tons of plastic waste produced globally, only 10% has been recycled [36]. However, with the significant amount of plastic waste in municipal solid waste, plastic recycling has a large potential to contribute to creating a circular economy [37] through industrial symbiosis.

An industrial symbiosis is a collective approach where two or more organizations exchange, share or transact unused materials and byproducts to reduce the consumption of virgin material, energy inputs, and waste generation and emissions [38]. Although recycling has been the main application of industrial symbiosis, the approach has the potential to be applied beyond waste recycling, for example, for infrastructure and service sharing [39]. Creating an industrial symbiosis requires intensive efforts and openness, such as the intense involvement of multistakeholders [38], database construction, and information sharing [40,41]. A study by Sellitto et al. [42] has identified the barriers, drivers,

and relationships in industrial symbiosis [42] that can guide the creation of a successful industrial symbiosis. The benefits of industrial symbiosis include faster economic growth, higher-quality profits, and reduced waste and energy use [43,44]. These are the qualities of an economy that Japan should aim for to remain globally competitive and survive the energy crisis.

The potential of reaping those benefits for Japan is further escalated as Asia is the largest plastic producer in the world, responsible for 51% of the global plastic production capacity in 2018 [45]. Furthermore, China and Japan are the leading countries in the region regarding plastic production, as they are home to highly competitive factories and business processes [45]. The other end of the product line, plastic waste recycling, is, however, less effective. As a result, Japan has become one of the largest exporters of plastic waste in the world [46] (Figure 1).

Since China's ban on plastic waste imports, a global restructuring of trade in waste plastics has occurred. As a result of this ban, Japan redirected its plastic waste export to several Southeast and East Asian countries [47]. However, these new destination countries have gradually posed similar plastic waste import bans [48]. With more countries closing their doors to plastic waste imports, it is clear that recycling plastic waste domestically will eventually be the major solution, alongside strengthening the creation of a circular economy and energy security, for Japan.

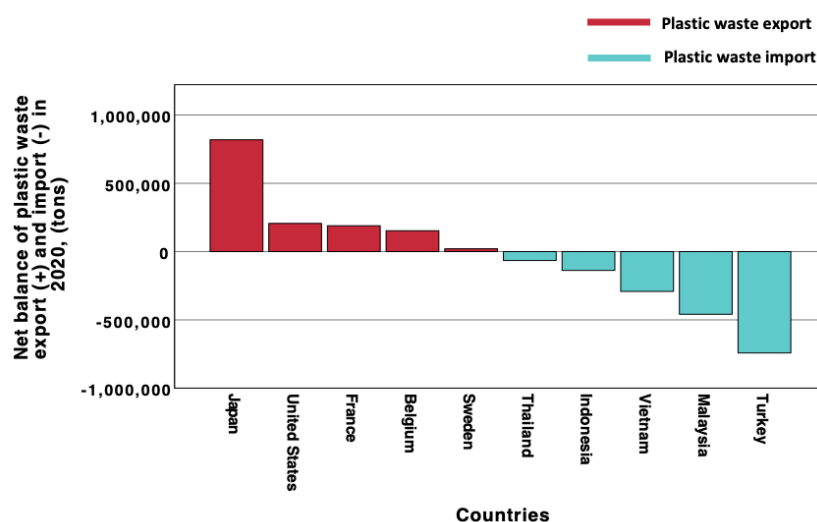


Figure 1. Japan is the world's largest plastic waste and plastic scrap net exporter, data from UN [46,49].

2.2. Mechanical, Chemical, and Thermal Plastic Recycling

There are multiple ways to recycle plastic waste (Figure 2). The Japanese plastic waste management institute [10] categorizes waste recycling into material recycling (MR), chemical recycling (CR), and thermal recycling (TR). Globally, most plastic recycling facilities use MR as the main processing technology. MR is technologically mature and commercialized. However, the low-quality product and higher costs compared to virgin plastics have rendered it uncompetitive. There are several routes of CR technology; the most common ones are pyrolysis and gasification. Gasification is a promising technology to convert plastic waste to new plastics of virgin material quality. Life cycle analysis (LCA) studies of plastic waste recycling technologies generally show that CR has a larger GHG footprint than MR, but is lower than TR [50]. Meanwhile, electricity decarbonization increased the GHG footprint of plastic waste incineration with energy recovery due to diminishing credits for avoided electricity production. Thus, the study in [50] implies that the GHG benefits from the direct CR of postconsumer mixed plastic waste will increase in a decarbonizing economy. TR technology includes the incineration of waste plastics in a cement kiln, waste power generation, refuse plastic fuel (RPF), and refuse-derived fuel (RDF). There is also a CR and TR combination, including gasification and liquefaction. TR is less desired and

was only considered in 2006 in Japan as a supplementary method with limitations [10]. Although TR is a way of recovering energy from plastic waste (Figure 2), its limited benefit in the creation of the circular economy and the discouragement from the Japanese government to use this type of technology have led to it being eliminated from the present study's analysis. This study compares the environmental impact and energy use of MR and two CR technologies: gasification and coke oven (conversion to fuel in Figure 2).

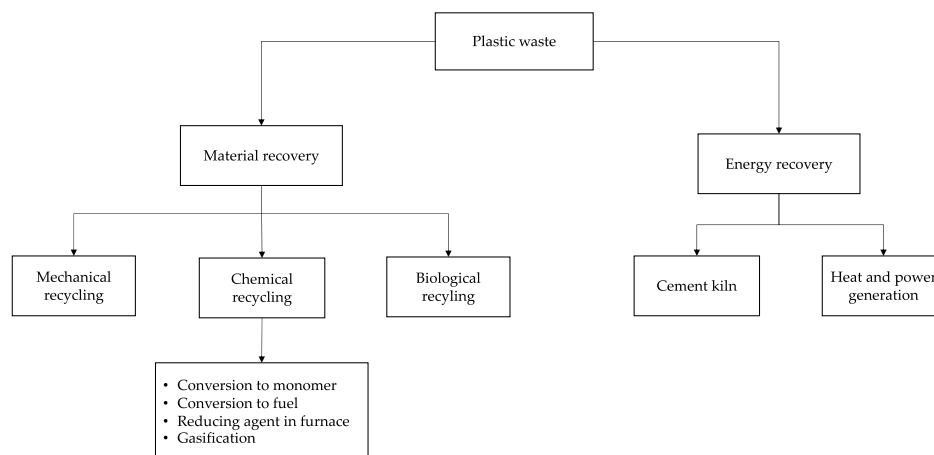


Figure 2. Globally available plastic waste recycling routes. Reprinted with permission from [37,51]. 2023, Elsevier.

Many studies have compared the advantages and disadvantages of MR and CR technologies [52–58]. We summarize the findings from these studies in Table 1. Although MR is generally considered to be more mature and popular than CR [55], the product quality of MR is poor, causing a loss of economic value [50,52,54,55]. Furthermore, specific plastic products require a high-quality standard, such as those for food packaging. MR recycled plastics usually do not meet such standards. Another challenge faced by plastic recycling is the greater number of mixed plastics. Mixed plastics are durable but pose challenges in recycling. CR technology is less tolerant to these types of plastic waste and other contaminants than MR technology [52,58]. Single-type plastics are more suitable for CR treatment; however, they often face the bottleneck of insufficient sorting technology for postconsumer waste [56].

The research in [59] summarized the current plastic waste recycling method problems as follows: (1) large energy consumption; (2) low utilization rate of recycled products; and (3) unutilized byproducts from the recycling process. Furthermore, a comparison study [55] argued that while both MR and thermal forms of CR are resource-efficient, it is important to investigate MR and CR more thoroughly on an industrial level. Our aim in this study is to analyze how MR and CR could address those challenges.

While MR technology is straightforward [52,53], CR has branched into different routes (Figure 2). Among the available CR technologies, pyrolysis is the most researched CR route and the most common method modeled using LCA [12]. Studies have acknowledged pyrolysis as a viable circular economy strategy [60] and the best CR technology [12]. However, another study [12] argues that the fact that this technology option is the most researched one may cause a bias in the results, as other CR technologies are underrepresented in the existing studies. This situation caused us to select coke oven and gasification to better represent other CR technology routes and to add a broader understanding of the literature. The different steps of MR, coke oven, and gasification are shown in Figure 3 in the next section.

Table 1. Advantages and disadvantages of MR and CR plastic recycling technologies.

	Advantages	Disadvantages	References
MR	Straightforward process	Mixed plastics separation difficulty and high cost are known as Mechanical Recycling (MR) challenges.	[52,53]
	Recycling facilities are simple and economical and use less energy and resources than CR.	Lower product quality. Products may not be able to be reused in high legal safety required products such as food packaging.	[50,52,54,55]
		Although it emits the lowest overall GHG emission but is not consistently distributed across cycles.	[54,55]
		Emits high NO _x emission.	[55,57]
	MR is known as being more popular and mature than CR.		[55]
	It can selectively convert plastic waste into high-value products such as refinery feedstock, fuel, and monomer.	Require high investment and clean feedstocks	[56,61]
CR	Higher potential for profitability	Readiness level for industrial scale has not been completely established	[52,55]
	Require much energy	Industrial implementation of CR is limited because it is less tolerant of contaminants.	[52,58]
	The pyrolysis route emits lower SO _x emissions.		[57]
	In the gasification route, polymer separation into different categories is not necessary. It also produces useful electricity and heat.		[61]
	Gasification is considered a mature technology.		[61]
	High process efficiency		[58]

3. Materials and Methods

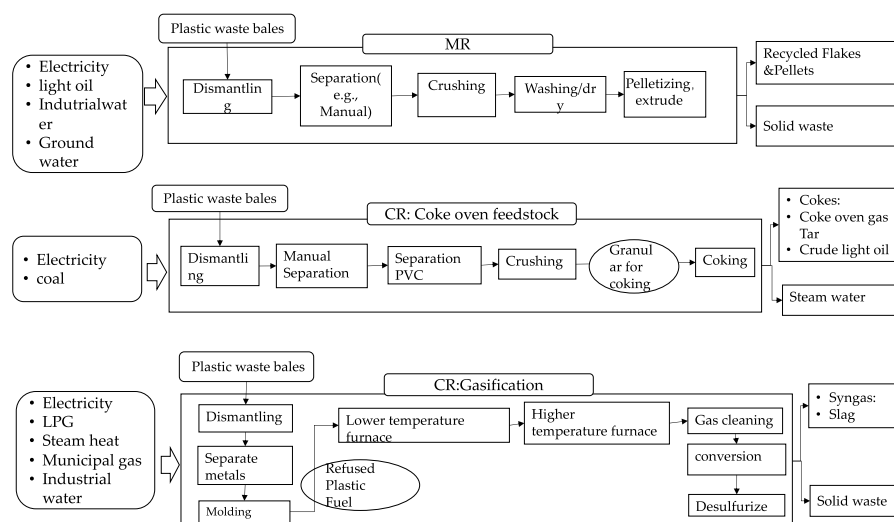
In this study, we compare the energy demand of the Japanese MR and CR technologies along its process chain using the 2022 inventory data from the life cycle assessment Society of Japan (ILCAJ) (Table 2). These data are based on the actual processes of Japanese recycling facilities. In particular, this study examines the CO₂, CH₄, N₂O, SO_x, and NO_x inventories from the emission intensity of energy based on thermal transformation. This study's environmental impact calculation method follows the ReCiPe2016 "Individualistic" method. There are three calculation methods in ReCiPe2016: "Individualistic," "Hierarchic", and "Egalitarian". In this study, we use the 'individualist' calculation method [62] for our analysis because the "individualist" (Table 3) calculation model has been reported to be able to address undisputed impact types and enforce technological optimism about human adaptation, which coincides with the present study's goal [63]. Therefore, this study uses the midpoint levels and impact categories guided by ReCiPe2016, the "Individualistic" method, as elaborated in Table 3. Consistent with the Life Cycle Assessment (LCA) guidelines [64], the impact categories are climate change, terrestrial acidification, photochemical oxidant formation, fossil resource scarcity, and water use (Table 3). This study also follows the LCA prototypes, including the (a) research goal; (b) scope definition; (c) inventory analysis; and (d) impact assessment (ISO14040:2006 [65] ISO 14044:2006 [66]).

Table 2. The energy consumption for 1 kg of plastic waste, data from JLCA-LCA database [67].

	Unit	MR	Coke Oven	Gasification	Reference
Publicity Electricity	kWh	5×10^{-1}	0.9×10^1	2×10^{-1}	JLCI
Light oil	L	5×10^{-4}	0	0	JLCI
Industrial water	m ³	2×10^{-1}	0	0.3×10^1	JLCI
Ground water	m ³	5×10^{-1}	0	0	JLCI
Liquefied petroleum gas (LPG)	kg	0	0	3×10^{-3}	JLCI
Steam Heat	kg	0	0	3×10^{-1}	JLCI
Municipal gas	kg	0	0	4×10^{-3}	JLCI
Coal	kg	0	0.9×10^2	0	JLCI

Research Scope, Inventory, and Environmental Impact Analysis

An analysis of the indirect impact of energy consumption is necessary to attribute the potential environmental impact of recycling. The specific technologies analyzed in this study are: (1) MR; (2) coke oven feedstock production and gasification. The input plastic waste is assumed to have been baled postconsumption and then dispatched to the recycling site. Figure 3 shows each recycling process's research boundaries, inputs, and outputs. The functional unit for disposing of plastic waste treated by the MR and CR technologies is 1 kg.

**Figure 3.** The gate-to-gate steps of the three plastic waste recycling technologies. Adapted from JLCA-LCA database 2022 edition [67].

The inputs (Figure 3) for MR and CR for plastic waste go to different process routes, but the source of energy and other inputs come from the same public electricity resource. Therefore, the calculation method reflected these similarities and differences. Moreover, the related electricity and energy supply emissions are summarized in Table 2. These emission data are fundamental for calculating the total emissions during recycling and steam production.

The differences between MR and the two CR methods are exposed in the technique; the primary component of MR is the comprehensive sorting pretreatment. When MR processes municipal plastic waste disposal at the designated location, it will undergo a crushing process accompanied by a 'screen machine' (e.g., drum screen, air separator, manual) to separate polymer-based products from other materials after being transported to 'sorting sites' and compressed into a bale for efficient transportation. The plastic waste bales will then be transferred to the recycling process, where: (1) tiny particles are removed using techniques such as magnetic separation; (2) plastic is cleaned from contamination and dried; and (3) new plastic flakes or plastic beds are produced by shredding and extrusion [13].

The coke oven recycling method has been successfully commercialized in Japan [68]. The technology can process up to 200,000 tons of plastic waste per year, and the plastic-waste kernel product is used to replace metallurgical coal [68], which is useful in reducing recycling plastic waste and the reliance on coal [68]. However, the products of this technology are primarily used in prime ironmaking factories and ‘coke oven intended’ steel industries.

Gasification technology involves a pyrolysis process, where plastic waste components are transformed into syngas for further refinery chemical production, such as ammonia. Ammonia is a significant feedstock for chemical plants used for nylon and acrylic fiber. The versatile usage of this technology’s product attracts investors’ attention [69]. The flowcharts presented in Figure 3 show the gate-to-gate process in the three types of recycling factories. These flowcharts are also the boundary of the environmental impact assessment of this study.

Based on the recycling flowchart (Figure 3) and the JLCI database energy-use categories, we tabulate each process’s energy consumption (Table 2), which displays the energy consumption for 1 kg plastic waste bales.

The unit energy-related emissions (Table 3) are calculated by the energy categories and the corresponding emissions in JLCI, which explain the emissions embodied in each unit of energy to prepare for the environmental impact calculation.

Table 3. The emission coefficients (Mi) of energy, data from the JLCA-LCA database 2022 edition and JCPRA [67,70].

Mi	Unit (MJ)	CO ₂ (Kg)	CH ₄ (g)	N ₂ O (g)	SO _x (g)	NO _x (g)
Publicity						
Electricity	0.4×10^1	4×10^{-1}	0	2×10^{-3}	0	2×10^{-1}
Light oil	0.4×10^2	0.3×10^1	n.a	n.a	1.4×10^{-1}	0.1×10^1
Industrial water	1.7×10^{-3}	1.1×10^{-4}	0	0.2×10^{-2}	0.5×10^{-5}	3.6×10^{-4}
Steam heat	0.4×10^1	2.6×10^{-1}	0	0.3×10^{-1}	0.2×10^{-4}	5×10^{-1}
LPG	0.6×10^2	0.4×10^1	9×10^{-1}	n.a	7×10^{-1}	0.2×10^1
Municipal gas	5.7×10^1	0.3×10^1	n.a	n.a	4.6×10^{-2}	0.12×10^1

To quantify the environmental impact score, the calculation is based on the ReCiPe 2016 methodology (Table 4), which shows the emission coefficients under each category. Individualist factors, which are short-term environmental impact outputs, are adopted in this calculation. Moreover, there is a region-specific terrestrial acidification potential (TAP) coefficient and a photochemical ozone formation potential for the ecosystem (EOEP) (Table 4) used according to the region-specific section of the ReCiPe2016 guidelines. We selected the coefficient based on the region of Japan. Other factors, such as global warming potential (GWP), fossil fuel scarcity potential (FFP), and water scarcity potential (WCP), are not influenced by regions. Therefore, we used the standard unit factors in the ‘individualist’s coefficient from ReCiPe2016.

The calculation formula is shown in Function (1). To attain the environmental impact values, we use the energy consumption (E) for 1 kg of plastic waste multiplied by the emission coefficients (Mi) from Table 2 and by the coefficient factor (CF) of the environmental impact category from Table 4.

$$I = E \times Mi \times CF \quad (1)$$

Table 4. The midpoint level environmental impact, data from ReCiPe 2016 [62,63].

Midpoint Impact Category Index	CF (Characterization Factors)	Emitted Factor Related Sources	Individualist	Unit
Climate change	GWP	CO ₂	0.1×10^1	kg CO ₂ -eq/kg GHG
		CH ₄	0.8×10^2	kg CO ₂ -eq/kgGHG
		N ₂ O	0.3×10^3	kg CO ₂ -eq/kg GHG
Terrestrial acidification	TAP	NO _x	3×10^{-1} (Japan)	kg SO ₂ -eq/kg
		SO ₂	8×10^{-1} (Japan)	kg SO ₂ -eq/kg
Photochemical oxidant formation: terrestrial ecosystems	EOFP	NO _x	8×10^{-1} (Japan)	kg NO _x -eq/kg
Fossil resource scarcity potential	FFP	Crude Oil	0.1×10^1	kg oil-eq/kg
		Natural gas	8×10^{-1}	kg oil-eq/Nm ³
		Hard coal	4.2×10^{-1}	kg oil-eq/kg
Water scarcity potential	WCP	Groundwater	0.1×10^1	m ³

4. Results and Discussion

The environmental impact of each recycling technology compared in this study is embodied in five categories (Figure 4). The environmental load of each category is displayed as a percentage. MR shows the best performance (17%) among the three technologies in terms of GWP. The GWP is attributed to electricity use and light oil for machine operation (5×10^{-4} L/1 kg plastic waste). MR’s water consumption slightly affected the WCP (7×10^{-1} m³/1 kg plastic waste). However, it is much smaller (only 9%) than the other two methods.

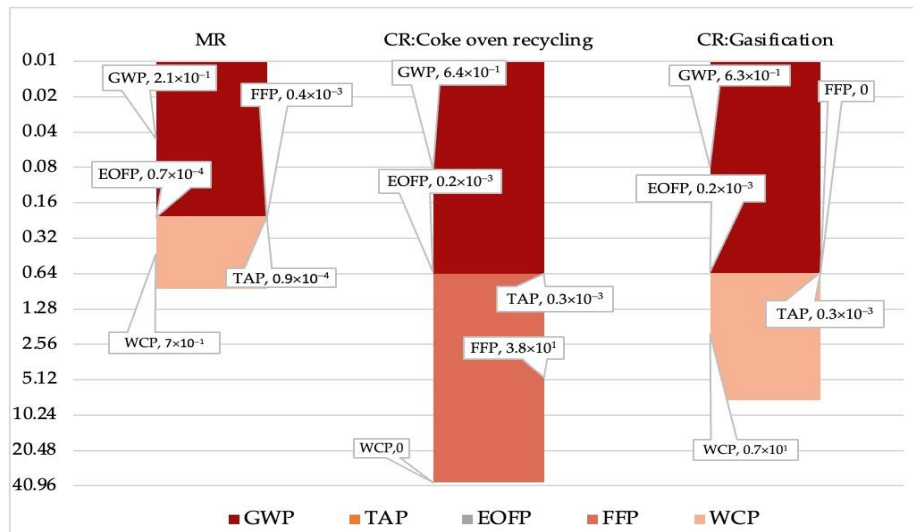


Figure 4. The environmental impacts of the three recycling technologies.

Gasification, on the other hand, has a significant effect on water resources. This technique involved two resources of water: steam and industrial water. The gasification process consumes 0.7×10^1 m³ of water for its chemical reaction, derived from the byproduct of its processes. Gasification technology utilizes more water than the other processes: 0.3×10^1 m³ of groundwater for its industrial water supply and 0.4×10^1 m³ groundwater for steam; it can self-provide 7×10^{-1} kWh of energy for the whole process from the byproduct (not from the public electricity system). Overall, the final environmental impact of the GWP category is lessened due to this partial self-sufficiency and the trade-off of CO₂ emissions.

Coke oven recycling uses a total of electricity 9 kWh/1 kg plastic waste, which includes pretreatment to fit the insert size of the coke oven. This process employs chemical elements, and plastic waste replaces some of the coals for the coking process to produce tar. Regarding the FFP category, which measures how much fossil fuel is consumed and its implication for future scarcity potential, the impact mainly comes from coal inputs, which is 0.9×10^2 kg/1 kg of plastic waste, which is higher than other methods involving fossil fuel resources. However, the pyrolysis process of the coals in the coke oven is not responsible for the emissions, as it comes from its byproducts.

In terms of TAP, the electricity consumption by MR technology resulted in SO_x emissions of 0.9×10^{-4} kg/1 kg plastic waste. Meanwhile, the TAP from gasification is higher at 0.5×10^{-2} SO_2 -eq/kg from the multiple energy sources it requires.

Furthermore, the three methods result in the EOEP index. The steam involving the NO_x emission from the coke oven and gasification routes produces approximately the same EOFP value of 0.2×10^{-3} NO_x -eq/kg plastic waste and 0.2×10^{-3} kg NO_x -eq/kg plastic waste.

It can be observed that the GWP category shows the most significant difference between the three technologies. The difference is primarily attributed to the electricity used in each technology. Our results can be compared with the report by the Japan Containers and Packaging Association (JCPRA) [71], as shown in Figure 5. The figure records ten years of operation in Japan's three technologies. In this report, the MR produces byproducts that must be incinerated in the blast furnace, resulting in an additional energy recovery potential. However, such a practice would result in additional emissions, such as dioxin. Overall, the ten-year performance, according to this report, shows that the coke oven has the highest energy reduction potential, followed by the MR + blast furnace, and then gasification.

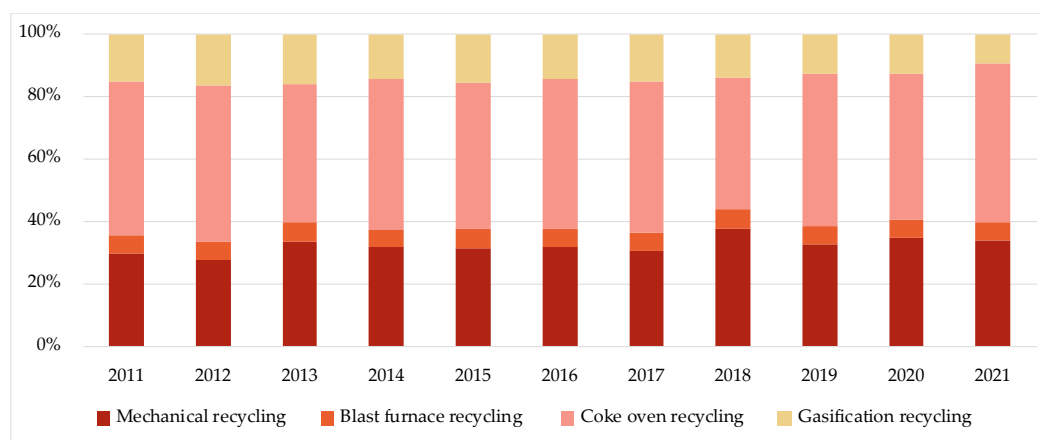


Figure 5. The energy reduction of different recycling methods in Japan (translated and adapted from the Japanese language by authors and used with permission from [72]).

While the rate of electricity consumption alone often plays a significant role in deciding which technology would be more efficient in its energy use, the use of other resources must not be overlooked. This is true, especially for Japan, where energy scarcity is becoming a major crisis because it relies on most of its energy necessities from imports [73]. Another study reported that while MR results in a better GWP, it has a worse impact on resource consumption and terrestrial acidification [55]. Furthermore, as high-quality products and byproducts are necessary for creating a circular economy [34] and addressing the challenges faced by the plastic recycling industry [59], priority should be given to these areas.

Considering all of these factors, coke oven recycling has the potential to maintain both high-quality products and byproducts, as well as significant energy reduction.

While it is generally challenging for newer technology to reach higher maturity and commercialization status, Japan has been practicing CR technology for over a decade [72]. As Japan is known as the most technologically innovative country in the world, CR technol-

ogy's further development could be incentivized through private initiatives. Furthermore, innovative circular technology can help to improve energy security in Japan. Over the years, technological stagnation has worsened Japan's energy insecurity [25]. Finally, adopting plastic waste recycling in industrial symbiosis must be supported by a corresponding policy, as more than economic incentives are needed [40]. It is then necessary to build awareness among business practitioners because if circular and industrial symbiosis becomes of interest to businesses, they will invest more resources in it [74]. Another thing that could help the development of CR technologies is to improve the collection systems so that less contaminated plastic waste can be obtained [37]. Economically and environmentally, the study by [58] has shown that CR is very feasible.

5. Conclusions

This study analyzed three different technologies: MR, coke oven feedstock production, and gasification. These technologies are more than just machines for the recycling sector, as they contribute varied environmental impacts and have the potential to contribute to the creation of a circular economy and better energy security. The focus of this research is to provide information on the environmental impacts of these technologies for decision-making on recycling routes. The ultimate goal of recycling plastic waste is not straightforward and is beyond the limit of electricity consumption. Several important factors in decision-making for plastic waste technology routes are as follows:

- (1) The quality of products and byproducts determine the utilization rates.
- (2) How good the collection and separation process are, as they determine whether more advanced technologies with lower contamination tolerance can be adopted.
- (3) The existence of mixed plastics is more costly and challenging to handle.
- (4) How ambitious the country is about progressing toward a circular economy.
- (5) How to accommodate policymakers and how cooperative and transparent stakeholders are about creating industrial symbiosis, as policy and data sharing are key to successful industrial symbiosis.

With Japan mainly relying on meeting its energy needs from abroad, the diversification of energy resources for its growing plastic waste recycling needs must be carefully considered. Among the three technologies compared in this study, MR showed lower total electricity requirements, resulting in better GWP performance. However, when the other impact categories were considered, it was clear that MR was less preferred than the other two technologies. First, both CR routes, coke oven and gasification, are known to have the potential to produce higher-quality products. Second, both CR routes also produce useful byproducts that can be reused in recycling processes, resulting in a lower overall environmental impact. For example, the coke oven process produces cokes, a crucial element for polymer chain-breaking reactions. On the other hand, the gasification route recycles most of its water use for the recycling process. Recycling also has the potential to reduce the environmental burden related to energy consumption and resource scarcity when technologies are scaled up. Therefore, gasification and coke oven recycling are exemplary technologies for creating a circular economy and achieving sustainable development.

The diversity of plants employing the same technologies leaves room for future research, as the current functional parts could be subdivided into detailed units for analysis by identifying each input and output of different machinery and processes. In addition, there is still room for further discussion about the recycling process module in detail; for example, the division of MR into two or three modules, such as crushing and shredding cleaning, which also requires further analysis of the embodied energy in each component.

This research provides a perspective on the predominance of recycling technologies for countries constructing their recycling plants in the future, taking energy consumption in the operating process into account. On the other hand, a better understanding of the relationship between energy consumption and environmental impact, coupled with an approach to attributing energy consumption to subsets of each industry, including recycling, could assist in recognizing the current recycling technology development states from an

environmental standpoint. A further approach to energy-saving technology scenarios will be a step toward a feasible future scenario for advanced recycling.

Performing case studies could fill in the gaps and discuss ways to address the various underlying causes of diverse environmental consequences. Additionally, survey-based research on the replacement ratio of virgin products and the extent of value as preparation would elucidate the advantages of high-quality recycled plastics. However, this study is limited by the lack of economic comparisons on energy prices of each recycling process; future research would benefit more from comparisons based on the economic value of the final product and energy prices, and a long-term environmental impact analysis of recycling is reserved for further discussion, especially the changes resulting from the change of electricity mix and the long-term effect on environmental impact and economic benefits.

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