

Article

Circular Economy in Poland: Profitability Analysis for Two Methods of Waste Processing in Small Municipalities

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Received: 18 July 2020; Accepted: 22 September 2020; Published: 4 October 2020



Abstract: The problem of diminishing resources on our planet is now getting due attention from the governments as well as scientists around the world. The transition from a linear economy to a circular economy (CE) is now among the top priorities. This article discusses the implementation of the circular economy paradigm in Poland through the analysis of the existing and planned mechanisms, and actions taken by the Polish government which can be replicated by other young European countries. Further, the article discusses the direction of change and projected measures planned by the Polish government to improve the quality of municipal solid waste management. In this context, profitability analysis is carried out for two methods of waste processing (incineration and torrefaction) intended for small municipalities and settlements in which district heating and trading of generated electricity are not feasible. The results of the analysis shows that torrefaction is clearly a more desirable waste processing option as a step towards the implementation of CE for civic society in the urban context, as well as profitability, in comparison to incineration. The analysis accounts for several scenarios before the lockdown caused due to the COVID-19 pandemic and after it was lifted.

Keywords: circular economy; profitability analysis; municipal solid waste processing; incineration; waste recycling; torrefaction; COVID-19

1. Introduction

The rapidly rising social awareness appeals for changes in the approach towards the use of resources in the widely understood economy and industry. Concern for the resources on our planet is undoubtedly a serious matter, as their volume continues to shrink while the demand continues to grow, due to a constantly increasing population and modernization of lifestyle. Projections by the United Nations (UN) show that the current global population stands at around 7.7 billion and that it will continue to grow to nearly 10 billion by the year 2050 [1,2]. According to the World Wide Fund For Nature [3], assuming that all people on the planet have the same lifestyle as in the European Union (EU), human beings would consume ecosystem resources intended for the whole year by May 10th [4]. The intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) document [5] discusses the highly negative impact of economic development on the environment and ecosystems. In particular, the areas occupied by cities have nearly doubled since 1992. Almost 33% of land areas and 75% of potable water resources are used for plant and animal production, while plastic pollution has increased from 4.86 (urban population 39%) billion in 1980 to 7.8 billion (urban population 56%) in 2020 [6]. This situation calls for a shift in the strategic perception

and immediate changes in the approach towards a responsible use of natural resources, including secondary resources and recycling of waste. In order for the changes to be effective, they must cover a wide range of entities and processes in various dimensions—including construction, production and technology, material, organizational, institutional, political, economic and socio-cultural aspects. This is emphasized in many scientific publications dedicated to the circular economy (CE) [7–11].

In 2015, all UN member states voted for the adoption of the 2030 Agenda for Sustainable Development, which highlights 17 Sustainable Development Goals (SDGs) and specific targets for each goal [12]. Among these 17 SDGs, Goal 12: ensure sustainable consumption and production patterns and Goal 11: make cities and human settlements inclusive, safe, resilient and sustainable, are directly related with the theme addressed in this article, whereas, Goal 7: ensure access to affordable, reliable, sustainable and modern energy for all and Goal 9: to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation, are also somewhat related to it. The idea of a CE is not new, since various solutions have already existed in the scientific and economic literature, e.g., the concept of sustainable development [13,14]. Researchers have argued that, even if well-off countries incur high spending to protect the environment, the relative effects of their actions would be rather weak [15]. The current linear model of the economy is a hindrance towards solving the problem of waste, CO₂ emission or extraction of natural resources, as it contradicts the business interests of the global economic powers. Moving together towards a CE model, which guarantees sustainability and competitiveness simultaneously, would be the most effective solution [9,15]. CE opens vast opportunities for various kinds of businesses and, increasing the material circularity within the economy, can also alleviate poverty, but systemic and disruptive changes would only take effect if significant changes to the existing regulatory structures were carried out [16].

The European Union (EU) adopted a CE Action Plan, in December 2015, to steer the existing economic development model towards a more sustainable one. This action plan mandates a continued commitment of all EU stakeholders for a transition to a more circular economy, where the value of products, materials and resources would be maintained as long as possible, and the generation of waste would be minimized [17]. In 2019, 4 years after its adoption, the action plan was finally considered to be fully complete and consists of 54 actions which have been delivered or are being implemented [18]. The 54 sections have been divided into various categories, such as: production, consumption, waste management, market for secondary raw materials, and sectoral action for plastics, food waste, critical raw materials, bio-mass and bio-based materials, innovation and investments, and monitoring. For waste management, one of the first actions was to revise the legislation enforcing the principles of the CE to the existing waste management policies. Through the directive (EU) 2018/851 of the European Parliament and the Council of 30 May 2018, the previous Directive 2008/98/EC on waste was amended [19]. Since this directive, different measures have been taken by the EU member countries and researchers have carried out various studies in this regard as well. In terms of municipal waste management, it has been found that the Central and Northern EU members are among the best performers, whereas, the worst are Eastern European countries [20]. The barriers found for waste management in Eastern as well as some Central European countries include: a focus on low-cost options, vast discrepancies of waste management performance across different regions and lack of cooperation between different layers of multi-governance in waste management [21]. Hence, it is safe to say that these countries would be more inclined to adopt a waste processing method following the CE principle, if there are higher profits or financial incentives involved as compared to the existing methods. This study, through the profitability analysis on empirical data, would recommend one such waste processing method, a vital practical implication.

As a member state of the European Union, Poland is obligated to implement and transpose all legal solutions established by the EU institutions onto the national legislation. However, not without a critical assessment. Polish postulates submitted to the European Commission in September 2015 addressed four important issues [22]: (i) support for innovative initiatives; (ii) consideration of the service sector in the CE implementation; (iii) enhanced flow of raw materials; and (iv) an

improvement of their quality by means of sustainable production and consumption. In January 2016, Poland announced its position in which it supported shifting to CE, however, under certain conditions enabling adjustment of goals to the capacity of individual member states. The formal state authority, responsible for the implementation of actions and preparation of Poland to the transformation of the Polish economy to CE is the Ministry of Development which, pursuant to the national legislation, appointed the Task Force for CE composed of the representatives of ministries involved in the economic transformation. The effect of works of the Task Force was publishing—as early as December 2016—of the draft concerning the Polish Circular Economy Roadmap. The direction of actions presented in the document is de facto compliant with the understanding of CE described above. As stated in the roadmap: “The concept of sustainable production is based, not only on the principle of increasing the resource productivity that is decreasing the volume of raw materials consumed for a unit of produced goods, but also on anticipating the reduction of negative environmental impact of the production processes, including, in particular, the context of reducing greenhouse gas emissions and volume of produced waste” [23]. This is why we focus in this article on waste management, in particular, municipal waste management.

There has been prior research on municipal waste management, and sustainable model solutions for it have also been proposed in Poland, other parts of EU and the world [20,24,25]. There has been intensive progress in Poland for waste management, however, studies in the literature do not address the cost effectiveness option, which is one of the barriers towards implementation of CE in this sector [21]. There is a lack of empirical studies which discuss the profitability of adopting CE concepts for waste processing, especially in this part of Europe. One of the reasons for this is the limited access to actual market data used by the waste management companies, which is usually guarded as a business secret. With this article, we wish to address this gap in the literature. In general, the aim of our research is to elaborate on the implementation of CE in Poland, one of the younger EU countries but also one of the largest member states, in terms of municipal waste management and to draw out the examples which could be useful for other young EU countries, especially the Visegrad four (Czech Republic, Hungary, Poland and Slovakia). Among the Visegrad four, Poland is leading the way in waste management [26,27], especially in terms of policies, and still there is scope for improvement. In particular we aim to carry out the profitability analysis, on empirical data, for two methods of waste processing, incineration and torrefaction, intended for small municipalities and settlements in Poland in which district heating and trading of generated electricity are not feasible, to show which method would be more beneficial in terms of profitability as well as CE concept.

The structure of the article is as follows. After giving a brief introduction to the article in Section 1, findings from the literature regarding municipal waste management, implementation of circular economy and actions taken by Polish government towards implementation of CE, are elaborated in Section 2. This is followed by the background of the case study and the description of data and methods used for the profitability analysis of two methods of municipal solid waste management, incineration and torrefaction, in Section 3 which include the results of the case study in Section 2. The case study accounts for the conditions that existed prior to the lock-down caused due to the COVID-19 pandemic and after the re-opening, in Poland. This is followed by the conclusions in Section 4 and lastly, Section 5 highlights the limitations of the current study and the future research horizons it opens up.

2. Circular Economy and Municipal Waste Management in Poland

2.1. Circular Economy—Actions Taken by Polish Government

Scientists, businesses and governments around the world have discussed various roadmaps towards achieving circular economy in general as well as waste management in particular [10,28–31]. Poland also drafted its own CE roadmap after a critical analysis of the prevailing conditions and the new directive by the European Commission [23]. This draft of the Polish CE Roadmap was included as one of the elements of the Strategy for Responsible Development (the official strategy of the Polish

government) and submitted for inter-ministerial and social consultations. The document consists of four parts concerning the identified economic issues (or actions): sustainable industrial production, sustainable consumption (SC), bioeconomy and new business models. There is a large interest among young EU countries, to integrate the idea of the economy in a closed system, to waste management, as a positive correlation between waste generation and recycling rates has been observed [32]. The main aim here is to minimize the amount of waste generated and to manage the resulting waste in accordance with waste hierarchy (waste prevention, preparation for re-use, recycling, other recovery, disposal). According to the implementation of the idea of the economy in a closed system, there is an obligation to collect detailed data on waste management. In Poland, the Central Statistical Office is responsible for keeping these detailed records. It prepares reports based on the “Waste Catalog”, dividing the waste into groups, subgroups and types, depending on the source of their generation [33]. The Sections 2.1.1–2.1.4 elaborate the four important actions towards CE by the Polish government and some related actions or literature from other countries, especially the Visegrad four.

2.1.1. Promotion of Life Cycle Assessment (LCA)

Implementation of control measures at each stage of the value chain and environmental impacts are not novelties in science, however, the CE perspective provided this approach with a more comprehensive method of production settlement. For example, see [34], where the authors compared the productivity in different production systems: conventional and innovative, with the use of various indicators. They presented direct, indirect and total emissions in a life cycle, recovered waste, consumption of primary resources, as well as carbon dioxide emission maps, presenting the effects for the entire supply chain. From the literature, it is evident that, an inclusion of CE principles to a sustainable supply chain management may give noticeable benefits for both, environmental protections and market volatility perspectives [34,35]. According to CE principles, product information disclosure must contain data concerning the chemical composition, decomposition and environmental impact throughout the entire life cycle. This applies both, to the cycle, understood as use period, and to all or selected elements related to acquisition of resources, transport, production process, using and withdrawal from the market [36]. Thus, the assessment covers the calculation of the volume of raw materials and energy consumers, as well as emissions into the environment. In a critical global review of LCA in municipal waste management Europe and Asia to be leading in such studies, whereas 178 countries having no published studies in this regard since 2013 [37]. In Poland LCA is a part of Environmental Protection Law, State Ecological Policies, Strategies for implementations of integrated product policy and changing production and consumption models leading to more sustainable and circular economy. LCA is also an integral part of waste management, assessment of new technologies, public procurements and eco-labeling [38,39]. Moreover LCA is also an evaluation criterion for access to public subsidies from structural funds, such as the Innovative Economy Operations Program. One of the cases for application of LCA in Poland was in the analysis of the life cycle of industrial water meters [40]. Complete information on the production of water meters, which covered factors including, e.g., supply of raw materials, transportation, production, its use and so on, were documented on balance tables for a set of quantities and, as a result, components were created. Based on these assessments, the criteria for the acceptance of industrial water meters were agreed upon. Another example is the study by [41], which compared the LCA of current and future electricity generation systems in Poland and Czech Republic. Various LCA models have been used to assess the municipal waste management in Poland which have lead to positive recommendations towards higher efficiency of waste management [39,42,43]. As compared to Poland, such assessments for municipal waste management have not been carried out in young EU countries, especially the Visegrad four [37].

2.1.2. Sustainable Consumption (SC)

Over the past several years, the European member states have formed various strategies to promote SC. Most of these strategies concentrate on improvements in technology for production and products itself and have little or no focus on the consumers' consumption practices. Nevertheless, communication with the consumers, through labels or information campaigns, to steer them towards more sustainable behaviour has been carried out to certain extent [44]. In Poland, the essence of the second action on SC, was to implement any and all activities aiming at changing the lifestyle of citizens including, primarily, the approach to widely understood consumption of tangible goods. Both the relative absence of wars, and large economic disasters in recent years, had contributed to a dynamic growth of consumption throughout Europe. Due to the COVID-19 pandemic, the subsequent lock-down and the on going after effects has brought about a change in the consumers' consumption patterns [45–47]. Scientists have raised the question whether COVID-19 would actually aid in increasing SC or due to the after effects, such as social distancing, would actually cause a negative effect on SC [48]. This remains to be seen in the coming years. Prior to the COVID-19 pandemic, the scientists studying SC reported that following the other EU Member States, Poland recorded a several percent growth in GDP in the period of 2003–2012 and, thus, a growth in consumption expenditures related to the general increase in wealth of the society [49]. However, the education level did not keep pace with consumption levels and the threats posed by this process to the natural environment. Change in the approach to consumption is neither swift nor easy, however, it can be supported by technological changes that take place globally throughout the world. For instance, Genus [50] describes the technological changes, for example: common access to the Internet, digitisation; and sociological changes, such as direct communication between the clients and fashion designers or change of attitude to “do it yourself” (DIY), which reduces mass production in favour of one's own production.

Issues, emphasized in the scientific literature, translate into political actions. This is why the communication of the European Commission clearly states that the choices made by the consumers may support CE development or impede it [17]. SC is supposed to satisfy basic human needs and, at the same time, minimize consumption of natural resources and reduce production of waste and emissions. The actions taken by Poland in this scope address the CE concept and the process itself accelerates by regulations in three core areas [22]:

- Municipal waste management by mandatory segregation into fractions (paper, plastics, glass, municipal waste)
- Disposal of so-called bulk waste to the city collection points
- Collection of used batteries in dedicated containers

Other regulations for the implementation of selective collection of hazardous waste from households, not covered by the existing collection system, are under planning. Another crucial element is the economic incentive applied by the government for the citizens to move towards CE. For instance, in the form of the My Current programme [51], the households receive reimbursement of partial costs for installation of solar cells, which promotes renewable electricity generation. The government had also lowered the excise tax for electric vehicles to 0%, encouraging the citizens to transition from conventional fuel vehicles to electric ones [52]. The government also initiated the Clean Air Program, which offers co-financing for replacing old and inefficient heat sources with solid fuel for modern heat sources that meet the highest standards, as well as carrying out accompanying thermo modernization works of the building [53]. The Clean Air program budget is set at the level of 103 billion PLN, with an implementation period until 2029. An equally important initiative, being undertaken for addressing the CE, is raising awareness and actions on food wastage. According to research performed for the Federation of Polish Food Banks in 2018, Poles waste nearly 235 kg of food per annum [54]. The change effort concentrates primarily on raising awareness on the consumer side, as building internal inhibitions for the consumer and society is the most effective long term solution.

2.1.3. Bioeconomy

EU has been leading the way when it comes to transitioning to bioeconomy, especially through the initiatives under the Horizon 2020 programme [55]. Poland on its road to implement CE, has taken several steps towards a bioeconomy, i.e., biological cycles in the economy [56]. To better understand the idea behind this term, one should differentiate between two cycles:

- The first applies to the essence of biological or natural raw material—in most cases—from which the product is made and which is a renewable resource
- The second applies to its technical aspect, including construction, functionality and technological quality, which is a non-renewable resource

Pursuant to the CE concept, both conditions must be present and have the so-called circularity value. In most cases, we can speak about bioeconomy in the context of renewable resource management options, where the resource is reusable and recoverable in the form of biomass. The agenda for bioeconomy in the Polish CE roadmap includes two aspects. The first about general actions aiming towards creating suitable conditions for the implementation and development of bioeconomy in Poland and the second about actions for specific areas such as creating local value chains for industrial sector in general and for the power sector in particular [23]. Application of bioeconomy in specific activities is reasoned in the industrial sectors with organic consumption, such as food, feed, wood and timber, cellulose and paper, pharmaceuticals, textiles, furniture, fisheries, agricultural and biofuel industries [57]. To date, biomass in Poland has been used primarily in the furniture sector as a raw material for the production of boards or energy raw material for the co-incineration process as an effective component to reduce CO₂ emissions. In terms of municipal waste management, in bioeconomy, the organic waste is considered to be a raw material which can further utilized to obtain useful output, such as value added-biofuels/chemicals from waste [58]. Both the methods of waste processing, incineration and torrefaction, analysed in this article are suitable under the bioeconomy concept.

Under the various actions taken in Poland towards development of bioeconomy, it has been recommended to develop a database assessing the potential of biomass of plant, as well as animal origin and biodegradables for the Polish economy as a whole. Assessing the economic and environmental impact in the individual sectors would be of key importance. Establishing the system for identification, reporting, statistics on individual types of biomass, along with coding and an assessment of production capacity, is also planned. This database will underpin the platform for, alongside cooperation with the industry, an establishment of bioeconomic clusters and coordinators at the inter-sectoral and supraregional level, aiding in eliminating the barriers for optimum economic development. Experts analyzing the role of the bioeconomy show its ability to expand in the total economy [59]. Reports have shown that Poland is among the top countries in Europe when it comes to bioeconomy. Among the Visegrad group, Poland is leading the way with bio based fuel, bioenergy, biomass processing and conversion, other bio industries such as biorefinery, biochemicals and biopharmaceuticals, whereas the others have made some progress in agro-food sector [60]. Nevertheless, there is still vast room for improvement for Poland for achieving a circular bioeconomy.

2.1.4. New Business Models

The fourth action, taken for implementation of the CE, was to specify the conditions for establishment of new business models. The design of the latter was based on combining the supply of value to the customer with simultaneous consideration of the so-called closing the loop concept, for example: designing of the rules for 'circular' logistics that will consider the entire flow of raw materials, semi-products and products from the producer by transport to the final consumer. While establishing the new business models, focus was on close cooperation between the producers from the same sector (which has been a standard for years) as well as in different sectors, such as cooperation at the level of raw material, technology, transport (car) sharing, sharing of production tools, premises, regeneration of used parts, human resources and comprehensive

economic symbiosis [61]. It has also been stressed in the CE roadmap of Poland that involvement of social cooperatives, associations, foundations and personnel would be utmost important for the new business models. The organizations and people have an in-depth understanding of the local communities due to which they could simultaneously contribute to economic, environmental as well as social objectives. To adapt to the new business models, incentives have also been offered as a motivation. The primary incentive included tax deductions, simplified accounting procedures, easy use of waste as a secondary raw material with various economic incentives and simplification of administrative decisions. Although actions have and are being taken, the available scientific literature emphasizes that, to accelerate the implementation of new business models, it is necessary to constantly identify them and study promising new tools and processes [62]. Case studies, such as the one in this article, give validation to adoption of new and advanced methods for businesses, which would be a step towards CE as well as prove to be more profitable.

Another important element of the road map is the extended producer responsibility (EPR), which is an important component of sustainable production [63–69]. It obliges the producer to collect and manage waste produced from the products sold by them in the market. In general, EPR results in the implementation of the polluter pays principle [70], which makes the producers consider the whole life cycle of the raw materials at the production planning stage. It also forces the producers to use solutions that would enable collection of waste and the highest possible recycling rate. In the EU legislation, the extended producer responsibility was implemented under Article 8 of the Waste Framework Directive (2008/98/EC) and incorporated by the Directive of the European Parliament and of the Council (EU) of 30 May 2018 [71]. In Poland, the EPR principle has been currently applied to packaging, end-of-life vehicles, electrical and electronic equipment, tyres, batteries and lubricating oils. While preparing the roadmap, the task force recommended to extend the currently valid provisions by imposing obligations on the producers. It was highlighted that the structure of provisions should be in a way that would encourage them to take care of the natural environment and reduce the volume of waste production, but, in such a manner as not to impede on business activity. The applicable legal solutions were planned to be implemented in a short time perspective, since Poland and the other EU Member States were obliged to deliver the goals planned at the level of the EU legislation. The planned objectives also set targets of recycling for packaging, of 65% of recycling by 2025 and 70% by 2030. The Task Force document also recommended comprehensive review of the legal acts in force, to check the extent to which they cover the product life cycle, with the EPR definition acting as a reference point and the Minister of Environment being the authority responsible for review. The review was to be supplemented with analysis of risks and benefits to the entrepreneurs. It should be emphasized here that, with regard to the objectives, Poland immediately expressed its positive attitude by considering them in the Resolution of the Council of Ministers no. 88 of 1 July 2016 [72].

Summarizing the actions taken by Polish government towards implementation of CE, detailed in Sections 2.1.1–2.1.4, the following Table 1 is presented. These steps could be replicated by the other young EU countries, especially the Visegrad four, in their efforts towards transition towards CE.

Although a number of steps are being taken in the direction of implementing CE concept in Poland, there is still a wide scope for improvement of structure implementations, especially in the municipal waste management sector [25].

Table 1. Summary of important actions taken in Poland towards implementation of CE [23].

1	Reviewing and updating of regulations in production and packaging sectors, to adapt them to the EU requirements and orient them towards implementation of CE.
2	Carrying out S.W.O.T. (Strength, Weakness, Opportunities, Threats) analysis for control and reporting of extended producer responsibility, followed by development of solutions to eliminate irregularities.
3	Running information campaign on benefit to the businesses' social image by fulfilling extended produced responsibility.
4	Adapting the methodologies developed by European Commission to develop information package for calculating the environmental impact of products and economic activities.
5	Developing recommendations to amend national regulations of municipal waste management, to adapt to CE concepts, through constant study of the effectiveness and efficiency of the existing regulations.
6	Recording all the municipal waste flows, especially the ones which have been unrecorded so far, in order to boost the recovery and recycling in the waste management sector.
7	Running social campaigns to promote sustainable consumption practices.
8	Developing government information platform on CE for citizens and businesses.
9	Building a formal and permanent team at governmental agencies responsible for individual areas of bioeconomy which would take up define the further direction for bioeconomy and supervise its implementation.
10	Review and analysis of regulations and supply potential at local and national level for biomass, preceded by building and adopting suitable methodology.
11	Carrying out comprehensive analysis of Research, Development and Innovation priorities for implementation of bioeconomy in Poland.
12	Scouting the local value chains and exploring the feasibility of establishment of bio-refineries.
13	Studying the feasibility of updating the tax system, in order to provide boost competitiveness of businesses abiding by the concept of CE.
14	Proposing legislation which would promote sharing of property, real estate and movable, especially for short term leasing of vacant passenger transport and residential spaces.
15	Proposing and updating the law of public procurement.
16	Creating a support ecosystem for businesses to enable them to transit to CE model.
17	Creating an internet platform encompassing multiple industry sectors for easy lending and sharing of products with low usage frequency.
18	Promoting introduction of CE in research programmes and curriculum at the university through an incentive system.
19	Monitoring through the "oto-GOZ" ["this-is-CE"] project (the Gospostrateg programme).

2.2. Municipal Waste Generation and Management in Poland

In 2016, Poland's industrial production amounted to 23.4%, compared to the average EU share of 17.4% [73] and Poland is being looked up to as Europe's new growth engine [74]. In 2004-2016 the average growth rate of the industrial production in Poland was 5.3% compared to 0.5% in the EU [73]. In terms of waste production, as per the data provided by Statistics Poland [75], the main sources of waste in Poland are listed below and also elaborated in Figure 1:

- Mining and extraction (nearly 48% of total produced waste)
- Industrial processing (23.8%)
- Energy production and supply (14.35%).
- Municipal waste (9.78%)
- Others (4.07%)

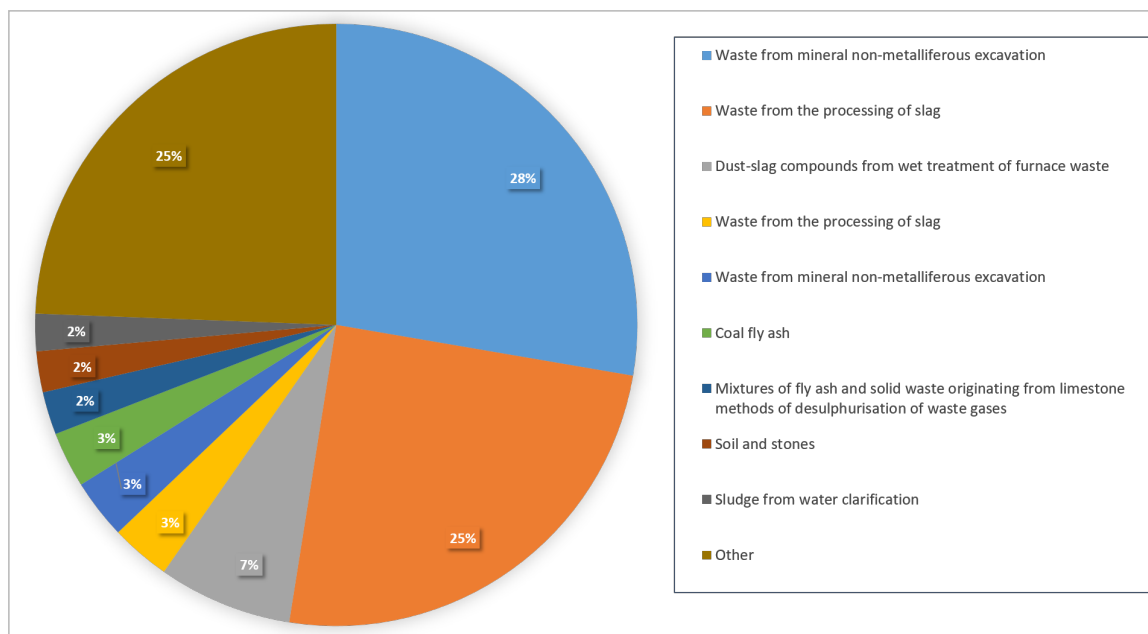


Figure 1. Structure of waste generated in Poland in 2017, by waste type and excluding municipal waste. Data source: Statistics Poland [75].

In terms of waste management, Poland faces challenges, for both industrial waste and a growing volume of municipal waste. Pursuant of the Polish Waste Act [76], municipal waste is interpreted as: “waste produced in households, excluding end-of-life vehicles, as well as waste containing no hazardous waste from the other waste producers, which, due to its nature or composition, is similar to waste produced in households; non-segregated (mixed) municipal waste remain as non-segregated (mixed) municipal waste even if processed, which did not change its properties significantly”. According to Statistics Poland data, in 2017, Poland generated 12 million tonnes of municipal waste, of which 6.8 million tonnes (57%) was recycled, 5 million (42%) for land-filling (EU target by 2035 is $\leq 10\%$ [77]), while 1% (nearly 0.2 million tonnes) was combusted without energy recovery [75]. The recycling activities included :

- recycling at the level of 3.2 million tonnes (27%)
- thermal processing with energy recovery at the level of 2.7 million tonnes (22%)
- composting at the level of 848 thousand tonnes (7%) [78]

As of 2018, Poland was the second lowest producer of municipal waste in EU (329 kg per capita), which is considerably lower than the average of EU28 (489 kg per capita) [77]. Figure 2, shows the stand of other EU member states in terms of kilogram of municipal waste generated per capita in 2005 and 2018. It can be seen that Poland has been successful in reducing its municipal waste by over 50% as compared to 2005. In the EU, only Romania recorded lower municipal waste volume as compared to Poland in 2018. There has been a steep increase in the municipal waste volume due to the COVID-19 pandemic, the affects of which has strained the waste management systems and has presented a massive challenge for the municipalities [79,80].

Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste, set forth common recycling targets, for EU member states. Recycling 85% paper, 55% plastic, 60% aluminium, 80% ferrous metal and 75% glass is expected to be achieved by 2030, as per the directive. This required a major overhaul of the waste collection systems (WCSs) as the first step, because of the need to segregate waste and divert materials to appropriate destinations for recycling [81]. In response to this, major investments have been made by the EU member states towards updating the existing WCS to meet the requirements. Poland also took the necessary steps in this direction.

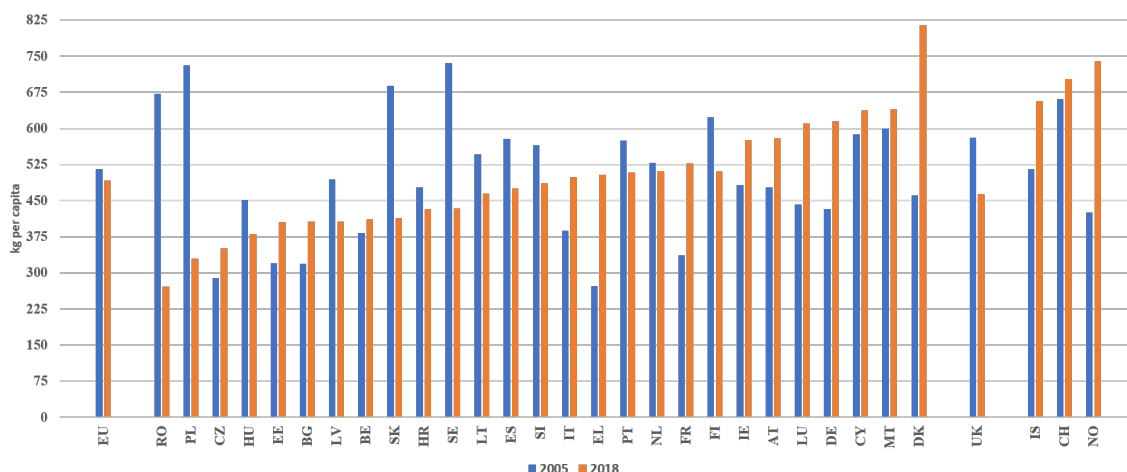


Figure 2. Municipal waste generation in the European Union (EU) 1995 and 2018 [77].

Polish municipal waste management system has seen a drastic change since the 1990s, when the responsibility of waste disposal shifted from the municipal authorities to the house owners, under the Poland's privatization program. This was governed by the Act of 13 September 1996 on maintaining cleanliness and order in communes, and was amended several times. It also completely changed the system of fees for waste management. It became the responsibility of the house owners to organize waste collection, obligatory inclusion of all municipal residents in the municipal waste collection system and imposing on them the obligation to segregate all types of waste: biodegradable (green), paper, glass, plastics and municipal waste, and then deliver them into the regional municipal waste treatment installations (RIPOKs—Regionalnej Instalacji Przetwarzania Odpadów Komunalnych) (art. 9e of the Act). Subsequently four other acts were passed: (i) the Act on maintaining cleanliness and order in municipalities (2012); (ii) the Act on waste (2012); (iii) the Act on management of packaging and packaging waste (2013); and (iv) Act of 23 January 2020 amending the act on waste and certain other acts. The responsibility of collection and disposal of municipal was again transferred to the municipalities and also brought made it obligatory for waste handlers to act in consistence with the national standards. Moreover to encourage the recovery and recycling, the fees on landfills was also hiked by imposing additional taxes [82]. This was in line with the EU's landfill directive which required all member to introduce higher taxed on landfill so as to encourage recycling [83]. A clear co-relation between higher taxes and decrease in the percentage of waste being landfill was observed and reported for the EU-28 [83], which made this a popular choice of strategy among the member states. Among the Visegrad four, apart from Poland, Czech Republic, Hungary and Slovakia have not yet made strides for implementation such strategies in their municipal waste management policies [84].

The present municipal waste management system, in Poland, is established on the basis of the National Waste Management Plan. It specifies the operation (obligations and tasks) of the entities acting as the RIPOKs. Majorly, these are self-governmental or private installations (currently approx. 200). Information on the operation of these entities are submitted to the Central Waste System, which handles all information related to waste management. To enable assessment of their operation, waste management is performed for a strictly defined area of activity (region), where the installation can collect and transport waste only within the voivodeship on which it performs the activity. It should be noted that transport of municipal (mixed) and green waste, outside the region, is currently illegal [76].

To date, the system anticipated that the RIPOKs have a sufficient capacity to accept and process waste from the area inhabited by at least 120 thousand inhabitants, meeting the requirements of the best available technique or technology [85]. Difficulties resulting from the inability to manage a significant volume of municipal waste pose a challenge related to their management under the CE paradigm. This applies to non-recyclable calorific fractions, which are fed in a form of alternative fuel to cement factories and residual waste fed to the incineration plants. These include waste fraction of

calorific value above > 6 MJ/kg, which, pursuant to the Polish legislation, are to be disposed through land-filling. In the process of adopting the shift towards CE, one of the preferable solutions was the construction of advanced waste incineration plants that have treated a vast majority of waste, along with industrial installations capable of treatment (incineration) in high temperatures or cement factories. At present, there are seven municipal waste thermal processing installations (incineration plants) operating, while construction of the other two are at the final stage: in Rzeszów to be launched in 2019 and in Gdańsk to be launched in 2021 [86,87]. Table 2, shows more details about these nine waste incineration installations in Poland.

Table 2. Municipal waste incineration installations in Poland, as of October 2019.

Site	Productivity [Thousand mg/Annum]	Power Capacity [MWe]	Production	Thermal Energy Production Capacity [MWt]
Poznań	210	15		34
Kraków	220	8		35
Bydgosz	180	9.2		27.7
Szczecin	150	13		34
Konin	94	6.75		15.4
Białystok	120	8.68		17.5
Warsaw ¹	330	20		60
Gdańsk ²	160	30		–
Rzeszów ²	100	15		7.84

¹ Undergoing modernization; ² Under construction.

Nominal capacity of the existing municipal waste incineration plants is approx. 1.3 Mt/a, i.e., megaton per annum, while incineration of fractions from municipal waste residue accounts for nearly 0.25 Mt/a and co-incineration of waste fuels, in the cement factory, is ca. 1.6 Mt/a. Considering the volume of municipal waste increasing on a year-to-year basis and including the unspecified consumption by economic migrants from Ukraine (approx. 1.2 million people [88] multiplied by the waste production per capita), demand for non-recyclable fraction treatment poses a serious problem. Poland presents a relatively restrictive approach to the emission of pollution in the process of energy carriers' incineration, regardless of whether these are fossil fuels or municipal waste of non-recyclable fraction coded 19-12-12 [89]. The Polish Ordinance on the emission standards for certain types of installation, fuel incineration sources and waste incineration or co-incineration installations follows the EU Directive 2010/75/EU on industrial emissions to the Polish legislation. Notably, the Directive describes the rules of control and monitoring of pollution emission, exploitation conditions, reporting, conditions and applications for the entities applying for the emission rights. Emission standards, compliant with the Ordinance, are presented in Table 3.

Table 3. Emission standards for installations for the thermal treatment of municipal waste.

Pollution Components	Average Daily Limits [mg/m ³]
Dust	10
Hydrogen chloride	10
Hydrogen fluoride	1
Sulphur dioxide	50
Nitrogen oxides *	200
Nitrogen oxides **	400
Carbon oxide	50
Total organic carbon	10
Heavy metals and their compounds ***	0.05

Data source: Ordinance of the Polish Minister of Environment of 1 March 2018. * For installations incinerating more than 6 mg per hour. ** For installations incinerating less than 6 mg per hour. *** Cadmium and Thallium, Mercury.

According to the data in Table 3, while maintaining the emission standards, the use of waste treatment as one of the carriers for energy and heat production, is beneficial to the Polish economy. It is estimated that incineration of 1 mg (Megagram) of municipal waste produces approx. 400 kWh of electric energy and 6.6 GJ of thermal energy. The principles of the use of waste is noticeable in the official communication of the government, indicating that the CE waste is a potential resource and should be used as a material. In this context, waste treatment (waste landfilling, incineration without energy recovery) is treated as a loss of resources and manifestation of economic ineffectiveness by resource wasting. Therefore, resource incineration, without energy production, cannot be treated as compliant with CE. However, the rule of thermal processing of waste with energy recovery only applies as a complement to the municipal waste management system, contributing to reduce their volume on landfills. The levels of reuse and recycling remain unaffected by this. About 30% of the total municipal waste undergoes thermal processing.

The National Fund for Environmental Protection and Water Management, a subordinate authority to the Ministry of Environment, initiated a consultation programme, in the form of sectoral conferences, was initiated. This resulted in a decision to use waste heat where there is infrastructure, that enabled all-year consumption of the produced thermal energy, and addressed the CE concept to form a kind of 'completion' in the municipal waste management system. The governmental agency published an announcement that it observed a growing demand of installations for handling a calorific fraction of waste at the thermal processing installations dedicated to municipal waste (with co-generation of thermal energy) [90]. The agency offers financial support to the initiatives aiming at a modernisation of local heat sources in the context of incineration of waste, under the Sustainable Waste Management programme [91], which is a positive and important step forward towards CE.

The CE roadmap [23] also further outlines the direction of actions and responsibilities of central administration authorities for their implementation. First of all, performing the capacity analysis for this area, along with preparation of the proposals for legislative amendments to increase the economical use of incineration by-products (IBPs) was considered a priority. Factors, such as determination of quality requirements (including environmental requirements) to be met by IBPs and creating the conditions for their use (including in the scope of ecodesign) were also considered in this. Such an approach is compliant with CE and may increase availability of raw materials for other economic sectors, while, at the same time, decreasing the volume of waste managed by landfilling. In addition, IBPs can be successfully used in the construction and road sector as a component for production of concrete blocks, access roads, embankments or other construction layers. The authority designated as the leading authority in the preparation of regulations for the roadmap is the Minister responsible for energy in cooperation with the Minister of Environment and the Minister responsible for construction,

spatial planning and development and housing. Supervision over the operational implementation rests upon the Inspection for Environmental Protection [23].

3. Case Study: Profitability Analysis for Two Methods of Municipal Waste Processing

3.1. Background of the Case Study

As of 2019, 38.4 million people live in Poland, producing an average of 330 kg municipal waste per year, which is 12.67 million kg of municipal waste per year in the whole country. There also should be added to these calculations 1.2 million immigrants from Ukraine who, due to their incomplete stay, generate less waste, as indicated in Table 4. The exact numbers, due to the increase in volume of waste generated due to the COVID-19 pandemic, remains to be seen.

Table 4. Volume of mixed municipal waste in Poland per annum. (Data source: Statistics Poland).

Category	Value
Number of inhabitants	38.4 million
Waste volume per capita	0.33 mg/person/a
Annual waste volume	12.67 million mg/a
Number of immigrants	1.2 million
Waste volume per capita (immigrants)	0.2 mg/person/a
Waste produced by migrants	0.24 million mg/a
Total waste volume in 2019	12.91 million mg/a

The thesis that, by far, the greatest impact on the amount of waste generated is influenced by economic factors, especially wealth of the residents, is confirmed by studies which were already carried out in 1996 and continued in the following years [92–95]. According to the experts, it can be assumed that GDP growth by 3.5 percent, will result in a 1.5% increase in municipal waste [96]. Based on the forecasts of the National Bank of Poland, projections of decrease in Poland's population according to the projection by UN as well as Statistics Poland, and together with immigrants from Ukraine [88,97] an extrapolation of the volume of municipal waste in Poland, has been prepared and shown in Table 5. Even though the number of inhabitants are projected to decrease the waste generated per capita is projected to increase. Hence, increasing the total amount of waste generated. The recent COVID-19 pandemic has also affected the municipality waste sector adversely in terms of recycling. It is not that there has just been an increase in the municipal waste volume, but there has also been a reduction in recycling during the lock-down due to COVID-19 [98].

Table 5. Trend extrapolation of the volume of municipal waste in Poland.

Year	Population (in Millions)	Increase in Waste Volume [mg/Person/a]	Annual Waste Volume [Million mg/a]
2019	38.48	0.330	12.7
2020	38.14	0.341	13.0
2021	38.09	0.365	13.9
2022	38.04	0.389	14.8
2023	37.97	0.429	16.3
2024	37.85	0.459	17.4

Considering the declining population of Poland, and the upward trend in the number of economic immigrants from Ukraine and the other countries, is clearly visible [97]. Combining this with the

increase in municipal waste due to the higher amount of time spent at home due to the pandemic and its after effect, will make the issue of municipal waste, that cannot be land-filled nor recycled, a more severe problem. In the process of implementing the CE in Poland, the actions aiming at increasing the awareness in the field of waste separation into fractions are required to be taken. In 2018, considering the upward trend in immigration, as well as municipal waste generation, representatives of Regional Municipal Waste Processing Installations (RMWPIs), dealing with waste processing, wrote a letter sent to the Minister of the Environment and pointed the requirement of actions to increase the number of professional recyclers and to use other treatment technologies, e.g., torrefaction [99].

In an interesting publication of scientists from many EU countries dealing with the problem of waste, in the context of the idea of a closed-loop economy, emphasized that the transformation of waste into energy can be one of the key elements of a CE that allows manufacturers to maintain the value of products, materials and resources on the market for as long as possible, minimizing waste and resources [21]. As we show in Table 5, municipal waste has significant volume to be managed and also has the potential to contribute towards CE, as well as generate economic benefits through the use of other waste management methods. The interest of doing so certainly exists in Poland. The current focus of the Polish municipal waste management sector is towards increasing the capacity of municipal waste processing through incineration plants [86,87,100]. Incineration is one step further towards CE but still lacks the ability to fully address the CE concept. During incineration of municipal waste, energy is recovered but there is residue in form of sewage sludge (SSA). Ordinance of the Polish Minister of the Environment of May 11, 2015 on the recovery of waste outside installations and equipment, allows for the recovery of the mineral fraction from the SSA. Recently, research was conducted into the possibilities of using ash from SSA produced in incineration plants as a secondary source of phosphorus (P), which resulted from European Union (EU) legislation that indicated that phosphorus is a critical raw material (CRM) [101]. This residue can be used to prepare eco-friendly cement [102]. However, these methods require additional processes and setup for recovering usable material from the residue. This issue can be over by implying torrefaction process instead of incineration. Studies have shown the torrefaction of mixed municipal waster would yield energy and usable fertilizer or fuel [103,104]. Torrefaction is also referred to as roasting i.e., the process of thermal and chemical processing of organic compounds in specific thermal conditions. In most cases, the literature provides the following parameters: temperature of 200–300 C, heating rate on the inside of the reactor <50 °C/min, input dwell time in the reactor 15–60 min, no oxygen, atmospheric pressure, the effect of which is the production of biocarbon [105,106]. Additionally, this technology is more economically advantageous for companies dealing with waste management in smaller towns.

By 31/01/2020, the Ministry of Climate (because it took over the “waste portfolio” as part of the division of competences between the Ministry of the Environment and the newly created Ministry of Climate in the Government of Poland) had started to update (on a national scale) the list of enterprises appearing in the Provincial Waste Management Plans (WPGO—Wojewódzkich Planów Gospodarki Odpadami). Thus, new companies, which have already started to work on building new incinerators, will appear in the list of WPGO, but the possibilities of applying for new incinerators will not be available. It results from the power of art. 35 b of the Waste Act, added by the Act of 19 July 2019, amending the Act on maintaining cleanliness and order in municipalities and amending certain other acts (Journal of Laws of 2019, item 1579). It reads: thermal treatment of waste will be allowed only in installations specified in the regulation issued by the Minister of Climate. Pursuant to Article 35 b para. 3 of the aforementioned Act, if the installation intended for the thermal transformation of municipal waste or waste from the treatment of municipal waste was not included in the list, i.e., new building permits, integrated permits or permits for processing waste in this installation, shall be refused. Considering that the investment process itself from the preparation of technical documentation to construction lasts on average of 3–4 years, it can be assumed that these installations will not be built anytime soon. Moreover, due to the COVID-19 pandemic further delays have taken place. The pandemic influenced the decision of the government administration, namely the Ministry

of the Environment, responsible for issuing administrative decisions regarding the construction of incineration plants in Poland. In accordance with the Polish law, incineration plants can be built only after entering them into the National Waste Management Plan, and then placing them in the Provincial Waste Management Plan (Article 186 of the Act—Environmental Protection Law; i.e., Journal of Laws of 2018, item 799), that clearly states that an investment that is not in accordance with WPGO cannot be implemented. Construction of new incineration plants was suspended due to COVID-19, and the local municipalities from Kraków, Tarnów, Zamość and Żywiec, Rybnik, and Wrocław lodged complaints against the decision and are making efforts to overturn it. So far, the Ministry of the Environment has not supported the construction of new installations, emphasizing that this is contrary to EU policy. The construction of new installations would increase the possibility of collecting waste by another 500 to 700 thousand tons, depending on the financial capabilities of investors.

Through empirical evidences from the Polish municipal waste management market, this study compares the profitability of two methods of municipal waste management, incineration, and torrefaction. The time of implementation from the approval to the first operation, cost of implementation, cost of waste processing, revenue from waste processing as well as revenue from the sale of byproduct has been taken into account for the analysis. The conclusions drawn from this analysis would add to the gap found in the literature regarding the empirical analysis of these two methods of waste processing. They would also serve as a recommendation for the policy makers and business investors in the field of municipal waste management regarding the choice between the implementation of incineration or torrefaction from the CE and profitability perspective

3.2. Material and Methods

In the Polish waste collection market, the local governments are responsible in accordance with the law of waste management (Act of 13 September 1996 on maintaining cleanliness and order in municipalities), to organize tenders for waste collection. The RIPOKs, which have the possibility to manage and sort individual waste fractions, place their bid on these tenders. The price from the auction is transferred to contracts concluded for one or two years of waste collection from the Commune. These companies analyze the possibilities of utilizing the oversize fraction through mechanical-biological processes or combustion in existing installations of this type. These companies, RIPOKs, do not have complicated methodologies supported by complex mathematical formulas or models, rather they rely more on their managers' updated market knowledge and their experts. Forecasting of the estimated costs and revenue are also not based on advanced models, such as machine learning based approach or multivariate time series, due to the small number of data points (one for each year and 10 in total, without a uniform time interval). Hence the estimates used by these companies, for contesting the tenders, rely more on the market awareness of the managers. The empirical data used for analysis in this study were collected by one of the authors, as the Director of Sales Department at EkoPartner Lubin (one of the RMWPIs in Poland). Following is the description of the the collected data and the steps followed in making the calculations used for the profitability analysis in this study. Such data and steps are followed by most of the RMWPIs in Poland to make their estimates for the tenders they bid for, hence gives an indepth empirical overview in-terms of profitability analysis:

1. **Data:** Information on the amount of municipal waste generated in Poland is collected daily by an employee of the company from Public Information Bulletins obligatory published on the website of municipal offices, from tender proceedings notices, or from auctions conducted through tender platforms (login trade, allegro, olx, market planet). The data are entered into the databases broken down into semi-annual, annual and two-year contracts.
2. **Data Analysis:** Based on the collected information, employees conduct price analyzes in relation to:
 - the size of the commune

- the amount of waste
 - distances to specific locations of municipal waste plants
 - the possibility of collection by individual locations—applies to both formal and legal integrated permit defined by volume in tonnes/month as well as real possibilities of mechanical and biological processing
 - transport costs
 - fixed and variable costs of own (internal) plants
3. **Based on the expert assessment of these data**, scenarios and variants of price forecasts for offer prices from each commune are generated separately.
 4. **Assessment of competition:** Price variants are collided with data on competitors, namely:
 - prices offered in tenders for a specific municipality and similar in size
 - the possibilities that competing companies have in terms of collection, storage and storage
 - having own transport
 - human potential (number of brigades/shift)
 - economic and financial potential (a single plant or enterprise belonging to Remondis or Tonsmeier networks).
 5. **Final offer evaluation:** Employees prepare final variants of the offer on the basis of their own options and the potential of competition together with the assessment of contract profitability for each commune separately, and then the Management Board of the company decides on the final price or price negotiable at auctions.

Based on the empirical data obtained directly from EkoPartner Lublin, six scenarios (A to F) were built. These scenarios show the forecasts for the amounts of municipal waste in the years 2020–2025 preceded by actual data from 2007 onwards. Initially only three scenarios (A, B and C) based on the amount of waste were forecasted, but due to the impact of COVID-19, revenues from the collection of the oversize fraction increased. There were several overlapping reasons for this increase. The first concerned the presence of a significant number of people at home by switching to home office or being in quarantine, and because of closing schools, colleges and some enterprises (hairdressers, cosmetics, cinemas, theaters, gyms, swimming pools, etc.). Increased consumption turned out to be a natural state, and this proportionally translated into waste production. According to the data from four municipal plants (located in Lower Silesia, Upper Silesia and in central Poland), the average amount of waste collected by these companies, especially municipal waste, i.e., the oversize fraction, increased by 5000 tons per month, i.e., by over 30%. Secondly, the collection price for municipal waste increased by 20%, reaching an average ceiling of PLN 1,000/tonne. This is the effect of both the increase in the amount of waste, but also the problems of many existing municipal waste collection facilities not only limited by limiting the capacity and mechanical and biological treatment of waste, but also from staffing problems—corona viruses and the inability to return some employees from Ukraine, who in some enterprises accounted for up to 60% of employees. Hence, additional three scenarios (D, E and F) which took into account the effects of the pandemic were also taken into consideration.

For Scenario A, the forecasts are based on: the possibility of utilization with the use of existing, as well as, under-construction incineration plants and cement plants; price paths determined by the author based on bilateral public tenders, in which the author participated and the contracts that were concluded by the company. The existing installations, along with the investments in progress—by 2025—will enable for treatment of 14.4 million tonnes of waste, which creates a market gap of nearly 4 million tonnes. Prices of waste, from the oversize fraction up to 2020, come from contracts concluded by the company, and, beyond 2020, are the company's projection. The market value is calculated as: $(\text{Annual waste volume} - \text{Total Capacity}) \times \text{Price}$, while 'Total Capacity' is the sum of Incineration plant capacities, Cement factories, Fraction 0-80 and Raw materials. It is to be noted here that this analysis does not take into account the cost for collection of the municipal waste. These costs are covered in

the fees for garbage collection from the residents, hence are not taken into account in the profitability analysis for the torrefying installation. The same principle applies to the receipt of biochar, which is the result of a process at the installation. It is companies interested in biochar that collect raw material from RIPOK with their own transport. Hence for RIPOK both of these costs do not apply. In scenario B, we assume that more incineration plants will be built from 2023, and their utilization capacity will be 2 million tonnes every year, and, in Scenario C, we assume that more incineration plants will arrive, and the utilization capacity will be 2.5 million tonnes from 2023. Scenarios D, E and F are in the same conditions as A, B and C respectively after the effect of real market conditions which arose due to the COVID-19 pandemic.

3.3. Results of the Case Study

Table 6 shows the calculations for various waste management options for scenario A, and the market value of the resulting overload fraction of the waste. The amount of waste (overload fraction) that is to be managed has been decreasing steadily since 2007. This is primarily because of the government's initiative to reduce the production of municipal waste. It can be seen, based on the projections, that in the years to come this overload fraction would start to increase again if additional capacity is not added.

Table 6. Waste management options and market value.

Year	Annual Waste Volume ¹	Incineration Plant Capacities ¹	Cement Factories ¹	Fraction 0–80 ¹	Raw Materials ¹	Total ¹	Price ²	Amount of Waste to be Managed ¹	Market Value ³
2007	10.67	0.06	1.4	0.0	1.1	1.82	90	8.7	787
2010	10.04	0.06	1.4	0.0	1.6	2.37	100	7.7	768
2012	9.58	0.06	1.4	3.2	1.6	5.58	110	4.0	440
2013	9.47	0.06	1.4	3.2	1.7	5.62	140	3.9	539
2014	10.33	0.06	1.4	5.2	2.0	7.89	140	2.4	342
2015	10.86	0.34	1.4	5.4	2.2	8.64	150	2.2	333
2016	11.68	1.2	1.4	5.8	2.3	10.08	170	1.6	273
2017	11.97	1.2	1.4	6.0	2.4	10.28	180	1.7	304
2018	12.50	1.2	1.4	6.3	2.5	10.65	250	1.9	463
2019	12.7	1.2	1.4	6.3	2.5	10.3	450	1.9	856
2020	13	1.2	1.4	6.5	2.6	10.5	500	2.0	998
2021	13.9	1.2	1.4	6.9	2.8	11.1	525	2.1	1079
2022	14.8	1.6	1.5	7.4	3	11.9	525	2.1	1101
2023	16.3	1.6	1.5	8.1	3.3	12.9	550	2.5	1391
2024	17.4	1.6	1.6	8.7	3.5	13.8	550	2.8	1552
2025	18.3	1.8	1.6	9.1	3.7	14.4	575	3.0	1715

¹ In [million mg/a], ² In [PLN/mg], ³In [million PLN].

Considering the five other scenarios, B to F, Figure 3, shows the graph with market values of the overload fraction, in all six scenarios A to F. Projections on the effects of the pandemic clearly show that the overload fraction of the municipal waste is bound to increase and its market value would be even higher. This simply indicates a need for swift action for increasing the processing capacity.

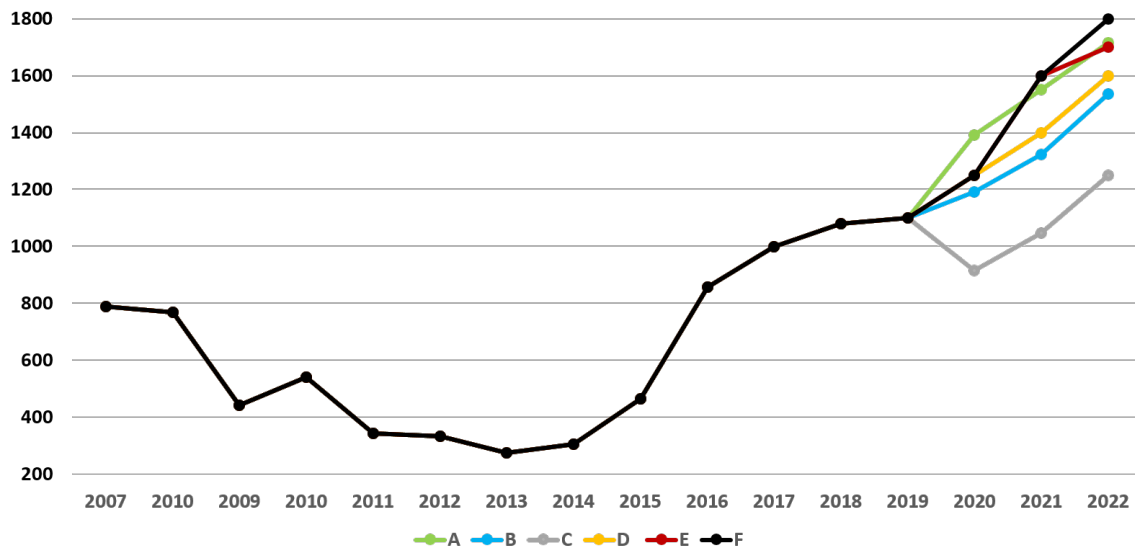


Figure 3. Market values (in million PLN) of the overload fraction to be developed.

Torrefaction and incineration plants have a lot of difference when it comes to implementation time, cost of establishment and waste processing, by products produced and maintenance. Table 7, shows the comparison between various elements for setting up incineration and torrefaction plants for a typical small region in Poland—a pivot with 30,000 tonnes of waste generated on average.

Table 7. Comparison of incineration vs. torrefaction installations.

Characteristic	Incineration	Torrefaction
Implementation timeline	5 years	3 years
Implementation cost	120 million PLN	22 million PLN
Waste processing cost	PLN 350/mg	PLN 110/mg
Generated product	Heat	Fuel
Requirements	Continuous monitoring	No requirements

Data source: EkoPartner.

It can be seen that torrefaction plants are clearly more advantageous as compared to incineration plants. Setting up a torrefaction plant is more than 5 times cheaper as compared to incineration plants, takes 40% less time for implementation, produces the byproduct of fuel and has no additional requirements like continuous monitoring. Moreover, The processing of waste through torrefaction is over 3 times cheaper than incineration, which results in higher profits. Figure 4, shows the comparison between the revenues, costs and profits for processing waste incineration and torrefaction, pre and post the COVID-19 pandemic for processing 30,000 Megagram per annum municipal waste.

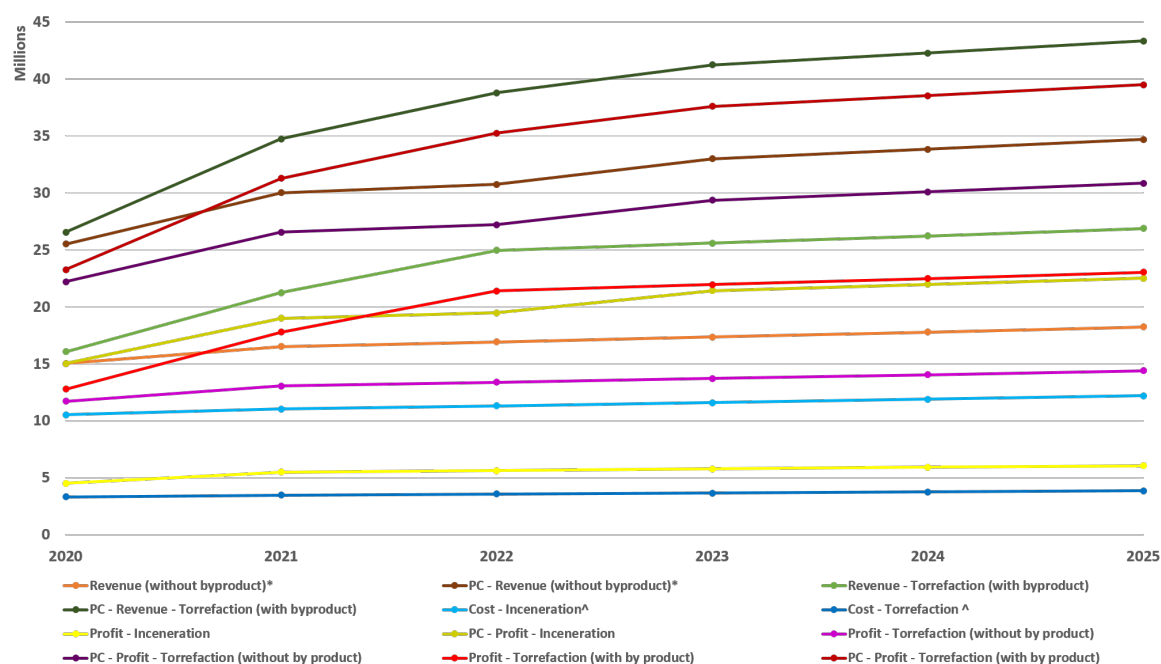


Figure 4. Comparison of revenue, cost and profit for incineration and torrefaction processes of waste processing in Polish municipalities from 2020 to 2025, for 30,000 mg/a municipal waste (data source: EkoPartner). * The revenue from waste collection is the same for both torrefaction and incineration, [^] Cost of processing the was remained same before and after the pandemic, (PC)—Post COVID-19 pandemic.

As shown in Figure 4, the revenues for both, torrefaction and incineration, are the same (shown by the “Revenue (without byproduct)*” line in the graph). The torrefaction process yields biochar as a byproduct, which is a fuel and can be sold directly for additional revenue without any further processing. When the additional revenue from selling the biochar is not considered, the corresponding profits for both the processes are shown by the lines “Profit-Incineration” and “Profit-Torrefaction (without byproduct)” in the graph. Even in this condition (without considering the revenues from byproduct sales), the profit for torrefaction process is higher than that for incineration. If the revenues from the sale of biochar is considered, the revenues and, consequently, the profits, rise (as shown by the lines “Revenue-Torrefaction (with byproduct)” and “Profit-Torrefaction (with byproduct)” respectively). In fact, the projected profits from 2021 onwards for the torrefaction process were even higher than the projected revenues when the sale of byproduct is not considered. This means that only the sale of biochar itself is more than enough for covering the costs of processing the waste. Due to the COVID-19 pandemic the revenue for waste processing increased dramatically, hence increasing the profits of these installations, the effects of which are also shown in the Figure 4. These results show that torrefaction is far more profitable as compared to incineration.

4. Conclusions

The growing environmental challenges and diminishing resources has led countries around the world to take action in moving towards a CE. The concept gains new followers in the world of science, as well as in business and amongst policy-makers. National and regional legislation have been established to facilitate the movement from a linear economy to a CE. COVID-19 pandemic has caused concerns for economies around the world and put severe strain on the resources as the world went under lockdown. Poland, one of the youngest EU countries, had been steadily putting efforts for transitioning towards CE. The Polish roadmap for a CE has introduced new and important elements, such as EPR, which would increase the recycling rates and also waste management. Primarily, the Polish government has taken action towards promoting life cycle assessment, SC, bioeconomy and new business models. It remains to be seen, how these policies are taken forward in the post

pandemic era, nevertheless, among the Visegrad four, Poland's actions (summarized in Table 1) can be considered as an example for forming strategies for moving towards CE.

Waste management is one of the challenges face by Poland, both for the industrial waste and the municipal waste. In terms of municipal waste, Poland was able to curtail the volume of municipal waste generate by over 50% as of 2018 in comparison to 1995 and was able to achieve 57% recycling rate in 2017. On the other hand there is still over 42% waste which is being land-filled and 1% combusted without energy recovery, which is against the principle of CE. As per the current capacity of the incineration plants with energy recovery, a little less than 50% of the recycled waste can be processed with thermal recovery and there is a large amount of overload waste fraction. Even before considering the effect of the COVID-19 pandemic, empirical projections showed that this overload waste fraction will grow further, because current incineration plants which are functioning of the ones which would be setup by 2025 shall not be able to cope with the growing municipal waste volume. More so as the people stayed home during the lock-down, caused by COVID-19 and the prevailing work from home policy of a number of organization post the lockdown. RIPOKs in Poland are estimating even higher municipal waste volume from 2021 onwards, which will add further to the overload waste fraction.

As of October 2019, there were six fully functioning municipality incineration installations, one of which is undergoing modernization and two are under construction. Installations of new incineration plants in Poland have to undergo a very length process. The recent amendments and changes at the ministerial level in the Polish government, had complicated things further. Furthermore, the effect of COVID-19 pandemic has delayed the implementation of the new plants which were approved as well as halted the approval process of new projects for such installations. It remains to be seen when the processing of new installations opens up again. Based on the empirical data taken from the actual implemented contracts and the ongoing contract (provided by EkoPartner, one of the RMWPIs in Poland), by 2025, the current incinerators were expected to have a capacity of processing about 14.4 million tonnes of waste, which would have created a market gap of about 4 million tonnes. Due to he prevailing condition this would be a difficult target to meet now, as the implementation period of setting up an incinerator is estimated at 5 years. Hence, any new incinerators (even if approved in 2020 despite the current hold off) could only begin functioning by 2025 and the delay in implementation of already approved projects would create a larger market gap. Torrefaction plants have a shorter implementation period of 3 years, which would prove to be an effective solution in this scenario. If, approved by 2021, these plants can be in service by 2024, and reduce the stress of the overload waste fraction.

The results of the comparison of the profitability analysis of torrefaction and incineration for municipal waste treatment, in this study, further warrants choice of torrefaction. Torrefaction has lower costs of implementation (120 million PLN for incineration as compared to 22 million for torrefaction), which means that five torrefaction plants can be implemented in the cost of 110 million PLN, 10 million PLN less than the cost of one incineration plant. Additionally, they would be ready 2 years earlier. Once implemented, torrefaction would also be more profitable in terms of waste processing, as shown in Figure 4, because of its low operating cost (one third of the cost of incineration). This would also be a strong step towards CE, as the byproduct (biochar—a fuel) does not require any further processing and can be re-introduced in the economy. Considering the revenue obtained from sale of biochar, the profits soar even higher. In fact, the revenue generated from the sale of byproduct would be more than enough to cover the cost for processing the waste from the 2nd year, onwards. This would lead to lower cost of waste processing for municipalities and the saved costs could be diverted towards implementation of more incineration plants. For Poland, it is even more profitable because of the high amount of coal being used in the production of electricity. Biochar is a suitable fuel for the production of electricity, hence it would not just add to the revenues, but also help in reducing emissions, reducing the amount of coal being used and thus leading to decrease in mining. Benefiting from all aspects that required to be added in CE. This fills the gap found in the literature for concert empirical evidence,

to concluded that torrefaction is more suitable and profitable option in a CE, as a waste processing option in for processing municipal waste as compared to incineration.

Currently, Poland has not implemented any torrefaction plants on a large scale basis for processing municipal waste. In the current circumstance, post COVID-19 pandemic, governments around the world are striving to strengthen the economies again, using new technologies, systems and solutions. This would also be a conducive time and opportunity for Poland as well as other young EU countries, to consider implementation torrefaction as an effective solution to solve their municipal waste management challenge.

5. Limitations and Future Scope of Research

This study has limitations that point to future works and research avenues. The profitability analysis carried out in this study was based on empirical data from EkoPartner, one of the RMWPIs in Poland. It would be interesting to carry out a study with data from all RWMPs in Poland. Similar studies can also be carried out in other countries and compared with the current study. It would also be interesting to study the profitability of the torrefaction process, where it has already been implemented, and compare it with the analysis in this study. The preliminary effect of COVID-19 has been accounted for in this study, but it would be interesting to see, in the coming years, on how the CE is implemented and municipality waste management system evolves, in Poland as well as around the world

Author Contributions: P.Z. conceived and designed the research; Y.C. reviewed the research design; P.Z. and Y.C. reviewed the literature; P.Z. gathered the data for the case study, P.Z. and Y.C. carried out the case analysis; P.Z. and Y.C. drafted and edited the paper; P.Z. and Y.C. reviewed the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Science and Higher Education (MNiSW, Poland) core funding for statutory R&D activities.

Acknowledgments: The authors are grateful to Prof. Rafał Weron for comments on an earlier version of the manuscript and to EkoPartner company for providing the data. The authors would also like to acknowledge the reviewers for their constructive remarks, which has greatly help in improving the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UN	United Nations
EU	European Union
IBPES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
CE	Circular Economy
SDGs	Sustainable Development Goals
CBP	Incineration By-products
EPR	Extended Producer Responsibility
RMWPIs	Regional Municipal Waste Processing Installations

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