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The Opportunities in Chemical Recycling of Tires in Egypt

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Abstract

This research outlines the opportunities of recycling tire waste chemically in Egypt. This will be done by identifying the waste to energy technologies that are most feasible to deal with tires. A deeper study will be made for a chosen waste to energy technology, namely pyrolysis. It will be examined to identify what are the governing process parameters, the different reactors and the products that can be expected from this process. Then the products will be studied to see how can they help in achieving an Egyptian circular economy. After which a brief LCA was done to know the amount of emissions to expect. The study also conducted an economic feasibility test which showed a return on investments of 54%. Lastly, the policies governing waste management in Egypt were identified as well as the challenges Egypt is facing. Then the highlights and recommendation for chemical recycling of tires in Egypt were explained.

Key words: chemical recycling, pyrolysis, gasification, circular economy, waste to energy technologies, LCA, economic.

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ELT	End-of-Life Tires
IFC	International Finance Cooperation
CE	Circular Economy
LCA	Life Cycle Analysis
CAPMAS	Central Agency for Public Mobilization and Statistics
W2E	Waste to Energy
CB	Carbon black
rCB	Recovered carbon black
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrogen oxide
O_3	Ozone
OPEC	Organization of Petroleum Exporting Countries
EIA	Energy Information Administration
EIU	Economist Intelligence Unit
WMRA	Waste Management Regulatory Authority
ROI	Return on investment
EGP	Egyptian pounds
MSEA	Ministry of State for Environmental Affairs
EEAA	Egyptian Environmental Affairs Agency
CBA	Cleansing and Beautification Authorities
SWM	Solid waste management
MSWM	Municipal solid waste management
WML	Waste management law

1. Introduction

1.1. Background

Two very significant issues have risen in the past decades due to population increase, urbanization and economic growth, as well as customer buying patterns. The first of set issues, is the health and environmental concerns, while the second is the depletion of non-renewable raw materials without finding an alternative. A common cause of these two problems is the poor waste management, as waste generation has risen massively across the world in recent decades, and there are no signs of slowing down. As Statistics show that by 2050, urban solid waste production in the world is projected to rise by about 70% to 3.4 billion metric tons (Kaza, S et al., 2018; Tiseo, I. ,2020; Qureshi, M., et al.,2020). These threats are considered globally, however in developing countries such as Egypt, poor solid waste management, i.e. free and unregulated waste disposal are prevalent. That makes developing countries suffer more compared to developed countries (ElSaid, S., & Aghezzaf, E. H., 2020). In Egypt, the amount of solid waste generated in 2015 was 21 million tones (Sweepnet, 2014) and increased to around 22 million in 2017 (Taleb, M. A., & Al Farooque, O. ,2021). Waste in general is considered to be a cause of these problems as some of these wastes such as tires are made using non-renewable materials and can cause environmental problems if managed in the wrong way. On the other hand, tires are essential for transportation, their annual production accounts for 1.5 billion units (Yaqoob, etal., 2021;Yasar, et al., 2021), this huge production of tires has resulted in annual waste tire generation (about 300 million tons) (Li, D, et al. 2021). While in Egypt a study done by the International Finance Cooperation (IFC, 2016), reported the generation of scrap tires being about 315 thousand tons. This estimation was calculated by using the amount of licensed vehicles in Egypt and the average lifetime of tires (IFC, 2016). Hence solutions to improve the waste tire management can be focused on reusing the materials that are within the scrap tires, this directly calls for Circular Economy[1] (CE) deployment. Reusing/recycling operations of tires can be done by mechanical and chemical recycling as it will be discussed further on. The main type of recycling that will be discussed and analyzed in this research is the chemical recycling, which enables extracting the useful materials from the waste that could be used to generate energy and be used in other applications. Some of the benefits of the chemical recycling of tires scraps are associated to the recovery of materials such as oil and carbon black which could be reused again after a few refinements.

Under this context, the focus of my research will be the chemical recycling of waste tires in Egypt, in particular this research will analyze the opportunities in extracting the useful materials from tires scraps through chemical recycling. The chemical recycling was chosen over the mechanical recycling because chemical recycling (pyrolysis and gasification processes) enable the breakdown of polymers to their constituent monomers in a way that they can be used again in chemical

[1] Circular economy is the economic system which aims to eliminate waste by gradually decoupling growth from finite resources (Ellen MacArthur Foundation, 2020).

processes (Dogu, O et al.,2021). With the purpose to analyze the chemical recycling from its environmental and economic feasibility in the Egyptian context, those aspects make part of this research and lastly the effectiveness of policies and regulations in Egypt were also analyzed, and if there is room for improvements on the regulatory framework, recommendations were done.

1.2. Problem statement

Egypt currently faces a major problem when it comes to solid waste management, as numbers show only around 12% of the solid waste is recycled (Taleb, M. A., & Al Farooque, O. ,2021; Bain, D. 2020), while around 88% percent are sent to landfills. In the capital and largest city, Cairo, solid waste generation is more than 15,000 metric tons/day (ElSaid, S., & Aghezzaf, E. H., 2020), of these wastes. And the topic of this research, waste tires, represent a high environmental risk when they are only disposed of in landfills. This is because the life span of the tire wastes is in average between 80 and 100 years, their thermostat polymer structure that neither melts nor distributes into its chemical constituents (Yasar, et al., 2021). Moreover, in Cairo only 22% of used tire are being mechanically recycled (Farrag, 2016). Thus around 80% of the scrap tires are left unprocessed, which can lead to many environmental impacts as well as human health problems when managed in the wrong way, this is mainly due to the hazardous substances that are within, as when dumping them in landfills this affects the quality of the soil and any water resources that are nearby (Yasar, et al., 2021; Turer, A., 2012). Even further, a cause of these low rates of recycling can be explained by the lack an effective legislative framework when dealing with waste tires or solid waste in general (Bain, D. ,2020).

1.3. Research Objective

The main purpose of this study is to investigate the opportunities in extracting the useful materials from used tires by chemical recycling in Egypt, this in line with CE principles. Along with the main objective there are other sub-objectives which complement the main one, such as: (i) to identify opportunities to reduce the consumption of virgin fossil fuels in the energy generation while decreasing the amount of compiled wastes; (ii) to identify what are the environmental impacts of chemical recycling using Life Cycle Analysis (LCA) method ; (iii) to assess the economic feasibility of chemical recycling of tires, and; (iv) to check the effectiveness of policies and regulation of waste tires and give further recommendations on how they can promote chemical recycling as a method to manage waste tires in Egypt.

1.4. Outline of this study

This study will first look into what tires are made of, what consequence can be expected if mismanaged and how they can contribute to CE. Then a research plan was made so that there is a plan of action which identifies the type of information needed to fulfill the study and how to obtain them. This will be done by identifying the waste-to-energy technologies that are currently being used and how they could contribute in achieving a full CE for the tire life cycle in Egypt. Moreover, a brief LCA was done to pinpoint the expected environmental impact from using these technologies. Furthermore, an economic feasibility study was done to ensure that investors would be interest in financing such projects. Last but not least, the policies in Egypt were assessed to identify the challenges and explain how the waste management system in Egypt operates, followed by the conclusion of this study and the recommendations for future research within this area.

2. Literature review

In this section the existing research works about important concepts and frameworks related to the chemical recycling of used tires are presented. This section starts with a description of the composition of tires, followed by studies explaining the process to recycle tires and how those processes can be in line with the circular economy principles. This latter and the waste to energy technologies frameworks that are currently applicable for tires are also introduced in this section. Lastly the situation in Egypt is explained and its regulatory framework.

2.1. Background information about tires

Tires are crucial for vehicle mobility as well as vehicle safety, as they serve a variety of purposes: carry the weight of the automobile, shifting the load to the surface; provide brake and acceleration grip between the vehicle and the road and function as vibration absorbers, improving road comfort and protection as well as the vehicle's overall performance (The International Market Analysis Research and Consulting Group - IMARC Group, 2020). In general, it can be said that a tire is composed of a number of materials, including many rubber components, each of which has a distinct and precise function. Natural and synthetic rubbers are used in tire casings since high durability is required, whereas synthetic rubbers are used in tire tread materials to provide tire grip (Araujo-Morera, J., et al., 2021). Chemicals function as antioxidants, curatives, and processing aids, carbon black and silica serve as reinforcing agents, while the stability and stiffness of the tires are provided by cords made of textile, fiberglass, and steel wire. According to the International Rubber Study Group approximately 14.8 million tons of rubber were used up in 2019 all over the world, with 60% being dedicated to the production of tires and it should be added that each tire produced consumes on average between 23.5 and 141 L of oil (Wu,Q.,et al., 2021). Tires can be mainly divided into two types: passenger/light weight vehicles tire and truck tires. And as it can be seen in Figure 1 (World Business Council For Sustainable Development - WBCSD, 2018), around 75% of the tire consists of components that belong to the rubber compound which includes thee rubber, fillers and chemicals. Even further, the raw material composition in weight ratio varies based on the tire type, this can be attributed to the ratio of materials chosen which is based on the desired mechanical and physical properties of the tires. This holds also for other constituent materials. A diverse range of desired properties to cope with the weight requirements from heavy trucks to light vehicles have a direct effect on the materials composition of the tires. (Araujo-Morera, J., et al., 2021)

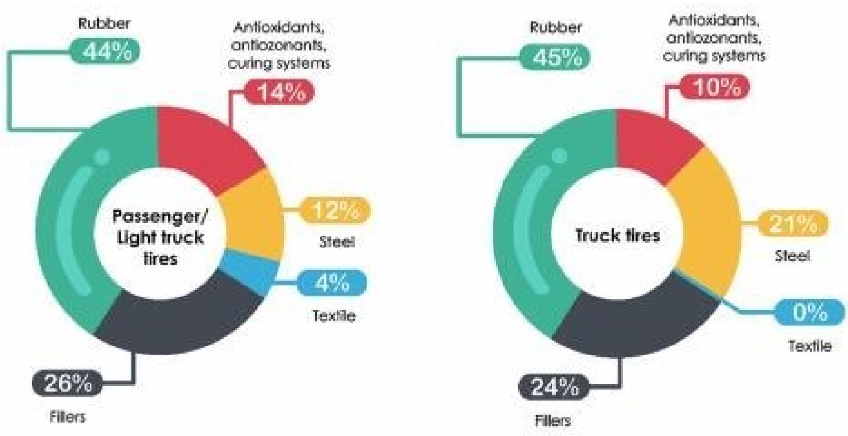

Figure 1: Different tires compositions(World Business Council For Sustainable Development - WBCSD, 2018)

Global population growth, accelerated urbanization, and rising customer purchasing power have all led to rising to the rising demand of tire production, as can be seen in figure 2 it was estimated by Araujo-Morera, J., et al. (2021) that around 17.1 million tons of tires were globally produced in 2018. Such a worldwide industry produces a substantial annual demand for tire replacement, resulting in a large volume of end-of-life tires (ELT). ELT are tires that can no longer achieve their original function and are typically discarded by cars and trucks. ELT recovery systems can be classified into three groups: material recovery, energy recovery, civil engineering and backfilling, all of which contribute to the industry efforts to build a circular economy (Araujo-Morera, J., et al., 2021). This concept is further defined and described in the following section.

Figure 2:Global waste tire in 2018 Araujo Morera, J., et al., 2021)

2.2. Circular economy

Ever since the industrial revolution a linear economy model has been deployed, a model that world widely follows ‘‘extract-manufacture-consume-dispose” paths to produce and consume products and services. Some of the tangible consequences of the linear model is the high generation of urban solid waste globally which was approximately 1,300 million tons per year in 2010 and is expected to grow to 2.200 million tons by 2025. (Araujo-Morera, J., et al., 2021). These circumstances made the circular economy (CE) model a promising way to cope with the linear economy challenges, as it advocates for replacing the disposal phase with restorative processes that allow the resources to be reused, repaired, restored and recycled. Based on the restorative principles, the value of the materials included in the products can be prolonged on a continuous basis (Ellen MacArthur Foundation, 2020). The CE model initially consisted of the ‘’3Rs’’ (Reduce, Reuse and Recycle), however the model has been modified to now include ‘’7Rs’’ as Redesign, Renew, Repair and recover have been added to widen the CE approach as illustrated in Figure 3 (Reike et al., 2018).

Figure 3:7Rs of circular economy (Reike et al., 2018)

In relation to the tires, the CE model is becoming more prominent, according to Araujo-Morera, et al. (2021) the reasons for that vary from easing the opening of new markets in the sustainable market, through pure survival in an increasingly challenging environmental legal context, till the genuine belief of businesses who are more mindful of the need to mitigate their environmental effects. In order to cover all those reasons, it should be noted that this thesis will cover the recycling and recovery of parts of the tires as they are the most relevant to the nature of this research, this however does not mean that recycling and recovery of ELT are the best preferred options as according to the waste hierarchy they come after prevention, minimization and reusing (Rossella R., 2020), but due to the substantial amount generated and their essential use prevention and minimization are difficult to manage. Recycling and recovery of ELT provides possibilities for handling raw material shortages and encouraging resource efficiency, as well as closing resource loops, as this will help reach the CE objectives (Antoniou, N., & Zabaniotou, A.

(2018). The future benefits of the chemical recycling process involve not only the ability to extract the organic fraction from the feedstock and improve energy generation, but also the recovery of many useful substances included in the raw material that can be used as energy sources or be used as new inputs for other applications as will be elaborated later in the research. Therefore, energy and material recovery from ELTs contributes significantly to the circular economy because it produces not only energy commodities, but also value-added goods that can be used in a variety of applications (Martínez, J. D. (2021).

2.2.1. End-of-Life Tires (ELT) management

Other than dumping and landfilling, ELT can be mainly re-used in three different ways: (i) mechanical recycling to shredded parts; (ii) to be used without mechanically or chemically interfering with the tires as shown in Figure 4 (Araujo-Morera, J., et al., 2021); (iii) chemical recycling and incineration. This latter is not described in this study because it is the least preferred option due to the environmental problems that it causes.

Figure 4: ways to reuse waste tires (Araujo-Morera, J., et al., 2021)

Mechanical recycling is considered to be the most common and preferred type of recycling, this is partly because it has cost advantages compared to chemical recycling, (Bucknall, D. G. 2020). Also when ELT are shredded they can be used in a variety of civil engineering applications due to its mechanical properties. But as mentioned in the introduction, among the different possibilities to recover and/or maintain the value of the tires components, this study is focused on the chemical recycling because of their energy generation potential. In the following section, waste to energy is introduced to frame the ELT potential of energy recovery as part of the chemical recycling process.

2.3. Waste to energy technology

In this subsection the different waste to energy technologies that are applicable to waste tires will be explained.

Incineration is mainly about burning the scrap tires in an oven to generate electricity, while it also helps in minimizing the volume of the waste by 85-95% and a mass reduction of around 60-70%(Ruwona, W., et al.,2019), this allows recover of energy. However, it raises many environmental concerns as tires contain around 17 heavy metals. Additionally, tires are produced from natural rubber trees in combination with synthetic rubber which is made from petrochemical feedstock, carbon black, extender oils, steel wire, other petrochemicals and chlorine (Turer, A., 2012). Regarding the chemical recycling. it revolves around breaking the long polymers chains into monomers or to other chemicals, this technique can be classified into two main types: pyrolysis and gasification (Banu, J, 2020). The pyrolysis process is a thermo-chemical decomposition process in which organic matter is converted into solid and stable carbon-rich material by heating in the absence of oxygen which allows the long polymer chains to be degraded into smaller ones (Fithri, N., & Fitriani, E. ,2020). In the case of gasification, this is a process in which the waste tires are indirectly combusted to fuel or synthetic gas by partial oxidation in the presence of oxidants.

According to previous literature, pyrolysis is considered as an efficient way to recycle the tires, it has been one of the most used technologies because it can separate the tire contents by thermo-chemical decomposition. (Turer, A., 2012; Xu, J., et al., 2020). Before the pyrolysis process starts, tires undergo throughout a pretreatment first, so that tires become first cleaned, then the steel that was once used in its making is then removed by using specific machinery and the tire is shredded into smaller pieces that can be fed to the pyrolysis process. (Battista, M., et al. ,2020)

During the pyrolysis process 3 main different outputs are derived: pyrolytic gas, pyrolysis oils and char. I will further discuss them later on, but it should be noted that the pyrolysis process yields can vary depending on many experimental parameters, these parameters are: temperature, residence time, operating pressure, selection of catalyst mixing conditions, granular size, heating rate. From that list, the most important parameters are the temperature, heating rate and selection of catalyst (Mikáczó, V., et al.,2017). As when the temperature and heating rates are higher it will be observed that the volatile products yield will increase and the reaction time is short. Moreover, the addition of catalyst will also decrease the reaction time and the energy used as it decreases the activation energy needed, and will favor the pyrolytic gas yields (Mikáczó, V., et al.,2017)

After pyrolysis there are mainly 3 yield products as mentioned earlier.

Char, also known as carbon black, which gives the strength to the tires to withstand heavy bumps, it is produced from the incomplete combustion of fossil fuels. After the pyrolysis process, char needs extra treatment so that it can be transformed to activated carbons, and be reused again instead of using virgin carbon black (Ruwona, W., et al.,2019).

Pyrolytic gas makes up around 10-30wt% of the tire and has a calorific value of 30-40MJ N/m^3, which makes it useable to run pilot plants. The dominant gases are methane and carbon oxides, which have the potential to be used as fuels (Ruwona, W., et al.,2019).

Pyrolytic oil is the oil obtained which potentially can replace fossil fuels, with its high calorific value of 37-44MJ/kg compared to 28MJ/kg of bituminous coal and 46MJ/kg of diesel. The oil obtained is similar in characteristics to oil number 6, which is currently the lowest grade of oil. However, it can still be used as a liquid fuel for various applications such as industrial boilers, furnaces and power plants. It could also be treated chemically and be further refined to improve its quality (Ruwona, W., et al.,2019).

In Figure 5 the pyrolysis process is clearly illustrated.

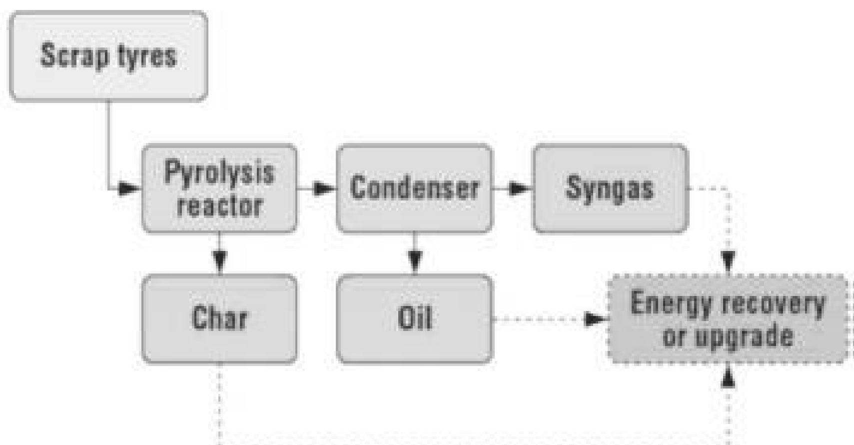

Figure 5:Process of tire recycling using pyrolysis (Ruwona, W., et al.,2019).

Gasification is a thermochemical method that is mostly used to transform carbonaceous material i.e. tires into syngas, and other hydrocarbons such as methane. Gasification is a type of pyrolysis that occurs at higher temperatures ,600–1000 ◦C, and in a specific partially oxidative reactive environment (air, steam, oxygen, carbon dioxide, etc.) which optimize the gas production (Oboirien, B. O., & North, B. C. (2017).

As explained by Labaki, M., & Jeguirim, M. (2016) a gasification system is typically made up of three components: a gasifier unit, a gas cleaning system, and an energy recovery system. Moreover, the gasification process is more complicated than pyrolysis since the former is a heterogeneous process in which chemical reactions occur over the surface of the substance from the gasification agent which make tire particle parameters like surface area, surface accessibility, carbon active sites, added inorganic matter, and the gasification agent composition have a role in the conversion rate of the tire. While the main parameters can affect the process outputs are the air equivalence ratio which is the ratio between the fuel and the air (Salaudeen, S, et al., 2019), pressure and temperature (Labaki, M., & Jeguirim, M. (2016). There are two main steps in the gasification of tiresty, which are the primary and secondary breakdown reactions: i) the primary decomposition reaction causes the degradation of tires into heavy and light hydrocarbons (organic chemical compounds that are only composed of hydrogen and carbon) as well as solid char; ii) while secondary reactions include heavy hydrocarbon cracking, light and heavy hydrocarbon reforming, and gasification of the solid char material in order to maximize the gas production (Rowhani, A., & Rainey, T. ,2016). The gas produced is also called synthesis gas or syngas or producer gas; which has a high calorific value. The product gas is a potential resource for electrical energy production by using a fuel cell, gas turbine, or gas engine (Labaki, M., & Jeguirim, M., 2016)

Table 1:Comparison between pyrolysis and gasification (Compilation from Nkosi, N., et al., 2021; Muzenda, E. 2014; Zhang, Y., et al., 2019); Fithri, N., & Fitriani, E. ,2020)

Process	Pyrolysis	Gasification
Process definition	The pyrolysis process is a thermochemical decomposition process in which organic matter is converted into solid and stable carbon-rich material by heating in the absence of oxygen which allows the long polymer chains to be degraded into smaller ones.	Gasification is a thermochemical process that produces syngas (also known as producer gas, product gas, synthetic gas, or synthesis gas) from the interactions between the fuel and the gasification agent.
Reactant gas	None	Air, pure oxygen, oxygen enriched air, steam
Process pressure	Slightly above atmospheric pressure	Atmospheric
Process temperature	400–800 ◦C	600–1000 ◦C
Produced gases	CO, CH_4, H_2, and other hydrocarbons.	CO, CO_2, CH_4, N_2O
Produced liquid	Oil of similar properties to diesel. It contains a high aromatic content, which makes it feasible as an industrial chemical feedstock.	Small amount of oil and, a condensable fraction of tar and soot is generated.
Produced solid	Small amounts of bottom ash and char.	Char with a high carbon content.

Pyrolysis and gasification are developing thermal treatments that occur under less severe circumstances than traditional direct combustion. Not only the gaseous fractions of pyrolysis and gasification may be utilized as a source of energy, but the liquid and solid fractions could also be valorized by burning or used as precursors to chemical synthesis or as raw materials. (Labaki, M., & Jeguirim, M. 2016).

In an analysis made by Mavukwana, A., et al. (2021), a comparison between the two methods was done, the study focused on carbon efficiency and chemical potential efficiency. This comparison examined how much carbon in the tire is moved to usable goods and how much energy content in the tire is transmitted to the product, indicating the possible environmental effect of each procedure. It was shown that both methods are suitable for removing hazardous waste and transforming it into usable items. However, the pyrolysis process outperformed the gasification method in terms of thermodynamic efficiency, with a greater total carbon efficiency and chemical potential efficiency as gasification losses around 45% of the carbon feed to carbon dioxide, while in pyrolysis the char produced sustains the carbon, which imply that the pyrolysis approach conserves carbon and has a low environmental effect. Moreover, the pyrolysis process is easier to construct and operate, as the gasification process is more complex and it needs more energy because of the high temperatures reached and requires a carbon capture system installation because of the high carbon dioxide levels that are emitted (Rekhaye, A., & Jeetah, P. 2017). Never the less, the quality of products obtained from pyrolysis are lower in quality and need few refinements when compared to the gasification process, as the syngas produced by the latter can be directly utilized after production. As a result of the higher purity of syngas, the revenue per ton of waste tire is higher in the gasification process, which makes it have a better economic feasibility (Labaki, M., & Jeguirim, M. 2016) ;(Mavukwana, A., et al. 2021).

In an interview with Mr Balan Ramani, a PHD student in recycling of tires in University of Twente, he stated that pyrolysis is considered more favorable than gasification as it enables the recovery of more materials and can help more in achieving a circular economy. And according to several authors (Rowhani, A., & Rainey, T. 2016); (Kommineni, R., et al., 2017) pyrolysis is considered a better way to manage waste tires, however after conducting this research it was shown that each process outperforms the other in different areas, as gasification produces higher quality gas and has higher revenue per waste ton of tires, while pyrolysis is more environmentally friendly and is easier to construct and maintain. Another aspect is that pyrolysis offers three different products while gasification is more focused on the gaseous production. All in all, both processes are viable to manage waste tires, and there is no clear superior, hence it was decided that the scope of this research centers only on pyrolysis and that further studies should be made on gasification.

2.4. The tires situation in Egypt

There is no special program for wasted tires collection in Egypt, this waste is collected with the municipal solid wastes. Nevertheless, waste tires are classified as hazardous waste under the Egyptian Law No.4 of 1994 (4/1994). As such, their management is subject of strict disposal and/or compliance of related recycling laws set by the Ministry of State for Environment and the Ministry of Industry and Trade (Sweepnet, 2014). Currently, the majority of waste tires are recirculated by informal markets. When leftover waste tires are not retreaded and resold for vehicular use, they are partly burnt to remove steel wires, and the resulting material is used in the manufacture of intermediate and final materials. This procedure entails the unchecked burning of gathered tires in open fields, which has a detrimental effect on the environment (IFC,2016). At present, only corporations, public and commercial agencies are subject to enforce the hazardous waste law, while persons managing unregulated tire mining operations in the informal sector face no regulatory implications for openly burning tires to collect steel at the lowest possible expense (IFC, 2016).

Currently in Egypt, there are three major sources of waste tires: garbage collectors, governments/private companies and major tire companies. The garbage collectors that acquire them from disposal tire shops, and then they sell it to individuals. According to an interview done by the IFC this is considered the most important source, accounting for approximately 22% of total annual quantities. The source of this stream mainly corresponds to abandoned tires from privately owned cars and trucks, which are disposed of in open dumps by tire workshops and then retrieved by tire scavengers. The price of these collected tires is very low as compared to the expense of collecting, transferring, and delivering used tires to end customers. The second set of supplier is the government or the private companies that own a big fleet of vehicles, as the Egyptian Ministries of Interior, Transportation, Industry, and Defense own a considerable amount of vehicles that generate high quantities of waste tires which can be sold at annual auctions. While that last supplier is the expired and used tires sold by major tire companies.

Presently in Egypt waste tires are sold by auctions or direct spot sales mostly to companies that make factory floor mats, tire bags, shoe heels, and companies that remove and recycle tire steel wires, and the imports of waste tires is prohibited by the law. An existing problem also in Egypt is that officially there is no official statistics regarding the amount of generated scrap tires. Nevertheless, the number of tires can be roughly estimated. Some of those estimations are reported by IFC, in their report the data gathered from the Central Agency for Public Mobilization and Statistics (CAPMAS) is disclosed. The total number of licensed vehicles in Egypt in December 2014 was around 6.8 million, by using the average lifetime of tires, it is possible to extrapolate those numbers from which an approximate annual projection of the generation of waste tire can be derived. See the estimations in Figure 6 (IFC,2016).

Type of Vehicle	Number of Vehicles in 2014	Number of Tires	Average Lifetime (years)	Expected Generation in 2015 (tons)
Passenger Cars	3,743,120	4	3	32,440
Buses	120,941	6 10	2	26,317
Trucks	965,149	6 10	2	210,016
Truck Attachments	68,700	12 16	2	21,723
Government	73,532	4	3	637
	49,022	6 10	1	16,001
Motorcycles	1,772,333	2	2	7,089
Tractors	16,984	2	3	1,132
Tricycles (Toctocs)	51,213	3	2	192
Total	6,860,994			315,548

Figure 6: Projection of waste tire in Egypt (IFC,2016)

As in figure 6, in the year 2015 the estimated generation was expected to be around 315,000 tons and it was expected to grow by 10% each year. The latest available figures are up to 2018 which according to CAPMAS (2018), the number of operating vehicles was around 7.5 million, which shows about 10% increase in the number of vehicles. Another estimate was done by the Egypt National Cleaner Production Center by using data gathered from the Ministry of Industry and the Egyptian Customs Authority. This study was about the usage of retreaded tires in different sectors, this estimate showed that around 209,000 tons of scrap tires was generated in 2014.

These two estimates are not considered accurate as they are not even close to each other, but at least they provide some grounds to conclude on the existence of substantial amount of scrap tires that is generated on a yearly basis in Egypt. However, it should be noted that not all the available waste tires are collected in Egypt, as the current annual scrap tire is Egypt is estimated to be around 60,000 tons yearly, from which only 11% are used directly, re-treaded and remolded and sold as a lower quality new tire as shown in Figure 7(IFC,2016). While around 50% are recycled and processed; as in addition to exporting shredded and powdered tires, crumb and ground rubber, recycled powder from inner tubes and nylon cord of tires, rubber producers use scrap tires to produce fine grind mesh crumb rubber, which is used in the manufacture of a wide range of goods as can be seen in figure 7.

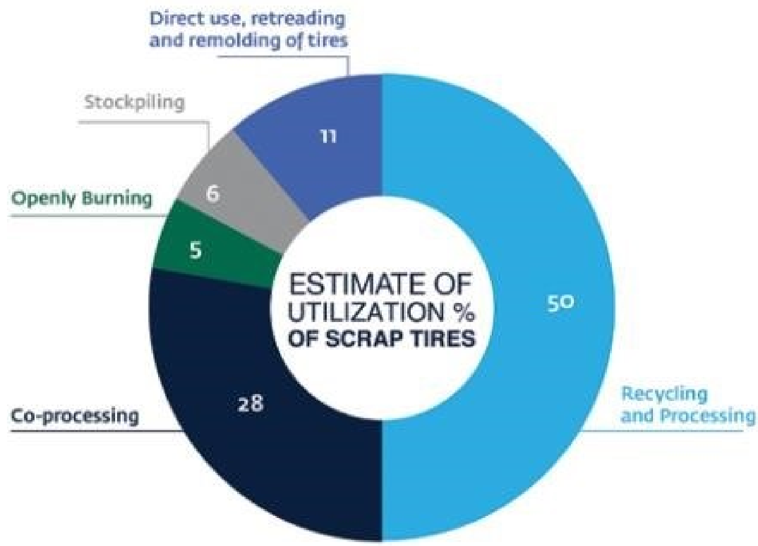

Figure 7:Utilization of retrieved scrap tires in Egypt (IFC, 2016)

2.5. Highlights for the analytical framework

After this preliminary literature revision, here are some elements to be taken to further develop the analytical framework of the research in hand. It has been identified that the main technique being used in chemical recycling is the thermal cracking process such pyrolysis and gasification. The pyrolysis technology which enables the transformation of tires to products that can generate energy or be used in other appliances is understood, and in the continuation of the research gasification also will be studied. Also it is now prominent that thermal cracking processes can generate oil and other energy dense products, but a deeper analysis should be made on the feasibility of using such products, this means looking into the refinement process that they have to undergo to be usable. The environmental impacts of pyrolysis and gasification can be studied by using LCA method. Lastly, an analysis will be made on the policies and regulations in Egypt, to identify the challenges that is currently being faced when dealing waste tires.

3. Research design

This chapter describes the step-by-step approach that will be done to answer the research question and sub questions which are presented in section 3.2. There are formulated in line with the main research objective introduced in section 1.3.

3.1. Research framework

In order to achieve the research objective a clear approach was followed for efficient performance during the research period based on (Verschuren & Doorewaard, 2010). This is done by giving a schematic overview of the research objective, by taking the appropriate steps that are vital to achieve it as mentioned by Verschuren & Doorewaard. The seven step that were used to build the research framework are as follows:

Step 1: Characterizing the objective of the research project

The objectives of this research are:

- Identify opportunities in extraction of the useful materials from waste tires through chemical recycling.
- Analyze how chemical recycling of tires affects the environment, the amount of compiled waste and the usage of virgin fossil fuels in Egypt.
- Analyze the economic feasibility of recycling the tires chemically in Egypt.
- Draw conclusions on how effective policies and regulations and how they can further promote chemical recycling of tires in Egypt.

Step 2: Determining the research object

The research objective is to identify the opportunities of using chemical recycling to restore the useful materials from waste tires in Egypt, such a process will be also examined from an economic and environmental point of view to see if it is feasible and how it affects the environment. Lastly this research aims at identifying the policies and regulations and how they can promote such a method to manage waste tires.

Step 3: Establishing the nature of research perspective

This research will highlight the opportunity of using chemical recycling as waste management method when dealing with scrap tires in Egypt. Chemical recycling is considered one of the Waste to Energy (W2E) technologies as some of the materials extracted from the waste tires can be used as energy source directly or after a few refinements. The W2E technologies will be further elaborated, after which only one technology will be chosen from pyrolysis and gasification. The selection of one of the technology will be based on its potential to recover more useful materials (CE principles), and higher applicability potential in the Egyptian context. After identifying the most feasible technology the outcome products will be further analyzed to see how can they play a role in achieving a circular economy when it comes to waste tires management. Afterwards, the environmental effects of the chosen technology will be assessed, this will be done using LCA approach. Followed by an economic feasibility test, this will be done by firstly doing a Business Model Canvas for the chosen technology to highlight who are the important actors and what this technology has to offer to the economy. Then to check the financial viability of chemical recycling in Egypt, two methods will be used, the input-output model and the return on investment model. As last, the effectiveness of policies and regulations of waste tire management will be analyzed and recommendations on how they can promote the usage of chemical recycling in Egypt will be elaborated. After identifying these key points, a recommendation will be made where all the opportunities and drawbacks are highlighted. It should be noted that this research is a holistic explorative research, thus the brief LCA studies and the economic feasibility test will not be made in depth due to the time constraint of the research period.

Theoretical framework of this research is developed by reviewing scientific literature as well as studying existing documentation. Theories to be used in this research are:

Step 4: Determining the sources of the research perspective

Table 2: Key concepts and theories

Key Concepts	Theories and documentation
Best available technologies Economic feasibility Environmental Impacts	Circular economy theory Waste to energy technologies theory LCA methodology

Step 5: Making a schematic presentation of the research framework

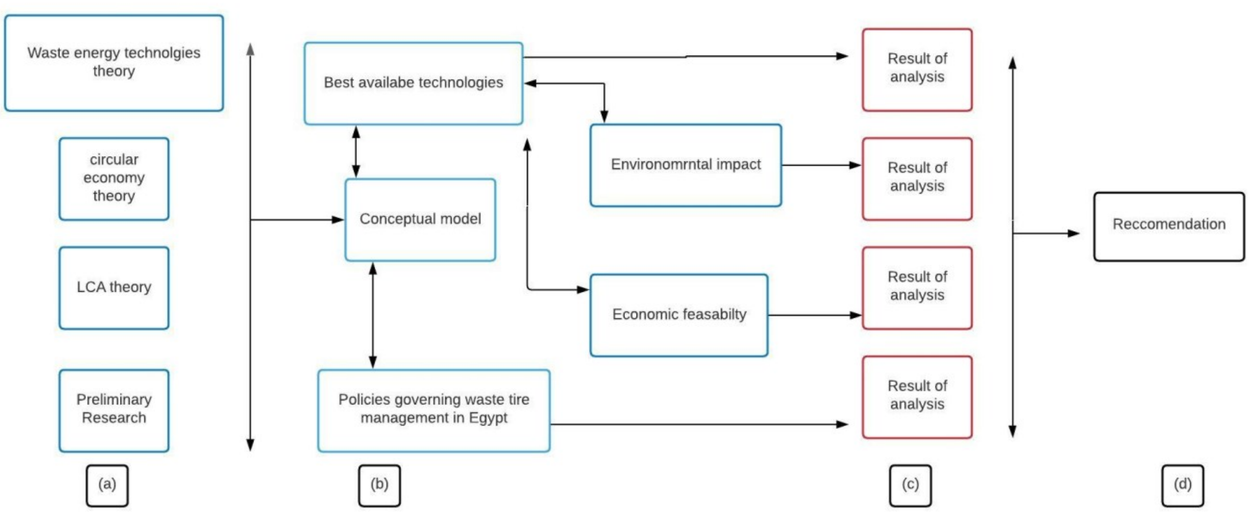

Figure 8:Schematic diagram for the research framework

Step 6: Formulating the research framework in the form of arguments

a) Literature review of the waste to energy technologies, their outcomes and how they can help in achieving a circular economy, and asses the environmental impacts using LCA approach.

b) Using the data, the research objectives will be assessed.

c) Confronting the result of analysis as the basis for recommendation.

d) Highlighting the opportunities and recommendations regarding chemical recycling of waste tires in Egypt.

Step 7: Checking whether the model requires any change

Since this research is an iterative process, hence as more data is collected about the research objects, changes could be made to the framework.

3.2. Research questions

Main question

- What are the opportunities in chemical recycling of tires in Egypt?

Sub questions

- What are the best available waste to energy technologies when dealing with waste tires, and what is are the extracted products from these processes?
- What is the economic feasibility of chemical recycling in Egypt?
- What is the environmental impacts of using chemical recycling to manage waste tires?
- What are the policies governing the waste tires in Egypt and what are their challenges?

3.3. Definitions of Key Concepts

Circular economy: is the economic system which aims to eliminate waste by gradually decoupling growth from finite resources.

Chemical recycling: is a process that converts polymeric waste to produce materials that can be used again as raw materials for the production of new products.

Pyrolysis: is a thermo-chemical decomposition process in which organic matter is converted into solid and stable carbon-rich material by heating in the absence of oxygen.

Gasification: is a process the waste plastics are indirectly combusted to fuel or synthetic gas by partial oxidation in the presence of oxidants.

Waste tire: tires that can no longer achieve their original function and are typically discarded by cars and trucks and will be used as a feed to the chemical recycling process.

Carbon black: also known as carbon black, which gives the strength to the tires to withstand heavy bumps, it is produced from the incomplete combustion of fossil fuels, and is one of the pyrolysis products.

Pyrolytic oil: the oil derived from the pyrolysis process.

Syngas: the gas derived from the pyrolysis process.

3.4. Research Strategy

A mixed research strategy was used, because the nature of the sub questions differs among them. A desk research was done to answer the first and last sub question, this was done through systematic literature review. Semi structured questions were used during interviews with specialist in the tire field, and employees from the Environmental ministry in Egypt to further discuss the technologies that are currently being used and to elaborate more on the role of policies and regulations. Moreover, a feasibility test was made for the second question to check whether such a project is economically viable.

3.4.1. Research Unit

The number of units chosen is only one, waste tires in Egypt. The research unit was limited to that one so that the researcher can have full focus on the chemical recycling of waste. As this unit was analyzed economically and environmentally when being managed chemically, as well as the role of policies governing waste tire disposal in Egypt.

3.4.2. Research Boundary

As mentioned due to the time constraint only waste tires were studied. So the research boundary that was made to make sure that research has attainable goals is as follows:

- The material chosen is waste tires.
- The study will look at waste to energy technologies that are used in similar developing countries.
- The geographic boundary of this research will be Egypt.

- The economic feasibility and LCA were analyzed for one technology.

3.5. Research Material

The data and information needed to answer each research sub-question was collected via several methods that include reviewing academic papers, documents, and semi structured interviews.

3.5.1. Data and information required

Table 3: Data and information required

Sub- research questions	Data
What are the best available waste to energy technologies when dealing with waste tires, and what is are the extracted products from these processes?	The technologies being used to chemically recycle tires. The outcome products of the process
What is the economic feasibility of generate energy from such wastes?	Economic data: Fixed cost (operating labor, machines, maintenance, land cost) Electricity and utilities cost The obtained products selling price The waste tire price Taxation in Egypt Customs for Importing machinery in Egypt The stakeholders
What is the environmental impacts of using chemical recycling to manage waste tires?	The inputs for the whole process. The emissions from pre-treatment such was steel removal and tire shredding. The energy consumption in the process and its emissions. The emission of the extracted gas that is used to reheat the process.
What are the policies governing the waste tires in Egypt and what are their challenges?	A review of the current policies and regulations governing the waste management.

3.5.2. Source and Method of Data Collection

Table 4: Source and method of data collection

Sub- research questions	Sources of Data	Accessing Data
What are the best available waste to energy technologies when dealing with waste tires, and what are the extracted products from these processes?	Secondary Data: Publicly available documents, articles, and reports and people that work in the plastic and tires industry Semi-structured questionnaires to be used during interviews	Content Analysis Search method Interviews
What is the economic feasibility of generate energy from such wastes?	Secondary data from the internet	Feasibility analysis
What is the environmental impacts of using chemical recycling to manage waste tires?	Secondary Data: Publicly available documents, articles, and reports Internet	Content Analysis Search method
What are the policies governing the waste tires in Egypt and what are their challenges?	Secondary Data: mainly governmental documents and policies Semi-structured questionnaires to be used during interviews	Content analysis Interviews

3.6. Data Analysis

3.6.1. Method of analyzing data

Both qualitative and quantitative data analysis methods will be applied in this research, this will depend on the data as for example; the economic data concerning the fixed costs, waste costs, etc. will be analyzed quantitatively. While the products of the process and the best available technologies will be analyzed qualitatively. The detailed method of analysis is as shown in the table below.

Table 5:Method of analysing data

Data	Method of analysis
What are the best available waste to energy technologies when dealing with waste tires, and what are the extracted products from these processes?	Qualitative: comparison of the different techniques used Qualitative: the outcome products of the process
What is the economic feasibility of generate energy from such wastes?	Quantitative: all the data gathered will be used to construct the input-output model and the return on investment model Qualitative: identifying all the stakeholders and further analyzing them
What is the environmental impacts of using chemical recycling to manage waste tires?	Quantitative: the emission data of the process will be gathered and compared with the emissions that arise when using normal disposal method. Qualitative: the reusability of some of the outcome products to reheat the process
What are the policies governing the waste tires in Egypt and what are their challenges?	Qualitative: analyzing the current governance system when it comes to dealing with waste tires

3.6.2. Validation of Data Analysis

Any data gathered for this research was validated by looking into multiple sources to ensure that the data is valid. Moreover, semi structured interviews were carried out with experts from the waste recycling industry to ensure that the data gathered is accurate, also interviews were done with government officials to ensure that the policies and regulations found online are up to date.

3.7. Ethical statement

This research followed and respected the guidelines of the academic ethical standards stated by University of Twente. The research also ensured that the analysis done had a straightforward, truthful, and autonomous mindset in the writing process. In this thesis semi-structured interviews were made with experts to find missing gaps, and before conducting any of the interviews an informed consent form was used to safeguard the rights of the interviewee, moreover the after the interview is finished a detailed script was sent to the interviewee to check if any data was misinterpreted and any data gathered from the interviews was stored in a safe location to ensure privacy for both the responses and the respondents. Also snow balling technique was used to get in contact with professionals that could add information to the research. Last but not least APA referencing style was used throughout the writing process to give credit and to respect the intellectual property of the researchers.

4. Findings

In this chapter the waste to energy technology, pyrolysis was furthered examined to know the different type of reactors and process parameters, also the products obtained from the process were studied and how they can contribute to an Egyptian CE. Then a brief LCA was performed to know an estimate of the amount of emissions that can be expected. Afterwards an economic feasibility test took place, and lastly the polices in Egypt regarding waste were examined.

4.1. W2E technologies

In the literature review the two most applied technologies to transform tire W2E were presented, i.e. gasification and pyrolysis. After that, a comparison was made which showed that each process outperforms the other in different criteria. However, due to the limitation of the research scope and time limitation, only one pyrolysis was further analyzed in this section. It was investigated in order to determine the most significant factors regulating thermochemical reactions that occur in certain types of reactors, which will also be presented. A deeper study on the outcome products and how can they be utilized to help in achieving a circular economy is also included in this section.

4.1.1. Pyrolysis

The process can be controlled by variety of conditions that could be made into numerous classification, however the process can be mainly divided into slow and fast pyrolysis as was explained by Czajczyńska, D., et al. (2017).

4.1.1.1. Slow pyrolysis

This type of pyrolysis, as the name suggests, considers a slow pyrolytic decomposition, it is typically employed in fixed bed reactors, where waste tires are degraded at low temperatures (Rowhani, A., & Rainey, T. 2016). Slow pyrolysis, is defined by its low heating rate and lengthy residence time, which stimulates secondary reactions that increase the char and gas output (Martínez, J. D., et al ,2013). In contrast to fast pyrolysis, the goal of slow pyrolysis is char formation, however tar and gases are sometimes produced but not always recovered. (Martínez, J. D., et al ,2013)

4.1.1.2. Fast pyrolysis

Fast pyrolysis, in contrast to slow pyrolysis, indicates a quick thermal degradation characterized by faster heating rates. According to Martnez, J. D., et al (2013), the goal is to produce fast decomposition and a short residence period, which favors the production of liquid oil. This method often necessitates a smaller tire particle feedstock and equipment with specialized designs to allow for the removal of rapidly produced vapors.

4.1.2. Reactors

The outputs and characteristics of the produced products are affected by a number of factors, including raw material properties, reactor design with the most commonly used pyrolysis reactors being fixed-bed, rotary kiln, and fluidized-bed (Alsaleh, A., & Sattler, M. L. (2014). It should be noted that there is also a variety of different reactors that can be used and other operating conditions that can influence the output products, nonetheless due to the scope of this research only a limited type of reactors and process condition will be discussed.

4.1.2.1. Fixed bed reactor

Fixed bed reactors, which are relatively simple in design and operation, are the most commonly utilized in waste tire pyrolysis, particularly in laboratory and bench-scale units (Lewandowski, W. M., et al., 2019). Nonetheless, due to the fixed bed reactor's poor heat transfer rate, challenges in continuous operation, and scale-up, there is minimal commercial interest in full-scale applications (T. Dick, D., et al., 2020).

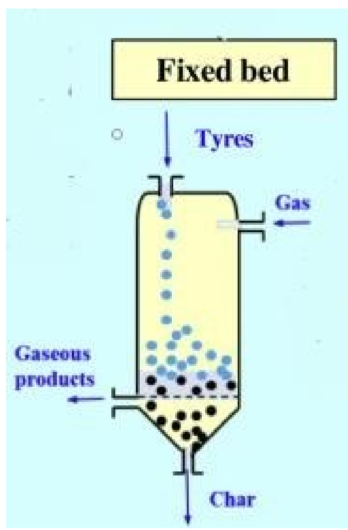

Figure 9:Fixed bed reactor (Lewandoski, W.M., et al., 2019)

4.1.2.2. Fluidized bed

Fluidized bed pyrolysis, as opposed to fixed bed pyrolysis, is a continuous process and therefore popular, particularly in commercial operations (Antoniou, N., & Zabaniotou, A. 2013). The main difference between this reactor and the fixed bed as can be noticed in figure 10 is the addition of a gas flow, thus due to the turbulent gas flow and rapid circulation within the reactor, higher heat efficiencies and control are obtained (Li, S. ,2017). Using this reactor increases oil output and allows for continuous operation, which is important for production scaling, however the complicated design and maintenance of this system, along with the significant investment required to run this reactor, limits the use of fluidized bed reactors (T. Dick, D., et al., 2020); (Kommineni, R., et al., 2017).

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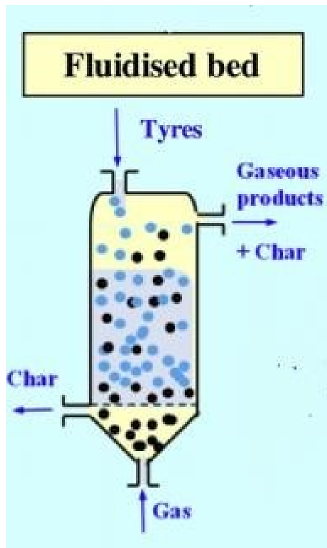

Figure 10:Fluidized bed reactor (Lewandowski, W. M., et al., 2019)

4.1.2.3. Rotary kiln

Rotary kilns are used to heat solids to the temperature necessary for the needed chemical reaction(s). It is considered as fast pyrolysis (Czajczyńska, D. , et al., 2017),the rotary kiln is an angled spinning cylinder where a hopper is used to feed the tires into the reactor as seen in figure 11 (Antoniou, N., & Zabaniotou, A. 2013). In this reactor the solid's residence duration is easily adjustable, it has good heat exchange during slow rotation, and it is capable of continuous operation (T. Dick, D., et al., 2020). There are several advantages to using rotary kiln pyrolysis over other types of reactors. They include readily adjustable solids residence time in the reactor, effective waste mixing due to the rotating mechanism, and also effective heat transmission during slow rotation of the inclined kiln, which results in homogenous pyrolytic products (Czajczyńska, D. , et al., 2017).

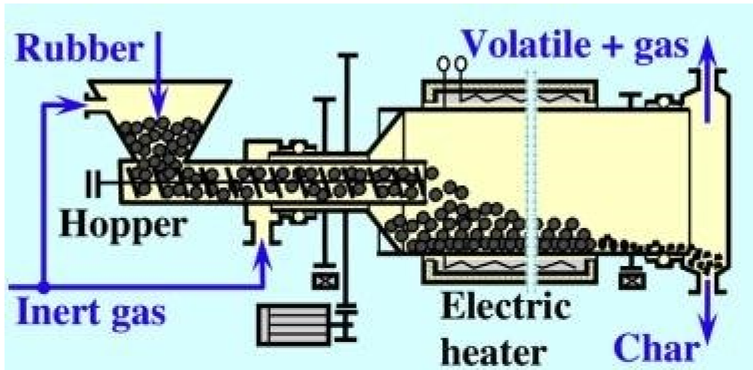

Figure 11: Rotary kiln reactor (Lewandowski, W. M., et al., 2019)

4.1.3. Process conditions

As described above the different reactor configuration can influence the yields from the process. Moreover, these yields can also be affected by the process parameters, with the dominant operating circumstances being temperature, heating rate, and residence time (Labaki, M., & Jeguirim, M. 2016); (Rowhani, A., & Rainey, T. 2016).

4.1.3.1. Temperature

Waste tire pyrolysis is an endothermic reaction that is controlled by temperature in the reactor. As a result, the temperature has a significant impact on the products and its conversion grade, and is considered the governing variable with the greatest influence on pyrolysis (T. Dick, D., et al., 2020). According to several authors (Martínez, J. D., et al ,2013); (T. Dick, D., et al., 2020); (Parthasarathy, P., et al., 2016) 500 ◦C appear appears to be the optimum temperature, at atmospheric pressure. If the temperature is too high >600◦C, the gas portion is increased on the expense of the liquid fraction. While if the temperature is low 300-450◦C, thermal degradation of the tire is not complete and the char is more produced.

4.1.3.2. Heat rate

In addition to temperature, the heating rate is critical in influencing the pyrolysis product yield. Typically, when waste tires are burned at a faster pace, less carbon black is produced, while the gas and oil outputs are increased (Parthasarathy, P., et al., 2016). It was also found that high heating rates increased the degradation rate of the tire while the opposite occurs when lower heating rates is used (Martínez, J. D., et al ,2013).

4.1.3.3. Reaction time

Also referred as residence time of the tire inside the reactor is a critical aspect in scaling up to an industrial system as less residence time entails reduced reactor volumes and, as a result, a lower system cost. The reaction time can vary based on the feedstock particle size, as bigger particle size tends to need longer reaction time when compared to smaller particles (Martínez, J. D., et al,2013).

4.2. Circular economy nexus pyrolysis of tires

According to Martínez, J. D. (2021) pyrolysis provides a highly appealing approach to dealing with the ELT problem, as well as a perfect illustration of how a circular economy strategy might be applied. As he further explained, this type of transformation to recover energy and materials is critical not only to cope with the amount of waste created, but also to develop value-added goods and so lessen the reliance on non-renewable resources in the next section will discuss how can the outputs products of the pyrolysis process be incorporated again to help achieve circular economy and how they can fit in the Egyptian context.

4.2.1. Output product of pyrolysis processes: Oil

Pyrolysis oil is the common term for the liquid phase of pyrolysis products. It's a black, murky, dense liquid with a distinctive smell. Post-pyrolytic oil is a very complex blend of hydrocarbons, and Oil yields range from 38 to 56 weight percent, with a heating value of 40-43 MJ/kg (Czajczyńska, D., et al., 2017). The oil may be burned directly in furnaces, steam boilers, gas turbines, and IC engines(Parthasarathy, P., et al., 2016), however as explained by Czajczyńska, D., et al. (2017)the main issue with utilizing pyrolysis oil as a fuel is the high Sulphur level and there are many ways of desulphurization that were mentioned in previous literature, such as adding alkaline additions distillation of oil, oxidation of sulphur compounds using hydrogen peroxide in the presence of an acidic catalyst, or hydro refining. Other than its use as a fuel directly or after refinements, other valuable materials can be extracted from the tire pyrolysis oil. Also it was mentioned by Czajczyńska, D., et al. (2017) that one of the critical component that may be produced from tire oil is d-limonene. D-Limonene has become an essential ingredient in the production of several solvents, resins, adhesives, and other products; it is used in pigments as a dispersion agent and as a scent ingredient in cleaning products; while it is utilized in the pharmaceutical sector to formulate medications used to treat cancer and bronchitis; and lastly it is employed also in the food sector as a flavoring additive in drinks and chewing gum. Hence its demand is expanding year after year as a result of its rising use in sectors such as pharmaceutical, chemical, and cosmetic. Also as mentioned by Martínez, J. D., et al. (2013) that another useful component is BTX (a hydrocarbon) which might be boosted if catalysts are used in the refinement process. BTX is frequently derived from fossil fuels and is employed in a variety of industrial applications (plastics, paints, pigments, explosives, pesticides, detergents, solvents, and others). As a result, pyrolysis oil might become a key source of renewable and sustainable hydrocarbons to meet the needs of the chemical industry.

In a review on the pyrolysis process and its output products made by Williams, P. T. (2013), it was stated that previous studies found that utilizing blended tire pyrolysis oil-diesel fuel blends had only a negligible effect on engine brake thermal efficiency (overall efficiency) as compared to using diesel fuel alone at blends of 10%, 30%, and 50% tire pyrolysis oil. In certain circumstances, the mixed fuel provided a minor gain in brake thermal efficiency. It was proven also that higher blend ratios could also be achieved, but prior to blending the tire oil was adjusted by sulphur reduction, moisture removal, and distillation at higher blend ratios. It was stated that the direct injection diesel engine could not run successfully on 100 percent modified tire pyrolysis oil, but it could run on 90 percent tire oil and 10% diesel fuel. The 90 percent tire oil mixture resulted in a slight (2%) drop in engine efficiency and an 11 percent rise in hydrocarbon emissions, while an 18% drop in NOx was found at peak load. However, there was a significant rise in smoke emissions. The important takeaway was that tire liquid fuel mixes may be utilized in diesel engines without sacrificing engine performance (up to 70% tire liquid) while reducing some engine emissions (Williams, P. T. ,2013); (Martínez, J. D., et al ,2013).

4.2.2. Output product of pyrolysis processes: Char

In general, pyrolysis allows for the conversion of organic materials into a carbon-rich solid (char). In the case of tires, this solid carbonaceous fraction, also known as pyrolytic carbon black (CB), corresponds to the original CB as well as the inorganics employed in tire manufacturing. As explained by Martínez, J. D., et al (2013) that apart from the liquid fraction, the char composition is determined by the pyrolysis conditions and the tire composition, and its quality and yield have a significant impact on the economic feasibility of waste tire pyrolysis. Furthermore, pyrolytic CB has a calorific value of 25 to 34 MJ/kg, making it particularly appealing as a solid fuel. Substantial virgin CB demands are regularly seen throughout the globe for the production of a variety of goods such as inks and coatings, plastics, construction and metallurgy materials, resins, paints, various rubber goods, and tires. As explained by Hardman, N. J. (2017) CB may be found in everything black and plastic, everything black and printed in black, and everything black and made of rubber. CB manufacturing is an energy-intensive process. Traditionally, the majority of CB (approximately 95 percent) is generated from crude oil by incomplete combustion, which requires 1.5 to 2.5 L of oil to generate 1 kilogram of CB Martínez, J. D. (2021) and that the current global CB production consumes more than 32,000 million liters of oil per year, releasing not only more than 35 million tons of CO_2per year, but also extremely polluting and toxic substances such as unburnt hydrocarbons, nitrogen oxide, sulphur dioxide, among others. These characteristics, among other things, indicate that the most basic rCB use is as a replacement for virgin CB. If virgin CB was replaced with rCB, significant CO_2 reductions would occur, and pyrolysis would therefore constitute a key example of circular economy in ELT management. However, one of the setback of rCB is that it is projected to have substantially coarser particle sizes than original CB (Martínez, J. D., et al ,2013) added to that it contains high sulphur and ash content. A possible solution that was mentioned in Kommineni, R., et al. (2017) report is the acidification/basification treatment which makes it equivalent to that of commercially available carbon blacks. As explained by Parthasarathy, P., et al. (2016) another common application of char is the manufacture of activated carbons from carbonaceous chars which necessitates the use of an activating agent such as steam or carbon dioxide. When steam is employed as an activator, it combines with the carbon in carbon black to produce hydrogen, carbon monoxide, carbon dioxide, and methane. The activation process, which uses carbon dioxide as an agent, produces carbon monoxide. After activation, it is commonly employed as adsorbents to adsorb phenols, basic dyes, metals, pchlorophenols, butane, natural gas, and other substances. The activated carbon is also efficient in removing both organic and inorganic contaminants from industrial effluents. Other minor applications include reinforcing filler for low-value rubber items, road pavement filler, printing ink pigment (Martínez, J. D., et al ,2013). In an interview done with Dr W.K. Dierkes an associate professor in University of Twente, she said that the carbon black retrieved from char can be recycled more than once and that in the future tire companies will shift towards using recovered carbon black, this was also agreed upon by Mr Raman Balani.

4.2.3. Output product of pyrolysis processes: Gas

The gas produced by the pyrolysis is known as pyrolytic gas, pyro gas, or syngas. Depending on the technology and process circumstances, it might vary from a few percent to more than 10 percent of the products (Czajczyńska, D., et al., 2017). This gas is mostly composed of methane and other hydrocarbons, as well as carbon oxides, hydrogen, and trace quantities of sulphur and nitrogen compounds. The most common use for the pyrolytic gas is in combustion in order to provide the energy required by the pyrolysis process, as it was reported in several studies that that the process was self-sufficient regarding energy needs when using the gas (Czajczyńska, D., et al., 2017); (Martínez, J. D., et al ,2013).

4.3. The Egyptian context in relation to the circularity of tires

In this sub section the applications of the products obtained from the pyrolysis process will be discussed, this will be done by looking at the Egyptian market and see where the products are or can be utilized.

Egypt is Africa's highest oil producer outside of the Organization of Petroleum Exporting Countries (OPEC), Egypt is Africa's largest oil consumer, accounting for around 22% of petroleum and other liquids consumption in 2016 (EIA,2018). Increased industrial production, economic expansion, energy-intensive natural gas and oil extraction projects, population expansion, an increase in private and commercial car sales, and energy subsidies have all contributed to the fast expansion of oil consumption. Egypt's oil consumption now exceeds production, and one of the country's biggest concerns is meeting rising oil demand while producing less. In a study done by the Energy Information Administration (EIA) (2018) it was stated that According to the Economist Intelligence Unit (EIU) and the 2017 BP Statistical Review of World Energy, Egypt's proved reserves have fallen from a peak of roughly 4.5 billion barrels in 2010 to nearly 3.5 billion barrels in 2016.The drop in reserves, according to the EIU, is due to ageing oil fields and a lack of fresh discoveries to completely balance the loss. Egypt has maintained a consistent level of exploration effort, though the majority of important discoveries have been natural gas rather than oil. Thus, One of Egypt's primary concerns is meeting rising domestic oil consumption while output is declining. As between 2007 and 2017 the oil consumption showed an increase of around 16% and is still expected to increase. As can be seen in figure 12.

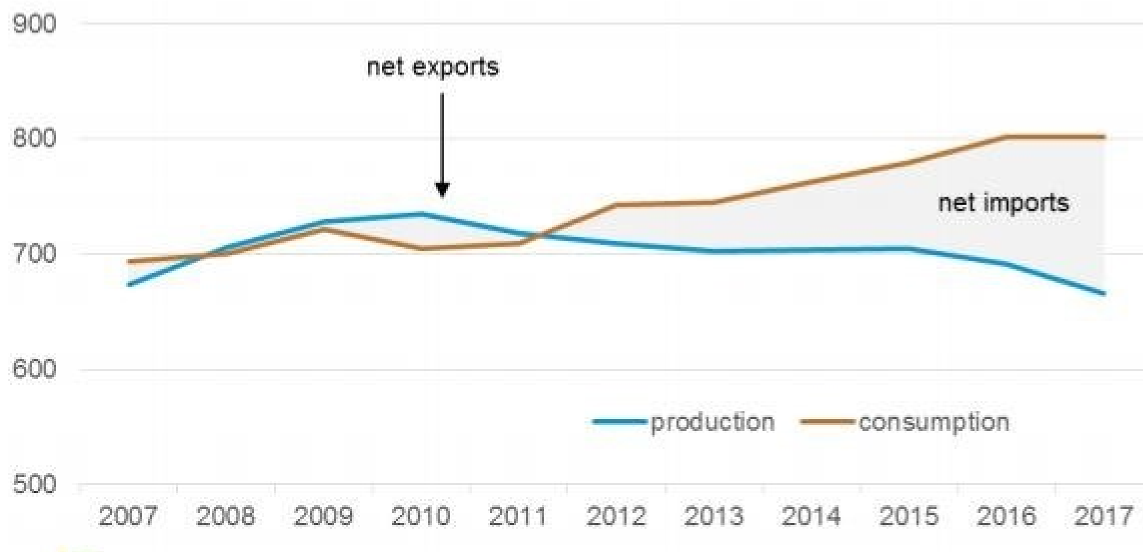

Figure 12:Annual oil production and consumption in Egypt/ thousand barrel per day (EIA,2018)

Egypt also possess Africa's biggest oil refining sector, however most refineries are working at less than capacity due to age and maintenance concerns. Its refineries mostly process crude oil produced in the country, and refined products are primarily marketed in domestic markets. The Egyptian government has attempted to increase refining capacity, however a number of renovations and greenfield refineries have been delayed. However, the country will invest over $38 billion in the development of its petrochemicals sector over the next four years (Energy Resource Guide, 2021). The petrochemical sector accounts for around 12% of industrial production and creates USD 7 billion in revenue, or approximately 3% of GDP (Energy Resource Guide, 2021). The chemical industry in Egypt has also bright possibilities. In 2019, output was predicted to increase by up to 6% (Egypt – Chemical Industry ,2019). For example, domestic manufacturing might provide a higher portion of the demand for plastics, which is expanding at a pace of roughly 10% per year. According to Global Markets International (Egypt – Chemical Industry 2019), Khaled Abo Al Makarem who is the president of the Chemicals and Fertilizers Export Council, predicted in April 2019 that Egypt could meet 50% of its plastics needs by 2023 as the country is still 70% reliant on imports. Moreover, the pharmaceutical industry was expected to show a rise in its growth, and currently Egypt is the biggest pharmaceutical producer in the MENA area, accounting for around 30% of the regional market. Local manufacture accounts for around 93 percent of the market, with the remaining 7 percent made up of highly specialized medicines that are not manufactured locally as provided by General Authority for Investment and Free Zones (Invest in Egypt, 2021.). This provides many applications for the usage of tire derived oil that contains useful materials such as BTX and d-limonene. Added to that, in an interview done by Egypt Oil and Gas Newspaper (2017) with the Head of the petroleum products division at the Federation of the Egyptian Chambers of Commerce, Hossam Arafat, it was stated that the daily consumption of diesel by Egyptians currently is believed to vary between 40 and 45 million liters and that the state imports 25%-30% of its diesel needs. As was explained earlier the tire derived oil can be used with diesel fuel, which can in turn lower the amount of imported diesel. In an interview with Dr Samia Galal consultant to head director of Waste Management Regulatory Authority (WMRA) in Egypt and technology expert, she explained that the oil from pyrolysis has many applications in Egypt and the process is considered sustainable as the materials are re circulated in the economy and will create jobs opportunities. She also stated that Egypt is looking more towards waste to energy projects and that pyrolysis of tire is considered promising since the virgin materials are more expensive and have a higher environmental impact while pyrolysis enables the saving of non-renewable resources and at the mean time produces valuable materials. While in another interview done with Dr W.K. Dierkes, she explained that pyrolysis is considered an energy recovery and recycling at the same time as the gas can be used for energies while the char and oil can have other applications.

4.4. Life Cycle Assessment of waste tire pyrolysis in Egypt

In this section the environmental impacts of using pyrolysis as method to manage waste tire will be analyzed, this will be done by using LCA method, however it should be noted that this LCA study will not be an extended one but still will try to accommodate the scope of this research and cope with time limitations. In general, it can be said that LCA is a useful method for assessing or comparing the possible environmental effects of various products/services, for this research the LCA will focus on the used tires (waste) management strategies. However, just a few LCA studies on the pyrolysis of scrap tires have been conducted (Banar,2015). Moreover, the investigation of environmental impacts of the pyrolysis of scrap tires through LCA has not been done in Egypt, and this research will try to contribute to that. Then the analysis will be from conceptual/theoretical standpoint. A life cycle assessment requires an investigation of all the consequences that occur as a result of and during the lifespan of a product or process. To accomplish so, this study will be completed by the following actions in the listed order: define the goal definition and scope, inventory analysis, and profiling (Banar,2015). Batch tire pyrolysis reactors generally have throughputs of 1–2 tons per day, and more modules might be added to enhance throughputs. On the other hand, for higher throughputs –up to 120 tons per day- continuous tire pyrolysis reactors are used, with the most prevalent reactor being rotary kiln (Williams, P. T., 2013).

4.4.1. Goal and scope definition

The goal of this not extended LCA study is to assess the environmental impact of waste tire pyrolysis in Egypt. However, due to the fact that there is no obtainable data about plants in Egypt. this study will be made based on previous studies that obtained emissions data of the pyrolysis process. The functional unit of this study was chosen to be 1 ton of ELT entering the pyrolysis process, this was chosen as reactors often have a capacity range of around 2 – 120 tons (Williams, P. T., 2013), also it was the most used functional unit when assessing previous literature (Banar,2015; Passarini, F. et al., 2018; Li et al., 2010).

4.4.2. System boundaries

It is critical to set the system limits correctly since they influence the depth of the research by determining what will be included and what will be excluded. The following assumptions were made before determining the system boundaries.

- The production and usage phases of tires, as well as the collecting of end-of-life tires, were not examined in this study because the goal was only to evaluate the pyrolysis process.
- The emissions considered to be emitted from the pyrolysis system are the gaseous emissions (Sulphur dioxide, carbon dioxide, nitrogen oxides, and particulate matter) produced from the reactor as a result of the burning of the syngas supplied back into the reactor as fuel.
- The emissions considered to be emitted from the rest of the system for electricity generation to heat up the reactor and power up the pyrolysis reactor for the first 3 hours (Banar,2015) and power up other machines (tire shredder and tire drawing machine) as shown in figure 1.
- The environmental impact of any additional applications of the pyrolysis process products indicated within the designated system boundary are not taken into account because they are usable in other sectors after being extracted from the pyrolysis process.
- Emissions from the manufacture of machinery employed in the system are not taken into account as well as any infrastructure.
- The emissions for the transportation of ELT to the pyrolysis plant should be taken into account, however the fact that there is not main tire supplier in Egypt as was mentioned in the literature review, added to the fact that there is not an actual tire pyrolysis plant in Egypt makes it complex and many assumptions would have to be made in order to calculate it, so due to the scope and time limitations of this research it was left out.
- It was assumed that all tires entering the system are truck tires, that is because truck tires need an extra procedure which is the tire drawing.
- For electricity generation, only carbon dioxide will be taken into account as it is the main emission from generating energy in Egypt (Abdallah, L., & El-Shennawy, T. ,2013).

- The reactor will valorize 40 ton of waste tire per day, the reactor chosen is fully continuous, which mean it has the ability to work 24 hours per day (LVKUN ENVIRONMENTAL, 2021).

The reactor chosen is a rotary kiln model LKP-40, this reactor has a capacity to valorize up to 40 ton of waste tire per day (LVKUN ENVIRONMENTAL, 2021). For the first 3 hours' external energy is needed to heat up the reactor, afterwards the syngas produced can make the process self-sufficient in terms of energy (Banar,2015). The emissions calculated will be divided into two parts, firstly the energy required for the usage of machines inside the system like the tire shredder and drawing machine, plus the initial energy needed to start up the pyrolysis reactor. For these energy consumptions, the emissions will be calculated by obtaining the carbon emission per KWh in Egypt and multiplying them. While the second part of the emissions which is due to the combustion of the pyrolysis produced gas that heats up the process, will be obtained from previous studies. After adding up both emissions the total emission per day will be obtained, then it will be divided by 40, since in one day 40 tons are treated, consequently the emission per 1 ton of waste tires will be found. The detailed system can be shown in Figure 13 where in the inputs are electricity and waste tires, while the outputs are emissions and materials.

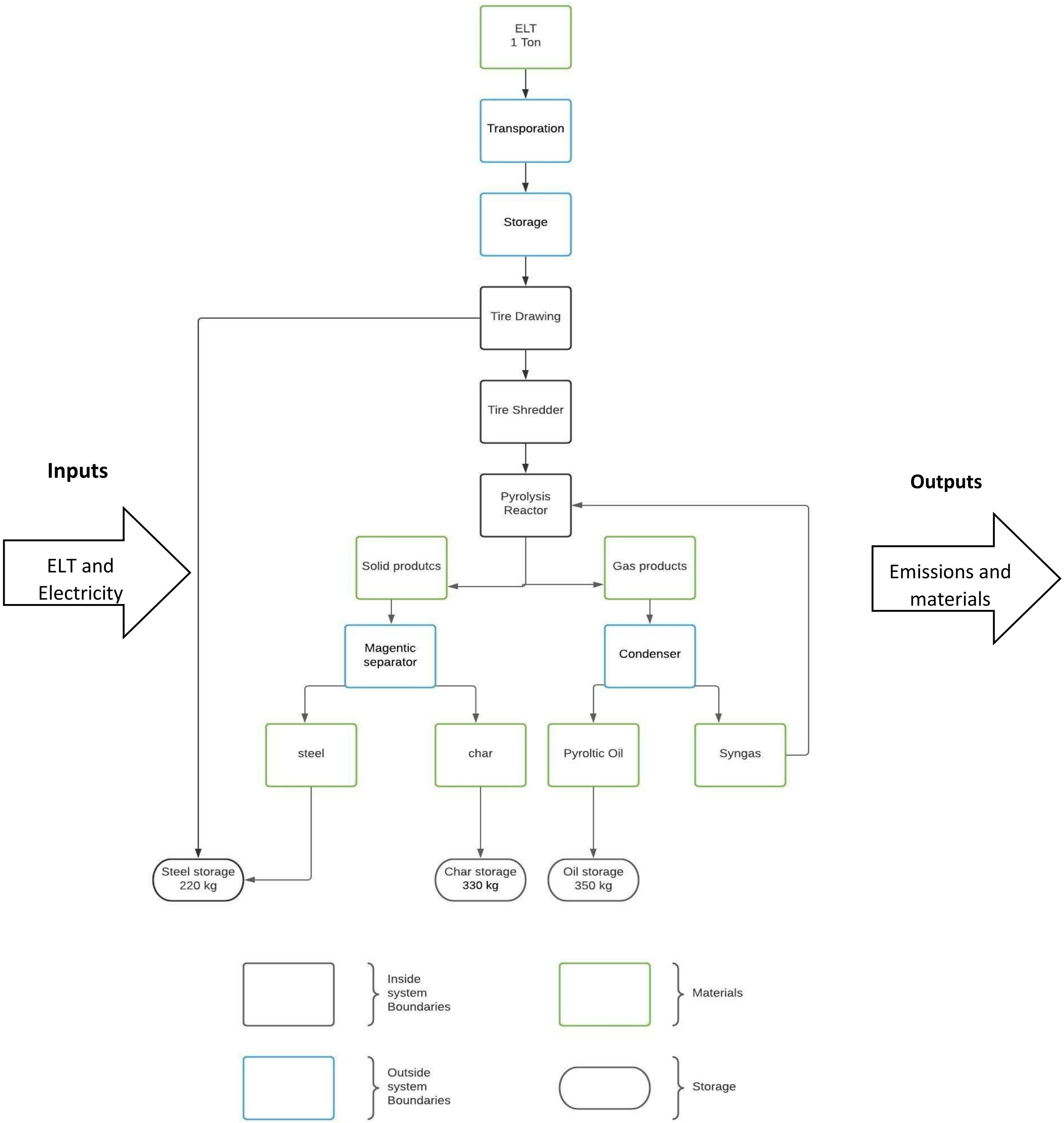

Figure 13:The pyrolysis system (Author's contribution)

4.4.3. Inventory analysis

Life cycle inventory analysis helps identify and quantify all resources used to produce products and services, such as energy, water, raw materials, and processed materials, as well as all substances released into the environment, such as pollutant emissions into the air, soil, and water (Nie, Z., et al., 2014). In this system the inputs are electricity and ELT, while the outputs are emission plus the valuable products as shown in figure 13. In table 5 all the electricity consumption to power up all the processes that are within the system boundaries was obtained, moreover the CO_2 emission per KWh for Egypt was used to calculate the total CO_2 emissions that are emitted because of the electricity usage (Abdallah, L., & El-Shennawy, T. ,2013). This was done by multiplying the factor for the Egyptian emission per KWh with the total KWh needed, which amounted to 956.68 kg of CO_2. This latter is the total daily emissions for the 40 tons of waste tire. To obtain the emission per ton, the total daily calculated emissions were divided by 40, which resulted in 56.5 CO_2 kg per ton. Moreover, as reported by Li., et al. (2010), the products output from 1 ton entering the system is 220 kg of steel, 350 kg of oil and 330 kg of char as visible in figure 13.

Table 6:Carbon dioxide emission generated due to energy consumption

Process	Quantity and Unit
ZPS-1200 Tire shredding machine with capacity 2-3.8 ton/hour (MoreGreen,2020)	150(KWh)
Tire shredding machine daily energy consumption	3600(KWh)
MWD-1200 tire drawing machine with capacity 40-60 tires (*Tire shredder,2021)*	11(KWh)
Tire drawing machine daily energy consumption	264(KWh)
Total energy consumption of drawing and shredding machine	3864(KWh)
LKP-40 rotary kiln reactor electricity consumption (LVKUN ENVIRONMENTAL, 2021).	108(KWh)
Total energy consumption of reactor for 3 hours	324(KWh)
Total energy consumption per day (KWh)	4188(KWh)
Carbon dioxide emissions per kwh of electricity generated in Egypt (Abdallah, L., & El-Shennawy, T. ,2013)	540(g CO2/KWh)

Total daily carbon dioxide emissions due to electricity generation used in waste tire pyrolysis per 40 tons	2261.5 (kg)
Carbon dioxide emissions per ton	56.5 (kg)

The carbon dioxide emitted was calculated by multiplying the carbon dioxide emissions per KWh of electricity generated in Egypt with the amount of kwh. After identification of the CO_2 emission, the next step is calculating the emission released from syngas that powers up the process, this information was obtained from previous work done by Li et al. (2010). As it can be seen in table 6, the emissions from utilizing syngas is not only Carbon dioxide, but there is also Sulphur dioxide, Nitrogen oxides, and particulate matter.

Table 7:Emission from utilization of syngas (Li et al. ,2010; Banar,2015).

Pollutant	Emission per 1 ton of waste tires (kg)
Carbon dioxide	68
Sulphur dioxide	3.55
Nitrogen oxides	1.40
Dust	0.58

To sum up, following an examination of the emissions resulting from the transformation of energy to power the selected operations evaluated in the system, as well as the burning of pyrolytic gas. The emissions of caused from the electric usage in the first 3 hours is 56.5 kg of carbon dioxide, while the emissions that arise from the burning of the syngas was reported by Banar (2015) to be 68kg of CO_2, and 60kg by Li et al. (2010). While the other emissions were not calculated by in the study made by Banar (2015), but Li. et al. (2010) calculated the to be 3.55 kg of Sulphur dioxide, 1.4 kg of Nitrogen oxides, and 0.58 kg of dust per 1 ton of waste tires as depicted in table 6.

4.4.4. Profiling

Following the determination of the emissions created by the described system in the inventory analysis, the Recipe2016 impact assessment technique is used to analyze the environmental consequences of waste tire pyrolysis (Huijbregts, M. A., et al., 2016). This method is an updated version of the ReCiPe2008 method, as seen in figure 14 this method looks at the problems caused by the emissions at two points. To start with, at the midpoint, which is the cause-impact effect of the process, these different impacts can lead to various damage pathways, and ultimately will only lead to one of the three endpoints, which cover mainly human health, ecosystem and resources. The pyrolysis process does not impact all midpoints and due to the limitations of this study, only the noticeably impacted midpoints will be discussed in the following paragraphs. It will be explained how the emissions can lead to impacting the midpoints, yet the degree to which the midpoint is affected will not be discussed as this required a more in depth LCA study with the usage of soft wares which would have needed more time than the given timeframe for this research.

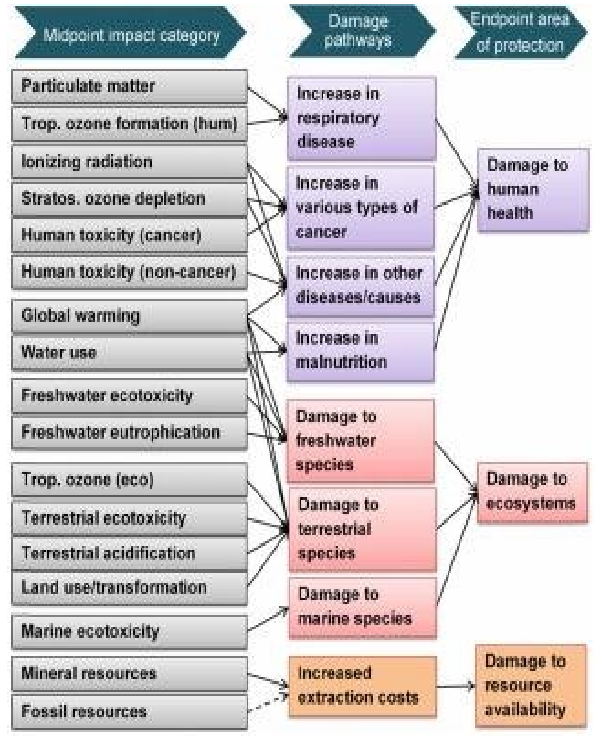

Figure 14:Recipe2016 method (Huijbregts, M. A., et al., 2016)

4.4.4.1. Climate change

Climate change is induced by the discharge of many gases into the atmosphere, including CO_2, CH_4, N_2O, and O_3 (Li et al., 2010). This occurs in this case due to the usage of electricity in powering up the process, and from the emissions caused by pyrolysis. There are several effects of climate change. Increased temperatures, landslides, wildfires, diminished water supplies, and floods and droughts are all examples of environmental consequences.

4.4.4.2. Terrestrial acidification

Acidic rain is created by the precipitation of sulphur dioxides and nitrogen oxides in emissions that produce sulphuric and nitric acid, thus consequently terrestrial acidification is caused. Pyrolysis emits sulphur dioxides and nitrogen oxides as was shown in table 2, thus necessary treatment to control them should be taken into account. The major environmental implications of acid rain are soil and water acidification, as soil acidification has an impact on vegetation owing to changes in the pH of the water absorbed by plants and changes in soil characteristics. Similarly, water acidification has an impact on marine life (Li et al., 2010).

4.4.4.3. Fossil resources

The use of non-renewable resources at a pace faster than their production in nature causes fossil fuel depletion. And as it was shown earlier Egypt currently has a higher consumption rate of fossil fuel when compared to its production, and with that being said, the energy generation in Egypt that powers up the pyrolysis process as shown earlier in the previous chapter depends mainly on fossil fuels particularly oil and natural gas.

4.4.4.4. Particulate matter formation

Particulate matter is formed in the atmosphere as a result of sulphur dioxide, nitrogen oxides, and ammonia emissions. If particulate matter generation increases, there are several severe health consequences, such as decreased life expectancy, lung cancer, chronic and acute respiratory and cardiovascular morbidity, chronic and acute mortality, diabetes, and bad birth outcomes (Humbert S., et al., 2015).

4.4.4.5. Human toxicity

Human toxicity refers to the harm done to the human body as a result of toxic emissions. Human toxicity is induced by the released carbon dioxide emissions in the studied system. Carbon dioxide emissions have a number of deleterious consequences on the human body, including a drop in blood pH (which causes respiratory, cardiovascular, and central nervous system disorders), disturbance of the normal cell division process, asthma, and other symptoms such as headaches and weariness (Humbert S., et al., 2015).

4.4.5. Highlights of LCA

All in all, from this brief LCA study the emissions that arise from a tire pyrolysis plant have been to some extent already estimated, nonetheless it should be taken into account that a much deeper LCA study should be made as due to the limitations of this research things like transportation of ELT, lighting up the facility and other smaller machines that operate within the system were not taken into account. Moreover, this study only stresses upon the effects the emissions have on the midpoints, yet how much damage is done to any of the midpoints was out of scope as it would have required the usage of software's such as Gabi, and that would have not been attainable due to the limited time constraint, yet it should be done in future research as it identifies all the environmental impacts and to which degree. Never the less, in a study done by Li et al. (2010) the different ELT treatment technologies from both an environmental and economic standpoint. Where it compared pyrolysis with dynamic devulcanization, ambient grinding and illegal tire oil extraction as a mean to manage waste tire in China, pyrolysis was identified to be the most eco-effective treatment. And according to several authors it was demonstrated that waste tire pyrolysis results in significant material and emissions reductions owing to the replacement of pyrolysis products, however this takes into account that pyrolysis products are fully utilized in the market (Banar, 2015; Passarini, F. et al., 2018). This implies that for pyrolysis to be done it should not only be environmentally friendly, but also attractive to investors as will be discussed in the next chapter.

4.5. Economic feasibility

In section 4.1 the technological potential of chemical recycling of tires was presented. Two chemical recycling technologies were analyzed and the pyrolysis process was selected to be further described in terms of pyrolysis reactors, the main parameters of the process and their effects on the process yields (efficiency). In section 4.2 a brief LCA was carried out where simple calculations were made based on the Egyptian energy generation mix. CO_2 emissions were also analyzed from previous literature for the pyrolysis process. In order to further explore the potential of pyrolysis of ELT in Egypt, an economic feasibility study was also relevant to be considered as part of this study. As any important investment, pyrolysis of ELT should prove to be profitable for investors. Hence, in this section, an overview of the expenses related to the installation (constriction) and operation of the pyrolysis plant are described. Even further, the revenues from the pyrolysis products were estimated based on the current Egyptian market prices. After calculating the monthly expenses and revenues, an approximation of the yearly net profits was calculated, to be followed by a sensitivity analysis to check what would occur if any fluctuation occurs either in the selling price or in the monthly costs. Lastly the return on investment (ROI) of the whole process was calculated to check if the pyrolysis of ELT in Egypt seems to be feasible or not. But before calculating the monthly expenses, fixed costs and revenues, a Business Model Canvas will be made to summarize what the core of this project is by compiling the different important actors.

4.5.1. Business model canvas

The Business Model Canvas splits the business model into manageable segments: Key Partners, Key Activities, Key Resources, Value Propositions, Customer Relationships, Channels, Customer Segments, Cost Structure, and Revenue Stream. This aids in identifying the needs of each stakeholder in the business development and what they have to offer. The business model applied in this part of the research corresponds to the one published by Osterwalder and Pigneur (2010) which has been compiled in the template showed in table 7, and was filled by the author according to the tire pyrolysis case.

Table 7: Business model canvas of tire pyrolysis (AltexSoft. 2019)

Business Model Canvas

Designed for: Tire pyrolysis plant in Egypt

Designed by: Ahmed Tharwat

Date:

Version:

Key Partners
- Tire producers
- Carbon black producers
- Oil consuming industries
- Steel companies
- Governmental agencies Financers
- Authorities concerned with the environment

Key Activities
- Recycling
- Assist in managing the waste tires

Key Resources
- ELT
- Machinery
- Financial support
- Specialized staff

Value Propositions
- Enhanced tire waste management system
- Business opportunity
- Job creation
- Energy production
- Production of materials that are currently being imported
- Waste to energy system

Customer Relationships
- Consumer awareness
- Green business

Channels
- Circular economy platforms
- Wholesalers

Customer Segments
Oil, carbon black, activated carbon and steel consuming industries.

Cost Structure
- Tire pyrolysis plant design and outlay (machinery, land, utilities, maintenance)
- Research and developments costs
- Raw materials and supplier selection
- Logistics

Revenue Streams
- The selling of retrieved oil, char and steel.

4.5.2. The fixed costs, monthly expenses and monthly revenues

In this subsection the fixed costs needed to start up the whole pyrolysis will be calculated, after that the monthly costs needed to keep the business operating and the monthly revenues will be calculated. Then it will be possible to calculate the yearly net profit and the ROI of the whole process.

4.5.2.1. Fixed costs

The investment or fixed costs are the expenditures incurred just once during the facility's construction. This covers mainly the pyrolysis plant and furniture of administrative facilities. The price for a 10 ton/day tire pyrolysis plant was obtained through contacting a company from China namely, Henan Doing Environmental Protection Technology Co., Ltd, which supplies tire pyrolysis plants, the amount was given to be 90,000 USD, then converting it in Egyptian pounds (EGP) that would amount to 1,408,218. While the furniture costs were taken from an economic feasibility test that was done previously for pyrolysis of plastics in Egypt, taking into account that the office furniture can be quite similar in both pyrolysis plants (Fahim, I, et al., 2021). Another thing that needs to be taken into consideration is that any machinery that is entering Egypt is subjected to 5% customs (Import, 2021), while according to Sinnott, R. K., & Coulson, J. M. (2005) in their book about chemical engineering design the shipping fees and installation costs are considered negligible and the contacted company offers a free 30-day installation period from the date of purchase, thus the setting up costs were not taken into account. In table 8, a summary of the mentioned fixed costs is displayed.

Table 8:Fixed costs

Pyrolysis plant	1,408,218 (EGP)
Furniture	50,000 (EGP)
Machinery customs for entering Egypt	70,410 (EGP)
Total	1,528,628 (EGP)

4.5.2.2. Monthly expenses

The monthly expenses are the projected money that has to be paid monthly, in order to maintain the plant operations. Among the monthly expenses, here a list of them: the waste tires that are used as feedstock, the pre-built factory rental and all utilities used, labor, other costs such marketing and overheads. The waste tires price was obtained through looking on trade platforms in Egypt (Egyptiresningbo,2021) and was found to be 1000 EGP per ton, while the monthly rent of the factory and the water and utilities was obtained through the research done by Fahim et al (2021), as this research is very similar case than theirs. The electricity was calculated, given that the plant has a consumption of 23.5 kWh (Henan, 2021) and the price per kWh for factories in Egypt is 1.151 EGP (Egypt electricity prices, 2020). Moreover, the salaries were computed by finding the average salary of an industry worker in Egypt (Factory, 2021), and knowing that the plant requires 4 workers, it should be mentioned that the plant is works continuously 24h/day thus 3 shifts of workers were considered, from the salaries expense the overheads could be calculated as according to Sinnott, R. K., & Coulson (2005). The overheads are 50% of the workers' salaries. Lastly, the marketing was calculated as done by Fahim et al. (2021), this Information was confirmed during their interview with accountant's experts in Egypt who indicated that the marketing expense is 5% of the goods sold. It should be noted that factory is assumed to be running 26 days per month and this the norm for Egyptian factories, this information was also confirmed during one interview done by Fahim et al. (2021) with an industrial expert. All the operational monthly costs are enlisted in table 9.

Table 9: Monthly expenses

Category	Monthly cost (EGP)
Waste tires	260,000
Monthly rental of a pre-built factory	35,000
Electricity	16,878
Water and utilities	13,312
Salaries	75,360
Marketing	2,893
Overheads	37,680
Total	441,123

4.5.2.3. Monthly revenues

The monthly income is calculated by knowing the amount of products being sold and how much they cost in the Egyptian market. As was elaborated by several authors (Banar, 2015; Li et al,2010) the derived oil and char are of lower quality when compared to fuels such as diesel or virgin carbon black, as a consequence when comparing between the retrieved oil and char with diesel and virgin carbon black a ratio of 1:0.5 is usually done. This means that each kilogram recovered can compensate to half a kilogram of the virgin materials, while the steel recovered had a ratio of 1:1. As a result, 1 ton of tires that has an output of 350 kg of oil will be recognized as having 175 kg of diesel and the same of char and carbon black (Banar, 2015; Li et al,2010), as this will make the revenue stream more concrete because there is no official price for tire derived oil or char in Egypt. The price per liter for diesel in Egypt is 6.75 EGP (Egypt diesel prices,2021), while the price of carbon black was obtained through looking at Egyptian suppliers that sell the product, the average price was between 3,129 – 4,694 (Hoppec,2021), thus an average of the two numbers was taken and the price of steel was 2,400 according to an interview done by Wamda with a tire recycling company called retyres (Cousin , E., 2016). After multiplying the daily revenues to 26, working days per month, this results in a total monthly income of 578,685 EGP as shown table 10.

Table 10:Revenues

Product	Production amount (tons)	Price (EGP)	Revenues (EGP)
Diesel	1.75	6,750	11,812
Carbon black	1.65	3,911	6,453
Steel	1.5	2,400	3,600
Total			21,866
Total monthly			568,507

Afterwards, the first yearly net profit was calculated and can be observed in table 11. Nonetheless, before that other costs should be taken into account. Namely, the taxes in Egypt which amount to 22.5% of the gross profit (Egypt,2021), and according to book the depreciation of the machinery amounts to 10% and the yearly maintenance cost is 15% of the total plant cost as was explained by Sinnott, R. K., & Coulson (2005) in their book. Which results in a calculated yearly net profit of 833,085 EGP.

Table 11:First yearly net profit

Description	Amount (EGP)
Total income	6,822,083
Total costs	5,293,476
Taxation	344,073
Depreciation	140,281
Yearly maintenance	211,233
Net profit	833,085

The economic analysis of a project can only be based on the best estimations of the investment and cash flows that can be made. Any changes in raw-materials costs and other operational costs will have an impact on the actual cash flows generated in any given year and will be highly depending on sales volume and price. Hence, a sensitivity[1] analysis should be done to try to reduce the involved financial risks. To carry out the sensitivity analysis, two different scenarios are taken into account, i) the first one is increasing the cost by 10%, ii) while the second one is by decreasing the price of which the products are sold by 10%, these two scenarios were chosen to check what would happen if any these cases happens. In both cases as seen in table 6, the project still attains a net profit.

Table 12:Sensitivity analysis

Description	Net profit (EGP)
After increasing the cost by 10%	422,887
After decreasing the price by 10%	304,374

4.5.3. ROI and highlights of this section

$$\frac{Net\ profit}{Total\ fixed\ costs} \tag{1}$$

After determining the fixed costs, monthly revenues and expenses, net profits and the sensitivity analysis, it is now possible to determine the ROI. The ROI is a formula used to calculate how much the net profit of a year is compared to their initial investment as seen in equation 1. In this case, 3 different ROI's can be calculated, the first ROI is calculated by dividing the net profit form table 11 by the total fixed costs from table 8, which results in 54%. This mean that in less than 2 years the initial capital invested will be returned, this number is quite high, however it should be noted that this is the case when 100% of all the products obtained from pyrolysis are sold. Hence if another scenario was taken into account, one where 90% of the products are sold, this would obtain a ROI of 20%, if also the costs are increased by 10% it would result in an ROI of 27%. However, a problem in running this business is the high costs incurred each month, which will need a high capital reserve just in case the products are not sold efficiently.

All in all, after calculating the ROI and doing the sensitivity analysis, it can be concluded that project is feasible from an economic point of view, however further economic analysis should be made as this one lacked a few things: i) the salaries of blue-collar workers; ii) the transportation

[1] Sensibility analysis is a method used for assessing the implications of forecasting uncertainty on the feasibility of a project (Kenton, W. ,2021).

used in for the waste tires and the products; iii) other managerial costs that were out of scope of this research.

4.6. Policies governing tires waste in Egypt

In this section the policies and regulatory system in Egypt regarding waste tire and waste in general is discussed. Waste will be looked into as well, since, to the knowledge of the researcher and in accordance to the information obtained from interviewees' and found in online documents, Egypt does not have a specific policy regarding waste tires, as it considered as a waste under the hazardous waste and is dealt with accordingly. The policy and regulatory framework was studied by looking into how the waste system is organized in Egypt and by identifying what authorities are responsible of collecting, managing and regulate all activities related to wastes. Afterwards, the legal framework was analyzed to see what are the laws that regulate the waste management, and the challenges that Egypt is currently facing

4.6.1. Institutional Frameworks and Key Players Involved in solid waste management

In Egypt, there are different important stakeholder participating in solid waste management. As Figure 15 (Mostafa El Gamal, 2012) depicts the division of the public sector into national and local entities that function under the umbrella of the central government, while there are two types of private sector waste collectors: formal contractual firms and informal traditional rubbish collectors, which respond to the name of ''Zabbaleen''.

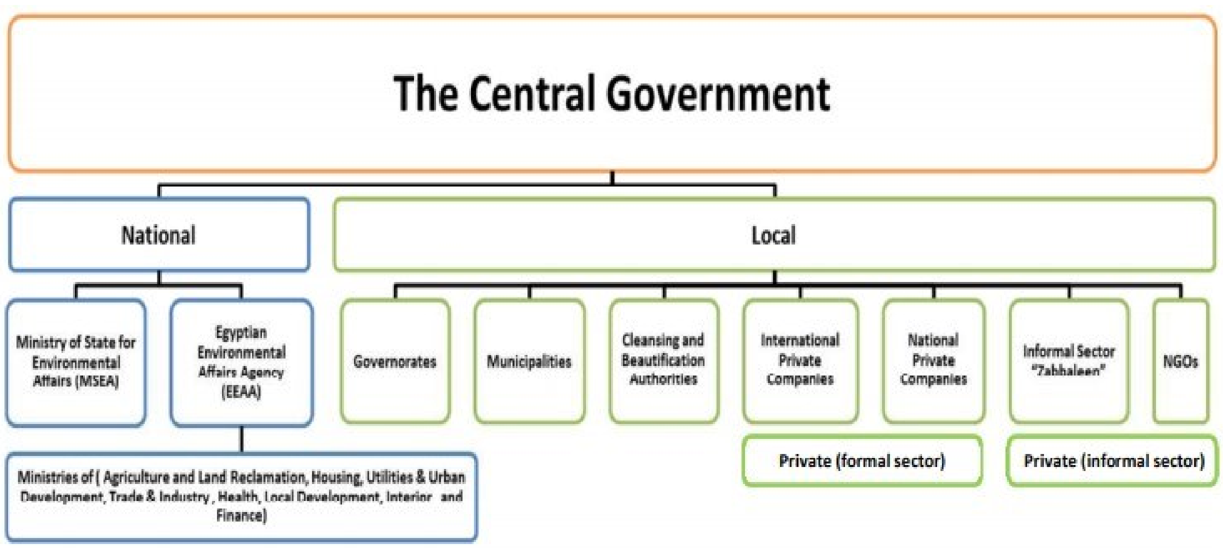

Figure 15:Key players in solid waste management in Egypt Mostafa El Gamal. (2012).

As described by Mostafa El Gamal (2012) the Ministry of State for Environmental Affairs (MSEA), in collaboration with the Egyptian Environmental Affairs Agency (EEAA), is primarily responsible for solid waste management at the national level. These two organizations work along with other organizations such as the Ministries of Local Development, Housing, Utilities, and Urban Development, Health, Water Resources and Irrigation, Agriculture, and Land Reclamation. The EEAA implements the country's environmental policy directives, including solid waste management (SWM), and serves as a general facilitator. The EEAA also guarantees that any environmental rules or legislation, such as laws and decrees, are followed. Furthermore, the EEAA supports governorates in finding waste management and treatment locations. Locally, governorates and municipalities, as well as Cleansing and Beautification Authorities (CBA) in large cities like Cairo and Alexandria, are responsible of Municipal solid waste management (MSWM) disposal, either directly or indirectly through the formal private sector, which is represented by some contracted international and national companies, or the informal private sector, which is represented by traditional garbage collectors ''Zabbbaleen'' and certain nongovernmental organizations NGOs. The following are some of the additional tasks of municipalities and cleaning and beautification authorities (Mostafa El Gamal ,2012):

- Granting permits to individuals in the above-mentioned official and informal private sectors who are in charge of garbage collection from empty lots, streets, markets, gardens, and waterway cleaning operations.
- Directly or via private firms, operate public composting facilities.
- Directly or via private businesses, supervising the operations of dumping and disposal sites.

The municipality, however, bears the primary duty for local MSWM. The public MSWM is often inefficient since it is an expensive operation with heavily subsidized equipment. Furthermore, there are certain legal concerns in terms of charging additional costs to customers. As a result, there are several examples of municipalities subcontracting and subletting a significant amount of garbage collection and street sweeping services to the private – formal and informal – sectors, which are considered more efficient than municipal services.

4.6.2. Policies and regulations

The next subsection will discuss the laws and policies governing the waste tire and solid waste. It will start by explaining the regulations that were prior to 2020, followed by the explanation of the first law of waste management that initiated in 2020 and what will differ after compiling with its new procedures.

Before Egypt lacked a legal framework when dealing with used tires and solid waste management (Sweep net, 2014; Azmy, A., & El Gohary, R. 2017). For tires, they were collected with other solid waste but were, and still are, considered as hazardous waste. Thus all laws for hazardous waste are applicable for tires, with the main laws governing the disposal of tires are law Number 4 of 1994 (4/1994) amended by laws 9/2009 and 105/2015 regarding the protection of the environment and its executive regulations, and Law 38/1967 amended by presidential decree 106/2012 regarding general public cleaning (IFC, 2016). The Environment Regulation, Law 4/1994, is one of the main system laws that govern urban solid waste management activities. The Law says that it is illegal to throw, handle, or burn garbage and solid waste except in designated areas, the most important articles regarding tires of law 4/1994 as stated in the IFC (2016) report are:

- Article 29 makes it illegal to handle hazardous chemicals and wastes without a warrant from the appropriate regulatory authority.
- Article 30 states that hazardous waste disposal must follow the protocols and legislation outlined in this Law's Executive Regulations.
- Article 32 prohibits the import of hazardous waste, as well as its entry into or movement through Egyptian territory.
- Article 31 prohibits the construction of any establishment for the treatment of hazardous wastes without a license from the appropriate regulatory authority and without first contacting the Egyptian Environmental Affairs Agency (EEAA). After consultation with the Ministries of Health, Industry, and EEAA, the Minister of Housing, Utilities, and New Communities shall assign the disposal sites and the necessary criteria to authorize the disposal of hazardous wastes.
- Article 40 mandates that when any kind of fuel is burned, whether for industrial, energy generation, building, or any other commercial purpose, the unhealthy smoke, fumes, and vapors generated by the combustion process be kept within allowable limits. And the individual in charge of such activity must take all appropriate steps to reduce the contaminants from the combustion products.

While solid waste collection and disposal are governed by law 38/1967 amended by 106/2012 regulates the collection and disposal of solid waste from rural neighborhoods, commercial and industrial enterprises, and public areas (NSWMP 2011). And that the local government is in charge of waste management and recycling, as well as licensing waste collectors and contractors.

This regulatory framework for solid waste management can be labelled as inadequate (NSWMP 2011), for instance, there are no provisions, for example, outlining in detail the functions and duties of governorates, municipalities, utility providers, or waste generators; requiring local governments to prepare and revise waste management plans; providing a waste collection service; or providing an interconnected network of waste treatment and disposal facilities; or the fact that only governmental and industrial entities and companies are entitled to the hazardous waste law, while individuals are not(IFC,2016). As a result, previous legal provisions were either too broad and vague, or provided insufficient explanations of a legal act, condition, or standard, or provided insufficient coverage of the spectrum of concerns that the laws and regulations were intended to address, resulting in gaps in legislation. Thus, Law 22/2020, Egypt's first waste management law was established. In the establishment of this law Waste

Management Regulatory Authority (WMRA) was tasked to have full authority with regards to this law, creating and implementing a nationwide waste management plan (Lynx, 2020; Shehata, I. 2020; EEAA, 2021).

- Regulating, monitoring, assessing, and creating integrated waste management activities.
- Creating investment possibilities in Egypt's waste management industry

As mentioned, another aim of the waste management law (WML) is to attract investment through financial, tax and other incentives for waste collection, transfer, treatment and final disposal. This includes extending eligibility for the tax breaks and incentives under Investment Law 72/2017 to companies whose main business is integrated waste management. With WMRA having the following tasks, implementing these penalties and facing the following challenges (EEAA, 2021; Lynx, 2020):

- Issuing the required licenses and permissions to conduct waste management operations.
- The WMRA will form a technical committee that will be in charge of regulating, auditing, and assessing all aspects of hazardous waste management techniques, as well as limiting their usage.
- A specific license issued by WMRA is required for the integrated management of hazardous waste and chemicals, and their approval is needed also for the circulation of these wastes.
- A record of hazardous waste and disposal techniques must be preserved.
- It is illegal to dump hazardous material in Egypt's territorial waters, continental shelf, exclusive economic zone, or high seas.
- Unlike before, Import, export, circulation, and distribution of hazardous waste must be done in line with the regulations established by the relevant ministry (Ministry of Local Development/Ministry of Housing) and after receiving the appropriate licenses from WMRA.
- The site of the plant producing hazardous waste must be sterilized and disinfected on a regular basis.
- In an interview with the head of hazardous substances in WMRA, Ms Elham Refaat, she explained that before law202/2020 the companies used to obtain a recycling facility license without having an inspection of what machinery they use, as they had to only state the machine used in a list that they submit. However, now WMRA has to come and inspect to insure that all listed machinery are present and being used, and if they comply with the listed machinery, then a license is granted.

4.6.3.1. Penalties:

- Fines for breaching Law # 202/2020 vary from EGP 1,000 (USD 65) to EGP 1 million (USD 65,000).
- The law requires offenders to face criminal charges and imprisonment for up to five years.

- Selected WMRA members may be given law enforcement authority to carry out the requirements of the Law.

4.6.3.2. Challenges:

- Previous legal provisions were either too broad and imprecise, gave inadequate explanations of a legal act, condition, or standard, or provided insufficient coverage of the spectrum of problems that the laws and regulations were meant to address, resulting in legislative gaps.
- Incentives for the private sector was lacking, as is the government's willingness to pay service fees to recyclers that manage garbage.
- Because of the fragmented institutional framework, institutional roles and responsibilities were unclear, there was duplication of efforts, and there was a lack of technical, administrative, institutional, and accountability competence.
- At the Governorate level, there is a lack of a legislative framework, planning, delivery, monitoring, liaison, and adequate and suitable understanding and competence.
- High cost of waste management in Egypt
- There are no clear instructions for local governments on how to execute Egypt's waste management legislation and policy.

Table 13: Waste collection coverage in Egypt Mostafa El Gamal (2012)

Governorate	Waste Collection Coverage (%)[19]	Governorate	Waste Collection Coverage (%)[19]
Cairo	70	Fayoum	65
Giza	60	Bani Souwaif	62
Alexandria	65	Menia	55
Kalyobiya	60	Assiut	65
Dakahliya	50	Sohag	60
Al Gharbya	47	Qena	60
Monofiya	40	Aswan	70
El-Beheira	50	Luxor	75
Kafr El-Sheikh	50	Red Sea	60
Sharqeia	45	Matruh	60
Damietta	55	North Sinai	60
Ismailia	60	South Sinai	80
Port Said	70	New Valley	60
Suez	70		

This led to many problems, one of which is the inefficient collection system, as mentioned earlier tires are considered as a hazardous waste yet they are collected with the solid waste. And that scrap tires are mainly collected by scavengers who seek to utilize them. As can be seen in table 13, throughout Egypt's 27 governances the collection rates are ranging from 40-80% with bigger cities like Cairo, Giza, Alexandria and Kalyobiya ranging from 60-70% (Mostafa El Gamal, 2012). In a study done by GIZ (2018), it was also found that only around 60% of the solid waste is being collected in Egypt. This is considered a major problem, as in order to manage the waste correctly, it has to be collected and transported to the necessary managing sites. And since no new reports have been issued since the passage of law 202/2020 the new collection rate is still unknown.

4.6.4. Highlights of this section

As described here above, it can be concluded that Egypt currently lacks a specific regulatory framework when dealing with waste tire particularly, yet it is addressed as a subpart of the hazardous substances and dealt with accordingly. And that the previous regulatory framework was not effective as it was too vague and responsibilities were scattered across different organizations. Thus Egypt is facing many challenges to manage tires and waste in general, however in the waste management law passed in 2020 looks promising as it addresses many topics that were mismanaged. With WMRA being in charge of waste management after law 202/2020, more promising waste management is expected as that law targets all wastes under one main organization. WMRA will be also in charge of regulating, auditing, and assessing, moreover it will encourage in creating investment possibilities in Egypt's waste management industry. In the interview, Ms Elham also explained that Egypt opened the import and export of tires, given that they are shredded into pieces which limit the fraud that may result in using waste tires as new ones after retreading. Another promising aspect according to Ms Elham is the extended producer responsibility which was included law 202/2020 which makes companies charge more for new tires, with the obligation to have the tires back once they are disposed and ensure that they are sold to recycling companies or managed in the right way. This organization, WMRA, has been established in 2015 however its increase in jurisdiction was only after the passing of law 202/2020, thus it is not possible to know if it is had any effect on the waste management in Egypt as no reports have been published yet. But in the interview with Ms Elham she stated that since the establishment of law 202/2020, illegal tire trading has decreased by around 70%, this was done by doing an accredited system where only licensed companies can buy waste tires at auction and only licensed tire sellers can sell. Lastly, tire pyrolysis is currently not being used as Egypt was lagging with innovative technological techniques to manage it, however with Egypt promoting waste to energy technologies as explained by Dr Samiaa Galal, pyrolysis of tires will have a bigger role in the future when dealing with waste tires.

5. Conclusions

In this section the highlighted findings of chemical recycling of tire in Egypt will be stated based on the results that are present in chapter 4 and from previous literature. Those findings represent building stones to construct step-wise the general conclusions of this research.

This research had the main focus of identifying the opportunities of using chemical recycling to manage waste tire in Egypt. This was done by firstly identifying the waste to energy technologies that are considered to be chemical recycling as they convert the waste to energy and simultaneously recover valuable materials that were once within the tire, with the mostly commonly used technologies being pyrolysis and gasification. After which the technologies were further analysed to show that pyrolysis and gasification are developing thermal treatments that operate under less severe circumstances than traditional direct combustion. Not only the gaseous fractions of pyrolysis and gasification may be utilised as a source of energy, but the liquid and solid fractions could also be valorised by burning or used as precursors to chemical synthesis or as raw materials. (Labaki, M., & Jeguirim, M. 2016). Furthermore, the working parameters of both process were studied, where it was found that pyrolysis produces mainly 3 products: syngas, oil and char, while gasification is used mainly for the production of syngas. And it was explained that in a study by Mavukwana, A., et al. (2021) where he conducted a comparison of the two techniques, focusing on carbon efficiency and chemical potential efficiency. It was demonstrated that both approaches are effective for eliminating hazardous waste and converting it into useful products. Nevertheless, the pyrolysis process outperformed the gasification method in terms of thermodynamic efficiency, with a higher total carbon efficiency and chemical potential efficiency, as gasification converts approximately 45 percent of the carbon feed to carbon dioxide, whereas pyrolysis produces char, which implies that the pyrolysis approach conserves carbon and has a low environmental impact. Moreover, it was concluded that pyrolysis is easier to construct operate and maintain than gasification facilities which is a more complex process that requires higher energy needs and the construction of a carbon capture system due to the high levels of carbon dioxide emissions. Rekhaye, A., & Jeetah, P. 2017). However, it was shown that by several authors (Labaki, M., & Jeguirim, M. 2016) ;(Mavukwana, A., et al. 2021), that when comparing pyrolysis to the gasification process, the quality of goods acquired from pyrolysis is lower and requires fewer refinements, since the syngas created by the latter may be used immediately after manufacturing. Because of the increased purity of syngas, the income per ton of waste tire in the gasification process is higher, making it more economically feasible and to continue the research within the time frame, only pyrolysis was deeper analyzed. Where it was shown that the most important process parameters were identified to be temperature, heat transfer and residence time, while the most commonly used reactors are the rotary kiln, fixed bed and fluidized bed. After which, how the pyrolysis of waste tires can contribute in fulfilling a circular economy was also studied. This showed that from the pyrolysis of ELT oil, syngas, char and steel can be produced. The oil will need a desulphurization process which is in the pyrolysis plant, after which it has quality similar of diesel and can be mixed with it. It also has many different applications other than being used as a fuel, as some crucial components like D-Limonene and BTX are used in several industries in a variety of applications. While the syngas produced is mainly used to heat up the process and according to several authors the process can be self-sufficient from the gas produced (Czajczyńska, D., et al., 2017); (Martínez, J. D., et al ,2013). While the char, which is also known as pyrolytic carbon black, can be also be deployed as a fuel, or can be upgraded to carbon black which has diverse applications, one of which is being re utilized in the tires again to replace virgin CB. Then it was explained that Egypt is currently in need of the usage of these recovered materials, as oil-consuming industries are growing and Egypt is currently consuming more than its production.

Afterwards, the process was assessed environmentally by a brief LCA using only manual calculations based on the Egyptian emission per Kwh and previous literature, which showed that it resulted in 65.5 kg of carbon dioxide emissions. Moreover, the emissions were analyzed according to Recipe2016 impact assessment technique, yet these midpoints were only discussed on how the emissions causes damage to the endpoints, but not by what extent.

Then the whole process underwent an economic feasibility test accounting for the inputs and out puts plus the fixed costs needed to start up such a project. This yelled a ROI of 54% if all the products were sold, while when 90% of the products are sold, a ROI of 20% was obtained. and the last scenario was increasing the costs by 10% which resulted in an ROI of 27%.

While regarding the last sub-question of this research may be stated that Egypt currently lacks a distinct legal framework for dealing with waste tires in particular, despite the fact that it is regarded as a subset of hazardous chemicals and dealt with accordingly. And that the old regulatory structure was ineffective because it was too ambiguous, with duties dispersed among several entities. Never the less, with WMRA in charge of waste management following the implementation of Law 202/2020, more promising waste management is envisaged, as the law targets all wastes under one primary organization. And since WMRA took control after the passage of Law 202/2020, it is impossible to determine if it has had any impact on waste management in Egypt as no reports have been released.

This all contributed to highlight the opportunities of chemical recycling of tires in Egypt, namely pyrolysis. As pyrolysis of tires will great contribute in accomplishing circular economy, and that the process is considered by several authors as well as the interview. The whole process yielded a ROI in around 2 years, given that all products are sold, and even if not all products were to be sold it still obtained 24% which is still considered a good ROI. Lastly, the policies in Egypt is are becoming more effective, which will facilitate the recycling of tire and as mention the country is moving towards waste and to energy and the pyrolysis of tires is considered a good example of waste to energy and at the mean time a contribute to obtain a CE.

5.1. Recommendations for future research

This study was done to highlight the opportunities of chemical recycling in Egypt. To do so this research was more exploratory rather than descriptive. As each section answered in this research should have a study alone in the future. The waste to energy and CE section should be studied in depth to know all the parameters involved in the process, and to know the exact quality of the oil and char obtained, this should be done using laboratory experiments. Moreover, a descriptive LCA should be done based on calculations that were obtained from experiments as well, afterwards the usage of a software, Gabi, or any similar software should be used to determine not only what are the midpoint that are affected, but to which degree as well. The economic feasibility should be done by doing more interviews with experts in the industrial business as market price differ each while. Lastly, one of the main problems that was faced in this research is the lack of papers concerning waste tire management or solid waste in Egypt. And that reports found were mostly published in the last decade, which makes things hard to evaluate whether the waste management in Egypt is getting better or not. Hence it is recommended that more reports are published and not only about solid waste management, but to divide the solid waste by compartments, as for example there were no reports or articles published about tires. Hence, it is also recommended that each waste has its own report rather than compiling them together under a solid waste management report.

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Appendix

Interviews

The interviewees were selected so that the missing information could be gathered and in order to make sure that the study's finding are in line with what happens in practice. Thus, two of the interviewees were selected to be technology experts that have the required knowledge about waste to energy technologies in the tire waste and rubber industry. While the latter two were from the policy taking side from Egypt, to know more about the current tire management system in Egypt and the challenges that they face, also to know if Egypt is promoting waste to energy technologies as a way to manage ELT. The interview is always started by giving a brief introduction about myself and the topic of this study.

List of interview participants

Name of the participant	Organization
Mr Balan Ramani	University of Twente
Dr Wilma Dierkes	University of Twente
Dr Samia Gallal	WMRA
Ms Elham Refaat	WMRA

Interview Questions

Introduction

I am a master student doing MEEM program, I am carrying a research about the opportunities of chemical recycling in Egypt, I am mainly looking into waste to energy technologies, namely pyrolysis and gasification to deal with the waste tires. After wards, due to the scope of the research and time limit it was decided that only pyrolysis will be looked into deeper, I will be looking into how the products obtained from the process can help in achieving a circular economy. I will also be doing a simplified LCA study and an economic feasibility test. And lastly I will be analysing how effective is the regulatory frame work in Egypt when dealing with waste tires.

Interview 1 questions

- Between pyrolysis and gasification, is there a preferred technology when dealing with waste tires?

The interviewee is not familiar with gasification.

In pyrolysis, one of the problems in the oil is the presence of high sulphur content, so the oil has to be fractionated before using it in chemical industries.

- To what extent pyrolysis considered a sustainable method to deal with waste tires?

Yes, as it recovers useful materials that can be used again, instead of using the virgin materials.

- Do you think pyrolysis of waste tire is considered attractive for investors in developing countries?

It's a good way to handle the tire waste problem, but I am not sure about the economic part.

- To what extent can the pyrolysis product help in achieving a circular economy?

Pyrolysis products can all be reused again and can help in achieving a fully circular economy with regards to waste tire management.

- If recovered carbon black is being reused again new tires, is it still possible to reuse it again, so basically recycling it twice?

I have not seen any study about this, it was planned in a project I am working on but for several reasons it did not happen. There will always be loss in properties when recycled, but the loss will not be noticeable, so yes it can be recycled more than one time.

- Can the tire derived oil be used as a high fuel after further refinements, I mean after desulphurization?

The interview is not familiar with any further technique.

- Bridgestone tire company started using recovered carbon black (rCB) in tires, do you think in the future all tire companies will utilize rCB in car tires again?

Yes, most companies are already researching to make it happen.

- Is pyrolysis considered recycling or energy recovery method?

Pyrolysis, is considered material recovery and energy recovery. In terms of the gas usage it is considered energy recovery, also if the oil is used as fuel that would be the same case. But the carbon black recovery is considered recycling of materials, also the oil could be used as a chemical commodity which is also considered as recovery of materials.

Interview 2 questions

- Between pyrolysis and gasification, is there a preferred technology when dealing with waste tires?

I would say pyrolysis is considered better, as it has 3 end products while gasification will only deliver syngas. But still it would depend on the application of course and the kind of market, but I would say if would like to achieve a CE, pyrolysis has the advantage that recovers materials, while gasification will produce new materials.

- If recovered carbon black is being reused again new tires, is it still possible to reuse it again, so basically recycling it twice?

in my experience and what I see in the lab, the pyrolytic CB is not fully used in the tire as it is a mix of virgin and recycled CB. And technically speaking, from the process side it should not matter and can be reused more than once.

- Can the tire derived oil be used as a high fuel after further refinements, I mean after desulphurization?

When using the oil in the cement, steel industry, you do not have to worry much about desulphurization. The advantage of desulphurization is that it makes the oil a chemical commodity and not only an energy resource, and that will affect the price of oil. But I am not sure if there are other refinement processes.

- Bridgestone tire company started using recovered carbon black (rCB) in tires, do you think in the future all tire companies will utilize rCB in car tires again?

As far as I know, Bridgestone is using rCB, Michelin is researching it and continental is using it also. So yes, in the future most tire companies will be using rCB. And that they may even use it not only the tires but in other rubber parts within the car.

- Is pyrolysis considered recycling or energy recovery method?

It depend on how it used, as it can be considered as both. Because if it is mainly used to recover the oil only to be used as a fuel then it considered energy recovery, but nowadays it is being used to recover also the carbon black not just the oil, so can be considered as a mix of both.

Interview 3 questions

- What are the current challenges with ELT management in Egypt?

For the companies that recycle tires, companies previously stated that they the required machinery that are set by the industrial ministers to operate, then they do an Environmental impact assessment which gets agreed upon by the ministry of environment. Then the companies do not imply with the machines that they said that operate with, hence now the company has to be visited by WMRA first before starting any operations unlike before where no inspections were made.

- Who sells the waste tires?
  A committee was formed from all stake holder’s ministries that have made accretion by the following:
  EIA, license and assessment
  Only companies that have the following criteria can enter any bids for tires. This will control who gets in the bidding, even the waste tires sellers have to get an accreditation from WMRA in order to sell its tires. This is closing the gaps on illegal tire selling and since that implementation of the law, illegal tire trading has been decreased by 70%.

- What kind of license would be needed to build a tire pyrolysis plant in Egypt?
  The license must be granted from the industrial ministry based on the type of machinery that is going to be used, also how are they going to store the waste tires.

- It is illegal to dump hazardous material in Egypt's territorial for companies or individuals?
  Yes it is for both now, and the extended producer responsibility is also now in the law which makes companies charge more for new tires , knowing that they have to get it back to ensure that they are sold to recycling companies or managed in the right way.

- Can you import/export waste tires after law22/2020?

Because of the low efficiency of the collection of tires, it is now possible to import and export waste tires but it has to be shredded.

Interview 4 questions

- How are tires being recycled in Egypt?

They are first mechanically stripped to take out the steel, then they are fragmented to smaller pieces, which can then be used in variety of products.

- Do you think pyrolysis is promising in Egypt?
  It is promising with the condition that the proper equipment is being used, due to the impurities such as sulphur that can be found in the oil.
  Moreover, Egypt is now moving towards a waste to energy, which enables the maximum extraction of energy from wastes. As Egypt is promoting any technology that enables the transformation of waste into materials of economic value that can be benefited from and save natural resources. And Egypt is also offering incentives for any waste to energy project, as the use of the virgin materials is environmentally not friendly. Also it is not only the environment that is being damaged, as when the air is polluted people get damaged which in turn affects the economy. Also, industrial services and tourism and deeply affected.

- Is pyrolysis considered sustainable?
  It is, since we will not stop using tires, this technology enables us to extract components that are needed. And it helps in achieving circular economy, creating jobs and minimizing the environmental effects.

- Which is more favourable for Egypt, mechanical or chemical recycling? And why?

It depends on the economic study of both process, I am not quite sure which is more favourable, but both can be used as they are both needed.

Consent forms

Consent form Prof. Dr. Samia Galal Saad,

Name of the project : The Opportunities in Chemical Recycling of Tires in Egypt

Consent to take part in research study interview

- • I, Prof. Dr. Samia Galal Saad, voluntarily agree to participate in this research study interview.

• • I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.

• • I understand that I can withdraw permission to use data from my interview after it, in which case the material will be deleted.

• • I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.

• • I agree to my interview being audio-recorded.

• • I understand that all information I provide for this study will be treated confidentially.

• • I understand that in any report on the results of this research my identity will remain anonymous if preferred to be so. This will be done by not explicitly mentioning my name and disguising any details of my interview which may reveal my identity or the identity of people I speak about.

• • I understand that I am entitled to access the information I have provided after the interview.

• • I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

Here as follow the names of the people involved in this research who guarantee the agreed use of this consent and the answers provided during the interview.

Researchers:
Ahmed El Mahalawy

Project Supervisor:
Dr. Laura Franco Garcia

Participant: Prof. Dr. Samia Galal Saad

Signature of participant:
Samia G. Saad

Date: 21/8/2021

Consent form Mr Balan Ramani

Name of the project : The Opportunities in Chemical Recycling of Tires in Egypt

UNIVERSITY OF TWENTE.

Consent to take part in research study interview

- • I, Balan Ramani, voluntarily agree to participate in this research study interview.

- • I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.

- • I understand that I can withdraw permission to use data from my interview after it, in which case the material will be deleted.

- • I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.

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Here as follow the names of the people involved in this research who guarantee the agreed use of this consent and the answers provided during the interview.

Researchers:
Ahmed El Mahalawy

Project Supervisor:
Dr. Laura Franco Garcia

Participant: Balan Ramani

Signature of participant: Balan Ramani

Date: 25/8/2021

Consent form Ms Elham Refaat

UNIVERSITY OF TWENTE.

Name of the project : The Opportunities in Chemical Recycling of Tires in Egypt

Consent to take part in research study interview

• • I, Elham Refaat, voluntarily agree to participate in this research study interview.

• • I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.

• • I understand that I can withdraw permission to use data from my interview after it, in which case the material will be deleted.

• • I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.

• • I agree to my interview being audio-recorded.

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• • I understand that in any report on the results of this research my identity will remain anonymous if preferred to be so. This will be done by not explicitly mentioning my name and disguising any details of my interview which may reveal my identity or the identity of people I speak about.

• • I understand that I am entitled to access the information I have provided after the interview.

• • I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

Here as follow the names of the people involved in this research who guarantee the agreed use of this consent and the answers provided during the interview.

Researchers:
Ahmed El Mahalawy

Project Supervisor:
Dr. Laura Franco Garcia

Participant: Elham Refaat

Signature of participant:
Elham Refaat

Date: 20/8/2021

UNIVERSITY OF TWENTE.

Consent form Wilma Dierkes,

Name of the project : The Opportunities in Chemical Recycling of Tires in Egypt

Consent to take part in research study interview

- • I, Wilma Dierkes, voluntarily agree to participate in this research study interview.

- • I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.

- • I understand that I can withdraw permission to use data from my interview after it, in which case the material will be deleted.

- • I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.

- • I agree to my interview being audio-recorded.

- • I understand that all information I provide for this study will be treated confidentially.

- • I understand that in any report on the results of this research my identity will remain anonymous if preferred to be so. This will be done by not explicitly mentioning my name and disguising any details of my interview which may reveal my identity or the identity of people I speak about.

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Here as follow the names of the people involved in this research who guarantee the agreed use of this consent and the answers provided during the interview.

Researchers:
Ahmed El Mahalawy

Project Supervisor:
Dr. Laura Franco Garcia

Participant: Wilma Dierkes

UNIVERSITY OF TWENTE.

Signature of participant:

Wilma Dierkes

Date: June 9th, 2021