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The sustainability assessment of activated carbon production from medium density fibreboard waste

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa*.*

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Abstract

Activated carbon is the preferred adsorbent in a great number of process applications thanks to its superb performance and wide availability. The common precursors for activated carbon production are coal-based. To decrease dependency on fossil resources, a lot of research has been carried out for determining viable alternatives. Act&Sorb has come up with an innovative technology to produce activated carbon from medium density fibreboard waste. This technology provides a feasible alternative to activated carbon production while at the same time it gives new value to a waste product and thereby contributes to the circular economy. Although the process shows a great potential regarding its sustainability, a comprehensive sustainability assessment is lacking. This study evaluates the carbon intensity of the process by estimating the carbon dioxide emissions resulting from the production and comparing them to the competing technology of waste incineration. The amount of fossil carbon dioxide emitted is negligible compared to the amount of biogenic carbon dioxide emitted and the total carbon dioxide emissions are for most configurations smaller than the resulting emissions from the waste incineration plant. Life cycle assessment is carried out for determining the major environmental impacts of the process and the factors that contribute to it. When applying a cradle-to-gate model, the medium density fibreboard has by far the highest environmental impact and the environmental impact categories affected the most are global warming and main air pollutants and particulate matter. Changing the location of the plant results in major differences in the overall sustainability.

Keywords

Activated carbon; Medium density fibreboard; Carbon dioxide emissions; Life cycle assessment; Environmental impact; Sustainability

Resumo

O carvão ativado é o adsorvente preferido em grande número de aplicações de processo graças ao seu excelente desempenho e ampla disponibilidade. Os precursores comuns para a produção de carvão ativado são baseados em carvão. Para diminuir a dependência dos recursos fósseis, muitas pesquisas foram realizadas para determinar alternativas viáveis. A Act&Sorb surgiu com uma tecnologia inovadora para produzir carvão ativado a partir de resíduos de painéis de fibras de média densidade. Essa tecnologia oferece uma alternativa viável para a produção de carvão ativado, ao mesmo tempo que agrega novo valor a um resíduo e, portanto, contribui para a economia circular. Embora o processo mostre um grande potencial em relação à sua sustentabilidade, falta ainda uma avaliação mais abrangente quanto a esse aspeto. Este estudo avalia a intensidade de carbono do processo estimando as emissões de dióxido de carbono resultantes da produção e comparando-as com a tecnologia concorrente de incineração de resíduos. A quantidade de dióxido de carbono fóssil emitido é insignificante em comparação com a quantidade de dióxido de carbono biogênico emitido e as emissões totais de dióxido de carbono são, para a maioria das configurações, menores do que as emissões resultantes na produção de incineração de resíduos. A avaliação do ciclo de vida é realizada para determinar os principais impactos ambientais do processo e os fatores que contribuem para isso. Ao aplicar um cradle-to-gate mode, o painel de fibras de densidade média tem, de longe, o maior impacto ambiental e as categorias de impacto ambiental mais afetadas são o aquecimento global e os principais poluentes atmosféricos e partículas. Alterar a localização da fábrica resulta em grandes diferenças na sustentabilidade geral.

Palavras chavre

Carvão ativado; Placa de fibra de densidade média; Emissões de dióxido de Carbono; Avaliação do ciclo de vida; Impacto ambiental; Sustentabilidade

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List of acronyms

AC	Activated carbon
CA	Competent Authority
CE	Circular economy
CO_2	Carbon dioxide
EI	Environmental impact
GAC	Granular activated carbons
GHG	Greenhouse gas
GWP	Global warming potential
HHV	Higher heating value
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MDF	Medium density fibreboard
MPt	Mega point
NG	Natural gas
PAC	Powdered activated carbons
PET	Polyethylene terephthalate
PM	Particulate matter
POP	Persistent organic pollutants
UBP	Eco-points (Umweltbelastungspunkte)
WI	Waste incineration

Chapter 1

Introduction

A general overview of the work is given in this chapter. The process being assessed is briefly described. The motivation for carrying out the research is stated, and a research question is formed. The structure of the work is provided at the end of the chapter.

1.1. Overview

Activated carbon (AC) is a valuable material that has found usage in a multitude of applications which affect our daily lives. Its high adsorption capacity and the possibility to produce sufficient amounts of AC relatively easily from inexpensive precursors has made activated carbon important world-wide as a product for purification processes. Manufacturing essential products that we consume with a required level of purity, cleaning the drinking water from harmful particles and limiting the emissions of environmentally dangerous compounds from electricity generation plants are just a few examples of the range of applications for AC. With the development of the world, increasing population and growingly stricter environmental policies, AC will continue to be of great importance in years to come [1].

Activated carbon can be produced from a wide range of carbon-containing precursors of both fossil and renewable origin. Despite the variety of suitable precursors, coal remains one of the most common sources for AC production due to its abundance and low manufacturing cost. As a depleting fossil resource that has also several other uses, including electricity generation, which is especially important for developing economies, a number of alternatives have been assessed for AC production in the past decades. While the activated carbons produced from the alternative sources often show comparable qualities to the ACs produced from coal, reaching the economic feasibility for the production processes is more challenging. One of the companies that has come up with a sustainable and economically viable precursor for activated carbon production is Act&Sorb. Act&Sorb has developed a technology for producing AC from medium density fibreboard (MDF) waste, thus providing a replacement for coal and creating a value-adding recycling solution for a waste stream [2] [3].

Medium density fibreboard is a very versatile wood product with numerous applications primarily for construction and furniture production. Every year, more than 70 million tonnes of MDF is produced worldwide. The Act&Sorb recycling process creates value from the manufacturing cut-offs and end-of-life MDF by converting the waste into high value activated carbon. This solution contributes to the circular economy concept by giving a new valuable life to a waste stream through recycling. Therefore, it is possible to revert from the traditional "take-make-consume-dispose" model and reach a higher level of circularity, in which MDF waste can be utilized as a resource for a new life cycle as activated carbon and the total waste of the system, which needs to be disposed of is minimized [3] [4] [5].

1.2. Motivation and contents

Producing activated carbon from MDF waste is a new and innovative technology. Although the general idea of the technology is expected to increase sustainability through the implementation of the circular economy concept, there is a need for improved data for assessing the sustainability of the process, as the industrial production has not been implemented yet. The goal of this thesis is to address that issue and assess the sustainability of the Act&Sorb process by utilizing the available information and assumptions taken. A research question was stated for accomplishing that task:

How sustainable is the production of activated carbon from medium density fibreboard waste?

As this question is rather broad and gives a lot of room for interpretation, it was divided into two sub questions for increased tangibility:

1. How carbon intensive is the production of activated carbon from medium density fibreboard waste?
2. What are the major life cycle impacts of the production of activated carbon from medium density fibreboard waste?

The answer to the first question focuses on the production process itself and analyses the carbon dioxide (CO_2) emissions resulting from the production of activated carbon from medium density fibreboard waste, whereas the answer to the second question gives a more holistic overview of the environmental assessment of the technology and defines the ecological hotspots, which need to be considered for this type of production. The combined result gives a good overview of the sustainability of the whole process and thereby provides an answer to the initial research question.

For the assessment of the carbon intensity of the process, a calculation model in Microsoft Excel was created to calculate the biogenic and fossil carbon dioxide emissions resulting from the process based on the data from an industrial equipment provider, laboratory tests and literature review. The calculations are done with non-detailed initial design data. An analysis of the system is carried out, taking into account the effect of each element. For the second question, life cycle assessment (LCA) methodology was implemented. Simapro 8.4 software with ecoinvent v3.0 database was used for the assessment and the data required as the inputs for the model were acquired from the calculation model developed for the assessment of carbon intensity.

The work is divided into five chapters with introduction being the first one. The second chapter gives an overview of the reviewed literature and provides background information about activated carbon and life cycle assessment and the research previously carried out in the field. The third chapter provides an analysis of the carbon intensity of the process. A full evaluation of the production plant is carried out and the role of every part of the system is determined. As a result, the carbon dioxide emissions, both biogenic and fossil are defined. In addition, a comparison is drawn to the competing technology of waste incineration (WI). A potential improvement to the system by maximising the electricity generation is proposed and analysed. The fourth chapter covers the life cycle assessment of the technology. The scope of the system is defined, and multiple scenarios are created for a comparative analysis. The LCA takes into consideration the effect of location and logistics by assessing the production in Belgium, Norway and Estonia, countries with remarkably different carbon intensity electrical systems, and transportation by trucks, rail and waterways. The obtained results are compared to the results for WI in the corresponding countries. The fifth chapter sums up the work carried out in the thesis and the results achieved. The research question and the sub questions stated are answered and an evaluation of the results is given. Recommendations for further research are proposed.

Chapter 2

Literature review

This chapter gives an overview of activated carbon, its applications, production methods, largest producers, precursors used and discusses the potential of using medium density fibreboard waste as a source material for activated carbon production. In addition to that the concepts of circular economy and life cycle assessment are explained. The final part of the chapter gives an overview of life cycle assessments carried out that are of importance to the life cycle assessment conducted in this study for the evaluation of the environmental impacts resulting from the implementation of the Act&Sorb process on industrial scale.

2.1. Activated carbon

Activated carbon is a porous carbon material, a char which has been subjected to reaction with gases, sometimes with the addition of chemicals (e.g. $ZnCl_2$) before, during or after carbonization in order to increase its adsorptive properties [6].

Activated carbons were the first adsorbents to be developed. Activated carbons are produced from a solid carbonaceous based material, which is non-graphitic and non-graphitizable, and has an initial isotropic structure. The precursor is transformed or “activated” by means of medium to high temperature treatments, which remove solid mass, and at the same time, create pores, where the removed mass was previously located. The common properties of activated carbons and other kinds of carbon adsorbents is their well-developed pore network and the similar ways in which they are produced [6].

2.1.1. Applications of activated carbon

The rapid development of modern society over the 20th century promoted a fast-growing production and utilization of activated carbon, especially in the second half of the last century due to the stricter environmental regulations regarding water resources, clean gas application, air quality control, energy storage/conversion and economic recovery of valued chemicals [1].

Activated carbon is considered as the universal adsorbent. Its high surface area, porous texture and surface chemistry are its distinctive features. The most common applications of activated carbons, from 1985 to 2016, according to Scopus database are depicted in Figure 2.1. The most studied field concerns the adsorption of heavy metals ions: mercury Hg(II), chromium Cr(III) and Cr(IV), cadmium Cd(II), arsenic As(V) and lead Pb(II); followed by the adsorption of dyes (mainly malachite green and methylene blue), organic compounds (benzene, phenol, toluene, formaldehyde and methyl tert-butyl ether), catalyst, CO_2 capture, adsorption of ammonia and methane storage [1].

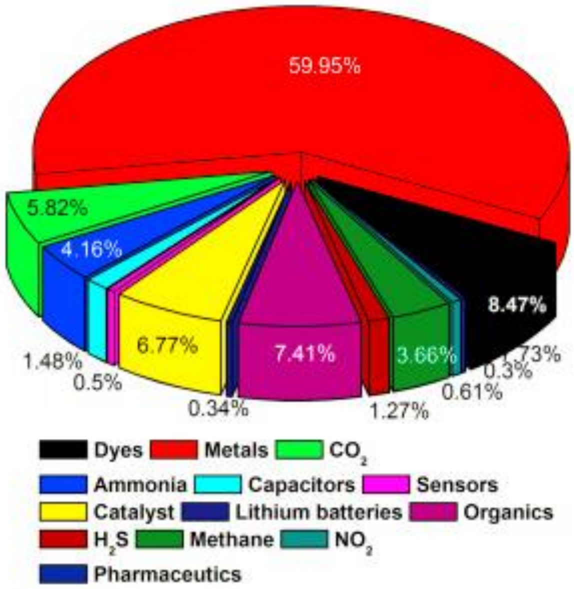

Figure 2.1 Percentage of the most common applications of activated carbons from 1985 to 2016 [1]

The major markets for AC in decreasing order of importance are: water treatment, decolorizing, chemical and pharmaceutical processing, food processing, air and gas purification and solvent vapour recovery. The market has been increasing constantly as a consequence of environmental issues, especially for water and air purification [6].

Other liquid-phase applications of activated carbon with lower consumption, but accounting for around 20% of the total liquid-phase consumption, include: mining (for the usage of low grade ores of silver and gold), household uses (home water taps for purification, oven hoods and aquaria), food, beverages and oils, pharmaceuticals, dry cleaning, electroplating, chemical processes and others [6].

2.1.2. Activated carbon production methods

The production methods can be grouped into: physical, or more properly thermal activation, which consists of thermal devolatilization followed by char gasification with an oxidising agent, and chemical activation, which consists basically of the inert carbonization of mixtures of the raw material with a chemical agent. An overview of different production routes is given in Figure 2.2. When the raw material is subjected to thermal activation, the higher the volatile content of the raw material is, the lower the yield is. This type of treatment, however, gives rise to a more accessible micropore structure, thereby ensuring a higher and more homogeneous pore development. On the other hand, low volatile raw materials (such as anthracites or cokes) lead to a greater density and hardness. Most activated carbon materials are produced in either granular or powdered forms, depending on the final application. The type of raw material used also determines, whether the AC produced from it will be in powdered or granular form [6].

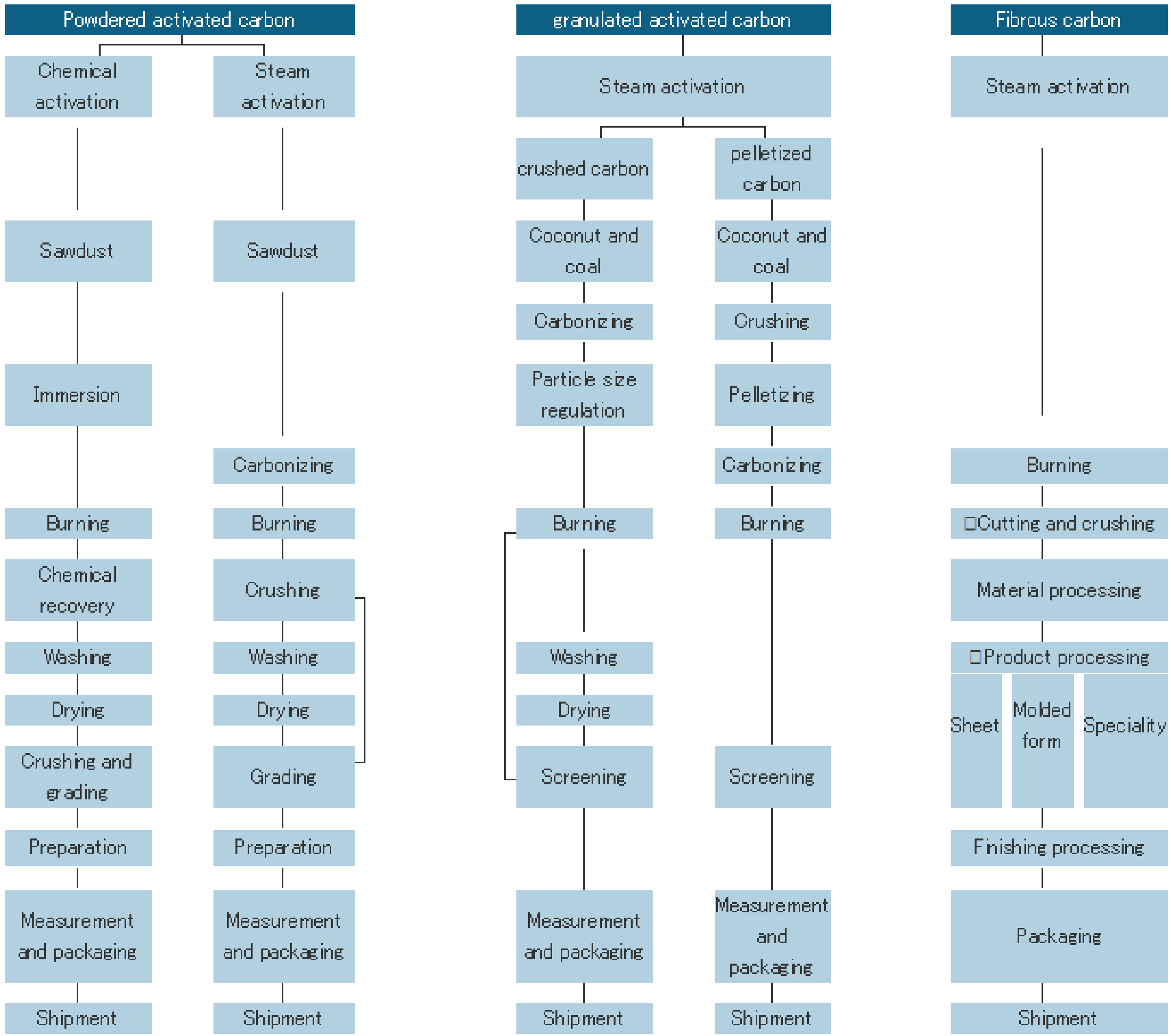

Figure 2.2 Activated carbon production methods [7]

Thermal activation or physical activation generally consists of two consecutive steps. The first step is thermal carbonization of the raw material, where devolatilization takes place, carried out at medium or high temperatures, to produce a char rich in carbon. The second step is activation, where the remaining char is partially gasified with an oxidizing agent, mostly steam. If both steps are carried out simultaneously, the process is called direct activation [6].

Chemical activation is carried out in a single carbonization stage. The raw material is first impregnated with appreciable amounts of a chemical agent and then heated up. The product must be washed to eliminate any excess chemical agent after carbonization. The thermal treatment temperature depends on what chemical agent is used. The most common are phosphoric acid, $ZnCl_2$ and alkaline hydroxides [6].

Steam activation is the most widely used method for producing activated carbons in the world. In terms of adsorption capacity, it easily reaches specific surface areas of 1000 $m^2\ g^{-1}$ at 50% of activation conversion degree, when an acceptable raw material with an initial ash content below 10% is used.

Basically, steam activated carbons are microporous materials, with a micropore size that increases with the activation degree, but with no mesopore development [6].

Thermal activation normally yields adsorbents with a medium to high adsorption capacity, a medium micropore size distribution and no mesopore formation. Phosphoric acid activation yields a carbon with a higher adsorption capacity than thermal activation and a wider micropore size distribution, whereas KOH yields extremely narrow microporous carbons. Each type of activated carbon is suited to a particular application [6].

Other properties of activated carbons, however, may be even more important than their textural properties. One example is particle size. A classification of carbon adsorbents based on size divides them into Powdered Activated Carbons (PAC) and Granular Activated Carbons (GAC). For certain specific applications a choice must be made between PAC or GAC regardless of porous properties. For example, in order to clean up a gas stream in a fixed bed, a granular material must be used. Otherwise the pressure drop would be enormous. Furthermore, granular carbon must be dense, hard and with a low abrasion index [6].

PAC is not a particularly well-developed carbon adsorbent. This is because some of the characteristics that are important for other forms of carbon adsorbents such as high density, hardness and abrasion index are irrelevant in the case of PAC. In addition, PAC must be discarded after use and cannot be reused. This implies that the cost of producing PAC must be kept to a minimum. At present investment in R&D for the development of better PAC adsorbents is negligible, most of the industrial research focuses on the GAC and the special forms of carbon adsorbents [6].

GAC has a mean particle size between 1-5 mm. It is usually used in fixed bed adsorbers in continuous processes and with low pressure drops, in both liquid and gas phase applications. Most of the gas phase applications (gas purification, solvent recovery, air filtering and gas masks, gas separation by PSA, catalysis, etc.) use GAC. In addition, GAC is displacing PAC in many liquid phase applications such as gold extraction and drinking water treatment. GAC has the advantage, compared to PAC, of offering a lower pressure drop along with the fact that it can be regenerated or reactivated and therefore reused more than once. However, GAC must have, in addition to the proper micropore size distribution, a high apparent density, a high hardness and a low abrasion index. To meet these requirements, a lot of R&D is focused on the development of better GAC [7].

2.1.3. Activated carbon producers

Activated carbon production is a relatively constrained business. The market is controlled by a small number of companies that each have a large market share. The producers in general are focused on a specific precursor that they have used for production for a long period. Although the business segment has been historically rather concentrated, there have been several mergers in the past years, which has further reduced the number of activated carbon producers and has given more control over the market to a limited group of companies [8] [9] [10].

The largest producer of activated carbon is the USA, which accounts for more than 40% of the total production capacity of the world. The United States is followed by Europe, Japan and the Pacific Rim countries [8].

The largest producer in the USA is Calgon Carbon Corporation, with plants in several locations. Its annual capacity represents around 42% of the total production capacity of the country; the main activation process is thermal, and the precursors used are bituminous coal, coconut shell and charcoal. The second largest producer is Norit Americas, Inc., with around 23% of total capacity. Thermal activation is carried out with lignite and bituminous coal and chemical activation (with phosphoric acid) is carried out with wood and peat. The third producer is Westvaco Corporation, with around 12%, sawdust being the main precursor for both thermal and chemical (with phosphoric acid) activation [8].

The largest producer in Western Europe is Norit NV with plants in the Netherlands and the United Kingdom. The annual capacity share of the company is almost 50% of the total capacity. Peat for thermal activation and sawdust for chemical (with phosphoric acid) activation are the main precursors used. Other producers are Chemviron with around 20% of total capacity, CECA, around 15%, and PICA, around 12%. A new company, ICASA, has started production of activated carbon in Spain from olive stones. Reactivation of spent activated carbon is important in Europe. Reactivation is normally carried out on-site for carbons used in gas-phase applications, but it must be carried out off-site for carbons used in liquid-phase applications like water treatment [8].

Production capacity of activated carbon in Japan is widely distributed among companies, the largest producers being: Takeda Chemicals Industries (23%), Kuraray Chemicals (18%), Futamura Chemical Industries (18%) and Mitsubishi Chemical Corporation (11%). Lignocellulosic precursors such as coconut shell, wood and sawdust are the more frequently used, with smaller proportion of coal, resinous pitch, etc. Some of the activated carbon is produced outside of Japan, mainly in Southeast Asia, where joint venture companies have been established [8].

Globally, some of the major competitors on the activated carbon production market are Cabot Corporation, which acquired Norit NV in 2012, Kuraray Company, which acquired the merged corporation of Calgon Carbon & Chemviron in 2018, Osaka Gas Chemicals, that is also the parent company for Jacobi Carbons, one of the largest activated carbon producers from coconut shells, Mindong Lianyi, Westvaco and the world's leading manufacturer and marketer of coconut shell activated carbon, Haycarb PLC, that carries out its main activities is Sri Lanka [11] [8] [9] [10] [7].

2.1.4. Activated carbon precursors

Activated carbon is produced from nearly all carbon-containing organic materials, mainly wood, sawdust, nutshells, fruit stones, peat, lignite, coal, petroleum coke etc. The use of a suitable precursor is mainly conditioned by its availability and cost, although it also depends on the main applications of the manufactured carbon and the type of installation available. A key element is the reliability and consistency of the resource [6].

The resulting properties of the product are dependent on the precursor, and consequently, the carbons can be tailored for selected applications. Furthermore, the resulting AC properties are also influenced to a great extent by the activation treatment. Selection of the appropriate raw material is based on the following criteria:

- Possibility of yielding a good activated carbon in terms of adsorption capacity, high density and hardness.
- Low in inorganic matter. The adsorption capacity is measured per mass unit, and since inorganic materials in organic matter are mostly non-porous, their presence reduces the adsorption capacity.
- Availability and cost. As with any other product, the price of the raw material affects the final cost, so a high availability is important to ensure stable prices. It should also be taken into account that there is a considerable mass loss in all the activation treatments, and the lower the product yield, the higher the cost. The product yields may vary considerably and can be as low as 5-10% for wood-based carbons. Moreover, raw material availability obviously depends on the part of the world in which the plant is located [7].

In general, there are two main precursors for activated carbon production; coal-based feedstock and agricultural by-products or lignocellulosic materials. Presently, the largest part of the commercial activated carbons is produced from fossil fuel-based precursors such as petroleum residues, hard coal, peat and lignite, which are expensive and non-renewable. Another drawback in utilising these fossil materials is related to their decreasing production trend, and intensive regeneration and reactivation of the commercial activated carbons may contribute to high pricing and result in sorbent degradation. In consequence, the economic feasibility will be affected. These factors have led to the increasing focus on biomass precursors, which are cheaper, readily available, renewable, structurally porous and environmentally friendly [2] [12] [13].

Over the past years, a variety of potential agricultural biomass precursors have been considered. These include materials like: corn hob, hazelnut shell, pruning mulberry shoot, olive stone, Jojoba seed, Chinese fir sawdust, coconut shell, wood, hazelnut bagasse, kenaf fibre, bamboo, rice husk, *petai*, groundnut shell, paper mill sludge, prosopis (*Prosopis juliflora*), coconut husk, *Jatropha* husk, tamarind wood, pistachio-nut, sugarcane bagasse, jackfruit peel, banana peels, casings from coffee beans, cassava peel, apricot shell, sunflower seed shell, rubber wood sawdust, oil palm empty fruit bunch, camellia oleifera shell, poplar wood, argan seed shell, palm kernel shell and many other organic waste materials. However, the collection from separated areas, transportation, bulk availability and seasonal variations in quality and availability are reasons why most of these resources are not used [2] [6] [13].

In practice, wood and coconut shells are the biomass precursors that are of significant importance for the production of commercial activated carbons, yielding to a global production of more than 300 000 tonnes per year. However, this is just a small fraction of the worldwide demand of 12 804 000 tonnes of activated carbon consumed just in 2015. These are inexpensive materials with a high carbon content and a low inorganic content, and consequently, are suitable for use as an activated carbon precursor.

As the carbon contents of wood and coconut shells are lower compared to the fossil precursors, the yield is also lower. However, this is compensated by the lower cost [7] [2] [1].

2.2. Medium density fibreboard waste as a potential precursor for activated carbon production

One of the potential materials for being the precursor for activated carbon production is medium density fibreboard. MDF is used widely in the production of furniture and in the construction sector. After the end of the product's usage, it needs to be disposed of. Common ways for doing that is to either incinerate the MDF waste at a waste incineration plant or landfill it. However, as the MDF waste has a high carbon content, it is possible to use it for activated carbon production. This way, the MDF waste can be enhanced through the production of added value materials, with a growing demand, and also provide a solution for the waste management with reduced environmental impact (EI) by the recovery and recycling of MDF waste [14].

Tests carried out with activated carbons produced from MDF waste have shown promising results that are comparable to the commercial counterparts. The activated carbons produced have shown different structural characteristics. Nevertheless, the produced activated carbons are essentially microporous carbon adsorbents with potential applications in both liquid and gas phase. In addition to the suitable qualities for adsorption, the mechanical behaviour and consequent resistance to the continuous flow of an aqueous solution through the produced activated carbons has also indicated good capabilities in further applications [14].

Using MDF as a precursor for AC production has also been researched from the economic perspective. It is a possible opportunity to avoid waste disposal costs and turn the waste stream into a profitable material resource. According to an analysis, a profitable production of AC can already be achieved with a rather pessimistic scenario that estimates a zero gate fee for MDF waste, which is likely to be higher in practice. Another factor to have effect on the profitability is the processing capacity. A larger manufacturing plant can produce carbons at a lower cost despite higher initial investment. As a result, a lower minimal selling price can be obtained [15].

2.3. Principle of circular economy

Looking beyond the current take-make-dispose extractive industrial model, a circular economy (CE) aims to redefine growth, focusing on positive society-wide benefits. Generally, the CE is outlined as a cycle of the extraction and transformation of resources and the distribution, use and recovery of goods and materials. It entails gradually decoupling economic activity from the consumption of finite resources and designing waste out of the system. An overview of the circular economy cycle is represented in

Figure 2.3. First, firms take resources from the environment to transform them into products and services. Then, they distribute the products or services to consumers at sale points or to other firms, and the products/services are used by consumers in the market. At this point, the CE proposes to close the loop through the recovery of goods. In this stage, the importance of innovation to recover and enrich the used materials either through the environment or industrial processing instead of disposing of them or simply wasting them needs to be stressed. It is expected that the adoption of CE will fundamentally transform economic activities away from reliance on non-renewable and emissions intensive carbon flows towards more sustainable production and consumption [16] [4] [17].

Figure 2.3 Circular economy cycle [17]

There is a general agreement on the fact that circular economy is characterized by three different levels of research and implementation: micro, meso and macro. At the micro, or enterprise, level, companies are focused on their own improvement processes. In addition, at this level there is a positive relationship between a company's environmental management maturity level and its willingness to implement CE because of the positive impact it has on its prestige among consumers and the associated reductions in cost. The meso level includes companies which belong to an industrial symbiosis that will benefit not only the regional economy, but also the natural environment. Lastly, the macro level is highly focused on the development of eco-cities, eco-municipalities or eco-provinces through the development of environmental policies and institutional influence [17].

Circular economy can be defined as an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels. The logic of turning from linear and wasteful to cyclical, restorative, reproductive and smart physical flow structures is appealing and positively provocative crossing sectoral, organizational, administrative and national boundaries and border in its message. Attaining this circular model requires cyclical and regenerative environmental innovations in the way society legislates, produces and consumes [17] [16].

2.4. Life cycle assessment

This subchapter provides an overview of the life cycle assessment process as well as gives examples of some life cycle assessment studies carried out, that are of importance to the LCA conducted in this work.

2.4.1. Definition of life cycle assessment

The increased awareness of the importance of environmental protection and the possible impacts associated with the manufacture and consumption of products, has increased interest in the development of methods to better understand and address these impacts. One of the techniques for this purpose is life cycle assessment [18].

Life cycle assessment (LCA) is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. The life cycle consists of consecutive and interlinked stages of a product or service system, from the extraction of natural resources to the final disposal. A schematic overview of the “cradle-to-grave” life cycle is given in Figure 2.4. The conversion stage is the so-called “gate-to-gate” part of the life cycle [19] [20] [21].

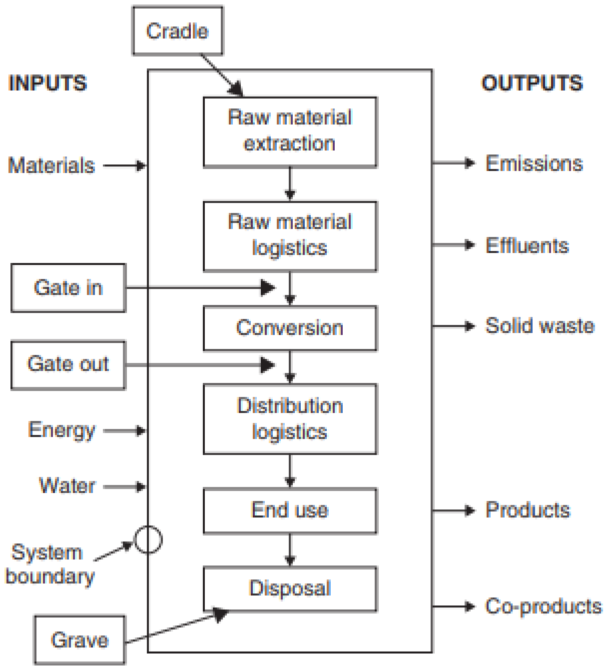

Figure 2.4 Complete life cycle from extraction of raw materials to disposal for product production [21]

LCA is a technique for assessing the potential environmental impacts and potential aspects associated with a product or service, by:

- compiling an inventory of relevant inputs and outputs,
- evaluating the potential environmental impacts associated with those inputs and outputs,
- interpreting the results of the inventory and impact phases in relation to the objectives of the study [19] [20].

The life cycle assessment framework with the four phases and the possible applications is depicted in Figure 2.5 [19].

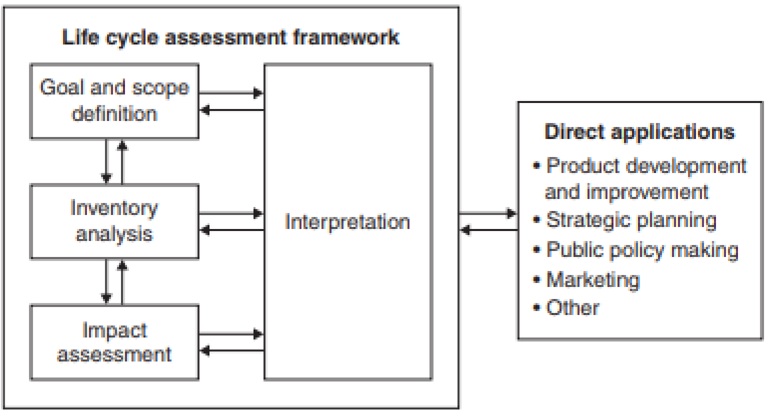

Figure 2.5 Four phases of life cycle assessment [19]

LCA can assist in

- identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),
- the selection of relevant indicators of environmental performance, including measurement techniques, and
- marketing (e.g. implementing and ecolabelling scheme, making an environmental claim, or producing an environmental product declaration) [18].

2.4.2. The Ecological Scarcity 2013 method

For the assessment of the environmental impacts of producing activated carbon from medium density fibreboard waste, the ecological scarcity 2013 method was chosen. The ecological scarcity 2013 method weights environmental impacts (EI) - pollutant emissions and resource consumption - by applying "eco-factors". An eco-factor measures the pressure on the environment based on the difference between the current situation and the targets set out in legislation. The distance to target principle is applied in the Ecological scarcity method. The eco-factor of a substance is derived from environmental law or corresponding political targets. The more the current level of emissions or consumption of resources exceeds the environmental protection target set, the greater the eco-factor becomes, expressed in eco-points (UBP). The quantities determined in the life cycle inventory are multiplied by their respective eco-factor. An example of the eco-point (UBP) calculation is given in Table 2.1. The more eco-points an environmental category obtains, the further away it is from reaching the environmental protection target set by policy-makers [22] [23].

Table 2.1 UBP calculation example [23]

Emission	**Impact category**	**Characterization**	**UBP per gram**	**Quantity**	**Total**
Carbon dioxide (CO_2)	Greenhouse gases	1 CO_2-equivalent	0,46	180 g	83 UBP
Methane (CH_4)	Greenhouse gases	25 CO_2-equivalents	12 (=0,46*25)	10 g	120 UBP
Nitrogen oxide (NO_x)	Nitrogen oxide	-	39	7 g	273 UBP
Total					**476 UBP**

The ecoinvent implementation contains nineteen specific impact categories, with for each substance a final score as characterization factor which compile the characterization, normalization and distance-to-target weighting. Weighting in the Ecological scarcity model is conducted on the basis of goals set in the Swiss environmental policy. The impact categories considered by this method are not defined as an impact indicator but rather as type of emission or resource:

1. Water sources
2. Energy sources
3. Mineral sources
4. Land use
5. Global warming
6. Ozone layer depletion
7. Main air pollutants and PM (particulate matter)
8. Carcinogenic substances into air
9. Heavy metals into air
10. Water pollutants
11. POP (persistent organic pollutants) into water
12. Heavy metals into water
13. Pesticides into soil
14. Heavy metals into soil
15. Radioactive substances into air
16. Radioactive substances into water
17. Noise
18. Non-radioactive waste to deposit
19. Radioactive waste to deposit [39] [37]

2.4.3. Life cycle assessment studies

A number of life cycle assessments published in scientific literature were reviewed for obtaining valuable information and insights about the methodologies used, for carrying out the LCA of the Act&Sorb process. Three of the studies that provided the most useful inputs for the assessment of the technology of producing AC from MDF waste are discussed in the following pages. The study by Arena et. al assesses the life cycle of AC production from coconut shells. Hjaila et. al also analyse the environmental impacts associated with activated carbon preparation, but their study focuses on olive-waste cake as the precursor for the production process. For improved understanding of an LCA with a waste material as an important input of the system, the LCA case study of PET (polyethylene terephthalate) bottle-to-fibre recycling by Shen et. al was reviewed. The study gives an overview of open-loop recycling and provides different approaches to the problem of allocating the environmental impacts of the waste resource to its different life stages [22] [23] [24] [25] [26].

2.4.3.1. Life Cycle Assessment of activated carbon production from coconut shells

A study by Arena et al. assesses the life cycle of activated carbon production from coconut shells. A comprehensive assessment of the environmental impacts of the manufacturing chain is established.

The study focuses on the specific case of AC produced from coconut shells in Indonesia, which is the major coconut producer country [22].

Using LCA, the study aims to quantify all the interactions with the environment across all stages of the life cycle (i.e. the “cradle-to-grave” chain of production, use and disposal) of coconut based activated carbon, in terms of inputs of energy and natural resources and of outputs of wastes and emissions to the different environmental compartments (air, water and soil). The study is carried out in accordance with the ISO 14040 series on LCA. Estimates for the total environmental burdens over the life cycle are obtained by developing mass and energy balances for each of the process units of adsorbent production [22] [19].

As a first step, the goal and scope of the study are defined. The study considers the production of activated carbons from waste coconut shells in Indonesia. The coconut shells are considered to be available as raw material for activated carbon production, with no direct or avoided associated burdens. A possible different (conservative) assumption is that coconut shell utilization could imply the environmental burdens associated with its missed utilization as a fuel for electricity generation. This alternative basis is assessed in the final stage of the study [22].

The aim of the analysis is to redress the lack of information about the environmental performance of an AC manufacturing chain that utilizes coconut shells as raw material. The goal of the study is thus to quantify the potential environmental impacts of producing activated carbon from coconut shells in Indonesia, where a large quantity of low cost AC is produced. The functional unit is defined as the production of 1 tonne of activated carbon. In the base case scenario, the AC is manufactured entirely in Indonesia. The shells are carbonized in situ and the char is then transferred to the activation process. Carbonization and activation are assumed to be performed in a modern facility equipped with gas emission control. The boundaries of the study are from “cradle-to-gate”, i.e. they include processes and transportations from raw material acquisition to the delivery of the product. Use and final disposal of the activated carbons are not taken into account. The boundaries of the system are schematically shown in Figure 2.6 [22].

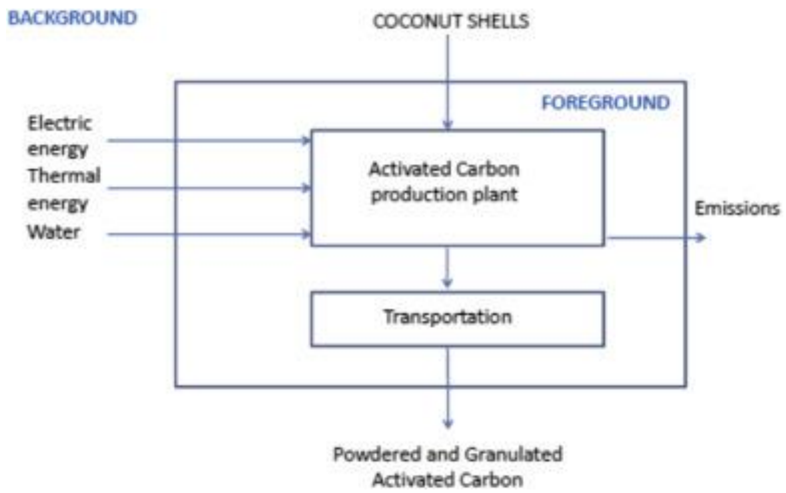

Figure 2.6 System boundaries for the activated carbon production from coconut shells in Indonesia [22]

The activated carbon manufacturing chain system is analysed by using an attributional approach and the life cycle environmental impacts are assessed using the CML-2001 methodology developed at the University of Leiden [22].

For the creation of the life cycle inventory (LCI), the modelling of emissions, material and energy consumptions of each process unit of the AC manufacturing chain are developed based on data and information obtained from industrial producers and scientific literature. Five different scenarios are created for the life cycle assessment of the manufacturing chain with all of them taking into account the composition and mass flow rate of the coconut shell raw material, the composition and mass flow rates of output streams from the carbonization process and the composition and mass flow rates of streams from the activation unit and furnace. As a result, the direct and avoided burdens for the production of 1 tonne of AC for the base case scenario and the alternative scenarios are defined. In addition to the base case scenario 4 alternative scenarios are considered for sensitivity analysis. Scenario 1 considers coconut shells as a possible fuel for electricity generation in Indonesia. Scenario 2 assumes that the distillate products from the carbonization unit are released into the atmosphere. Scenario 3 assumes that coconut shells are sent to New Zealand, where an AC factory is located. Scenario 4 considers coconut shells as feedstock for AC production in Indonesia and biofuel for internal consumption of electricity [22].

The details of the positive or negative contributions from all the stages of the manufacturing chain are identified and quantified, in terms of truly global or more localized impact categories. These results are normalized in terms of person equivalent units, where one-person equivalent represents the average impact in the specific category caused by a person during one year in the world. The results for the base case scenario are depicted in Figure 2.7 [22].

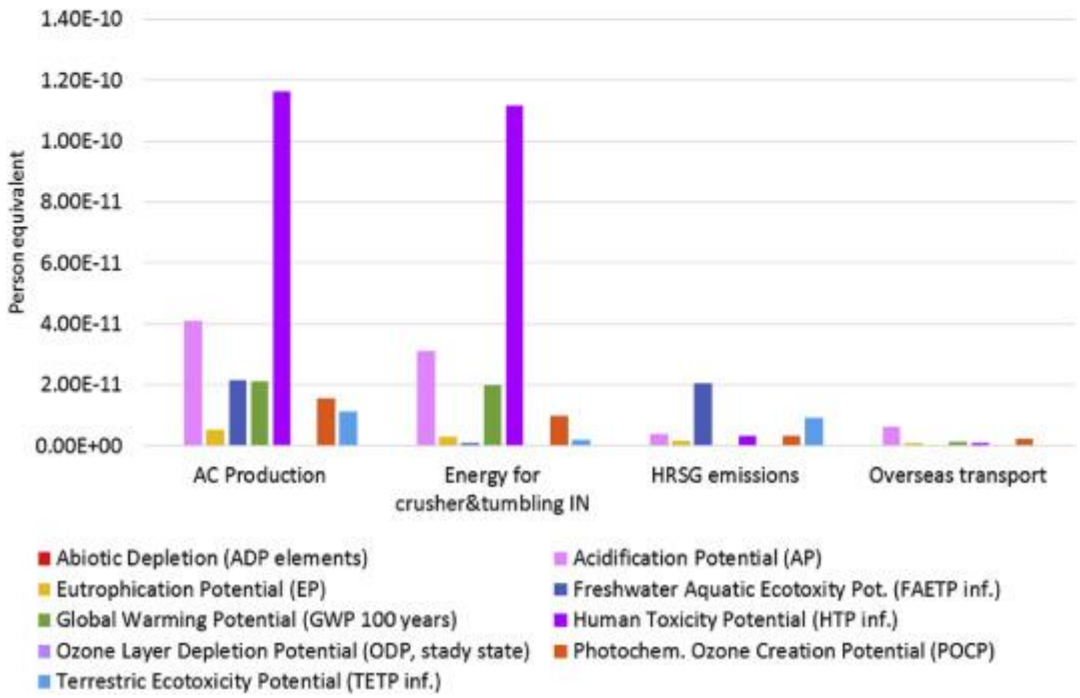

Figure 2.7 Normalized results of life cycle impact assessment of activated carbon production from coconut shells for the base case scenario [22]

Human Toxicity and Acidification are the most important localized impact categories, while Global Warming Potential (GWP) turned out to be one of the most significant global impacts. The overall environmental performance of the manufacturing process is dominated by the stages of crushing and tumbling and that of heat recovery and steam generation. Their large contribution to the overall impact is mostly related to the high consumption of electricity, which in the Indonesian energy mix is largely generated from hard coal. This explains the strong impact on the midpoint categories of Human Toxicity, Acidification and Global Warming. The role of overseas transportation from Indonesia to California appears negligible [22].

By implementing Scenario 1 over the base case scenario, the overall GWP impact associated with the AC production is increased about seven-fold, due to the strong contribution of hard coal combustion. For this scenario also the primary energy demand is the highest. For Scenario 2, the distillate products are released into the atmosphere, as is the case for some small-scale or old carbonization facilities. The overall environmental efficiency of the process is poor and dominated by steam generation and inefficient heat recovery. Freshwater Aquatic and Terrestrial Ecotoxicity potential are the most significant local impacts, mainly resulting from the high emission of tars. The impact related to international transportation increases remarkably for Scenario 3, but it is largely compensated by the improvement in performance related to the more sustainable national energy mix. This scenario shows the lowest impacts for Human Toxicity Potential and Freshwater Aquatic Toxicity Potential and has impacts very close to the lowest for all the other categories, highlighting the relative significance of locating production in countries where electricity is generated from low-carbon sources with clean generation. Scenario 4 has one of the best environmental performances. In particular, the reduction of the GWP is as much as 80%. The comparison of all the results is reported in Figure 2.8. The worst environmental performances refer to Scenario 1 and Scenario 2. Figure 2.9 shows the results of the base case scenario and the two best alternative scenarios, which both show overall better environmental performance [22].

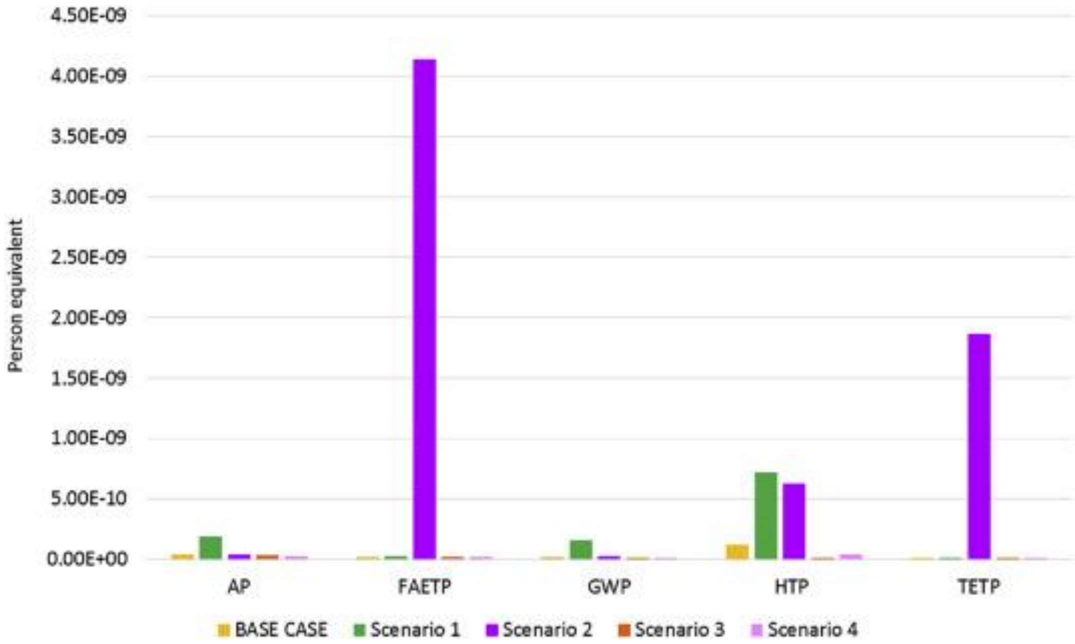

Figure 2.8 Comparison between the base case and all the alternative scenarios, with reference to the predominant impact categories [22]

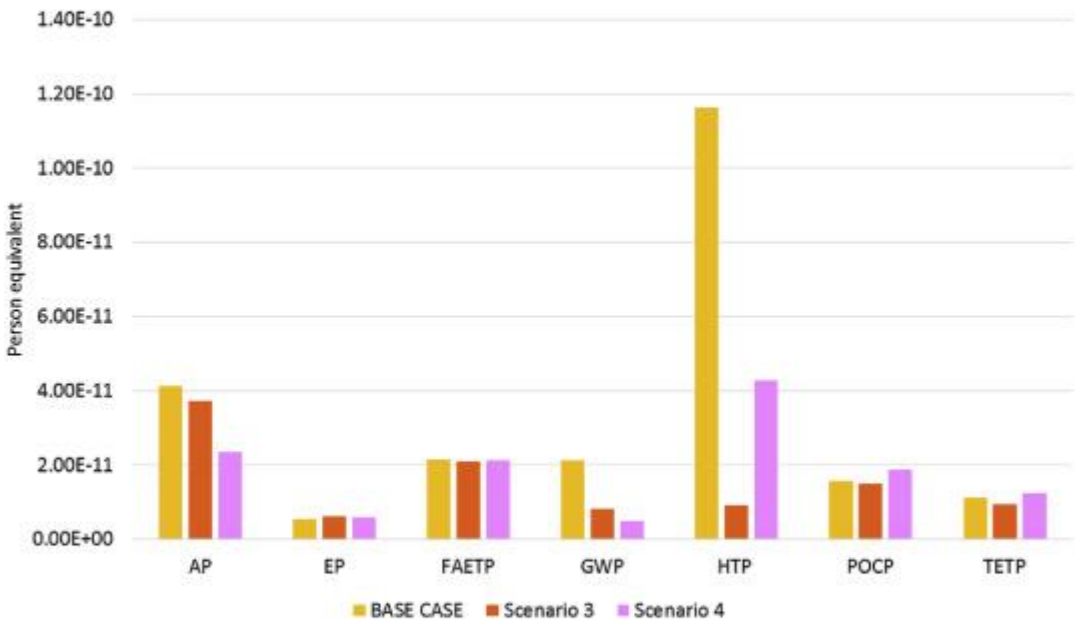

Figure 2.9 Comparison between the base case and the two best scenarios, in terms of the most significant categories [22]

In conclusion, the analysis of alternative scenarios suggests that the sustainability of activated carbon production in Indonesia could be improved greatly, reducing the contribution to global warming and local human toxicity, by reducing the electricity consumption in the process units of crushing and tumbling, but also by using electricity from renewable sources, such as biomass. This would help to reduce the local contribution to human toxicity by 60% and the global warming by 80%. The release of carbonization gases as wastes rather than using them as fuels causes significant environmental impacts in terms of freshwater aquatic and terrestrial ecotoxicity. International transportation appears of rather limited environmental significance and moving activated carbon processing to countries where electricity is generated from low-carbon sources shows to be beneficial [22].

2.4.3.2. Environmental impact associated with activated carbon preparation from olive-waste cake via life cycle assessment

A study carried out by Hjaila et al. implements the life cycle assessment environmental tool to quantify the potential environmental impacts associated with the AC production process from olive-waste cakes in Tunisia. The LCA functional unit chosen is the production of 1 kg of AC from by-product olive-waste cakes. When deciding on the system boundary for the life cycle assessment, it was decided to exclude the raw material preparation stage from the LCA. The remaining system analysed with the LCA methodology consists of nine stages:

1. transporting the exhausted olive-waste cakes to the laboratory
2. drying the raw material
3. crushing the dried raw material
4. impregnation using H_3PO_4
5. pyrolysis
6. cooling
7. washing with water and filtering
8. drying the washed AC
9. crushing the final AC [23]

The input/output flows were identified for each step. The production process flowchart is given in Figure 2.10.

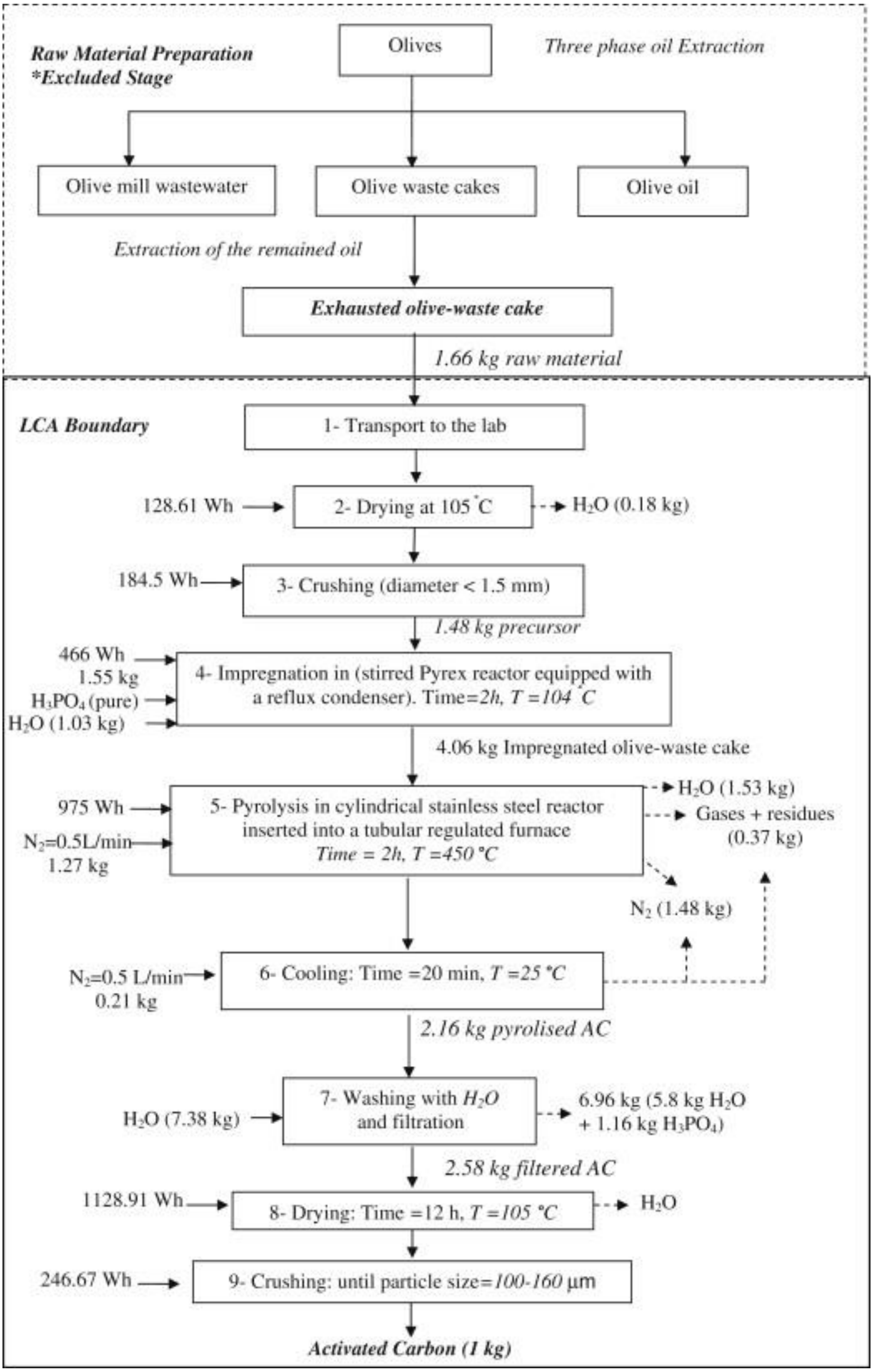

Figure 2.10 Production process flowchart to produce 1 kg of AC from olive-waste cakes [23]

The required inventory data is assembled with the primary data that is collected from the laboratory-scale experimental process and with secondary data obtained from the literature and the ecoinvent database. The environmental impacts were evaluated using the SimaPro 7.3 software based on the ecoinvent v2.2 database. The impact assessment method used was CML 2 Baseline 2000 [23].

By analyzing the AC production, only the steps of impregnation, pyrolysis and cooling and drying the final AC product are considered. The steps involving transport, raw material drying, crushing and washing the final AC present reduced environmental impacts (0%-6,4%) and therefore are excluded from the impact assessment. The majority of the impacts is mainly due to three steps: the impregnation of the raw material using phosphoric acid, followed by the pyrolysis step and finally drying the washed AC step. The impregnation step presents the highest environmental impact regarding the majority of impact considered in the study, particularly for eutrophication potential (96,31%), terrestrial ecotoxicity (92,47%), fresh water aquatic ecotoxicity (90,02%), human toxicity (63,99%), acidification potential (62,32%) and ozone layer depletion potential (44,31%). The main contribution is due to the use of phosphoric acid, especially for acidification potential and human toxicity impacts; the H_3PO_4 contributes to 90% and 91% to these impacts respectively. The abiotic depletion category involves three steps, impregnation, pyrolysis and cooling and drying with percentages of 29,13%, 26,35% and 29,44%, respectively. The pyrolysis and cooling step present the highest relative photochemical oxidation potential impact (45,3% out of 0,007 kg C_2H_4 eq/kg AC), and this is due to the C_2H_4 (eq.) emissions contained in the gases released from the pyrolysis of the precursor olive-waste cakes. The environmental impacts are shown in Figure 2.11 with AD: Abiotic depletion; AP: Acidification potential; EU: Eutrophication; GWP: Global warming potential; ODP: Ozone depletion potential; HT: Human toxicity; FEW: Fresh water aquatic ecotoxicity; TE: Terrestrial ecotoxicity; PO: Photochemical oxidation; CED: Cumulative energy demand [23].

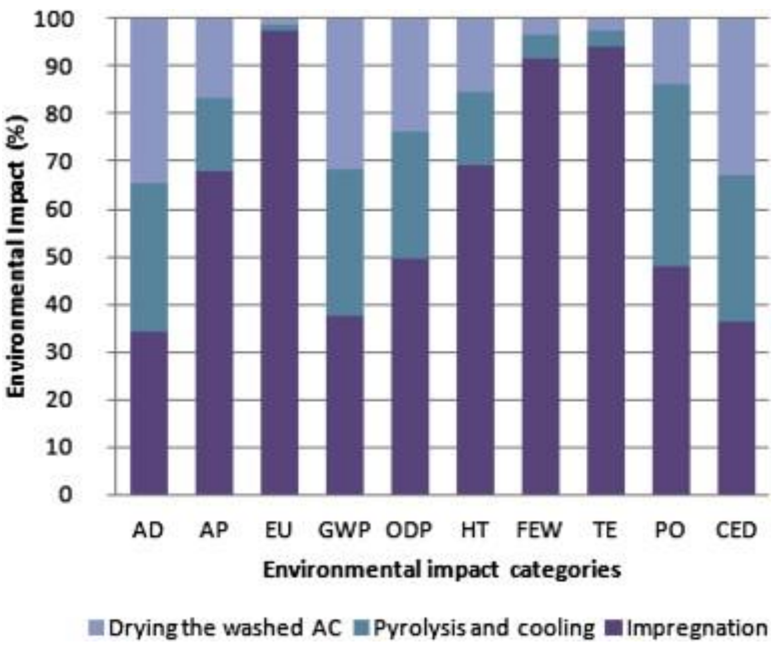

Figure 2.11 Environmental impacts of AC production process from olive-waste cakes [23]

The results show that the environmental impacts are dominated by impregnation, followed by pyrolysis of the impregnated precursor, and finally by drying the washed AC. The global warming potential impact was found to be 11,10 kg CO_2 eq/kg AC, which is comparable to a granular activated carbon prepared from hard coal reported in literature. The impregnation step presents the highest environmental impact regarding the majority of impact factors considered in the study. The main contribution is due to the use of phosphoric acid, which could be expected due to the use of chemical activation process. The total cumulative energy demand (167,63 MJ) is shared equally between the steps involving impregnation, drying the washed AC and pyrolysis [23].

2.4.3.3. Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling

A study by Shen et al. assesses the environmental impact of PET bottle-to-fibre recycling using the methodology of life-cycle assessment. Three allocation methods are applied for open-loop recycling, i.e. the “cut-off” approach, the “waste valuation” approach and the “system expansion” approach. Open-loop recycling occurs when the recycled material goes to another product system and the inherent material properties are changed to such an extent that the recycled cannot be used in its original system. Plastic recycling is open loop recycling when the recycled plastic from i.e. packaging is recycled into other products like e.g. plastic poles. Nine environmental impact indicators are analysed, i.e. non-renewable energy use (NREU), global warming potential (GWP), abiotic depletion, acidification, eutrophication, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidant formation. The primary purpose of the study is to understand the environmental impacts of recycled PET fibre compared to virgin PET. The second purpose is to apply different allocation methods for the open-loop-recycling case [25] [26].

The scope of the LCA is cradle-to-factory gate. For a virgin product, this includes all steps from the extraction and transportation of raw materials and fuels, followed by all conversion steps until the product, the fibre, is delivered at the factory gate. The production of the end product, the use phase and the post-consumer waste management are excluded [25].

For open-loop recycling, it is typically a problem to define the “cradle” stage of the recycled product. As default case, the conventional “cut-off” approach to define the system boundary is chosen. The concept of the “cut-off” approach is illustrated in Figure 2.12. The first life and the second life are cut into two independent product systems. Based on the “cut-off” principle, the used bottles from the first life are considered to be waste; waste does not bear any environmental burden from the first life. This rule is followed and the “cradle” of the second life is defined as the collection and transportation of used PET bottles [25].

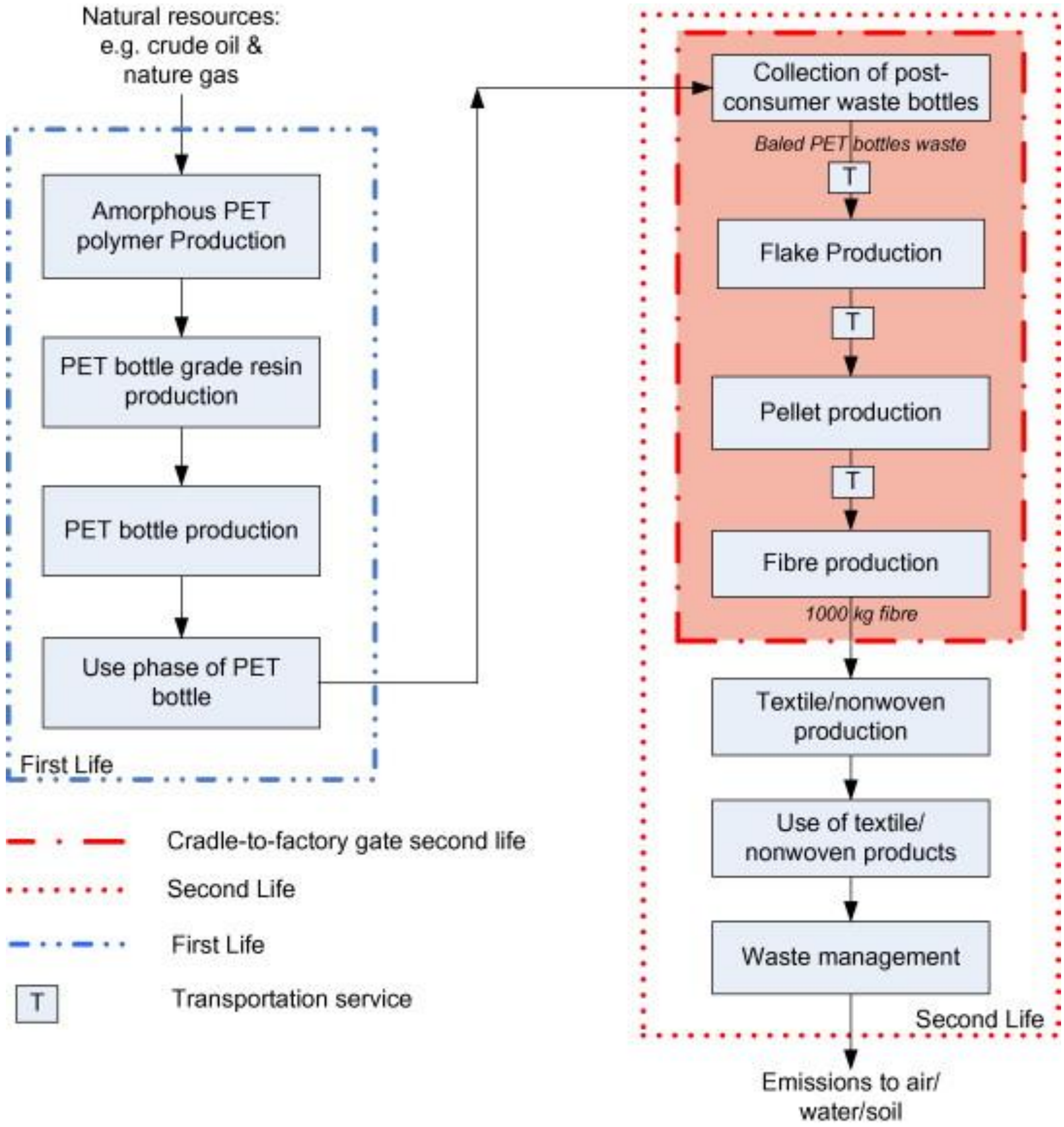

Figure 2.12 Cradle-to-factory gate system boundary of recycling PET fibres from waste bottles, splitting the first life and the second life based on the "cut-off" approach [25]

The CML 2 baseline 2001 impact assessment method is used for the life cycle impact assessment [25].

With the "cut-off" approach, the environmental burden of the first life is not considered in the system boundary. However, it can be argued that this method is oversimplified, because in reality bottle waste is traded and it does have a commercial value. Thus, the environmental impact of the production of virgin polymer should be shared between the first life and the second life. In the study economic allocation is implemented for this and the alternative method is named "waste valuation". For the "waste valuation" method, the determination of the allocation factor is the key step. The allocation factor is defined as the ratio of the market value of baled bottle waste to the market value of virgin PET bottle grade resin [25].

Neither of the two methods discussed are entirely satisfactory. The "cut-off" method cannot be justified if waste is considered to be a valuable resource. The results from the "waste valuation" method depend on market prices, which are determined by supply and demand, the crude oil price and other economic aspects. If the product system is extended to the “grave” stage, according to the “cut-off” principle, the environmental impact of end-of-life waste management would be entirely allocated to the last recycled product, the recycled PET fibre [25].

The third approach that is investigated, the “system expansion” method, takes the real “cradle” and “grave”, merges two life cycles into one product system and compares systems with and without recycling. The most important advantage of this method is that it avoids allocation. This method applies life-cycle thinking to the whole system. The disadvantage of this method is that it is not easy to apply; it results in large systems and the data requirements from extended product systems can be demanding [25].

Based on all three methods, recycled PET fibre offers 40-85% non-renewable energy savings and 25-75% GWP savings compared to virgin PET, depending on the technology, the chosen allocation method and/or system boundaries. Based on all three methods, bottle-to-fibre recycling reduces impacts for most of the environmental categories studied [25].

The three methods applied in this study take different perspectives. The “cut-off” method is easy to apply and straightforward to communicate. It focuses only on the recycled product and no data is required outside of the investigated product system. However, it simplifies the open-loop allocation issues especially for the “cradle” and the “grave” stages. The “waste valuation” method can be seen as an elaborated “cut-off” method. It uses economic values to allocate the environmental impacts of the production of virgin polymer. This method follows the suggested procedures by ISO/TR 14049 for recycling. However, the price fluctuation may lead to significant uncertainties for this method. The “system expansion” takes the perspectives of life-cycle thinking. The “system expansion” method is the preferred method to deal with open-loop recycling, although this method is not easy to apply, because it requires detailed data outside of the life cycle of the investigated product [25].

2.4.3.4. Conclusions from the life cycle assessment studies

The studies analysed provided valuable inputs to carrying out the life cycle assessment of producing activated carbon from medium density fibreboard waste. Specific knowledge was acquired from each of the studies.

The process reviewed in the study by Arena et al. has a similar premise to the Act&Sorb process, however the scope for different scenarios from the environmental perspective is broader. For the Act&Sorb solution, releasing harmful gases straight into the atmosphere is not an option. However, the possibilities presented in other scenarios, such as utilizing the coconut shells only for electricity generation, locating the production facility in another country and using the feedstock also for on-site electricity generation can be transferred to the process converting MDF waste into activated carbon. The environmental impact of generating only electricity from the feedstock is evaluated in this work by assessing a waste incineration facility in comparison to the Act&Sorb solution. Production location can have a significant effect on the environmental performance of a production process as can be seen from the study, therefore, the impact of producing in alternative locations is also assessed for the process under consideration in this work. The on-site electricity generation is incorporated in the design of the Act&Sorb solution, therefore the effect of self-provided electricity in comparison to the power acquired from the grid is assessed.

The study by Hjaila et al. chose to omit the raw material preparation stage from its life cycle assessment boundaries considering that the raw material for the process is a waste material. MDF waste as a feedstock has a different nature from olive-waste cake, as the first is originally a specifically produced product, whereas the other is just a residue from the olive oil extraction process. Therefore their environmental impacts should be considered differently and in this work, the impacts resulting from the previous stages of the MDF waste life cycle are taken into account by expanding the boundaries of the system.

The factors of the process providing reduced environmental impacts are excluded from the impact assessment in the study by Hjaila et al. When researching a single process, it is reasonable to focus on the system components that result in negative environmental impacts, however in comparison to other processes, the parts of the system providing reduced impacts should be considered for the assessment, as they can result in a valuable advantage over the alternative process. The produced activated carbon and the on-site generated electricity provided to the grid from the Act&Sorb process are considered as factors providing reduced environmental impacts and their contribution is taken into account in the life cycle assessment carried out in this study.

Converting MDF waste into activated carbon can be seen as an open-loop recycling process as is the case for transforming plastic bottles to fibre. The definition of the “cradle” stage is also a complicated matter for the Act&Sorb process, therefore the three approaches suggested in the third study assessed, were considered for the MDF waste recycling process as well. The method chosen for the life cycle assessment in this study is the “system expansion” method, as this avoids neglecting important environmental impacts resulting from the MDF waste and the allocation factor is difficult to determine. The use and end of life stages are omitted for the Act&Sorb process due to the large variety of possible applications for activated carbon. Therefore, the assessment in this work follows a “cradle-to-gate” system.

Chapter 3

The evaluation of carbon intensity of the process

The aim of this chapter is to provide an answer to the first research question stated in the introduction of this work:

- How carbon intensive is the production of activated carbon from medium density fibreboard waste?

To fulfil that task, a full evaluation of the process is presented in the chapter, taking into account each component of the system that affects the carbon intensity of the total. As a result of the evaluation, the carbon dioxide emissions resulting from the production process itself and the related carbon dioxide emissions from electricity consumption and transportation are defined. For an assessment of the values, a comparison is drawn to waste incineration, a competing technology, on the grounds of electricity generation and CO_2 emissions. A potential improvement of the system by maximising the electrical output is recommended and the results of this scenario are compared to the waste incineration technology.

3.1. Process description

For the industrial production of activated carbon from waste medium density fibreboard five different plant configurations are considered. The primary difference of those plant set-ups is the production capacity, however, there are also other aspects that alter the layouts. The two smaller production capacity configurations are prototypes for demonstration purposes, whereas the three larger production capacity models are commercial set-ups. Based on the production capacity, the models can be listed as:

- 150 kg/h
- 600 kg/h
- 2100 kg/h
- 3000 kg/h
- 6000 kg/h,

where the quantity denotes the input of MDF waste.

The common main components for all of the configurations are the carbonization kiln, the activation kiln, the excess syngas burner and the cooling system. The general flow from MDF waste to marketable AC is shown in Figure 3.1. MDF waste is brought to the location of the plant. On location the waste is transported with a front-end loader that lifts the product onto a loading elevator. The MDF waste is then transported into a chisel hopper, which chips the MDF waste into smaller pieces to achieve a more uniform particle size distribution before it is fed into the carbonization kiln with a screw feeder. During the carbonization, the MDF waste is converted into a char. The char falls down from the end of the carbonization kiln through a double dump valve. It is then fed by a screw feeder to another chisel hopper for further milling. Afterwards, the char is transported into the activation kiln. In addition to the char, water is injected to the kiln with a ratio of 1:1 to the char. At the end of the activation process, activated carbon is produced that exits the activation kiln. The activated carbon is transported with a cooling screw, where additional water is sprayed to enhance the cooling. The product then passes through a double dump valve and is ready for packaging.

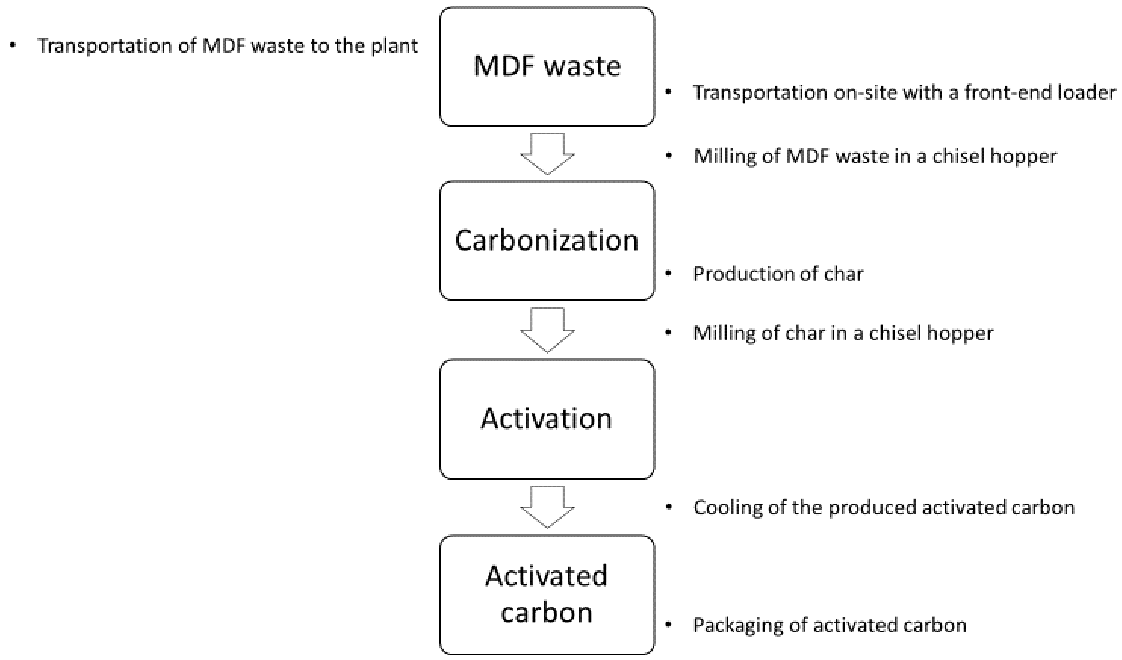

Figure 3.1 Simplified process flow diagram of producing activated carbon from MDF waste

A useful side-product of the process is syngas. During the carbonization and activation processes syngas is formed in the kilns, which is captured. The produced syngas is used in different ways depending on the specific configuration. The simplest approach is to directly use it as a fuel for heat generation. However, this method is rather inefficient, therefore for most of the configurations the syngas from the carbonization kiln and the activation kiln goes through a gas treatment stage, after which it can be utilised for providing heating power to the kilns and run gas generators for electricity generation with the excess syngas being incinerated with the excess syngas burner.

The 150 kg/h feed model is the smallest model in the series of configuration options. It is designed as a demonstration plant that can fit into two shipping containers and can be easily transported from one site to another. For system simplification purposes, this design does not include electricity generation and the excess syngas remaining after the need for the kilns is satisfied, is incinerated in the excess syngas burner.

The 600 kg/h feed model has also a simpified design. It is an industrial prototype designed only for demonstration purposes. In this case, all of the produced syngas in the carbonization and activation processes is directly sent to the excess syngas burner where it is incinerated. This means that there is no need for a gas cleaning section of the plant, which also reduces the electricity requirement for cooling and the capacity for wastewater treatment significantly. Some of the heat that is generated in the excess syngas burner is recovered with an oil heat exchanger and can be utilized for other purposes. One of the ideas is to use this model as a part of a larger processing plant, so that the excess heat could be used for other processes. As there is no syngas used for supplying thermal power to the kilns, the required power is supplied by natural gas.

The 2100 kg/h, 3000 kg/h and 6000 kg/h feed models are all similar in principle. For those models, the syngas produced during the carbonization and activation goes through a cleaning stage, where it is converted into a higher purity syngas with a higher heating value than the initial syngas, that can be used in the process. During standard operation, the primary usage for the syngas is to provide thermal power for the kilns. The secondary usage for the syngas is to feed the gas generators to generate electricity on site and if the gas generators can not consume all of the remaining syngas, then the rest of it is incinerated in the excess syngas burner.

The process parameters for the activated carbon production plants are based on the information provided by the equipment manufacturer. The calculations carried out in this work are done with non-detailed initial design data. Where there was no data available for a specific configuration, the necessary values were covered by literature review and assumptions based on the existing values from other configurations.

The plants are expected to run continuously throughout the year with regular stoppages for maintenance and repair. The process yield of activated carbon for the smallest capacity plant is smaller than for other configurations. This model is essentially planned as a mobile demonstration plant that has a lower process efficiency. The power consumption of internal utilities includes the electrical power need of all the system components and is an estimated value, as specific products have not been defined. The largest share is consumed by pumps, fans, hoppers, compressors and screw feeders. These elements run continuously as the whole plant is operating. The excess syngas burner is run non-stop during the plant operation with a natural gas pilot flame to ensure the ignition of produced syngas at all times. This is done to prevent safety hazards such as uncontrolled ignition of syngas that can lead to explosions and the release of syngas to the atmosphere. Natural gas is used for start-up of the kilns after a stoppage.

3.1.1. Production capacity

The production capacity per annum denotes the amount of MDF waste recycled per year with the corresponding model. The energy content of the input is calculated based on the higher heating value (HHV) of the MDF waste. The HHV is 17 MJ/kg and it is acquired as an average value from laboratory measurements carried out by Act&Sorb. The produced activated carbon per annum shows the total production of activated carbon in tonnes in a calendar year dependent on the yield and the operating hours. The corresponding daily value is averaged over a 365-day calendar year. Based on the HHV of 32,8 MJ/kg for activated carbon, the energy contained in the end product was calculated [27].

3.1.2. Consumption of natural gas

Natural gas is needed for the operation of all the configurations. Although the produced syngas covers most of the fuel needs for the larger models it is still necessary as a start-up fuel for the kilns and as a start-up fuel and a pilot flame fuel for the excess syngas burner. The annual energy need for the excess syngas burner start-up is calculated based on the given amount of stoppages per year, the start-up power needed and the average start-up time. The annual energy need for the pilot flame is calculated based on the power of the pilot flame and the number of operating hours. The total mass of natural gas needed for the excess syngas burner per year was calculated based on the HHV of 14,5 kWh/kg. The volumetric equivalent is calculated assuming natural gas to be at standard conditions [28] [29].

In addition to the excess syngas burner, natural gas is also required for the start-up procedure of the kilns.

3.1.3. Production and consumption of syngas

3.1.4. Generation and consumption of electricity

As mentioned previously, there is no electricity generation incorporated into the processes for the 150 kg/h and 600 kg/h demonstration plant models, on-site electricity is only generated with the three larger production capacity designs.

The total electricity consumption of the plants is strongly dependent on the cooling solution chosen for the process. Two different approaches are considered. In the first scenario, all of the cooling required for the process is carried out with chillers and for the second scenario a combination of chillers and dry coolers is used.

The electricity consumption for cooling is calculated based on the power requirement for cooling for different designs. A scenario with maximal electrical output is discussed in the sub chapter focusing on the potential improvement of the process.

3.2. Carbon dioxide emissions of the process

During the production of activated carbon from MDF waste with the Act&Sorb process, carbon dioxide is emitted. In general CO_2 emissions are divided into fossil and biogenic based on the precursor used in the combustion process. Burning fossil fuels releases carbon that has been locked up in the ground for millions of years, while burning biomass emits carbon that is part of the biogenic carbon cycle. A comparison of the carbon cycles is depicted in Figure 3.2. The common view is that these two sources should not be equated as the combustion of biomass is a part of the global cycle of biogenic carbon and does not increase the amount of carbon in circulation, whereas the combustion of fossil resources releases carbon into the atmosphere that has been stored in the ground for a long period of time [30] [31].

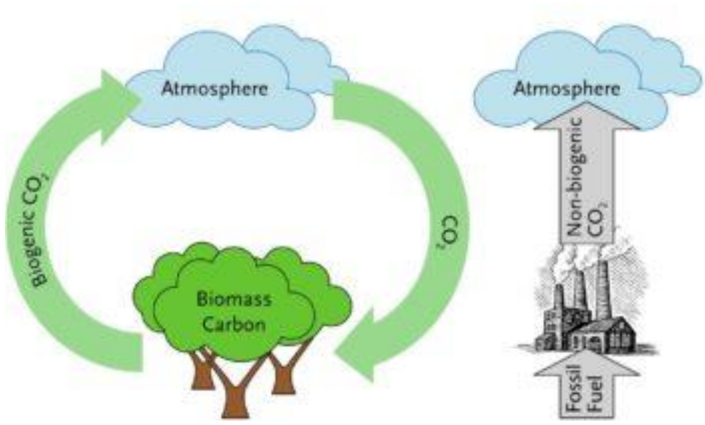

Figure 3.2 Biogenic and fossil carbon dioxide [30]

In the context of this work, MDF waste is seen as a biomass resource and the resulting carbon dioxide emissions as biogenic. Therefore, the syngas produced from the MDF waste produces biogenic carbon dioxide, when incinerated either in the kilns, the gas generators or the excess syngas burner. The combustion of natural gas, which is also used in the process, is responsible for fossil carbon dioxide emissions. Another factor to be considered for the process' carbon dioxide emissions is the consumption of electricity from the grid, when there is no electricity generation on-site or the existing generation is not large enough to cover the needs of the installation.

The carbon dioxide emissions of the process are calculated under the assumption of complete combustion at all conditions. Therefore, there are no unburnt carbohydrates, with a global warming potential different from carbon dioxide, in the exhaust gases and all carbon containing components are oxidised to carbon dioxide. Complete combustion is assured with a high amount of excess air.

The chemical composition of natural gas is dependent on the location of extraction with natural gas composing of methane, ethane, butane, propane and other gases of varying quantity. However, the main component of natural gas in all cases is methane. As a simplification natural gas is viewed as pure methane in this work, which forms carbon dioxide and steam during combustion as depicted in Equation 1.

Equation 1

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

The chemical composition of the syngas was defined as 2,6 wt% H_2, 52,9 wt% CO, 23,3 wt% CO_2 and the remaining 21,3 wt% is mostly various and other by the equipment provider. For calculation purposes, it is assumed that the mixture of hydrocarbons and other are made up of methane. The oxidisation reaction for hydrogen is shown in Equation 2 and the oxidisation reaction of carbon monoxide is depicted in Equation 3. Carbon dioxide is inert in principle and does not react during the combustion of syngas.

Equation 2

$$2H_2 + O_2 = 2H_2O$$

Equation 3

$$2CO + O_2 = 2CO_2$$

The mass of carbon dioxide produced from the natural gas and syngas combusted was calculated based on the molecular weights of the components [32].

3.2.1. Carbon dioxide emissions from the combustion of syngas and natural gas

The combustion of syngas results in biogenic carbon dioxide emissions, whereas fossil carbon dioxide is emitted due to the combustion of natural gas. For most of the configurations, natural gas is only used as a start-up fuel for the kilns and therefore the resulting fossil CO_2 emissions are relatively small, when comparing to the biogenic CO_2 emissions from the combustion of syngas under standard operating conditions. In case of the 600 kg/h feed model, natural gas is used throughout the operation as the only fuel for heating the kilns and therefore the resulting fossil CO_2 emissions are much higher than for the other models.

Gas generators for electricity generation are applied for the three configurations with a larger production capacity.

As the design criteria for the excess syngas burner are the same for all the models except the 150 kg/h feed model, the resulting carbon dioxide emissions from natural gas combustion for start-up procedures and as a pilot flame are equal for the four larger production capacity models. The amount of biogenic carbon dioxide emissions is dependent on how much of the syngas is left after being allocated for heating the kilns and for electricity generation. By having as low as possible amount of syngas incinerated in the excess syngas burner, the CO_2 emissions are shifted to more useful production by taking better advantage of the syngas capacity.

3.2.2. Carbon dioxide emissions from electricity consumption and potential displaced carbon dioxide emissions from electricity sales

Another element of the process that is responsible for carbon dioxide emissions is the consumption of electricity, when there is insufficient electricity generation on-site. This needs to be considered for the two smaller production capacity models, which do not have any electricity generation on-site and for the two larger production capacity models for electricity scenario 1, in which case the on-site electricity generation is not sufficient to cover the needs of the installation. For estimating the carbon dioxide emissions from the electricity consumed, the carbon intensity of electricity supplied in Belgium of 257 g/kWh was considered [33].

In the context of this work, the carbon dioxide emissions from electricity consumption are seen as fossil carbon dioxide emissions and are comparable to the CO_2 emissions resulting from the combustion of natural gas. Therefore, the capability of generating sufficient electricity on-site from a carbon neutral source has a large effect on the overall fossil carbon dioxide emissions of the installation. However, if there is a generation of excess electricity, some of the CO_2 emissions can also be offset by allocating the excess electricity to the grid [33].

3.2.3. Carbon dioxide emissions from transportation

The previous calculations for carbon dioxide emissions consider the emissions of the installation itself. However, as transportation has a major importance for the process, the system was expanded to include the CO_2 emissions from transporting the MDF waste to the processing facility in the overall carbon intensity of the process.

Road transport was chosen as the method for transporting MDF waste to the recycling facility. The distance to be covered by truck was estimated to be 500 km. The distance used is longer than, what would be expected for Belgium, however choosing a longer distance enables to include transportation from surrounding countries and also take into consideration that the trucks need to make return trips in which case the truck will be driving back to the MDF waste source from the activated carbon production plant without a load. Choosing a longer distance avoids the underestimation of emissions from transportation. Based on the average emission factor of 62 gCO_2/tonne-km, the carbon dioxide emissions for the different plant capacities were calculated. The resulting annual carbon dioxide emissions are given in Table 3.1 [34].

Table 3.1 Annual fossil carbon dioxide emissions resulting from the transportation of MDF waste

Transportation		**150 kg/h**	**600 kg/h**	**2100 kg/h**	**3000 kg/h**	**6000 kg/h**
CO_2 emitted	t	39,1	148,8	520,8	744,0	1488,0

3.2.4. Fossil carbon dioxide emissions per annum

The total annual fossil carbon dioxide emissions of the process consist of the emissions from natural gas combustion, emissions from electricity consumption and the emissions from transportation.

3.2.5. Total annual carbon dioxide emissions

To calculate the total carbon dioxide emissions from the installation in a year, the biogenic emissions from the combustion of syngas are added to the fossil carbon dioxide emissions from the combustion of natural gas, consumption of electricity and transportation.

3.3. Comparison to a waste incineration facility

This subchapter gives a comparison of the activated carbon production plant to the waste incineration facility, which is a competing technology for the utilization of MDF waste. The net electrical output of each technology is compared as well as the carbon dioxide emissions resulting from the treatment of MDF waste.

3.3.1. Comparison of electricity generation

To have a better evaluation of the Act&Sorb process, it was compared with a municipal waste incineration plant, as this is a common facility for disposing of MDF waste. To compare the benefits of generating electricity from MDF waste, it is assumed that the WI plant has an incorporated electricity generation. The average electrical efficiency of such an installation lies between 15-27%. WI plants can also be utilised in a combined heat and power mode, in which case the heat can be provided to district heating or other consumers, however in this work the heat generation is not considered, and the installation is viewed as a condensation plant as the same approach was taken for the Act&Sorb installation [35].

The annual electricity generated with the WI plant from the same amount of feed of MDF waste as for the Act&Sorb process capacities for two different electrical efficiencies is shown in Table 3.2. The total electricity generation was calculated based on the HHV of 17 MJ/kg of the MDF waste and the electrical efficiencies of the plant. Due to the own consumption of the plant, not all the generated electricity can be supplied to the grid. The own consumption of power for auxiliaries was taken as 10%. This results in the net outputs of electricity as shown in Table 3.2.

Table 3.2 Annual amount of electricity generated by the waste incineration plants and the amount of electricity provided to the grid

		150 kg/h	**600 kg/h**	**2100 kg/h**	**3000 kg/h**	**6000 kg/h**
Total generation 15% efficiency	GWh	0,9	3,4	11,9	17,0	34,0
Total generation 27% efficiency	GWh	1,6	6,1	21,4	30,6	61,2
Net output 15% efficiency	GWh	0,8	3,1	10,7	15,3	30,6
Net output 27% efficiency	GWh	1,4	5,5	19,3	27,5	55,1

3.3.2. Comparison of carbon dioxide emissions

The carbon dioxide emissions of the Act&Sorb process consist of the fossil CO_2 emitted from natural gas combustion and electricity consumption and of the biogenic CO_2 emitted from the combustion of syngas. For this work, the waste incineration plant is seen as incinerating only MDF waste and the resulting carbon dioxide emissions are biogenic. As for the Act&Sorb process, complete combustion is also assumed for the WI facility and all of the carbon contained in the MDF waste is oxidised to carbon dioxide. Half of the MDF waste is expected to use melamine urea formaldehyde as its resin and urea formaldehyde is used for the other half. Based on the elemental composition of the medium density fibreboards, the average carbon content of the MDF waste was defined as 44,2 wt%. Based on the oxidisation reaction of carbon to carbon dioxide, the annual CO_2 emissions were calculated for the five different production capacity models. The resulting annual carbon dioxide emissions from incinerating MDF waste with a waste incinerator are in increasing order: 2,0 tonnes, 7,8 tonnes, 27,2 tonnes, 38,9 tonnes and 77,8 tonnes [36].

3.4. Potential improvement of the system

During the assessment of the Act&Sorb process, it became evident that there is a possibility to increase the efficiency of the configurations by making maximum use of the syngas produced and limiting the amount of it incinerated in the excess syngas burner to a minimum. The easiest and most logical way for utilizing the syngas more efficiently as stated in the design criteria is to use it for enhancing the electricity generation. The two smaller production capacity models do not have electricity generation incorporated into the design, which means that all of the syngas that is not used for other purposes ends up being incinerated by the excess syngas burner. For the three larger production capacity models there is a possibility to generate and additional amount of electricity from the excess syngas incinerated in the excess syngas burner. The incorporation of electricity generation for the 600 kg/h feed model would also mean that a further gas cleaning stage is required, which on the other hand increases the plant's electricity consumption, however this can easily be compensated, as based on the design criteria, the syngas generated in the process is incinerated in whole with the excess syngas burner.

To assess the potential of increasing the electricity generation, a new electricity scenario, scenario 3, was created. This is considered as an ideal scenario, therefore for the cooling the more efficient combination of a dry cooler and chiller is implemented. For the 150 kg/h demonstration plant the cooling in scenario 3 is still carried out with a chiller package, which keeps the model's electricity consumption constant. Due to the need for a syngas cleaning system for the 600 kg/h feed model, the cooling power requirement for the plant increases. As the syngas from the kilns is cleaned to produce a sufficient purity level syngas, the amount of combustible gas for the 600 kg/h feed model decreases, but the higher heating value of the syngas increases to the same level as for the syngas of other configurations.

The increase in net electricity generation with scenario 3 makes the Act&Sorb solution more competitive with the waste incineration facilities when it comes to the amount of electricity provided to the grid.

The implementation of scenario 3 has an impact on the total emissions from the activated carbon production plant by limiting the amount of fossil carbon dioxide emissions, which with other scenarios are emitted due to electricity consumption from the grid.

In conclusion, maximising the on-site electricity generation from the syngas produced has a positive effect on the performance of the system regarding both the carbon intensity and the created additional value. For the two smaller production capacity units it enables to reduce their fossil carbon dioxide emissions by eliminating the need for using electricity from the grid. As the maximum utilisation of excess syngas for the generation of electricity creates an electricity excess, it can also be provided to the grid thus displacing the carbon emissions from the fossil energy generators active in the market. The increased electricity generation provides a further competitive advantage for the activated carbon production in comparison to the waste incineration facility. For the waste incineration plants generated electricity is the goal of the process, but for the activated carbon production plant electricity is a side-product and an additional benefit to the production of activated carbon.

Chapter 4

Life cycle assessment of the process

The aim of this chapter is to provide an answer to the second research question stated in the introduction of this work:

- What are the major life cycle impacts of the production of activated carbon from medium density fibreboard waste?

For answering that question, a life cycle assessment of the process is carried out. The impact of location and method of transportation is taken into account by creating different scenarios. The results obtained are compared to the corresponding results for the waste incineration process. In total, the environmental impacts of 15 scenarios are compared. Based on the results obtained from the life cycle assessment, conclusions are drawn and the second research question is answered by defining the scenario with the least environmental impact, the environmental impact categories, which are influenced the most for each scenario and the components having the largest impact on those categories.

4.1. Overview of the methods used for carrying out the life cycle assessment

Following the analysis of carbon dioxide emissions resulting from the recycling of MDF waste to activated carbon versus the incineration of MDF waste, a life cycle assessment was performed to expand the scope of the impacts analysed. The life cycle assessment was carried out in accordance to ISO 14040 and ISO 14044 standard for the production of activated carbon from MDF waste and the same assessment was executed for the incineration of MDF waste in a waste incineration plant for a comparative analysis. The analysis was carried out using SimaPro 8.4 software and the data used is from the ecoinvent v3.0 database. The method chosen for the assessment of impacts from the number of methods worked out by different institutions, is the Ecological scarcity 2013 method. The ecological scarcity method inspects a wide range of impacts that are valuable for the assessment of the system under consideration. It also provides a single score evaluation of the impact results, which makes different set-ups easily comparable and indicates clearly the elements of a system with the largest contribution [37] [38] [18] [19] [39] [40].

A life cycle assessment consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results. Each of those phases are described in more detail in the following sub-chapters [18] [19].

4.2. Goal and scope definition

The goal of this study is to assess the environmental impacts of producing activated carbon from medium density fibreboard waste. The study was carried out to have a better overview of a novel technology and determine the environmental benefits of the system, while also figuring out aspects with a potential for improvement. The study is an extension to the calculation model discussed previously in this work. Whereas the results from the calculation model provide clear statements about carbon dioxide emissions and electricity generation potential, the life cycle assessment study gives a broader overview and enables to incorporate elements from outside the scope of the calculation model.

For the life cycle assessment, a cradle-to-gate model was studied. The system under investigation is in principle an open-loop recycling process, in which case it is difficult to define the “cradle” stage of the recycled product. In case of the open-loop recycling, the recycled material goes to another product system and the inherent material properties are changed to such an extent that the recycled material cannot be used in its original system. Therefore, it was decided to include all processes preceding the waste treatment, from the extraction of raw materials for the production of medium density fibreboard to the transportation of MDF waste to the treatment facility, as well as all processes taking place at the waste treatment plant in the environmental assessment. This approach guarantees that no important impacts are left-out by a “cut-off”, whereas configurations using the same approach are easily comparable and differences between them can clearly detected. The system is created as a waste treatment facility with the produced activated carbon being an additional benefit. Therefore, the functional unit used in the analysis is 1 tonne of MDF waste recycled in the process [25] [26].

The 3000 kg/h production capacity model was the configuration that was analysed. This model was chosen as it is the standard set-up for the Act&Sorb process and as a result provides the most valuable insights about the general environmental impacts of the process. As an expansion over the calculation model, different transportation and location scenarios are implemented. In the base case scenario, the production takes place in Belgium and the transportation of MDF waste to the production facility is carried out by freight trucks. For the alternative transportation scenarios rail transportation and shipping are considered. The electricity generated during the process from a carbon neutral source has the capacity of displacing emissions of the local electricity systems. The total impact depends strongly on the carbon intensity of the country in which the production takes place. Two different electricity scenarios are compared in the scope of this work with electricity scenario 2 being the base case scenario and electricity scenario 3 the scenario that can provide enhanced reductions in impacts. To compare the achievable impacts in Belgium to other locations, a country with a low carbon intensity in the electricity sector, Norway, and a country with a high carbon intensity in the electricity sector, Estonia, were chosen. As for Belgium, the three different transportation methods are also considered for these countries [41].

The life cycle assessment was also carried out for the waste incineration plant with an equal MDF waste input capacity to create a comparison to the results gathered for the activated carbon production plant. The plant with a higher electricity generation efficiency, at 27% was used for the assessment. Locational impact is also taken into account with production assessed in the same three countries as for the activated carbon production plant. The impact of a different transportation method is not considered and the MDF waste is expected to be gathered with the municipal waste collection service for all situations. However, the distance to be covered is expected to be half of the corresponding distance for the Act&Sorb facility due to WI being a more widespread technology than activated carbon production. A schematic overview of all the 15 scenarios assessed with LCA methodology is given in Figure 4.1. The scenarios are labelled as LCA1…LCA15 for increased clarity in the following sections.

Act&Sorb process in Belgium

- Truck transportation - LCA1
- Rail transportation - LCA2
- Waterways transportation with electricity scenario 2 - LCA3
- Waterways trasnportation with electricity scenario 3 - LCA4

Act& Sorb process in Norway

- Truck transportation - LCA5
- Rail transportation - LCA6
- Waterways transportation with electricity scenario 2 - LCA7
- Waterways transportation with electricity scenario 3 - LCA8

Act&Sorb process in Estonia

- Truck transportation - LCA9
- Rail transportation - LCA10
- Waterways transportation with electricity scenario 2 - LCA11
- Waterways transportation with electricity scenario 3 - LCA12

Waste incineration in Belgium

- Transportation by municipal waste collection service - LCA13

Waste incineration in Norway

- Transportation by municipal waste collection service - LCA14

Waste incineration in Estonia

- Transportation by municipal waste collection service - LCA15

Figure 4.1 A graphical representation of the 15 scenarios assessed

4.3. Life cycle inventory

The data required for the life cycle inventory was taken from the values established in the calculation model of the previous chapter. Input/output data covers the whole production process from cradle to gate. The process is viewed as a system and instead of having input/output data for each production step, the data is mostly clustered to have an overall characterization of the full process. The life cycle inventory was created with SimaPro software and ecoinvent v3.0 database is used [37] [38].

For MDF waste, the global market information of medium density fibreboard was used as there was no specific data for the corresponding waste product. Therefore, the whole life cycle of the medium density fibreboard from the collection of raw materials through the production and utilization of the medium density fibreboard is taken into account in the assessment. As a result, the medium density fibreboard carries with it significant environmental impacts, which could be attributed to the previous stages of life prior to the recycling process. The option to use allocation was not employed due to the complex nature of deciding the correct allocation percentage. The environmental impacts of MDF waste are balanced out when comparing the results of different scenarios as they all have the same amount of MDF waste input.

For process water, global market values for decarbonised water at user was applied. For natural gas, the chosen data depended on the location under analysis. For Belgium, the Belgian high pressure natural gas market values were used, whereas for Norway, the Norwegian off-shore gas production values were used and for Estonia the average European values were used, since there was country-specific data available. The loader considered in the design of the process is a front-end loader, however in the life cycle inventory this was replaced with a forestry loader due to the lack of a front-end loader in the database. For transportation, 500 km was assumed to be covered to transport the MDF waste to the production facility. When multiplying the transportation distance of 500 km with the amount of 24 000 tonnes of MDF waste to be transported per annum, the annual transportation need can be defined as 12 000 000 tonne-kilometres. This unit of measure of freight transport enables to compare transportation methods with a different capacity. Three different transportation scenarios are assessed in this work: transportation by truck, by rail and by waterways. For transportation by truck, a EURO5 category lorry with a capacity greater than 32 metric tonnes was considered for all the countries. For transportation by rail, the European average freight train data was chosen for the three countries. For transportation by waterways, inland waterways barge data was chosen for Belgium due to the countries network of rivers and channels that connect it to neighbouring states, whereas for Norway and Estonia larger transoceanic ships were chosen from the database due to the relative isolation, yet good accessibility by sea ports of those two countries.

The activated carbon as an output is taken as an avoided product as is the electricity supplied to the grid. In principle the activated carbon produced from MDF waste creates a change in activated carbon supply and displaces the same amount of activated carbon produced from coal. By doing so, the impacts resulting from the equal amount of AC produced from coal can be avoided. For AC, the global market data for granular activated carbon was used for assessing its avoided impacts. The same logic applies for the electricity provided to the grid from the MDF waste recycling facility. In this case, the impacts resulting from the generation of the equivalent amount of electricity with the electricity generation technologies in the grid can be avoided. For an example, if the recycling process provides 10 GWh of electricity to the grid that is powered by gas-fired power plants, then it displaces the emissions of 10 GWh of electricity generated by those gas-fired power plants. Medium voltage electricity was expected to be supplied to the grid with the data evaluating the corresponding location of production. Fossil carbon dioxide from the process results from the combustion of natural gas in the excess syngas burner and the kilns. The biogenic carbon dioxide emissions stem from the combustion of syngas, which itself is not defined in the inputs-outputs table, since it is fully produced and consumed within the process [37] [42].

The life cycle inventory for a waste incineration plant with the same MDF waste input capacity as for the Act&Sorb process is given in Table 4.1. The WI plant with a higher efficiency (27%) is used for the analysis. For the WI plant, no natural gas or process water consumption is assumed and therefore, no fossil carbon dioxide is emitted and there is no waste water produced to be treated. The loader chosen for the WI facility is the same as for the AC production plant. The transportation of MDF waste is carried out by municipal waste collection service and the distance estimated to be covered is half of the distance for the Act&Sorb plant with 250 km. For the analysis, municipal waste collection service by 21 metric tonne lorry was chosen from the database. All of the carbon dioxide emissions resulting from the waste incineration are taken as biogenic.

Table 4.1 Life cycle inventory for the waste incineration plant

Inputs	
MDF waste	24 000 tonnes
Loader operation	8 000 h
Municipal waste collection service	6 000 000 tkm
Outputs	
Electricity	27 540 MWh
Biogenic carbon dioxide	38 921 tonnes

4.4. Life cycle impact assessment of activated carbon production from MDF waste

This subchapter gives an overview of the life cycle impact assessment process and the results obtained for activated carbon production for three countries and three different transportation method scenarios under consideration. The subchapter is divided into further subchapters based on the location of the production process. The results obtained for the three countries are eventually compared to each other to signify the differences in environmental impacts resulting from the location of production and the transportation method chosen. The effect of increased electricity generation is evaluated in the last part of this subchapter.

4.4.1. Life cycle impact assessment of activated carbon production from MDF waste in Belgium

The base case scenario with production in Belgium and transportation of MDF waste over 500 km carried out by truck was the first case to be analysed with the SimaPro tool. The impact is assessed by summing up the eco-factors of the previous components of the system for the 19 EI categories under consideration.

The environmental impacts related to medium density fibreboard are accumulated from the previous life stages including everything from the extraction of raw materials for the production of medium density fibreboard. One of the largest contributors to the EI of the medium density fibreboard is the resin used as an adhesive in the production process.

The AC produced, and the electricity supplied to the grid have a positive environmental impact on the production process as they result in avoidance of producing AC with the currently prevailing methods and generating electricity from the sources used in the Belgian power grid.

The single score approach gives a clear visualisation of the total environmental impact of the elements of the process based on their eco-factor.

The two categories, in which impacts are avoided, are the activated carbon produced and the electricity provided to the grid.

The same analysis as for the scenario with truck transportation was carried out for the two alternative transportation methods, rail transport and transport by waterways with a river barge. As the only factor changed was the method of transportation, the overall differences between the set-ups are only linked to the chosen transportation method.

The difference between the three transportation scenarios as a single score evaluation is not large. There is no EI category to result in a significant difference and the total distinction comes from the accumulation of small imbalances in the categories assessed.

4.4.2. Life cycle impact assessment of activated carbon production from MDF waste in Norway

The analysis for three different transportation scenarios was also carried out for Norway, where a large share of the electricity is generated by hydropower, thus resulting in a low carbon intensity electricity sector. As nuclear power is not utilized in Norway, there is no impact avoidance for radioactivity from electricity generation as is the case for Belgium.

4.4.3. Life cycle impact assessment of activated carbon production from MDF waste in Estonia

Estonia has a carbon intense electricity sector due to large share of oil shale used for electricity generation. The electricity generation from oil shale also results in a lot of air pollutant and particulate matter emissions. The three scenarios with different transportation methods were assessed [43].

4.4.4. Comparison of the nine scenarios based on their environmental impacts

Once the assessment of the three transportation methods for the three countries was carried out, it was possible to create a comparison between all nine scenarios.

There is a clear difference in impacts related to the location of the production plant.

4.4.5. Life cycle impact assessment of activated carbon production from MDF waste with improved electricity generation

In chapter 3, the potential for enhancing the electricity generation was assessed by creating a scenario 3 for electricity balance. According to this scenario, the electricity output of the plant is maximised and the cooling is carried out with the less energy intensive solution, which results in the maximum net output of electricity. The life cycle impact assessments up to this point were carried out with electricity scenario 2. To have an overview of how the increased electricity generation would affect the overall impact of the system, the same assessment was implemented with electricity scenario 3 and the results were compared to the ones from electricity scenario 2.

4.5. Comparison to waste incineration

The incineration of MDF waste in a waste incineration plant was assessed to be able to create a comparison of the technology to the Act&Sorb process. For the assessment, the data from the higher efficiency, 27%, WI plant was used. The transportation of MDF waste in this case is expected to be carried out by municipal waste collection service and the distance to be covered is half of the distance for the Act&Sorb solution, 250 kilometres. The distance was taken with the presumption of WI being a well-established technology and therefore the number of installations is greater and the distance between them is smaller. Other transportation methods were not considered in this case. The impact of location was considered as for the activated carbon production facility with Belgium being the base case scenario, Norway the location with a low carbon intensity electricity system and Estonia with a high carbon intensity electricity system. Since electricity is the only valuable output of the WI plant, it is also the only aspect to provide avoidance of impacts.

The impacts resulting from MDF waste incineration were first assessed for the base case scenario with incineration taking place in Belgium. The characterization results can be seen in Figure 4.2. The green represents MDF, blue stands for electricity, yellow for municipal waste collection service and orange for loader operation. The medium density fibreboard has the highest impact in most categories, while at the same time provides an impact avoidance for the water resources category. The electricity generated provides impact avoidance for nearly all categories with the greatest impact avoidance for categories related to radioactivity, however it also has a large effect on water resources, energy resources and ozone layer depletion. Transportation, even though the distance is only half of the distance for the competing technology, has a significant relative impact on several categories with ozone layer depletion and water pollutants having the largest relative share. The on-site loader operation is of relatively insignificant importance considering its impact on the characterization categories.

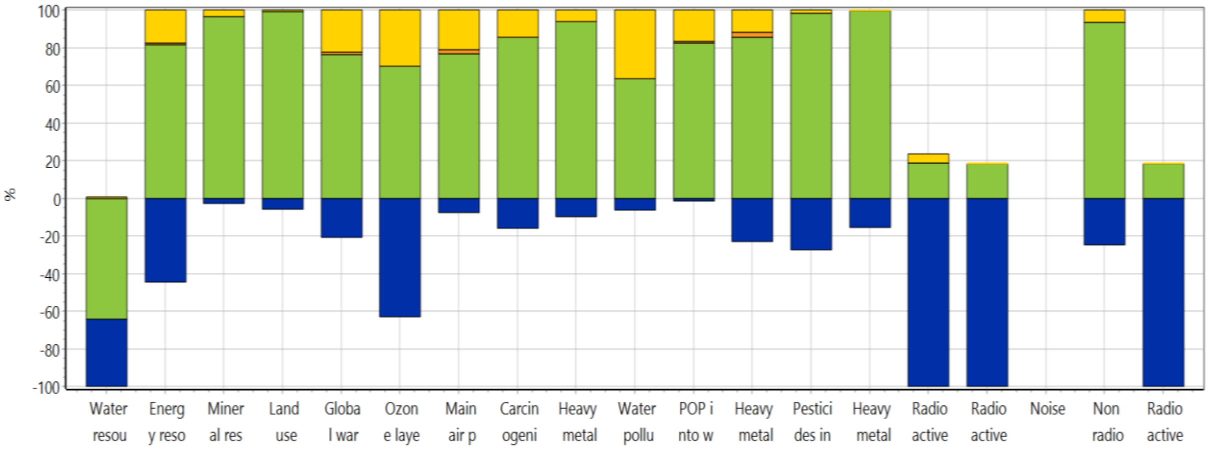

Figure 4.2 Characterization of impacts for LCA13

The analysis was carried out for the other two locations and the resulting single score comparison of MDF waste incineration can be seen in Figure 4.3. MDF incineration in a WI plant has the lowest ecological impact in Estonia and the highest ecological impact in Norway. The large difference is strongly related to the impact on global warming as is the case for the AC production facility. For Belgium, the additional benefit of avoiding impacts for the category radioactive waste to deposit is achieved with the WI plant as well as with the recycling of MDF waste to activated carbon.

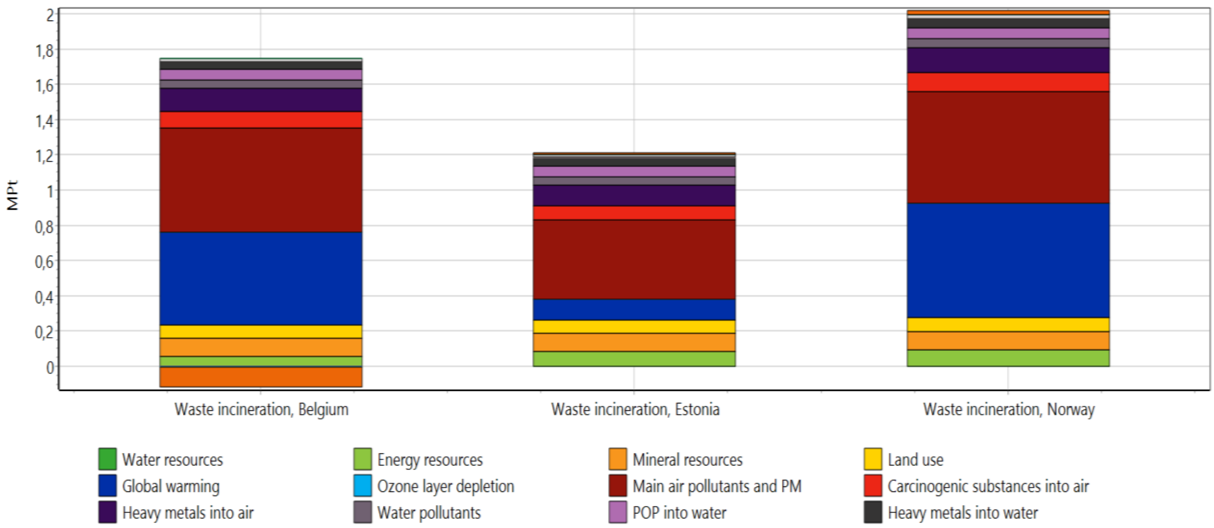

Figure 4.3 Waste incineration countries' comparison single score evaluation

4.6. Interpretation of results

The life-cycle assessment carried out gives valuable knowledge about the environmental performance of the systems compared. The elements, which lead to higher impacts were determined and at the same time the potential of avoiding impacts by producing a valuable product in a more sustainable way was determined. By changing one part of the configuration, the total outcome can experience a significant change. For the Act&Sorb process three locations were considered for the production with each of them resulting in distinct environmental concerns and benefits. The chosen transportation method also plays a role in the outcome of the assessment.

Medium density fibreboard, as the input to the process, is the part of the system carrying the highest ecological burden for all configurations for the Act&Sorb process and the waste incineration facility. This environmental impact cannot be reduced by any waste treatment technology, since the impacts have accumulated in the material prior to it becoming a waste. When the MDF has become a waste, it needs to be treated, and by choosing the more environmentally-friendly method for doing that, the further impact resulting from the MDF waste can be reduced by recycling it into valuable products.

The production location has a significant effect on the environmental impact of MDF waste treatment primarily because of the carbon intensity of the electricity sector in different countries.

Transportation does not have a significant effect on the overall results of the life cycle assessment, however the common logic of transporting larger amounts with larger capacity transportation methods such as ships provides an improvement over rail transportation, which in turn has a smaller impact than road transportation by truck. The waste collection service used as a transportation method for the analysis for the waste incineration plant has a significantly higher relative share of total impacts than the transportation methods considered for the Act&Sorb process even though the transportation distance considered for that method is only half of the corresponding distance chosen for the Act&Sorb process.

Chapter 5

Conclusion

This chapter summarizes the results obtained in this work and thereby provides answers to the research questions stated in the introduction. The sustainability of the process under consideration is determined. In addition, recommendations are given for future work.

5.1. Overview and evaluation of the results obtained

The aim of this research was to assess the sustainability of the innovative process of producing activated carbon from medium density fibreboard waste, developed by Act&Sorb. For more concreteness, the research question was divided into two questions, with the first one focusing on the carbon intensity of the process and the second one determining the major environmental impacts of the life cycle of the technology. The questions raised in the introduction of this work were answered and a comprehensible assessment of the sustainability of the process was achieved.

The carbon intensity of the process was evaluated by calculating the carbon dioxide emissions resulting from the operation of the five different production capacity configurations suggested. The required data for carrying out the calculations was acquired from the quotations of the equipment provider, laboratory scale tests and literature review.

The carbon dioxide emissions of the process result from within the production plant through the combustion of natural gas and the on-site generated syngas as well as from outside the borders of the production facility by consuming electricity with a certain carbon intensity from the grid, when the on-site generation is not sufficient and from transportation of the MDF waste to the recycling facility. A clear distinction was made between the carbon dioxide emissions resulting from the combustion of syngas and natural gas, by claiming that the combustion of syngas emits biogenic carbon dioxide, whereas the combustion of natural gas emits fossil carbon dioxide. The components of the production facility that are responsible for CO_2 emissions from the combustion of syngas and natural gas are the carbonization and activation kilns, the gas generators used for electricity generation and the excess syngas burner.

For the estimation of the total fossil carbon dioxide emitted by the production facility, the emissions resulting from the combustion of natural gas, consumption of electricity and the emissions related to transportation were summed.

When comparing the total annual carbon dioxide emissions of the process, it becomes clear that the combustion of syngas and the resulting biogenic carbon dioxide emissions form the bulk of the total carbon dioxide emissions for all configurations.

For a better understanding of the values acquired in the calculation, the Act&Sorb process was compared to a waste incineration facility by comparing their net electricity generation potential and carbon dioxide emissions per same amount of MDF waste recycled. A low electrical efficiency, 15%, and a high electrical efficiency, 27%, waste incineration plants were considered. Considering that for the Act&Sorb solution electricity generation is an additional benefit to activated carbon production, the electrical output achieved in comparison to the waste incineration facility is positive.

During incineration all the carbon contained in the MDF waste is released into the atmosphere as CO_2, whereas for the Act&Sorb solution a large part of the carbon is contained within the desired product, activated carbon.

Since none of the production capacity models generate the maximum amount of electricity considering the syngas available, a potential improvement to the system was assessed. For all the configurations, the electricity generation was maximised by utilising more gas generators and avoiding syngas being incinerated in the excess syngas burner. The increased amount of electricity provided to the grid also enables to displace larger amounts of carbon dioxide emissions from electricity generation from regular sources of the power grid.

A life cycle assessment of the process was conducted to better understand the environmental impacts of the process and the factors contributing to these impacts. The ecological scarcity method was used for the evaluation. Multiple scenarios were assessed to have a comparison of the effects of production location and the transportation method used for delivering MDF waste to the production facility. Belgium, Norway and Estonia were chosen as the countries for the assessment due to their varying carbon intensity electrical systems and for transportation truck transportation, rail transportation and waterways transportation were considered. As in the carbon intensity calculation, the life cycle of the scenarios of the Act&Sorb process were compared to those of waste incineration in the corresponding countries.

The life cycle inventory for the life cycle assessment was created based on the values obtained in the previous evaluation of the carbon intensity of the system. No allocation was used and therefore all of the impacts accumulated in the previous life cycle stages of MDF waste were taken into account in the assessment of the process. The activated carbon produced, and the electricity provided to the grid are viewed as avoided products that can displace the environmental impacts resulting from activated carbon production from coal and electricity generation from the power sources of the national grid respectively.

Medium density fibreboard waste that is carrying all of the environmental impacts accumulated in the previous life stages, turned out to be by far the biggest contributor to the overall environmental impact of the process. However, the impact of medium density fibreboard can be limited by the production of activated carbon as it provides a positive environmental impact by displacing the impacts resulting from the production of the corresponding amount of activated carbon from coal.

The choice of location for production can have a significant influence on the outcome of the environmental impact assessment

The different transportation methods assessed in this work did not have a large effect on the total environmental impacts of the process. However, there is a clear trend that using a transportation method that can transport larger quantities at once is more environmentally friendly than transporting smaller quantities with a required larger number of trips. The waste collection service chosen as the transportation method for the waste incineration process showed relatively larger environmental impacts although the average distance chosen to be covered was only half of the corresponding distance for the activated carbon production facilities.

In conclusion, the production of activated carbon from medium density fibreboard waste shows great promise regarding sustainability. The process developed by Act&Sorb can effectively convert a waste resource into a valuable product, thereby giving it a new life. The process shows great performance values in comparison to its primary competitor, waste incineration. Overall, producing activated carbon from medium density fibreboard waste offers a sustainable alternative to prevailing activated carbon production technologies and at the same time providers a more environmentally friendly option for disposing of medium density fibreboard waste than waste incineration.

5.2. Recommendations for future research

The research carried out in this work is largely based on laboratory test results, assumptions taken from literature review and the engineering experience of the equipment provider. Therefore, the results can be seen as an estimation to a technology, which has not yet been implemented in industrial scale. A common perception is that for an innovative technology, the actual operating data acquired after the implementation of the technology can somewhat vary from the calculated expectations due to unforeseen circumstances. Therefore, this pre-analysis presented in this work should be followed by a post-analysis with real operational data once the production plants have reached normal operating conditions and it is possible to collect reliable information from the production process. It would also be possible to carry out a sensitivity analysis with estimated divergences from the assumptions taken, however the value of carrying out that extra work depends on how much time it is going to take before the industrial production is started. If the production is started in the near future, then the sensitivity analysis is of less importance, due to the operational data becoming available.

When it comes to the life cycle assessment, the consideration of the environmental impacts from MDF waste presented a major challenge. As the decision of the correct allocation percentage was impossible to make under the conditions of a lack of data, a system expansion approach was taken to include all impacts of the MDF waste starting from the cradle stage. However, this approach distorts the life cycle assessment results and does not give a possibility to compare the results to processes, which do not follow the same approach. Therefore, as future research it would be of great value, if the allocation percentage of medium density fibreboard waste is defined, so that the environmental impacts resulting from the life cycle of the Act&Sorb process could be compared to a multitude of other processes.

One of the aspects that was not comprehensively considered in this work is the generation of heat. During the production, heat is primarily released with exhaust gases and cooling water. The cooling water is cooled using either chillers or a combination of chillers and dry-coolers and the heat is released to the environment. The potential to use less energy intensive methods for cooling such as cooling by natural flowing water could be researched. Another recommendation would be to explore the potential of utilizing this heat for other purposes e.g. district heating. Due to the relatively low temperature of the cooling water it probably cannot be used for the benefit of the process itself, however this aspect could also be explored. Making better use of the heat generated could lead to a significant improvement in the overall sustainability of the process.

Following the principle of circular economy, new uses for resources previously considered as unusable waste have become to emerge. This also applies for medium density fibreboard waste. Whereas this work focused on the assessment of converting medium density fibreboard waste to activated carbon, there could also be alternative recycling ideas. It would be a good idea to explore the potential alternative uses for medium density fibreboard waste and assess their sustainability to find the most sustainable solution for taking advantage of this waste resource.

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