The sustainability assessment of activated carbon from medium density fibreboard waste

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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. 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

I. INTRODUCTION

A. 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. With the development of the world, increasing population and growingly stricter environmental policies, activated carbon 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. 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].

B. Motivation and contents

Producing activated carbon from medium density fibreboard 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 six 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. In addition, a comparison is drawn to the competing technology of waste incineration (WI). The fourth chapter covers the life cycle assessment of the technology. The obtained results are compared to the results for WI. 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.

II. LITERATURE REVIEW

A. *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 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].

Activated carbon is considered as the universal adsorbent. 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 because of environmental issues, especially for water and air purification [1] [6].

The production methods of AC can be grouped into: physical, 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 [6].

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 the installation available. A key element is the reliability and consistency of the resource [6].

B. *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 [7].

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 [7].

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].

C. Principle of circular economy

Looking beyond the current take-make dispose industrial model, a circular economy (CE) aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources and designing waste out of the system. 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 material loops and facilitate sustainable development. The logic of turning from linear and wasteful to cyclical, restorative, reproductive and smart physical flow structures is appealing and positively provocative [9] [4] [10].

D. Life cycle assessment

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 [11] [12] [13].

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 [11] [12].

The life cycle assessment framework with the four phases and the possible applications is depicted in Figure 1 [11].

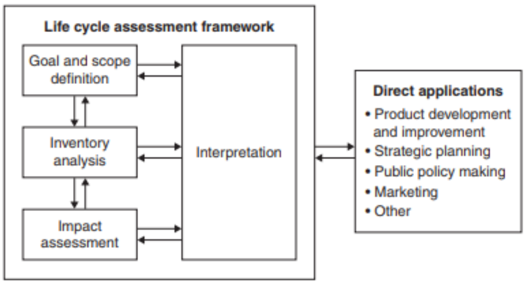

Figure 1. Four phases of life cycle assessment [11]

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 the following. 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 [14] [15] [16] [17] [18].

III. THE EVALUATION OF CARBON INTENSITY OF THE PROCESS

A. Process description

For the industrial production of activated carbon from waste medium density fibreboard five different plant configurations are considered. 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 MDF waste input capacity, the models can be listed as:

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

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 as follows:

- Transportation of MDF waste to the plant
- Transportation of MDF waste on-site with a front-end loader
- Milling of MDF waste in a chisel hopper
- Production of char in the carbonization kiln
- Milling of produced char in a chisel hopper
- Activation of char in the activation kiln
- Cooling of the produced activated carbon
- Packaging of the activated carbon

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 and 600 kg/h feed models are designed as industrial prototypes for demonstration purposes and they have some limitations in comparison to other configurations. Neither of them has electricity generation incorporated. The excess syngas of the 150 kg/h model after having supplied the kilns is incinerated in the excess syngas burner, whereas for the 600 kg/h model, natural gas is used for powering the kilns, therefore all the syngas produced is incinerated in the excess syngas burner. However, this approach means that there is no need for a syngas cleaning stage for the 600 kg/h feed model, which makes the design more simplified and reduces the electricity requirement for cooling and the needed capacity for wastewater treatment significantly. Some of the heat generated by the excess syngas burner is captured with an oil heat exchanger for the 600 kg/h model and can be utilized for other purposes.

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 cannot consume all the remaining syngas, then the rest of it is incinerated in the excess syngas burner.

The plants are expected to run continuously throughout the year with regular stoppages for maintenance and repair. The process yield of activated carbon ranges from 10% for the smallest production capacity configuration to 14% for the larger models. Gas engines with a power output of 500 kWe are applied for the electricity generating models. 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. Natural gas is also used for start-up of the kilns after a stoppage. The thermal power requirement of the kilns under standard operating conditions is given in Table I.

TABLE I. NOMINAL THERMAL POWER OF THE KILNS

Power input to kilns		***150 kg/h***	***600 kg/h***	***2100 kg/h***	***3000 kg/h***	***6000 kg/h***
Carbonization kiln	**kW**	139	569	1573	2247	4494
Activation kiln	**kW**	171	194	838	1198	2396
Total	**kW**	311	764	2412	3445	6890

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 consumption of natural gas was calculated based on the design criteria of the specific configurations and the properties of natural gas. As a result, it was found that the largest amount of natural gas per year is consumed by the 600 kg/h capacity model, which does not utilize syngas for the benefit of heating the kilns. In total the 600 kg/h feed model consumes 6518 MWh of natural gas per year. The corresponding values for other configurations are in the range of 400-700 MWh [19] [20].

The syngas produced during the carbonization of MDF waste and the activation of char is a mixture of steam, carbon dioxide, hydrogen and carbon monoxide along with small amounts of paraffins, olefins and aromatic compounds. For every configuration but the 600 kg/h feed model, the syngas passes through the gas cleaning stage, where the gas is cooled and most of the steam condensed and directed into water treatment. Based on the chemical composition of the syngas, acquired from the equipment provider's quotation, the higher heating value (HHV) of the syngas was determined as 18,2 MJ/kg and for the initial impurified syngas 14,5 MJ/kg.

The usage of syngas for different applications varies significantly amongst the five designs. For the 150 kg/h feed model roughly 60% of the generated syngas is used for heating the kilns and the remainder is incinerated by the excess syngas burner. Due to not having a gas cleaning stage, all the impurified syngas produced with the 600 kg/h capacity model is incinerated by the excess syngas burner. This corresponds to an energetic value of nearly 20 GWh. According to the design criteria, 9,89 GWh of that heat can be recovered per year using a thermal oil heat exchanger. Based on the system design, the 2100 kg/h production capacity model makes the most efficient use of the produced syngas, with only 30% of the it incinerated in the excess syngas burner. For the two larger configurations, approximately one third of the syngas is used for heating the kilns, a quarter is used for generating electricity and the remaining 41,5 % is incinerated in the excess syngas burner. A possibility to utilize all of the produced syngas for electricity generation is discussed later in this chapter [21].

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 2100 kg/h and 3000 kg/h feed models use two gas generators each with a nominal electric power of 500 kWe per generator. This gives a total nominal power output of 1000 kWe. The 6000 kg/h feed model uses four gas generators that results in a nominal power of 2000 kWe. The electrical efficiency of the gas generator is taken as 36,5% based on the efficiency of the gas generators chosen for the system by the equipment provider. Based on the electrical efficiency of the gas generator, the required syngas input per gas generator is 1370 kW to run at nominal capacity. For all the electricity generating configurations there is a sufficient amount of syngas available for the gas generators to run at nominal capacity. This results in an annual electricity output of 8 GWh for the 2100 kg/h feed model and for the 3000 kg/h feed model and an annual electricity output of 16 GWh for the largest production capacity model.

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. For the 150 kg/h demonstration plant model, a set of chillers is incorporated for cooling in all scenarios, therefore the electricity need for this configuration remains constant regardless of the electricity scenario. In case of the second scenario for the other set-ups, most of the cooling is done by the dry-coolers and chillers are only used during warmer periods of the year, when dry-coolers are unable to reach the low temperatures required. Dry-coolers would still be used to lower the temperature as much as possible to reduce the work that needs to be done by chillers. According to an equipment provider, considering the climatic conditions of Belgium, the annual electricity consumption for the second scenario forms roughly 18% of the corresponding electricity consumption for the first scenario. This is primarily due to the high power intensity of the compressors used in the chillers.

An overview of the annual electricity consumption for the two scenarios and the resulting electricity balance can be seen in Table II.

TABLE II. ANNUAL ELECTRICITY CONSUMPTION AND BALANCE FOR THE TWO ELECTRICITY SCENARIOS

Scenario 1		***150 kg/h***	***600 kg/h***	***2100 kg/h***	***3000 kg/h***	***6000 kg/h***
Cooling	**GWh**	0.57	1.09	7,64	10.91	21.92
	%	88.6	79.6	88.6	88.6	88.6
Total	**GWh**	0.65	1.37	8.62	12.31	24.62
Scenario 2						
Cooling	**GWh**	0.57	0.20	1.37	1.96	3.93
	%	88.6	41.2	58.4	58.4	58.4
Total	**GWh**	0.65	0.48	2.35	3.36	6.73
El. balance						
Scenario 1	**GWh**	-0.65	-1.37	-0.62	-4.31	-8.62
Scenario 2	**GWh**	-0.65	-0.48	5.65	4.64	9.27

B. *Carbon dioxide emissions of the process*

During the production of activated carbon from MDF waste with the Act&Sorb process, carbon dioxide is emitted. 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 **Error! Reference source not found.**. 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 [22] [23].

In the context of this work, MDF waste is seen as a biomass resource and the resulting carbon dioxide emissions as biogenic. The combustion of natural gas, which is also used in the process, is responsible for fossil carbon dioxide emissions.

The combustion of natural gas and syngas forms the bulk of the carbon dioxide emissions of the facility. The 600 kg/h capacity model has the highest share of fossil carbon dioxide emissions with nearly 15% of the CO_2 coming from the combustion of natural gas. For the three larger configurations, fossil CO_2 emissions form only a minor part of the total emissions with the share of the biogenic emissions reaching above 99% for each case, increasing as the capacity increases. The 600 kg/h model emits the largest amount of fossil carbon dioxide per year, with more than 1200 tonnes of CO_2 emitted, whereas the corresponding amount for the other models is around 100 tonnes.

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 three 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. 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 [24].

As the prior sources of carbon dioxide emissions consider the emission of the installation itself, the system was expanded to include the CO_2 emissions from MDF waste transportation. Road transport with and average emission factor of 62 gCO_2/tonne-km 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 [25].

For the calculation of the total carbon dioxide emissions from the installation, the biogenic emissions from the combustion of syngas and the fossil carbon dioxide emissions are added. The total annual carbon dioxide emissions per component are shown in Figure 2. EL1 and EL2 depict electricity scenarios 1 and 2. As it can be seen, biogenic carbon dioxide emissions form the bulk of the total annual emissions with fossil CO_2 making up just 3.2% of the total for the 6000 kg/h production capacity model with electricity scenario 2.

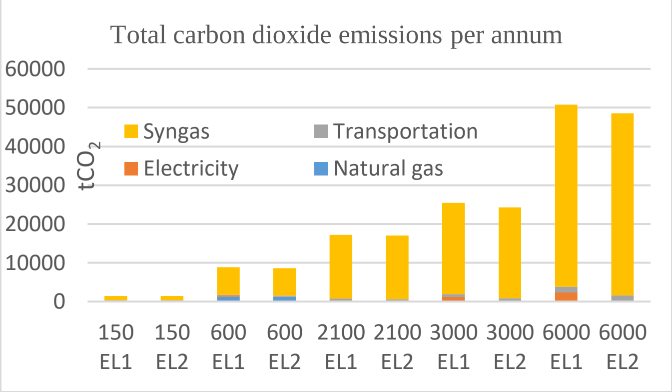

Figure 2. Annual carbon dioxide emissions per component

C. Comparison to a waste incineration facility

For a better evaluation of the Act&Sorb process, it was compared to a municipal waste incineration (WI) plant, as this is the common facility for disposing of MDF waste. The average electrical efficiency of such an installation lies between 15-27%, which enables to compare both the electricity generation potentials and the carbon dioxide emissions [26].

Figure 3 depicts the annual electricity provided to grid from the two Act&Sorb process scenarios and the high and low efficiency WI plants. As it can be seen, WI has a higher net output for both efficiencies than for any of the Act&Sorb configurations. With electricity scenario 2, the 2100 kg/h production capacity model reaches 53% of the net electricity generated with the less efficient waste incinerator and 29% of the net electricity generate with the more efficient waste incinerator, achieving the highest shares for the Act&Sorb configurations. Considering that electricity is a side-product for the Act&Sorb solution, it still reaches a significant share of the net output of the WI facility.

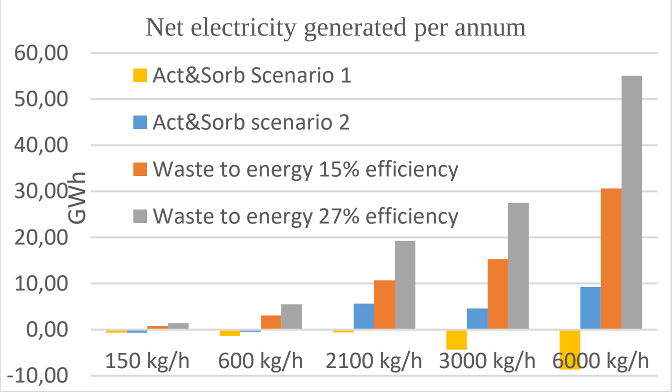

Figure 3. Net electricity generated per annum

While the carbon dioxide emissions of the Act&Sorb process consist of the fossil CO_2 emitted from natural gas combustion and electricity consumption and the biogenic CO_2 emitted from the combustion of syngas, the carbon dioxide emissions resulting from the WI facility are purely biogenic. The carbon dioxide emissions resulting from the WI plant were defined based on the average carbon content of MDF waste. The total annual carbon dioxide emissions for the two Act&Sorb scenarios and WI are shown in Figure 4 [27].

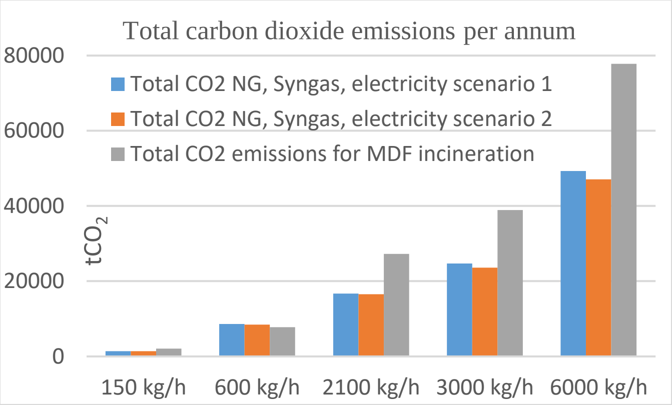

Figure 4. Total carbon dioxide emissions per annum

The total carbon dioxide emissions for the WI plant exceed the emissions of the Act&Sorb process for every configuration and for both electricity scenarios except for the 600 kg/h production capacity model. The primary reason for the smaller amount of carbon dioxide emitted is due to carbon being captured in the activated carbon, the end product for the Act&Sorb solution, whereas for the WI facility all of the carbon is converted to CO_2 during incineration. By using the Act&Sorb process for treating MDF waste instead of the WI solution, it is possible to avoid emitting more than 30 kton of carbon dioxide emissions per annum with the recycling capacity of 6000 kg/h.

D. Potential improvement of the system

Over the course of 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. The easiest way for utilizing the syngas more efficiently is to use it for enhancing the electricity generation.

To assess the potential of increasing the electricity generation, electricity scenario 3 was created. This scenario implements the more efficient approach for cooling while maximising the electricity generation for all configurations by directing the syngas formerly incinerated in the excess syngas burner to additional gas generators. With the implementation of electricity scenario 3, a net positive output of electricity is achieved for all configuration except for the 150 kg/h production capacity model. The resulting net electricity generated per annum and comparison to other scenarios is given in Figure 5.

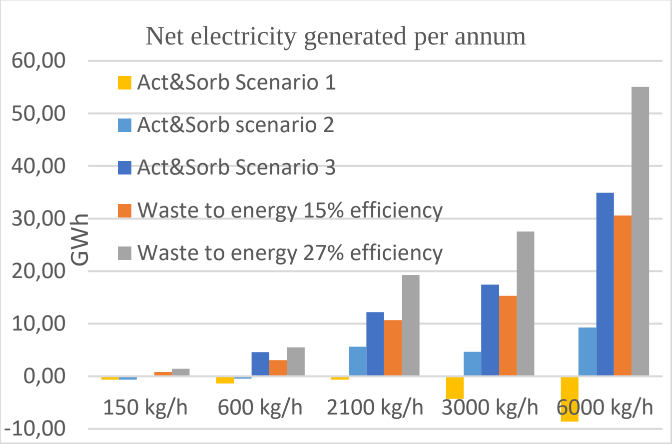

Figure 5. Net electricity generated per annum

The increased electricity output with scenario 3 makes the Act&Sorb solution more competitive with the WI facility. Considering that providing the grid with electricity is merely a side-benefit for the Act&Sorb solution, the result is positive.

When it comes to the carbon dioxide emissions, electricity scenario 3 manages to achieve a slight reduction in the CO_2 emitted from the two smaller production capacity models as it reduces the amount of electricity needed from the grid and thereby the fossil carbon dioxide emissions are decreased. For the larger models there is no additional benefit, as they were already generating a sufficient amount of electricity with scenario 2.

In conclusion, maximising the on-site electricity generation from the syngas has a positive effect on the overall performance of the system. It makes the Act&Sorb solution more competitive with WI and utilizes the potential of syngas in a beneficial way.

IV. LIFE CYCLE ASSESSMENT OF THE PROCESS

Following the analysis of carbon dioxide emissions resulting from the recycling of MDF waste to activated carbon in comparison to 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 standards 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 are from the ecoinvent v3.0 database. Ecological scarcity 2013 was chosen as the method for the assessment of impacts [28] [29] [30] [11] [31] [32].

A. *Goal and scope definition*

The goal of the study is to assess the environmental impacts of producing activated carbon from medium density fibreboard waste. 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. It was decided to include all processes preceding the waste treatment as well as all the 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". 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 [17] [18].

The 3000 kg/h production capacity model was chosen as the configuration to be analysed. As an expansion over the calculation model, different transportation and location scenarios are implemented. In total 15 scenarios are created for the Act&Sorb solution and the WI with production taking place in either Belgium, Estonia or Norway and transportation being either carried out by truck, train or ship for the Act&Sorb solution and by municipal waste collection service for the WI facility. Norway was chosen as a country with a low carbon intensity electricity system, Estonia as a country with a high carbon intensity electricity system and Belgium is a base case scenario [33].

B. *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 shown in Table III covers the whole production process from cradle to gate for both the Act&Sorb solution and the waste incineration facility.

TABLE III. LIFE CYCLE INVENTORY FOR THE ACT&SORB PROCESS AND FOR THE WASTE INCINERATION PROCESS

Inputs	**Act&Sorb**	**WI**
MDF waste	24 000 tonnes	24 000 tonnes
Process water	3 864 tonnes	
Natural gas	35 413 m^3	
Loader operation	8 000 h	8 000 h
Transportation/Municipal waste collection service	12 000 000 tkm	6 000 000 tkm
Outputs		
Activated carbon	3 392 tonnes	
Electricity	4 636 MWh	27 540 MWh
Fossil carbon dioxide	77.9 tonnes	
Biogenic carbon dioxide	23 487 tonnes	38 921 tonnes
Waste water	7 728 tonnes	

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

The base case scenario for the assessment is with production located in Belgium and transportation carried out by truck

The single score overview of the EI of the input and output components and their impact categories are depicted in Figure 6. MDF depicted in the second column shows the biggest environmental impact with global warming and main air pollutants and particulate matter (PM) being the most affected categories. AC produced has the highest impact avoidance which is primarily related to the same EI assessment categories as for MDF waste with global warming being the primary benefactor.

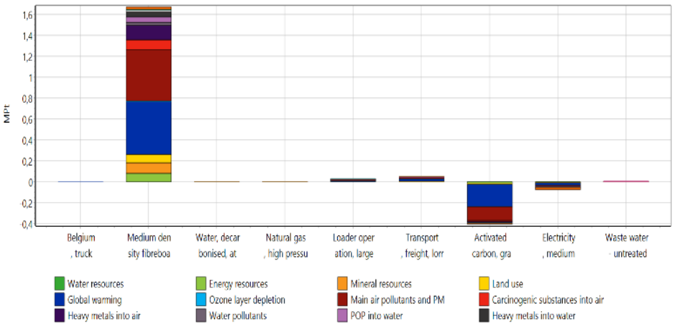

Figure 6. Belgium single score evaluation for truck transportation

The same assessment was carried out for the other two locations and the results achieved were as expected, with Estonia, the country with a high carbon intensity electricity network achieving the best result thanks to the electricity generation avoided and Norway showing the worst result due to low carbon intensity electricity network. Transportation by ship has the lowest total environmental impact for all locations and transportation by truck has the highest total EI for all locations.

Improved electricity generation resulted in a great improvement in environmental impacts for production in Estonia, with the impact for global warming becoming positive in the total EI evaluation. Maximised electricity generation also showed vital improvements for production in Belgium, with a great avoidance of radioactive waste to deposit impacts. For Norway the effect was not remarkable.

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

The single score evaluation of the twelve Act&Sorb scenarios and the three waste incineration scenarios is shown comparatively in Figure 7. As it can be seen, the AC production in Estonia with maximised electricity generation has the lowest ecological impact of the processes compared. On the other end of the scale lies the WI in Norway. The total value for the Norwegian WI is about 2.5 times larger than for the Estonian AC production with electricity scenario 3.

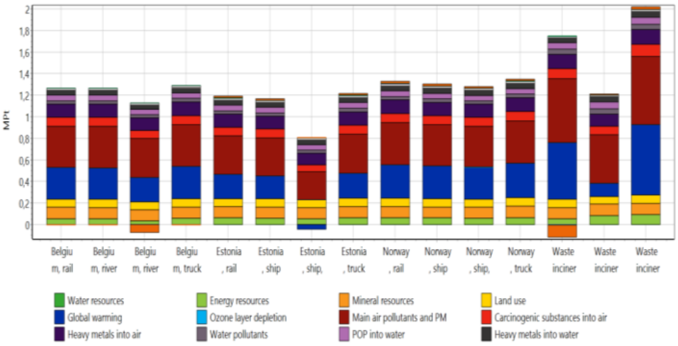

Figure 7. Comparison of all MDF waste treatment scenarios with a single score evaluation

E. *Interpretation of results*

Overall the comparison showed that the configuration with the lowest EI is the production of AC in Estonia with electricity scenario 3 and transportation carried out by ship. When disregarding the electricity scenario 3, the AC production in Estonia with transportation carried out by ship remains the option with the lowest EI, however the competing WI technology in the same country reaches a similar result.

Medium density fibreboard carries the highest ecological burden for all configurations for the Act&Sorb process and the WI facility. This impact is compensated by electricity generation with both technologies and the activated carbon production gives a further impact reduction advantage for the Act&Sorb solution over the WI facility.

The production location has a significant effect on the overall environmental impacts due to the great differences in the electricity systems of the countries chosen. At the same time the effect of transportation is smaller, however it is still possible to achieve a saving in impacts resulting from transportation by choosing the right method.

The two impact categories with the largest relative impact for all the configurations studied, except for the Act&Sorb process with electricity scenario 3 for Estonia, are global warming and main air pollutants and PM. The majority of the EI in those two categories is carried into the final process with MDF waste.

V. CONCLUSIONS

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. The questions raised in the introduction of this work were answered and a comprehensible assessment of the sustainability of the process was achieved.

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. The amount of total emissions increases as the production capacity increases with the largest model with electricity scenario 1 emitting nearly 51 kton of CO_2 per annum from the combustion of fuels, use of electricity and the transportation required.

The comparison of the total carbon dioxide emissions per kg of activated carbon produced gives a value of around 7 kg of CO_2 for the three larger production capacity models. The two smaller production capacity models are more carbon intensive, with the 600 kg/h feed model reaching a value of nearly 13 kg of CO_2 with electricity scenario 1.

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. The waste incineration plants have a higher net electricity output for every configuration regardless of its electrical efficiency. The 2100 kg/h production capacity model, which utilizes the highest share of syngas for electricity generation, can reach 53% of the net electrical output of the less efficient waste incineration plant and 29% of the net electrical output of the more efficient waste incineration plant. 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. The deviation from the trend for the 600 kg/h feed model can be explained by the combustion of a large amount of natural gas. With the largest production capacity model of the Act&Sorb solution, it is possible to avoid more than 30 kton of CO_2 per annum in comparison to a waste incineration facility with the same capacity. This amount forms nearly 40% of the total carbon dioxide emissions of the corresponding waste incineration plant, which gives the Act&Sorb solution a significant edge regarding the sustainability of the process.

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. When utilising electricity scenario 3, the electricity balance is positive for all Act&Sorb configurations. 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. With electricity scenario 3, the largest production capacity model can displace nearly 9 kton of CO_2 emissions.

The boosted electricity generation also makes the Act&Sorb more competitive with waste incineration by achieving net electricity output values, which exceed the corresponding values for the lower efficiency waste incineration facility. This gives the Act&Sorb solution a valuable competitive edge, since providing the grid with electricity is only a beneficial side-activity to activated carbon production.

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. 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. The environmental impacts resulting from the systems with increased electricity generation according to electricity scenario 3 were also evaluated. 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.

As a result of the comparison of the environmental impacts of the 15 scenarios under consideration, it became clear that the production of activated carbon in Estonia with maximised electricity generation and transportation carried out by ship has the lowest total environmental impact. Waste incineration in Norway has the highest total environmental impact, which is about 2,5 times greater than the relative impact for the best-performing scenario. With electricity scenario 2, the production of activated carbon in Estonia with ship transportation has the lowest environmental impact, however, the competing waste incineration technology in the same country also reaches a comparably low value.

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. This gives the Act&Sorb technology a clear advantage over waste incineration, in which case only electricity is generated, and the amount of impacts avoided is considerably smaller.

The choice of location for production can have a significant influence on the outcome of the environmental impact assessment. By locating the production in Estonia, it is possible to have a lot more sustainable production of activated carbon than by having the same production in Norway.

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.

Overall the processes studied show the largest environmental impact in the categories of global warming and main air pollutants and particulate matter, except for the Act&Sorb process in Estonia, in which case the impact on global warming is balanced out by the displaced impacts from electricity generation.

In conclusion, the production of activated carbon from medium density fibreboard waste shows great promise regarding sustainability. The process shows great performance values in comparison to its primary competitor, waste incineration. The carbon dioxide emissions are significantly smaller due to carbon being captured in the produced activated carbon and the share of fossil carbon dioxide emissions is kept to a minimum level. The Act&Sorb solution can also compete to the waste incineration in terms of net electricity output, even though the electricity generated is only a side-benefit for the process. The produced activated carbon and the electricity provided to the grid offer the Act&Sorb solution valuable advantage over the waste incineration technology, when comparing the resulting environmental impacts. 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.

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