



Activated carbon from co-pyrolysis of particle board and melamine (urea) formaldehyde resin: A techno-economic evaluation

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ABSTRACT

The disposal and environmental problems associated with waste resin produced during the production of melamine (urea) formaldehyde and wood waste (i.e. particle board) containing these aminoplasts requires a processing technique which results in products of added value and which meets both ecological and economical needs. Several published results demonstrate that nitrogen incorporation in activated carbon can play a significant role as a key parameter for the adsorption properties, as well as for the catalytical activity and the dispersion of carbon supported catalysts.

The production of high value nitrogenised activated carbon, after thermal treatment in an oxygen deficient environment and subsequent activation, is considered as a possible opportunity.

This research paper investigates the feasibility of a process design for the production of a high added value nitrogenised activated carbon by co-pyrolysing a mix of particle board and melamine (urea) formaldehyde waste. A process design and an economical model for estimating the total capital investment, the production costs, the possible revenues, the net present value and the internal rate of return is developed based on various literature sources. In addition, Monte Carlo sensitivity analysis has been carried out to determine the importance of the main input variables on the net present value. It is assumed that the manufacturing facility obtains its waste from various sources and operates continuously during 7000 h a year. The study investigates the plant's profitability in function of processing rate and mixing ratio.

Even though the current assumptions rather start from a pessimistic scenario (e.g. a zero gate fee for the melamine (urea) formaldehyde waste, a first plant cost, etc.) encouraging results for a profitable production of activated carbon are obtained. Moreover, the ability to reuse two waste streams and possible production of a specialty carbon enhances the value or usefulness of the activated carbon manufacturing facility.

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1. Introduction

During the production of melamine (urea) formaldehyde resins (both further abbreviated as MF) for the production of particle board (PB) a considerable amount of waste resin is produced that cannot be re-used or recycled at this moment.

In addition, classical thermo-chemical conversion (e.g. combustion) of wood waste containing these aminoplasts resins might cause pollution because it results in the production of toxic gases

like ammonia, isocyanic and hydrocyanic acid and nitrous oxides [1–3].

A sustainable solution is more and more required to avoid environmental problems and landfilling costs, and to turn this waste stream in a rather profitable material resource. A possible opportunity, is the production of high value activated carbon (AC) after thermal treatment in an oxygen deficient environment and subsequent activation.

ACs are produced for a large number of dedicated applications both as structural and functional materials. ACs are generally used for air, water and gas purification, chemical and pharmaceutical processing, food processing, decolourization, solvent vapour recovery, fillers in rubber production, refractory materials, catalysis and catalyst support [4–6].

Marsh and Rodriguez-Reinso [5] estimated the world annual production capacity of AC to be around 400 kt in 2006, excluding countries without accurately known figures like China and

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some other Eastern countries. Furthermore the market is increasing constantly, due to the environmental awareness and the growing industrialization. Girods et al. [7] expect a growth of 5.2%/year to 1.2 Mt by 2012. In Europe, Japan and the USA the growth is 1–5%/year, whereas this rate is much higher in the developing countries. The price of AC is a function of demand, quality, production cost, etc. A typical price range is 1.4–6 kUSD/t, but for very special carbons the price can increase to 20 kUSD/t [5,8]. Girods et al. [7] state that the average production cost of AC from the major producers was on average 2.5 kUSD/t.

The wide range of applications exists thanks to the high volume of pores, high surface area and the variety of surface chemistry of ACs. The final properties of the AC are related to the precursor material and the activation process (physical or chemical). It is stated that the physicochemical properties of the ACs are strongly influenced by the presence of heteroatoms like oxygen, nitrogen, sulfur, etc. In normal conditions the amount of nitrogen in the AC is negligible [4,6]. Several published results however, demonstrate the positive effect of nitrogen incorporation as a key parameter for the adsorption properties of the AC [9], especially for the removal of acid gases like hydrogen sulfide, sulfur dioxide and phenolic compounds [2,3,7]. Nitrogen incorporation can also play a significant role for the catalytic activity and dispersion of carbon supported catalysts [9]. According to Girods et al. [2] the value of such a nitrogenised activated char from PB (in 2006) is on average 2.5 kUSD/t (≈ 2.0 kEUR/t), whereas normal ACs are sold (in 2008) at prices between 0.8 kEUR/t and 1.7 kEUR/t (≈ 1.2 – 2.5 kUSD/t) [10]. According to Infomil [10], impregnated ACs (i.e. including pick-up of the saturated carbon) have a higher selling price (in 2008) of 4.0 kEUR/t to 6.0 kEUR/t (≈ 5.9 – 8.8 kUSD/t) due to higher costs incurred by the impregnation step.

Because the chemical properties of the PB and MF waste materials result in in situ nitrogen incorporation during char formation and activation, the production cost of nitrogenised activated char is considerably reduced in comparison with post impregnation of nitrogen containing components on AC. In addition, these waste materials have the economic advantage of representing a negative cost [1] for a waste processing company, which means that the latter does not have to pay for obtaining resources such as PB and MF waste, but instead receives a *gate fee* for processing the waste material.

The objective of this work is to identify the crucial variables for rendering the production of AC from PB and MF waste profitable. For this purpose, a preliminary economic feasibility study has been carried out for a process design especially developed for the production of AC from PB and MF waste. After developing a process diagram of an AC production technique (co-pyrolysis combined with physical activation), the net present value of the cash flows generated by an investment in co-pyrolysis and char activation has been calculated. The minimum selling price of the produced AC has been determined, taking into account uncertainties by performing Monte Carlo sensitivity analysis. Finally, this preliminary economic feasibility study is used to identify the key variables for the profitability of the production of AC from PB and MF waste.

2. Process design

The preliminary process design for the production of AC from PB waste co-pyrolysed with MF is shown in Fig. 1. The process can be divided in four parts: pretreatment, pyrolysis, activation and packaging. After shipping the raw materials to the AC production facility, they are first mixed and milled into a smaller particle size (a few millimetre), dried and transported to a silo. It is difficult to predict the moisture content of the incoming waste. Girods et al. [2] determined the moisture in wood board to be about 7%.

Next, the grinded and dried waste will be transported to a rotary pyrolysis furnace (operating at 800 °C). Here the waste is pyrolysed in an oxygen-free environment for a few minutes (2–5 min). The developed chars (solid fraction) are then transported to a second rotary kiln furnace where they are activated during 30 min at a temperature of 800 °C in the presence of steam as activation agent. The pyrolysis and activation are carried out in two separate but connected furnaces to achieve a continuous system. Both the pyrolysis and activation kiln have a cross-sectional area occupied by material which is 10% of the cylinder's length to ensure an adequate heat transfer and mixing [11,12]. The produced pyrolysis gases and aerosols are conducted to a thermal combustor followed by a cyclone for complete combustion at a temperature of around 1000 °C with a residence time of at least 2.5 s. This reduces formation of harmful compounds or promotes their breakdown [13]. By using a multiple zone oxidizer the formation of NO_x can be further controlled by managing the oxygen inflow in the different zones, but this is not implemented at this stage. The hot flue gases are used as a heat source for pyrolysis/activation and the steam generator. After cooling, the produced AC is transported to a storage silo before screening and packaging. The remaining gases are cooled to recover water from the steam generator. After cooling they are discarded. A pelletisation device and an extra gas cleaning unit before emission can also be installed, but are at the moment not incorporated in this analysis. The possible extra investment costs for this equipment can be found in recent literature e.g. Lima et al. [11] and Lemmens et al. [14].

3. Economical feasibility model

Poor capital investment decisions can alter the future stability of an organisation. Investors deal with this problem by using investment decision rules which evaluate the profitability of the project or investment. Biezma and San Cristóbal [15] have categorized many various investment criteria methods. Two of these criteria, the net present value (NPV) and the internal rate of return (IRR), are used to evaluate the economics of the MF–PB pyrolysis/activation. The NPV is the best criterion for selecting or rejecting an investment, either industrial or financial [16,17]. The NPV is today's value of current and future cash flows, which are the result of an investment using a predetermined discount rate [17,18]. The NPV is calculated with Eq. (1) [17–20].

$$NPV = \sum_{n=1}^T \frac{CF_n}{(1+i)^n} - I_0 \quad (1)$$

With:

- CF_n = cash flows generated in year n ;
- I_0 = initial total capital investment (see Table 1, row 19) in year 0;
- T = the life span of the investment;
- i = discount rate.

The cash flow in a given year is the difference between revenues (R) and expenditure (E) after tax (t) generated by the investment. To calculate the cash flow, depreciation (D) also needs to be taken into account because it lowers tax payments [19,20]. According to Kuppens et al. [19] and Thewys and Kuppens [20] cash flows can be calculated using the following equation:

$$CF_n = (1-t) \times (R-E) + t \times D \quad (2)$$

The discount rate of the invested money is set at 9% incorporating the market interest rate and some risk premium [19,21]. Taxes on profits to be paid amount up to 33% in Belgium ($t=0.33$). The life span of a reactor is described as 20 years [19,20,22]. Because MF is easy to coke, all the results are based on a rather

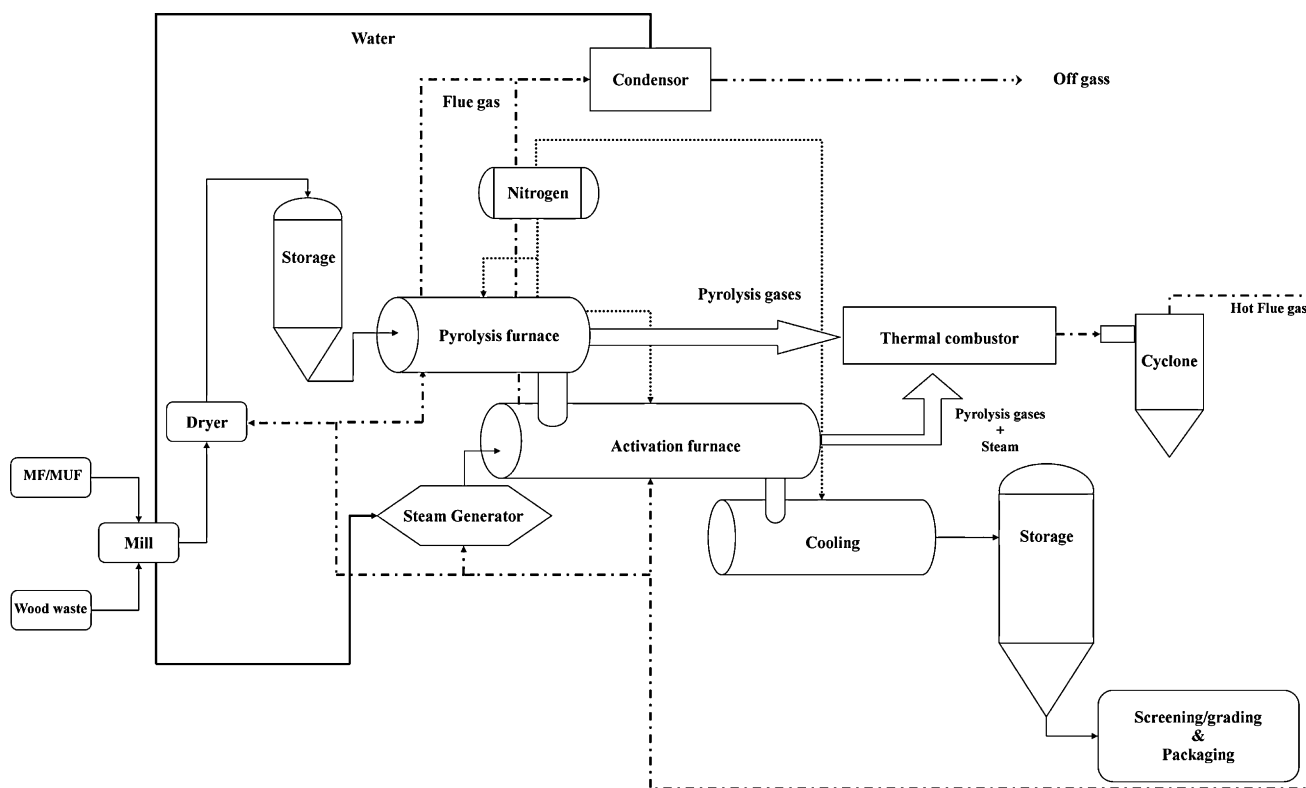


Fig. 1. Process flow.

low average operating time of the reactor of 7000 h, the rest of the year (or 20% of the year) is used for maintenance etc. In general, when the NPV is positive, the investment is a good decision.

The IRR is the discount rate (i) at which the present value of expected cash inflows from a project equals the present value of expected cash outflows of the project. In other words, it is the discount rate that makes the NPV equal to zero. It is frequently used in financial markets because it gives the return that the investor can expect for a given level of risk [17]. If the IRR is lower than the required return (discount rate) then the project should be rejected.

Additionally the minimal selling price of the AC has been calculated. This is the minimal price at which the AC should be sold so that the NPV breaks even or in other words the NPV equals at least 0.

In order to have an idea about the impact of uncertainties on the NPV, Monte Carlo sensitivity analysis is performed. The sensitivity analysis repeatedly calculates the NPV corresponding to numerous random draws for the value of uncertain variables following a presupposed distribution. Monte Carlo simulations typically result in a distribution of NPVs that can be declared by the degree of uncertainty of each individual variable. Each variable with its corresponding range of values and distribution is partly responsible for the total uncertainty of the NPV. The variables with the high-

Table 1
Multiplying factor for the delivered-equipment cost.

	Cost component	Percent of equipment cost
Direct costs	Delivered equipment	100
	Installation	39
	Piping (installed)	31
	Instrumentation and controls (installed)	26
	Electrical systems (installed)	10
	Buildings (including services)	29
	Yard improvements	12
	Service facilities (installed)	55
	Land	6
	Direct plant costs (DPC)	308
	Indirect costs	Engineering, supervision
Construction expenses		34
Legal expenses		4
Contractor's fee		19
Contingency		37
	Indirect plant costs (IPC)	126
Fixed-capital investment		434
Working capital (15% of total capital investment)		76
Total capital investment		509

est influence on NPV sensitivity should be identified and should be the subject for further research so that they can be controlled when putting the project into practice. In our study 10 000 runs are carried out using the @Risk software from Palisade Decision Tools.

Finally, these uncertainties have been taken into account when calculating the minimum selling price at which the AC should be sold in order to guarantee a 95% chance on a positive NPV.

4. Model assumptions

The first step in NPV calculation is the estimation of the initial investment expenditure. For preliminary economic feasibility analysis, the Percentage of Delivered-Equipment cost is commonly used, with an expected accuracy of 20–30%.

Before an industrial facility can be put into operation, a large sum of money needs to be spent on the necessary machinery, equipment and their delivery: i.e. the cost of delivered equipment. The total capital investment however also consists of costs of the building itself, the land on which the equipment is installed, piping, electrical systems, etc. These are all direct plant costs. But also indirect plant costs have to be taken into account: such as costs for engineering, legal expenses, contingencies, etc. The sum of these investment costs, i.e. the cost for delivered equipment, the direct plant costs and the indirect plant costs are called fixed-capital investment. The amount of money required for a stock of raw materials and cash kept on hand, i.e. the working capital, should be added for estimating the total capital investment. The working capital and the direct and indirect plant costs are expressed as a percentage of the delivered equipment cost. The percentages determined by Peters et al. [23] are used in the calculation and are displayed in Table 1.

All costs have been updated to 2009, based on the US Dollar/Euro exchange ratio provided by the European Central Bank [24] and the Marshall and Swift Index [25] (see Eq. (3)):

$$\text{Cost of Equipment (2009)} = \text{cost of Equipment (year)} \times \frac{\text{Cost index (2009)}}{\text{Cost index (year)}} \quad (3)$$

4.1. Total capital investment

The total investment cost for production of the AC is determined by the Percentage of Delivered-Equipment cost method. The equipment cost information was provided by literature (Table 2). A delivery allowance of 10% on the purchased equipment cost is used [23].

One of the problems in cost estimating is that cost data are not always available for the particular size or capacity involved. Predictions can be made by using Eq. (4) which is known as the six-tenths factor rule and is widely used in approximations of equipment and even total process costs [23].

$$\text{Equipment cost reactor} = \frac{40.8 \times 10^3 [(Q_{\text{feed input pyrolysis}} \times 10^3)^{0.6194} + (Y_{\text{Char}} \times Q_{\text{feed input pyrolysis}} \times 10^3)^{0.6194}]}{490.1\%} \quad (8)$$

Cost of unit (new) = cost of unit(ref.)

$$\times \left(\frac{\text{capacity (new)}}{\text{capacity (ref.)}} \right)^{\text{capacity exponent}} \quad (4)$$

The actual value of the cost capacity exponent in Eq. (4) can vary from less than 0.3 to greater than 1.0. Yassin et al. [27] stated that the capacity exponent is in the range of 0.6–0.8 for gasification and pyrolysis facilities. In this calculation a capacity exponent of 0.7 is

used as suggested by Henrich et al. [28], Tock et al. [29] and Gassner and Maréchal [30].

The equipment cost of the pyrolysis and activation reactor (which is on its turn a pyrolysis reactor) is derived from the fixed-capital investment (FCI) of a pyrolysis plant presented by Bridgwater et al. [22] in Eq. (5) with $Q_{\text{feed input pyrolysis}}$ the flow ratio of the feed (ton dry matter per hour):

$$\text{FCI pyrolysis plant} = 40.8 \times 10^3 \times (Q_{\text{feed input pyrolysis}} \times 10^3)^{0.6194} \quad (5)$$

Eq. (5) calculates the cost of the fast pyrolysis reactor, the feeding system and liquids recovery. Eq. (5) is a result of a regression from 14 cost data performed by Bridgwater et al. [22], and the data are assumed to be first plant costs from a novel technology. This is important, because there can and probably will be a considerable cost reduction from the ‘learning effect’. Henrich et al. [28] state that, if the same type of facility is designed, built and operated several times the investment and operating costs decrease exponentially with the number of built plants. According to Henrich et al. [28], it is reasonable to set the total capital investment at about two-thirds of the first plant cost. In this paper the first plant cost is used. Therefore, it may be inferred that a rather pessimistic investment cost scenario is applied.

Because Bridgwater et al. [22] used other and less factors to calculate the indirect plant cost and direct costs, the fixed capital investment of the pyrolysis plant is recalculated to the equipment cost. Bridgwater et al. [22] stated that the total plant cost is 169% of the direct plant cost. The percentages of the direct cost factors that Bridgwater et al. [22] used are not defined, but the factors can be found in Peters et al. [23]. So they are assumed to be 39% for erection, 31% for piping, 26% for instruments, 10% for electrical systems, 55% for civil works and 29% for structures and buildings. The expenses for lagging are included under the equipment installation and piping costs like Peters et al. [23] suggested. The equipment cost of the pyrolysis reactor can thus be calculated by Eq. (6).¹

$$\begin{aligned} \text{Equipment cost pyrolysis reactor} &= \frac{\text{Direct plant cost}}{290\%} \\ &= \frac{\text{FCI pyrolysis plant}}{490.1\%} \end{aligned} \quad (6)$$

It is also important to note that the feed input of the activation reactor is related to the feed input of the pyrolysis reactor as defined in Eq. (7):

$$Q_{\text{feed input activation}} = Y_{\text{Char}} \times Q_{\text{feed input pyrolysis}} \quad (7)$$

With Y_{Char} the char yield from the pyrolysis step which can be found in Table 4 and $Q_{\text{feed input activation}}$ the input of the activation reactor in t/h dry matter.

From the foregoing discussion the total equipment cost for the pyrolysis and activation reactor can be calculated by combining Eqs. (5)–(7) to form Eq. (8).

¹ Direct plant cost = equipment cost pyrolysis reactor × (100% + 39% + 26% + 31% + 10% + 29% + 55%) = 290% × equipment cost pyrolysis reactor
Direct plant cost = $\frac{\text{FCI pyrolysis plant}}{169\%}$

Table 2
Major equipment cost and their scaling factors used.

Item	Sizing parameter	Unit cost year	Reference
Crusher	2 t/h	44.94 kUSD (2002)	[13]
Dryer	10 t/d	51.27 kUSD (2002)	[13]
Silo (raw material)	500 m ³	380 kEUR (2009)	[26]
Nitrogen storage tank	1.92 m ³	19.26 kUSD (2002)	[13]
Pyrolysis and activation reactor	/	Eq. (8)	
Steam boiler and condenser	3781 kg/h	116.84 kUSD (2002)	[13]
Thermal combustor	1000 N m ³ /h	40 kEUR (2004)	[14]
Cyclone	1000 N m ³ /h	1.5 kEUR (2004)	[14]
Silo (activated carbon)	500 m ³	380 kEUR (2009)	[26]
Screening and Grading	139.9 kg/h	25.0 kUSD (2005)	[11]
Packing of activated carbon	139.9 kg/h	25.0 kUSD (2005)	[11]

The formula is used in the assumption that condensable gases (pyrolysis liquids) will not be condensed (i.e. direct diversion to the combustion system), but instead the AC needs to be cooled. Therefore it is assumed that the cost of the liquids recovery of Bridgwater et al. [22], is the same as for the AC cooling.

The produced gases can be considered as a mixture of flammable (toxic) compounds at enhanced temperature. From an energy and environmental point of view there is a need to (re)use this heat or “combustion” energy and decompose or separate the toxic compounds. Thermal treatment of the volatile combustible gases will be performed by a direct fired thermal oxidizer combined with a cyclone. The temperature of the combustion chamber is maintained at ~1000 °C with a residence time of minimum 2.5 s. This reduces the formation of NO_x and harmful materials, like dioxins, will be destroyed [13]. For complete combustion, the flue gases pass through a cyclone where possible solid particles are separated out. Lemmens et al. [14] calculated a cost estimate for these systems. With a maximum cost of 40 kEUR and 1.5 kEUR for a gas stream of 1000 N m³/h for the combustion chamber and the cyclone is used respectively.

4.2. Expenditure

The total expenditure of the project consists of the operating cost and the yearly interest payments. Thewys and Kuppens [20] assumed that an investment is financed by means of a loan with a yearly interest of 4.60% in Belgium. The macro-economic database Belgostat [31] gives an average initial interest provision for more than 5 years of 3.9% on new credits (in 2009) for the euro area for an amount of more than 1 MEUR. In this model an interest rate of 4.0% is applied as a realistic compromise. The annual operating costs of pyrolysis and activation consist of maintenance, labour, insurance, overhead, delivered feed, energy and water costs which are generally expressed as a percentage of the total fixed-capital investment [20] except the last three items.

Table 3
Summary of the fixed annual operating factors.

Annual operating cost	Expressed as	Reference
Maintenance	3% of fixed-capital investment	[19,20,32,33]
	5% of fixed-capital investment (for a gasification system)	[13,27,30]
	3% of fixed-capital investment (for a combustion process)	[27]
	4% of fixed-capital investment	[34]
	6% of fixed-capital investment	[35]
	2.5% of fixed-capital investment	[22]
Insurance	2% of fixed-capital investment	[20,33]
	1% of fixed-capital investment	[35]
Insurance and general	1% of fixed-capital investment	[32]
Overheads	4% of fixed-capital investment	[34]
	2% of fixed-capital investment	[20,33]

A summary of literature percentages to calculate the annual operating cost is displayed in Table 3.

In this model, the annual maintenance cost is accounted for 3%, the annual overhead and insurance cost for 2% of the total fixed-capital investment. The cost for maintenance labour is incorporated in Eq. (9) (Labour cost) [19,20].

The labour costs are calculated with Eq. (9) based on Bridgwater et al. [22]. The calculation is in function of the flow rate of the dry feed (t/h) $Q_{\text{feed input pyrolysis}}$ and will always be rounded up.

$$\text{Labour cost} = 1.04 \times ([1 + Y_{\text{Char}}] \times Q_{\text{feed input pyrolysis}})^{0.475} \times 3 \text{ shifts} \times \text{annual salary} \quad (9)$$

FPS Economy [36] states that the annual salary of one person, employed in the industrial sector in Belgium was on average 48 kEUR in 2004. By using the annual nominal unit labour cost data from Eurostat [37] the average annual salary in industry is estimated to be around 55 kEUR in the year 2009. In this model it is assumed that 3 shifts are sufficient for a good and secure operation of the AC production facility.

The delivered feed cost consists of the cost of the PB waste and the MF waste. For processing PB waste a gate fee of 70 EUR/t [7] is paid, which is an incoming cash flow for the AC production plant. Disposing of MF waste to a landfill site costs a MF factory 220 EUR/t (including transport) in Belgium. This could mean that this waste also represents an income stream for the AC production facility, as the MF factory is already satisfied when it has to pay less than 220 EUR/t for disposing its MF waste stream. In this model the cost of the MF is set at 0 EUR/t to have a worst case scenario.

To provide an oxygen free environment, nitrogen gas is applied to act as a purging gas. In this study a rate of 8 kg nitrogen gas/t feed input (based on [35]) with a cost of 2.5 EUR/kg is applied.

Bridgwater et al. [22] used 18.5 m³ water/t input material for cooling the produced pyrolysis liquid and Ko et al. [35] used 13.5 m³

Table 4
Estimated costs and yields of the input feed.

Ratio (MF/wood)	4 MF–1 PB	3 MF–2 PB	2 MF–3 PB	1 MF–4 PB	0 MF–5 PB
Yield Char ^a	22%	29%	36%	43%	50%
Yield active carbon ^a (vis-à-vis char)	44%	45%	47%	48%	50%

^a Girods et al. [7] determined the carbon yield after pyrolysis (400 °C) typically 50% and again 50% after pyrolysis combined with steam activation (800 °C). Own laboratory experiments on MF give a yield of 15 and 42% respectively (800 °C).

water/t input material to generate steam for the activation and cooling water for the produced pyrolysis liquid. The quantity of cooling water (from surface water 20 °C) needed to cool the produced AC from 800 °C to 20 °C is 13 t/h. In this calculation it is assumed that the specific heat capacity of AC is equal to the specific heat capacity of graphite (709 kJ/(t °C)) and the maximum temperature of cooling water that needs to be discharged is 30 °C as defined by the Belgian legislation. Here, the water requirements are assumed to be 15 m³ water/t input material with a cost of 1.5 EUR/m³.

Another utility required in the process is energy which can be split in two parts, power and heat requirements. Ko et al. [35] estimated that a 1.25 t/h processing plant producing AC uses 200 kW electricity. So it is assumed that for a 1 t/h facility the electricity consumption is 160 kW. In this estimation the price of electricity is set at 0.0725 EUR/kWh. The heat of pyrolysis for municipal solid waste is calculated by Baggio et al. [38] as 1.8 MJ/kg. For biomass a range of 2 MJ/kg to 3.47 MJ/kg can be found in literature [39–42]. In our case a value of 2.5 MJ/kg for both the pyrolysis and the activation step is taken. In the activation step steam is also needed. Heating water from 20 °C to 800 °C requires 5.5 MJ/kg. For the drying process 2.67 MJ/kg water in the wood is needed. In most pyrolysis reactors (for the production of pyrolytic oil) the required heat is provided by the combustion of the gas and/or the char. In this application, as explained before in Section 4.1, only AC and gases (as by-product) are produced. The gases will be thermally destroyed and provide the required heat. In the presented model a higher heating value of 16–17 MJ/kg for the gases is assumed.

4.3. Revenues

It is expected that the AC can be sold at a price between 1 kEUR/t and 4.5 kEUR/t AC. Net present values have been calculated for processing capacities of 1 t/h and 2 t/h waste in different ratios of MF resin and PB waste. Different ratios result in different yields (see Table 4) and different qualities and hence different costs are incurred.

Table 4 provides a guideline for the char and AC yields. It is shown that the AC yield increases when the share of PB increases in the mixture. So the highest yield is obtained by the 0 MF–5 PB ratio and the lowest by the 4 MF–1 PB.

In some countries subsidies can be applied such as ecological (governmental) premium, a discount for waste treatment, ..., recovery and selling of other possible by-products, possible

production of green electricity and heat. However, these are not taken into account in this process because these are mostly meant as temporary regulations, which differ from country to country.

5. Results and discussion

5.1. Economic evaluation of the base case

The NPVs corresponding to a 1 t/h processing facility are outlined in Fig. 2 as a function of the selling price of AC and the MF–PB ratios. The total investment and operating costs for this facility are displayed in Table 5. A higher AC yield (i.e. less MF in the feed mix) and thus a larger installation are the cause of slightly higher investment and operating (without feed cost) costs. This small increase is compensated by the income provided by the gate fee of the waste and higher yield (revenue) of AC: i.e. in the 0 MF–5 PB ratio the gate fee (490 kEUR/year) is responsible for a decrease of 30% of the total operating cost (1726–490 kEUR/year = 1236 kEUR/year). The analysis of Table 5 and Fig. 2 illustrates that the lower operating costs and higher AC yields in the successive range (4 MF–1 PB → 0 MF–5 PB) of ratios are responsible for the higher NPV.

The minimal selling price (NPV=0 EUR, break-even point) of the produced AC can be found in Table 5 and Fig. 2. By increasing the share of PB in the ratio the minimal selling price for AC that needs to be achieved gradually decreases from 4.2 kEUR/t to 1.7 kEUR/t which corresponds respectively to a 4 MF–1 PB and a 0 MF–5 PB ratio. The accompanying IRRs are presented in Table 6.

Only the cases in the green box (full line) where the IRR is higher than the discount rate can be accepted. The 2 MF–3 PB, 1 MF–4 PB and 0 MF–5 PB feed mixture appear to be the most likely to result in an acceptable investment project (i.e. when IRR > 9%). When the major share in the mix comes from MF waste (i.e. 4 MF–1 PB or 3 MF–2 PB) an investment is only acceptable a high AC prices.

A clear view on the situation can be made by combining Fig. 2 and Tables 5 and 6. For example: a 1 t/h processing facility with a feed mixture of 1 unit MF and 4 units PB would yield a NPV of the cash flows of 4.2 MEUR, an IRR of 14% and a yearly output of 1.4 kt AC when selling the product at a price of 2.5 kEUR/t. The minimum selling price of a mixture of 1 unit MF and 4 units PB to yield at least a 0 EUR NPV is 2.0 kEUR/t. A feed mixture of 3 MF and 2 PB however requires a higher minimum selling price of at least 3.2 kEUR/t in order to break even.

Table 5
Summary of costs for the production of active carbon by this model.

1 t/h	4 MF–1 PB	3 MF–2 PB	2 MF–3 PB	1 MF–4 PB	0 MF–5 PB
Total capital investment	10 221 kEUR	10 764 kEUR	11 263 kEUR	11 733 kEUR	12 180 kEUR
Operating cost (without feed cost)	1547 kEUR	1595 kEUR	1641 kEUR	1684 kEUR	1726 kEUR
Gate fee delivered feed	98 kEUR	196 kEUR	294 kEUR	392 kEUR	490 kEUR
Total operating cost	1449 kEUR	1399 kEUR	1347 kEUR	1292 kEUR	1236 kEUR
Produced activated carbon	678 t/year	914 t/year	1184 t/year	1445 t/year	1750 t/year
Minimal selling price activated carbon	4.2 kEUR/t	3.2 kEUR/t	2.5 EUR/t	2.0 kEUR/t	1.7 kEUR/t

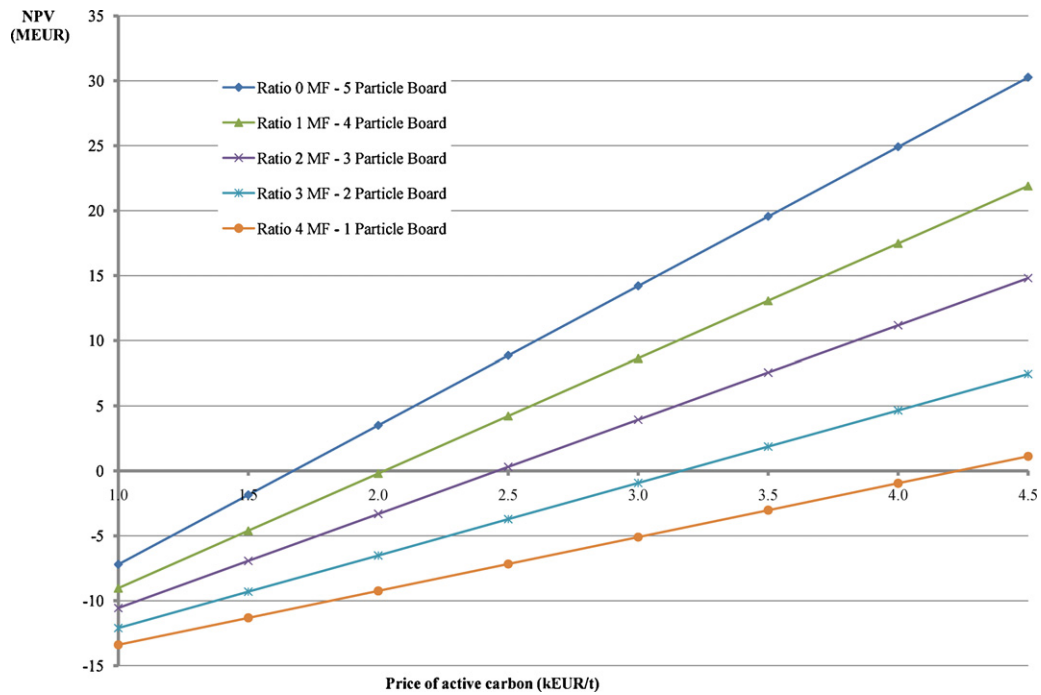


Fig. 2. Net present value for a 1 t/h processing facility.

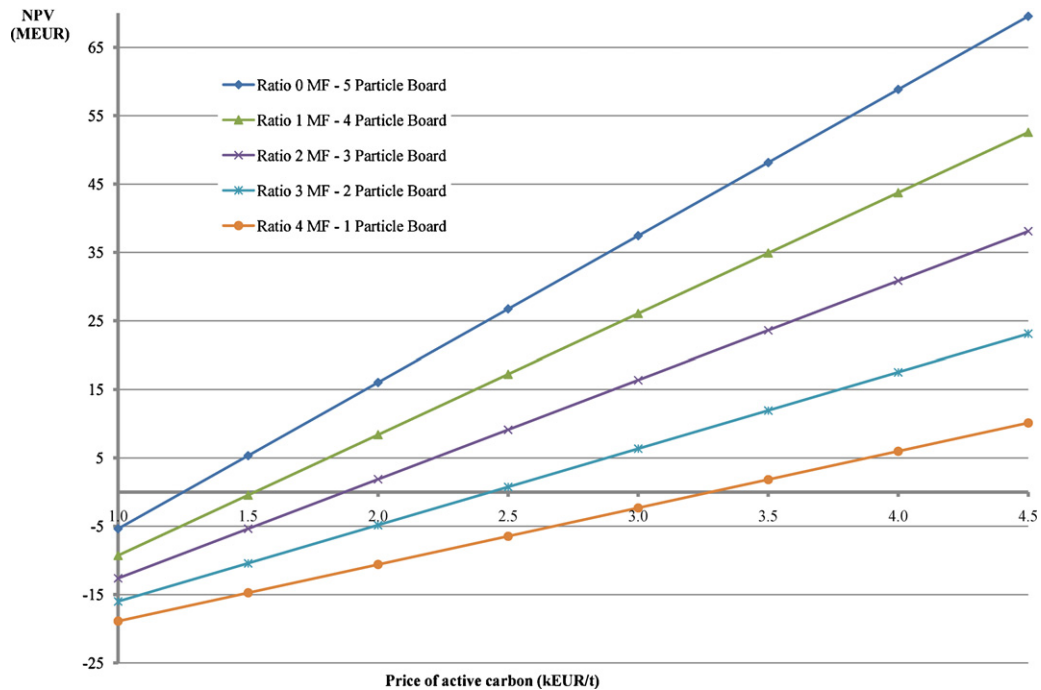


Fig. 3. Net present value for a 2 t/h processing facility.

5.2. Economic impact of the nitrogen content of the AC

When looking at the previous analysis (and Fig. 2 and Tables 4–6) one could argue that it is only useful to study the 0 MF–5 PB ratio. Because this mix has the lowest minimal selling price of 1.7 kEUR/t and the highest output of AC (1.7 kt/year), it results in higher NPVs compared to mixes with a higher share of MF. However, the quality of the resulting AC needs to be considered. Bandoz [4], Marsh and Rodríguez-Reinoso [5], Menéndez-Díaz and Martín-Gullón [6]

state that a higher nitrogen content corresponds to a better performance of the AC resulting in higher attainable selling prices. It can be seen that the nitrogen content of the resulting AC decreases in the successive range (4 MF–1 PB → 0 MF–5 PB) of ratios. Girods et al. [7] have produced an AC from PB with a nitrogen content of 1.5–2 wt% with an estimated value of 2.0 kEUR/t. They state that a higher nitrogen content could be obtained by optimizing the activation conditions, and hence probably better adsorption properties and thus yield a higher value. Therefore, if AC production from pure

Table 6
IRR for the 1 t/h feed input factory.

AC selling price	AC selling price				
	4 MF- 1 PB	3 MF - 2 PB	2 MF - 3 PB	1 MF - 4 PB	0 MF - 5 PB
1.0 kEUR/t	< 0%	< 0%	< 0%	< 0%	< 0%
1.5 kEUR/t	< 0%	< 0%	< 0%	3%	6.8%
2.0 kEUR/t	< 0%	< 0%	4.6%	8.8%	13%
2.5 kEUR/t	< 0%	3.7%	9.4%	14%	18%
3.0 kEUR/t	1%	7.8%	14%	18%	23%
3.5 kEUR/t	4.5%	11%	18%	23%	28%
4.0 kEUR/t	7.6%	15%	21%	27%	33%
4.5 kEUR/t	10%	18%	25%	31%	38%

PB is optimized, a somewhat higher selling price – with an expected maximum of 2.5 kEUR/t corresponding to an NPV of 8.8 MEUR can be achieved.

In our case of mixing the PB with MF, AC with an even higher nitrogen content could easily be achieved. In recent literature, the estimated selling value of specialty (impregnated) carbons is in the range of 4.0–6.0 kEUR/t (incl. pick-up of the saturated carbon and selling prices of 2008) [10]. An example of such a specialty AC is impregnation with NaOH to trap acidic components. Our case, provides the incorporated nitrogen for the basic properties of the AC thus a similar sales value can be expected. In addition,

in some “extra specialty” cases even higher prices can be achieved.

Therefore, one should take the nitrogen content into account, which is the highest in the feed mixture of 4 MF–1 PB and gradually decreases as the share of MF in the ratio decreases. It means that the mixtures with a higher share of MF have a higher chance of reaching a selling price of 4.0 kEUR/t to 6 kEUR/t. From Fig. 2 and Table 5, it can be seen that, a feed mixture of 3 MF and 2 PB requires a higher minimum selling price of at least 3.2 kEUR/t in order to break even. However, this mixture is more likely to reach a sales value of 5.0 kEUR/t with a NPV of 10.2 MEUR (compared

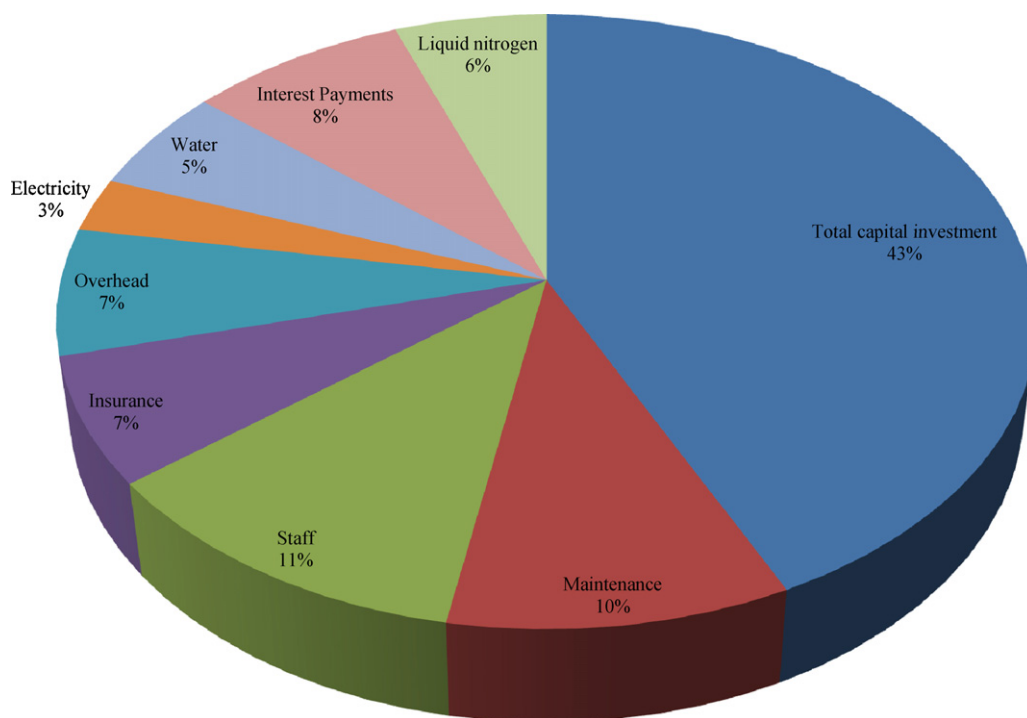


Fig. 4. Importance of the distinct expenditure items.

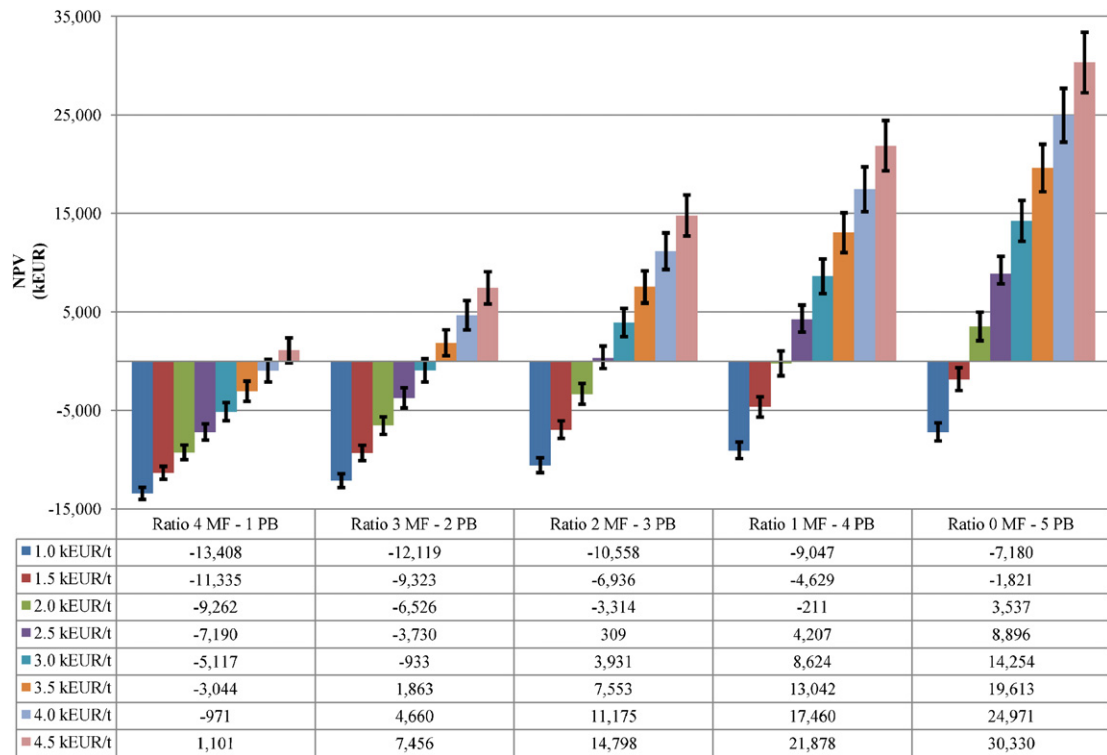


Fig. 5. Mean NPV output after Monte Carlo analysis.

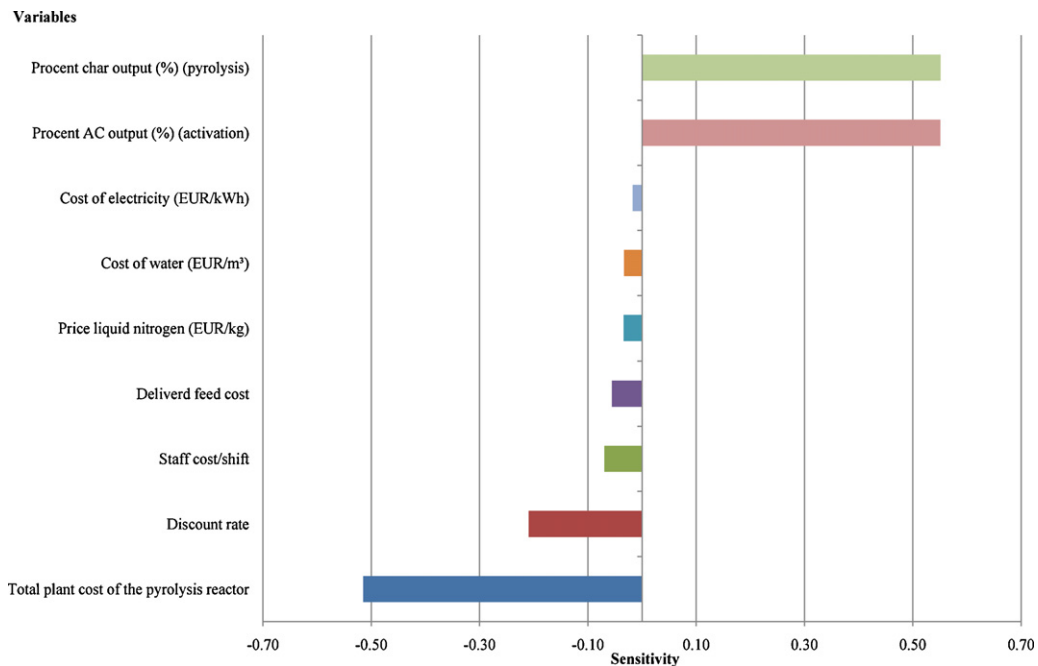


Fig. 6. Average sensitivity of the crucial variables on the NPV for a 1 t/h facility.

to pure PB NPV of 8.8 MEUR). In the case of 2 MF–3 PB a NPV of 18.4 MEUR is achieved. However, its nitrogen content will be lower, so this price (of 5.5 kEUR/t) may not be achievable. A key point is that the mixture of 4 MF–1 PB at a selling price of 6.0 kEUR obtains a NPV of 7.3 MEUR. This is somewhat smaller than the pure PB in the situation of a selling price of 2.5 kEUR/t, at a price of 2.0 kEUR/t the NPV of the pure PB (3.5 MEUR) is lower. Taken the expected price of the 0 MF–5 PB (between 2.0 kEUR/t and 2.5 kEUR/t) into account, it is possible to select the ratios in function of their sell-

ing prices which yield an equal or more positive result than this mixture. These ratios with their accompanying IRRs are presented in Table 6 in the shaded area in the case of a price of 2.0 kEUR/t and in the dashed box in the case that the maximum selling price (2.5 kEUR/t) for the AC of the pure PB is reached. As illustrated by Table 6, the 4 MF–1 PB ratio neither appears in the shaded area, nor in the dashed box. This ratio would only be comprised in the shaded area if Table 6 would be expanded to prices of 5.5 kEUR/t and more. The 4 MF–1 PB ratio would only appear in the dashed

Table 7
Variables with their profitability distribution.

Input variable	Profitability distribution	Most likely value	Variance of the distribution
Delivered feed cost	Triangular	Dependent of the ratio	±10%
Discount rate	Triangular	9%	±10%
Electricity cost	Triangular	0.0725 EUR/kWh	±10%
Cost of water	Triangular	1.5 EUR/m ³	±10%
Char output (%) (pyrolysis)	Triangular	See Table 4	±10%
Active carbon output (%) (activation)	Triangular	See Table 4	±10%
Staff cost/shift	Triangular	55 kEUR	±10%
Total Capital Investement	Triangular	Dependent of the ratio	±10%
Liquid nitrogen	Triangular	2.5 EUR/kg	±10%

Table 8
Percentage of Monte Carlo simulation runs that gain a positive NPV.

AC selling price	AC selling price				
	4 MF- 1 PB	3 MF - 2 PB	2 MF - 3 PB	1 MF - 4 PB	0 MF - 5 PB
1.0 kEUR/t	0	0	0	0	0
1.5 kEUR/t	0	0	0	0	2
2.0 kEUR/t	0	0	0	42	100
2.5 kEUR/t	0	0	62	100	100
3.0 kEUR/t	0	17	100	100	100
3.5 kEUR/t	0	96	100	100	100
4.0 kEUR/t	16	100	100	100	100
4.5 kEUR/t	85	100	100	100	100

box if Table 6 is expanded to contain prices above 6.5 kEUR/t. It is important to keep this in mind, as the 4 MF–1 PB ratio is potentially interesting if higher nitrogen content can be scientifically proved, which means that these high selling prices can be attained.

5.3. Economies of scale

Another important factor affecting the NPV is the processing capacity, i.e. the hourly flow ratio of the input material ($Q_{\text{feed input pyrolysis}}$). Doubling the processing rate of the AC plant from 1 t waste/h to 2 t waste/h results in higher NPVs (compare Fig. 3 to Fig. 2). This is a consequence of the economies of scale that are incorporated in the total equipment cost equation (Eq. (8)). As the power exponent in Eq. (8) is smaller than one ($0.6194 < 1$), doubling the processing capacity (in other words multiplying $Q_{\text{feed input pyrolysis}}$ by 2) does not result in a proportional increase of the total equipment cost. Doubling the processing rate thus augments the total capital investment with only 57% instead of 100%. Consequently, also the total operating costs – which partly depend on the height of the total capital investment – increase with only 39% to 52% (depending on the mix ratio of MF and PB waste). As a consequence the break-even selling price of AC decreases on average with 24%.

5.4. Share of expenditure items in total expenditure

Fig. 4 presents the share of the distinct expenditure items expressed as an average percentage for all ratios of the total dis-

counted expenses (over 20 years). The total capital investment represents on average the major share of 42.9% (with a maximum deviation down of 0.9% and a maximum deviation up of 0.7%). Staff and maintenance present the main operating costs with respectively a share of 11% (with a maximum deviation down of 0.7% and a maximum deviation up of 0.8%) and 10% (with a maximum deviation down and up of 0.2%) of the total expenses. The interest payments amount to 8% (–0.2%; +0.1%) of the total expenditure closely followed by insurance, overhead, liquid nitrogen, water and electricity. The fixed operating costs (insurance, overhead, interest payments, maintenance) are considered as unchanging during the lifetime of the project (20 years). The impact of the total capital investment and the cash flows generated by the staff cost, liquid nitrogen, water and electricity on the NPV will be analysed in Section 5.5 by means of Monte Carlo sensitivity analysis.

5.5. Monte Carlo sensitivity analysis

As described in Section 3, results are only valid in the case of 100% certainty of the base case variables. Some variables however are uncertain by definition, other variables might strongly influence the NPV if their value changes slightly. Nine main variables that are expected to affect the economic attractiveness of the production plant are selected. The variables, listed in Table 7, are allowed to change following a triangular distribution characterized by a most likely, a minimum and a maximum value. Monte Carlo simulations are performed, in which each run of the Monte Carlo simulation draws a random value for each of these variables, between the min-

Table 9

Minimal selling price at which the AC should be sold to guarantee a 95% chance on a positive NPV.

Ratio (MF/wood)	4 MF–1 PB	3 MF–2 PB	2 MF–3 PB	1 MF–4 PB	0 MF–5 PB
Minimal selling price	5.0 kEUR/t	3.7 kEUR/t	2.9 kEUR/t	2.5 kEUR/t	2.5 kEUR/t

imum and maximum value and in accordance with the selected distribution. Each run results in a NPV corresponding to the values drawn for each of the nine uncertain variables. Numerous runs (10 000 per ratio in this research) of the Monte Carlo simulation result in a NPV distribution.

Fig. 5 illustrates this distribution, characterized by the mean of the Monte Carlo analysis with their respective standard deviations for the 1 t/h processing plant. Similar results for the other input rates can be calculated.

By means of Monte Carlo simulations also the probability of obtaining a positive NPV is calculated. The results are listed in Table 8.

For example, a 1 MF–4 PB ratio that yields an AC quality with a sales value of only 2.0 kEUR/t has a 42% chance on a positive NPV. If the product is of better quality and can be sold at 2.5 kEUR/t or more, 100% of the cases have a positive NPV. The green full line box summarizes the ratios and selling prices that would yield at least in 95% of the cases a positive NPV. These are the most promising scenarios for an AC production facility put into practice. Comparing the selected cases (full line green box) of Tables 6 and 8 the scenario of the ratio 2 MF–3 PB with a selling price of 2.5 kEUR/t and the 4 MF–1 PB at a selling price of 4.5 kEUR/t are supplementary rejected by the Monte Carlo simulation, because the chance on a negative NPV is higher than 5%. The minimal price corresponding to this minimal 95% chance on a positive NPV is determined (see Table 9).

These selling prices are somewhat higher than the values defined in the base case (see Table 5) because the latter did not consider uncertainties in the assumed values of the base case variables. Based on these results one can say that it is, from an economical point of view, not interesting to study the 4 MF–1 PB and ratios with an even higher MF portion. Nevertheless, in order to analyse these results, one should follow the same consideration (expected price of the 0 MF–5 PB ratio) as in Section 5.1.

The shaded area in Table 8 represents the scenarios which yield an equal or more positive NPV than the 0 MF–5 PB mixture (from the Monte Carlo simulation, Fig. 5) at a price of 2.0 kEUR/t and in the dashed box the cases where the maximum price (2.5 kEUR/t) for this ratio is applied. For the 3 MF–2 PB and the 4 MF–1 PB ratio the dashed box starts at a sales value of 5.5 kEUR/t and at 6.5 kEUR/t for respectively. In addition, for the 4 MF–1 PB ratio the shaded area starts at 5.5 kEUR/t. The conclusions in Section 5.1 thus still hold.

Nevertheless, we need to keep in mind that these results represent a rather worst case scenario, with a zero income from the MF-waste and first plant costs. In normal conditions the MF waste will probably yield a gate fee and will make the projections more positive. Another important fact is the likelihood of producing a specialty carbon of very high added value 4.0–6.0 kEUR/t (as described in Section 5.5).

5.6. Identification of the key variables

Finally, the sensitivity of the NPV to the diverse input variables is determined, in order to identify the crucial process parameters for further investigation. The sensitivity of the NPV for a given variable is defined as the extent to which the variability of the NPV is dependent to the variability of the variable under consideration. For each variable of Table 7 an average NPV sensitivity is given in Fig. 6 for a 1 t/h facility. The coefficients on the graph are normalized by the standard deviation of the output and the standard deviation

of the input and not in actual euro's. The higher the coefficient of an input variable (the longer the bar), the greater the impact that the selected variable has on the NPV. The variability of the NPV for every factor can be calculated by using Eq. (10).

$$\text{sensitivity} = \frac{\Delta_{\text{NPV}}/\sigma_{\text{NPV}}}{\Delta_{\text{variable}}/\sigma_{\text{variable}}} \quad (10)$$

A positive value (the bar extending to the right) means that an increase in the variable leads to an increasing NPV. In the case of a negative sign the NPV decreases by an increase of the variable. (1) The char and AC yield are on average the most determining factors for the NPV variability, both have an average sensitivity of 0.55. This means that for every k fraction of a standard deviation increase in char/AC yield, the NPV will increase by 0.55k standard deviations of the NPV. (2) The total capital investment is on average the 3rd most important variable in declaring the NPV's sensitivity. A key point is that, depending on the mix ratio and the AC selling price, the investment cost is sometimes more important than the AC and char yield, but the three main variables are always the char yield, the AC yield and investment expenditure. The negative average sensitivity results of the discount rate and the delivered feed costs clearly indicate that a lower discount rate and a higher gate fee for the waste respectively result in a higher NPV. (3) The cost of water, liquid nitrogen, electricity and staff have also negative sensitivity factors. However these are almost negligible relative to the total capital investment, discount rate, char and AC yield.

6. Conclusion

A feasibility study to process MF and PB waste for the production of AC has been performed. A preliminary process design has been based on various literature sources, for an input feed of 1 t/h and different mixing ratios of the two waste products. The economic feasibility of the preliminary process design has been investigated, by calculating the NPV and IRR of the cash flows incurred by an investment in a pyrolysis and activation plant for the production of AC. A sensitivity analysis has been performed in order to determine the most crucial variables that influence the profitability of the investment.

Really encouraging results are obtained for a profitable production of AC, as the current assumptions start from a rather pessimistic scenario: e.g. a zero gate fee for the MF waste (which will probably be higher in practice). Besides that, the in situ incorporation of nitrogen can result in a high quality product which can be sold at a high price or even in a niche market. In addition, the value or usefulness of the AC production plant is enhanced by its ability to reuse two waste streams. Also the processing capacity plays a significant role. A larger manufacturing plant is able to produce carbons at a lower cost despite the higher initial investment. By doubling the input rate to 2 t/h (dry matter) a reduction of average 24% of the minimal selling price is obtained.

The sensitivity analysis reveals that the AC plant economies are very sensitive to the investment cost, the product yield and the AC selling price which is an indication for product quality.

Future research needs to focus on these prime properties to create a marketable high value product.

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