SOCIETAL TECHNO-ECONOMIC ASSESSMENT OF BIOCHAR PRODUCTION AND USE AS SOIL AMENDMENT

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ABSTRACT: The current research aims to determine whether the production of biochar and its use as a soil amendment is desirable from a societal point of view. This means that external effects are included, in addition to the private benefits to the biochar producer. Therefore, the production of biochar from two biomass residue streams (medium-density fiberboard and tree bark) and its application as a soil amendment are evaluated using a societal techno-economic assessment. In a societal techno-economic assessment, all three pillars of sustainability should be considered, i.e., the economic, environmental, and social aspects. The indicators for these pillars are measured in different units, and to integrate all aspects for decision-making, they are converted into monetary values using shadow prices. We find that, when integrating environmental and economic indicators of sustainability, the production of biochar from tree bark is desirable from a societal point of view because the net present value to society is greater than zero. For medium-density fiberboard, the desirability is dependent on the inclusion of the previous life cycle. We note that social indicators of sustainability are not included in this study.
Keywords: biochar, pyrolysis, economics, environmental impact, sustainability, assessment.

1 INTRODUCTION

Biochar is the solid residual of pyrolysis [1]. The other products resulting from pyrolysis are bio-gas and bio-oil [2, 3]. Pyrolysis is the thermochemical decomposition of organic material at elevated temperatures, but contrary to combustion or gasification, pyrolysis happens in the absence of oxygen [4]. Biochar is a very diverse product, mainly depending on the feedstock used and the pyrolysis temperature. The choice of feedstock determines, amongst other things, density, porosity, hardness, and ash content [1, 3]. The temperature determines the biochar yield of the pyrolysis process and chemical properties like acidity and alkalinity [5-7]. There are also different pyrolysis techniques [2] where one of the main differentiators is the speed of the pyrolysis process. For example, it was found that slow pyrolysis has a higher char yield than fast pyrolysis [1, 2]. So, if the primary aim is to produce biochar, slow pyrolysis is preferred over fast pyrolysis.

According to Spokas et al. [1], the first use of the term biochar dates from around 1998. Biochar has long been an unwanted waste product of pyrolysis, with the focus being on bio-gas and bio-oil for energy conversion.

However, in recent years it has become clear that there are many potential benefits to the use of biochar. The most common use is as a soil amendment to increase soil productivity or crop yield by improving the soil properties [3]. Soils amended with biochar have been found to retain up to 350% more water, which will improve crop productivity in arid regions [8]. However, there is some uncertainty concerning the effect biochar has on soil properties: whether this effect is positive, negative, or non-existing [1, 9]. Because biochar is such a carbon-rich material, applying it to soils is also a way of sequestering carbon, thereby mitigating global warming [10].

However, these are only two of the many anticipated advantages of biochar. Further in light of climate change mitigation, biochar can be used as a peat substitute in growing media or a feed additive for cattle [11]. It can also be used to clear pollutants from soils or water, either wastewater or surface water [3]. Additionally, biochar can be made from waste, reducing its production cost and providing a solution for residual biomass streams.

Notwithstanding this multitude of expected benefits from the use of biochar, the large-scale commercialization of biochar is still absent [12-14]. This is surprising because a previously published techno-economic assessment (TEA) has shown that biochar production is profitable [15]. A TEA takes on a private perspective, so from the point of view of the producer. Here, we hypothesize that looking at it from a societal perspective, thereby highlighting the value to society, might provide further incentives for developing the biochar industry. That is in case biochar production and use would create value to society. If this is not the case, no further action would be required. To determine the societal value of a technology aiming for sustainable development, a societal TEA can be used [2, 16, 17].

In this paper, a societal TEA was performed for a biochar system consisting of its production from biomass waste and its use as a soil amendment.

2 METHODS AND MATERIALS

2.1 Case description

The process is discussed extensively in the previous publication that reports on the techno-economic assessment (TEA) [15]. A schematic representation of the production process can be found in **Figure 1**. The main assumptions regarding the pyrolysis process are an input rate of three tons of biomass waste per hour and the principle of self-sustainability. The latter means that the produced syngas is used to fire the reactor. In fact, there is an excess of syngas that is valorized by firing gas turbines to produce electricity.

Even though the previously published TEA considered six different input streams (coffee husks, medium-density fiberboard (MDF), palm date fronds, AB wood mix (which consists of different kinds of treated, but uncontaminated wood-like multiplex wood, MDF or painted wood, as well as impurities like plastics), tree bark, and olives stone kernels) and two pyrolysis technologies (conventional and microwave-assisted), only two input streams and one technology are considered here. The reason for doing so is a lack of available data for the life cycle assessment (LCA).

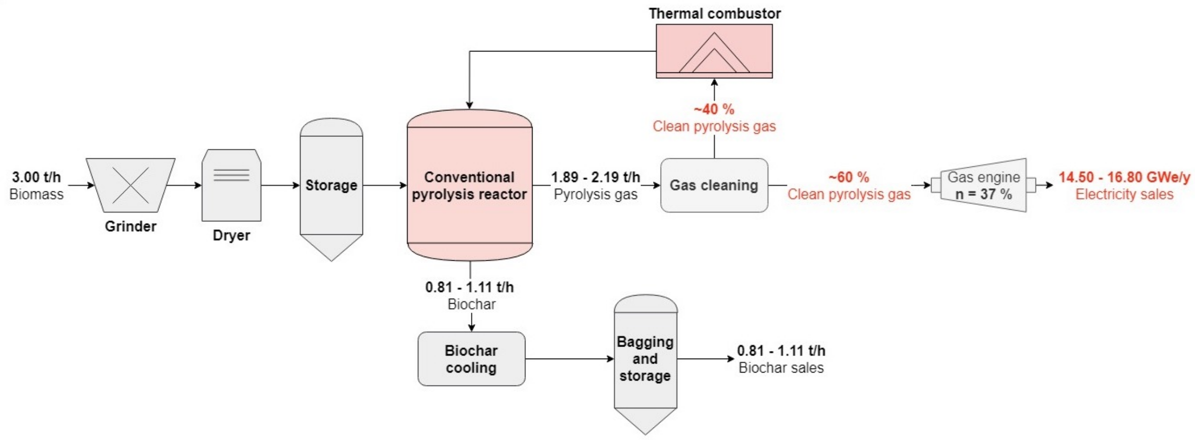

Figure 1: Process description [15]

2.2 Techno-economic assessment

To assess whether biochar production to be used as a soil amendment is desirable from a societal perspective, we use a societal TEA. As may be implied by its name, the basis for a societal TEA is a TEA. A TEA can be defined as "*the evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision-makers in directing research and development or investments*" [2]. Technological and economic parameters are integrated and linked to get a complete picture of the technology, instead of doing a technical and economic analysis separately [18]. In practice, this usually comes down to building a model with a net present value (NPV) analysis where both economic and technical parameters can be varied. The TEA in this research was published separately, and more information on the TEA model can be found there [15].

The inherent shortcoming of a traditional TEA is that it takes on the private investor's perspective setting up the biochar production. This means the TEA only looks at the value created for this investor and, therefore, not all of the value is accounted for. What is missing is the value of environmental and social effects. Integrating these effects can have significant implications [19]. A technology can be judged to be unviable when looking only at classic revenues like the sales of (by-)products, energy conversion, and so on. If external value is included as well, the technology can be found to be a desirable option after all. Therefore, it is believed that environmental and social value – positive and/or negative externalities – should also be included in order to come to a complete understanding of the economics of the technology. This would then be a measure for the societal value, in this case, of biochar production and its use as a soil amendment.

2.3 Life cycle assessment

The first step in determining the value of environmental and social effects is to quantify these effects. This can be done using an LCA. For the social impacts, this would mean a social LCA would have to be performed. However, this methodology is not as developed or standardized as is the case for environmental LCA [20-24]. Also, the monetization of social LCA results is still in its infancy [25]. Therefore, it was decided to leave social effects out of consideration here.

From now on, when referring to LCA, we mean an environmental LCA. This LCA can be defined as "*an analysis tool used to compute and evaluate the environmental impact and resource utilization of a product, a process, or an activity in the whole life cycle, including raw material mining, raw material transportation, products production, products transportation, products use, products maintenance, recycling, and final treatment.*" [26]. There are four steps in an LCA: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation [27].

The goal of the LCA is to quantify and compare the environmental impact of biochar production from two types of feedstock, namely waste tree bark and waste MDF, through a conventional pyrolysis process.

There is some debate concerning an appropriate system boundary [28]. Because waste materials are used as an input, some literature suggests using a zero burden assumption. This means that, when the wastes are equal, one assumes that all emissions associated with the waste product can be ignored [29]. The complete opposite of the zero burden approach could be termed the full burden approach. This implies that all of the emissions of the previous life cycle would be incorporated into the analysis. This assumption will never be used, but it is included here for informational purposes. Arguably, an agreement could be found somewhere in between, but this would need additional research. Therefore, both cases will be analyzed and reported here.

The functional unit for the analysis is one ton of biochar. The outputs of the production system are biochar and electricity. To divide the environmental burden between the two outputs, system expansion is used. The produced electricity is assumed to displace electricity produced in Belgium.

For the inventory analysis, data is gathered from scientific literature, industrial data from Act&Sorb, and the ecoinvent database in SimaPro. Concerning the emissions from pyrolysis, one has to keep in mind that the inputs are – at least partly – biogenic. Emissions from biogenic materials do not have to be taken into account in LCA [30]. Therefore, the pyrolysis of tree bark is considered to have no emissions. The pyrolysis of MDF only has emissions from the anthropogenic – the opposite of biogenic – components like glue and dust. For the use phase of biochar, only the carbon abatement potential is calculated. This is added manually to the SimaPro output. Based on literature, this is the highest resulting impact on the environment when amending biochar to soil compared to other categories like human toxicity, freshwater eutrophication, or fossil depletion [31].

The impact assessment is performed using the ReCiPe midpoint methodology, hierarchist version, available in SimaPro. The selected impact categories are climate change, human toxicity, freshwater eutrophication, fossil depletion, and ionizing radiation.

2.4 Societal techno-economic assessment

Once the environmental effects have been quantified, they need to be integrated into the TEA. The purpose of the integration is not only to take the value of the environmental impacts into account but also to exploit direct linkages and synergies between the technical, economic, and environmental aspects [18]. The problem one faces when integrating TEA and LCA results is that the results from a TEA are expressed in monetary units, but the results from the LCA are not.

There are mainly two ways of integrating environmental and economic effects: a techno-sustainability assessment (TSA) [32] or a societal TEA. They differ only in the way in which they tackle the problem mentioned before. In a TSA, multi-criteria decision analysis is used. In other words, the TEA and LCA results stay in different units and are integrated through a weighting approach [32].

Alternatively, a societal TEA monetizes all the effects. Shadow prices are used for environmental impacts. A shadow price represents the total opportunity cost, or the social value, of a good [33-35]. This is not necessarily the same as the market price, as it might be distorted by externalities or might not exist at all [33, 35]. In the case of environmental pollution, the shadow price can also be defined as the unit cost of pollution [33]. By monetizing the environmental effects, the NPV can be calculated [16]. For a societal TEA we term this the societal NPV. Because it results in a single numerical value, we believe a societal TEA is a helpful tool: when the societal NPV exceeds zero, the technology is desirable.

3 RESULTS

3.1 Techno-economic assessment

The techno-economic assessment (TEA) is discussed extensively in a previous publication [15]. In this previous publication, six different biomass residue streams and two pyrolysis technologies were subjected to a TEA. However, the discussion in the current research is focused on biochar made from tree bark and biochar made from medium-density fiberboard (MDF), both through conventional pyrolysis.

The TEA results can be summarized as follows. For both types of feedstock, biochar production has a positive net present value (NPV). The highest NPV was observed for biochar made from tree bark. The minimum selling price is about €570 per ton for biochar made from MDF and €495 per ton for biochar made from tree bark. These prices align with current market prices. Risk analysis through Monte Carlo simulations showed that the biochar selling price is the most critical determinant of the NPV.

More detailed information (e.g., assumptions on capital and operational expenditures, and revenues) can be found in the previous publication [15].

3.2 Life cycle assessment

The life cycle assessment (LCA) was carried out using the SimaPro software. The output of this software for the selected impact categories is shown in the first three columns of **Table I**. The comparison between biochar made from MDF and biochar made from tree bark, using the full burden approach, shows that tree bark as the feedstock has a much better impact on the environment. In the zero burden approach, the effects of the two types of feedstock are more comparable. The impact category ionizing radiation is negative in both the full burden and zero burden cases. This is a consequence of the displaced electricity, a consequence of the system expansion. The difference between electricity produced from syngas and the Belgian electricity mix is that the Belgian electricity mix contains nuclear energy. This nuclear energy is the factor that influences ionizing radiation. Avoiding it is beneficial to the environment.

Table I: Life cycle assessment results

Impact category	MDF (no CAP)	Tree bark (no CAP)	Difference (no CAP)	MDF (with CAP)	Tree bark (with CAP)	Difference (with CAP)
	(1)	(2)	(3) = (1) – (2)	(4)	(5)	(6) = (4) – (5)
CC	6 910.85	-357.22	7 268.07	4 417.52	-2 694.72	7 112.24
	-141.95	-363.89	221.94	-2 635.28	-2 701.39	66.11
HT	223 576.20	-5144.13	228 720.33	223 576.20	-5144.13	228 720.33
	-7041.21	-5244.88	-1796.33	-7041.21	-5244.88	-1796.33
FE	2.10	-0.07	2.17	2.10	-0.07	2.17
	-0.10	-0.08	-0.02	-0.10	-0.08	-0.02
FD	2 258.20	-114.05	2372.25	2 258.20	-114.05	2372.25
	2 258.20	-114.05	2372.25	2 258.20	-114.05	2372.25
IR	-326.57	-488.23	161.66	-326.57	-488.23	161.66
	-658.45	-490.50	-167.95	-658.45	-490.50	-167.95

The top number represents the results in case a full burden approach is adopted, while the bottom number represents the zero burden assumption. The impact categories are: CC = Climate change (expressed in kg CO_2 eq.), HT = Human toxicity (expressed in kg 1.4-DB eq.), FE = Freshwater eutrophication (expressed in kg P eq.), FD = Fossil depletion (expressed in kg oil eq.), IR = Ionising radiation (expressed in kBq Co-60 eq.). MDF = medium-density fibreboard. CAP = carbon abatement potential.

The carbon abatement potential of the produced biochar, when applied to soil, is not included in the SimaPro output. This was calculated manually and then added separately. Based on industrial data obtained from Act&Sorb, the carbon content of biochar made from MDF and tree bark is 80% and 75%, respectively. It is assumed 85% of the carbon in biochar is still stable in the soil after 100 years [31, 36, 37]. Using the carbon content and the amount of stable carbon, the amount of carbon sequestered in the soil is calculated. To find the amount of CO_2 sequestered, this is divided by the molar mass of carbon and multiplied by the molar mass of CO_2. **Table II** summarizes these calculations. The last three columns of **Table I** show the adjusted impacts (only the climate change impact category changes).

Table II: Calculation of carbon abatement potential

	MDF	Tree bark
Biochar (kg)	1000	1000
Biochar carbon content (%)	80%	75%
Biochar carbon content (kg)	800	750
Stable carbon (85%)	680	637.5
Factor for CO_2 eq. (44/12)	3.666	3.666
CO_2 eq. sequestered (kg)	2493.33	2337.50

3.3 Integration through shadow prices

The next step in performing a societal TEA is to put a monetary value on the environmental effects, enabling their inclusion in the private TEA. As was mentioned before, the valuation will be done using shadow prices obtained through a literature review. For each impact category, the shadow price is obtained by taking the average of the shadow prices found in the literature [38-45]. **Table III** shows these average prices, together with the minimum and maximum for each impact category.

Table III: Shadow prices

Impact category	Minimum	Average	Maximum
CC	10	84	431
HT	0.0004	0.75528	2.512
FE	1.944	5.264	11.904
FD	0	0.0001304	0.0005106
IR	/	0.0425	/

CC = Climate change (expressed in €/ton CO_2 eq.), HT = Human toxicity (expressed in €/kg 1.4-DB eq.), FE = Freshwater eutrophication (expressed in €/kg P eq.), FD = Fossil depletion (expressed in €/kg oil eq.), IR = Ionising radiation (expressed in €/kBq U235 eq.)

Two assumptions had to be made regarding these shadow prices. First, the ReCiPe method used in this research expresses fossil depletion in kg oil equivalents. However, the prices found in literature are expressed in €/MJ. To convert these units, a calorific value of 47 MJ/kg crude oil is used [46]. Second, an assumption was needed about ionizing radiation. Using the ReCiPe method, results are obtained in kBq Co-60 eq. In the literature, no shadow price could be found for this unit. This was remedied by using €/kBq U235 eq. as a proxy [39]. This was tested by running the SimaPro software using the ILCD 2011 Midpoint+ method, which reports ionizing radiation in kBq U235. This result appeared to be sufficiently comparable to the one obtained with the ReCiPe method. Therefore, the shadow price expressed in €/kBq U235 eq. is used here and multiplied with the LCA results expressed in kBq Co-60 eq.

The TEA calculates the NPV over 20 years based on annual cash flows. To calculate the yearly monetary value for each of the impact categories, some steps are needed. First of all, the yearly biochar production needs to be calculated because the LCA results are based on a functional unit of one ton of biochar. A full operative year is assumed to consist of 8,400 working hours. The feed rate is three tons of waste biomass per hour, and the biochar yield is 27% and 37% for MDF and tree bark, respectively. For the impact category of climate change, the carbon abatement potential should be included as well, so columns (4) and (5) in **Table I** should be used for MDF and tree bark, respectively. The environmental impacts from the LCA can then be multiplied by the annual production of biochar. This yields the annual environmental impacts, which can be multiplied by the average shadow price from **Table III**.

3.4 Societal techno-economic assessment

Finally, the private TEA can be extended to a societal TEA. The resulting societal NPV is a means of assessing biochar's impact on society, expressed in a single monetary metric.

To extend the private TEA to a societal TEA, two steps are needed. First, the monetized impact categories should be added. This leads to additional revenues in case of environmental benefits or to additional costs in case of environmental harms. Therefore, the calculated annual net benefits are directly impacted. Second, because the analysis is now performed from a societal perspective, transfer payments should be excluded [47]. This means that both subsidies and taxes included in the private TEA should now be excluded. This is because transfer payments are monetary streams that impact society as a whole, and it does not matter who owns this money [48]. These payments should therefore not be seen as revenues or costs to a firm or process.

Table IV: Net present value comparison (million €)

	Private NPV*	Societal NPV (zero burden)	Societal NPV (full burden)
MDF	20.34	438.00	- 13,410.00
TB	33.64	462.57	454.20

* Taken from [15].

Four different scenarios can be distinguished based on the two inputs, MDF and tree bark, and the difference between the zero and full burden approaches. The resulting societal NPVs are shown in **Table IV** next to the NPVs from the private TEA [15]. The societal NPVs are of very high magnitude, and their exact interpretation should be explored in future research. Nevertheless, the results provide interesting insights. As was mentioned before, the decision rule when using NPV is whether it is greater than zero or not. As shown in **Table IV**, three of the four scenarios show a positive societal NPV, meaning value is created to society. Only when considering the full burden case for biochar produced from MDF, the societal NPV is negative. This is because the impact on human toxicity is about 30 times higher than in the zero burden case. According to SimaPro, this toxicity stems from polluting components in MDF like formaldehyde. However, it is important to remember that the full burden approach was included only for informational purposes. On the other hand, the zero burden approach is commonly used, although it is debated [28].

4 CONCLUSIONS

This research has built upon a previously published techno-economic assessment (TEA) of a biochar production system [15]. Here, we investigated how to integrate the environmental impacts caused by biochar production and its use as a soil amendment, into the TEA, by monetizing these effects using shadow prices. This yields a societal TEA and provides us with a single metric for the value to society, namely the societal net present value (NPV). This was done for two types of input material: medium-density fiberboard (MDF) and tree bark. Both are supposed to be waste streams.

The environmental effects of biochar production and use as a soil amendment were quantified using a life cycle assessment (LCA). The considered impact categories are climate change, ionizing radiation, fossil depletion, freshwater eutrophication, and human toxicity. The quantification of the effects for each impact category depends on the selected feedstock and a methodological choice. Because this research deals with a process using waste as an input, two approaches can be distinguished: the full burden approach and the zero burden approach. The zero burden assumption is commonly used but debated, while the full burden approach is only included for informational purposes. In the case of a full burden approach, the entirety of environmental effects throughout the previous life cycle of the input is accounted for. In the case of a zero burden approach, this previous life cycle is ignored. Consequently, total environmental effects are higher in the case of a full burden approach compared to the zero burden approach. Concerning the use of biochar, only one environmental impact was considered, namely the carbon abatement potential of biochar. This impact falls within the climate change impact category. When using biochar as a soil amendment, carbon is stored in the soil, thereby avoiding CO_2 emissions. The avoided emissions amount to about 2.3 to 2.5 tons of CO_2 per ton of biochar amended to soil.

After quantifying these environmental effects, they were monetized to allow for their integration in the TEA. This was achieved by using a shadow price for every considered impact category. These shadow prices were found through a review of literature, and they convert the LCA results, expressed in physical units, to monetary values. The environmental effects can then be included in the TEA as revenue or cost, thereby extending the TEA to a societal one.

A societal TEA helps determine whether biochar production as a soil amendment is desirable from a societal perspective. Our results indicate that this depends on the used feedstock. Using tree bark as an input to the process, biochar production as a soil amendment is desirable from a societal perspective in both the zero and full burden cases. The biochar produced is desirable because the societal NPV is positive. However, when using MDF as the input, the societal desirability depends on the methodological assumption made. If one uses the zero burden assumption, biochar production is desirable. However, if one decides to include the entirety of the previous life cycle of MDF, the full burden approach, the societal NPV decreases and becomes very negative. This means that biochar production is not desirable. In principle, this will not be a problem for two reasons. First, the full burden approach is only included for informational purposes and will never be used in reality. Second, the NPV from the investor's point of view is higher for tree bark than it is for MDF. This means that, if given a choice, a private investor will opt to produce biochar from tree bark instead of from MDF.

5 DIRECTIONS FOR FUTURE RESEARCH

Future research is needed to address the limitations of this research.

The life cycle assessment (LCA) should be improved in two ways. Firstly, it should be investigated to what extent the environmental effects of the waste input should be accounted for. Secondly, a broader scope for the use phase is required. In the present research, only the impact category of climate change is addressed in the LCA by calculating the carbon sequestration potential. Biochar's application to soils is expected to have other impacts as well. These should be studied and quantified to add to the LCA.

For the integration of the environmental effects into the techno-economic assessment (TEA), shadow prices were used. Here, these shadow prices were collected through a literature review, taking the average shadow price for each impact category. Future research should aim at tailoring the shadow price for each impact category to the specific case at hand, as these shadow prices are time and location-dependent.

Finally, next to the environmental effects, social effects should also be added for this societal TEA to really be a societal one. In the current research, these social effects were left out of consideration because the social LCA methodology and the monetization of its results are not well established yet. However, once this is the case, the current societal TEA model is easily expanded with these social effects. One should then merely add a category of revenues and a category of costs.

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