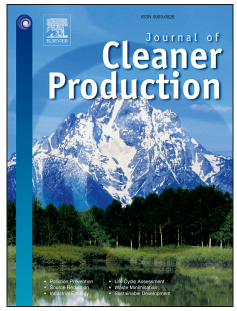

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ABSTRACT

The main barrier in the commercialization of phytoextraction as a sustainable alternative for remediating metal contaminated soils is its long time period, which can be countered by biomass valorization. From an environmental point of view, fast pyrolysis of the biomass is promising because its lower process temperature prevents metal volatilization. The remaining question is whether fast pyrolysis is also preferred from an economic point of view.

Therefore, a techno-economic assessment of fast pyrolysis has been performed for a case study in the Campine region in Belgium. For this region, willow trees cultivated in short rotation have the right characteristics to serve as a phytoextracting crop. A techno-economic assessment requires by definition a multidisciplinary approach. The problem statement urges for a focus on the economic profitability from the viewpoint of an investor, including economic risk analysis.

Fast pyrolysis seems more profitable than gasification. The profit is dependent on the scale of operation, the policy support (subsidies) and the oil yield. The economic risk can be reduced by increasing the scale of operation by means of complementing feedstocks, and by valorization of the char byproduct by subsequent processing to activated carbon.

KEYWORDS[1]

techno-economic assessment; phytoremediation; pyrolysis; short rotation coppice; biopolymers; activated carbon.

1 INTRODUCTION

The evaluation of (aspects of) the biobased economy requires a method that allows for a uniform analysis (RED 2009/28/EC). At the moment a systematic analysis tool that integrates both technical and economic calculations is lacking. Often economic calculations are added to get a first idea of the economic feasibility of developed concepts, however, detailed information on the used parameters are in many cases not provided. For instance, Njomo (1993) assessed plastic cover solar air heaters thoroughly from a technology perspective, but provided only one graph representing some economic figures without explaining how he calculated them. Also an insight in the parameters which influence the economic feasibility most, is often not integrated in the used models (Tahon, 2013).

A techno-economic assessment, also called techno-economic evaluation or techno-economic analysis, is a rather new term which is more frequently used since 2010 and which is often linked to biomass. Moreover, regional, national and transnational funding programs (e.g.

[1] Alphabetical list of abbreviations and symbols: ϕ = hourly throughput of dry biomass in tonne per hour; AC = activated carbon; Cd = cadmium; CEPCI = Chemical Engineering Plant Cost Index; CHP = combined heat and power; EUR = euro currency; GIS = geographic information system; GPC = green power certificates; HPC = heat and power certificates; IRR = internal rate of return; kt = kilotonne; LCA = life cycle analysis; m% = mass percent; MEUR = million euro; MW = megawatt; NABC = National Advanced Biofuels Consortium of the United States; NPV = net present value; PHB = polyhydroxybutyrate; PLA = polylactic acid; PTC = product transformation curve; t_{dm} = tonne dry matter; TEA = techno-economic assessment; TPC = total plant cost; yr = year

Horizon 2020) more often require techno-economic modelling tools aimed at illustrating the valorization potential of the technologies under investigation. Although the use of techno-economic assessments is significantly increasing, no clear guidelines exist on how to perform a TEA. On top, many scholars incorrectly call their analysis a techno-economic analysis whereas they perform a technical and an economic analysis separately. As a consequence, the economic information provided in many articles is rather static, instead of dynamic, i.e. the information does not reflect uncertainties or potential changes in technologic parameters. Therefore, this paper provides some recommendations on how to perform a TEA for biomass projects based on a case study in which contaminated biomass is used as a feedstock for fast pyrolysis. The recommendations include the different phases of a TEA (which can be repeated several times during each iteration), and their corresponding most appropriate methodologies required during application of the phases.

In the next section, a theoretical background is provided on TEA in general and on the methods used. The main steps of a TEA are highlighted. Next, the case study is presented and motivated, including a brief review about the fast pyrolysis technology. Then, the TEA is applied on the case study. Finally, the paper concludes with a presentation and discussion of the results.

2 THEORETICAL BACKGROUND

A techno-economic assessment (TEA) is often carried out on new technologies that are designed for environmental purposes. The diversity of these technologies studied by a TEA is illustrated by examples such as recycling practices of municipal solid waste (Athanassiou and Zabaniotou, 2008), coal gasification processes with and without CO_2 capture (Man et al., 2014), emission abatement options (Geldermann and Rentz, 2004), and hydrogen production from sugar beet molasses (Urbaniec and Grabarczyk, 2014), among many others. Techno-economic assessments have also been executed specifically for fast pyrolysis. These TEAs differ in theme: for instance, Westerhout et al. (1998) compared different pyrolysis technologies and found that a rotating cone reactor has operational advantages for processing mixed plastic waste. Bridgwater et al. (2002) on the other hand compared power production by biomass fast pyrolysis with other thermochemical technologies such as gasification and combustion.; Mullaney (2002) investigated the technical, environmental and economic feasibility of bio-oil production by fast pyrolysis for a specific case study: the low-grade wood chips market in New Hampshire.Finally, pyrolysis has also been studied as a pre-treatment step in international bioenergy supply chains (Uslu et al., 2008).

Analysis of these examples shows that there are no standards on how to perform a techno-economic evaluation, which makes it difficult to use and compare existing TEAs. Besides, until now no generally accepted definition exists for techno-economic assessments. Any good techno-economic analysis should start with a clear understanding of the underlying technology (Tahon, 2013). For biomass conversion technologies, heat and electricity requirements need to be determined and mass and energy balances are required (Van Dael et al., 2013).

Next, the economic feasibility is explored, which can provide information for decision making (Ma, 2011). The National Advanced Biofuels Consortium of the United States for instance integrates the financial viability within the goal of a TEA (NABC, 2011). Smits et al. (1995) conclude that TEAs “can play an important role in increasing the social and economic returns on investments in the development of new technology”. Sometimes the discussion on the economics of a new technology is quite superficial, and an in depth analysis of economic risk is often lacking (Tahon, 2013). Therefore, the basic elements of an economic investigation have been identified. For each element, the preferred methodology has been explicited and the proposed methodological framework has been tested on the biomass case study.

3 METHOD

A techno-economic assessment is actually an iterative process that can be divided in several steps. First, a preliminary process design should be defined and translated into mass and energy balances. Second, this information should be integrated in a dynamic model which estimates capital and operational costs (CAPEX and OPEX), and revenues. Then, the information is used to calculate projected discounted cash flows so that one has a first idea of the process' profitability. Next, risk analysis is performed in order to identify potential technological and non-technological barriers. The output of risk analysis is used to formulate risk reduction strategies. For each risk reduction strategy all of the steps can be repeated. The case study is described first, so that one can understand the main steps of the techno-economic assessment in the light of the presented case study.

3.1 Description of the case study

The techno-economic assessment has been performed for a case study in the Belgium, where some agricultural soils have been historically polluted with Cd by the pyrometallurgical processes adopted by the non-ferrous industry until the seventies. As a consequence of atmospheric deposition the soils in the vast surroundings of the zinc factory have been diffusely polluted with heavy metals. Because of the vastness of the contaminated area, conventional physicochemical remediation techniques are not appropriate in order to remove the metals. Phytoremediation, i.e. the use of plants to degrade or remove contaminants from soil and water (Nie et al., 2010), is suggested as a sustainable alternative for conventional remediation of agricultural soils polluted with heavy metals (Witters et al., 2012). When soils are polluted with heavy metals such as cadmium (Cd), another problem arises. Because heavy metals are elements that cannot be degraded by living organisms, decontamination of soils requires the uptake or “phytoextraction” of the toxic metals (Vangronsveld et al., 2009). Dickinson and Pulford (2005) found evidence that willow cultivated in short rotation might clean up land contaminated with Cd within a realistic crop lifecycle. Lewandowski et al. (2006) studied the economic value of the phytoremediation function of willow because field trials in a cadmium contaminated case study in the Rhine valley showed that willow is most effective in taking up heavy metals.

The main barrier in the development of phytoremediation is the long time period for effective soil remediation. To make phytoremediation economically viable for farmers, additional benefits should be provided by bioenergy production (Licht and Isebrands, 2005) or by phytomining, i.e. the extraction of metals with the aim of selling them (Harris et al., 2009). Economic profitability of biomass conversion though is a prerequisite if one wants to provide farmers with an adequate price for the biomass. Therefore, the objective is to compare the profitability of thermochemical conversion technologies by means of a techno-economic assessment from the point of view of a company investing in biomass conversion.

The Cd in the harvested willow stems now needs to be collected and deposited in a safe manner (Berndes et al., 2004). This might be a motivation to choose for fast pyrolysis, i.e. rapid heating of the biomass to moderate temperatures (350 – 650 °C) in the absence of oxygen. As a consequence, not real combustion but only a thermal cracking of the willow molecules takes place, first resulting in the production of char and gases (Bridgwater et al., 1999). Fast pyrolysis also implies short vapour residence times of only a few seconds, meaning that the hot gases need to be quenched rapidly so that part of the gases are then condensed into a dark brown fluid, i.e. the pyrolysis oil. The fluidized bed, in which an inert solid is used as the heat transfer medium to the biomass particles, is the most common reactor type used for fast pyrolysis. Pyrolysis of willow is often cited to yield between 50 m% and 80 m% of pyrolysis oil on a dry feed basis. Because the pyrolysis liquid is formed by rapid quenching, secondary reactions are prevented so that the product has a tendency to age. Besides, both the original water content in the feed and the pyrolysis reaction itself result in the production of water in the fast pyrolysis oil that cannot easily be separated. Whereas increasing water reduces viscosity, it can also lead to poor ignition. Pyrolysis oil has a calorific value which is more or less half that of fossil fuels and can be used in diesel engines for static applications, whereas the gas is often used for internal energy provision. Furthermore, a life cycle analysis (LCA) showed thatpyrolysis oil from wood waste is environmentally friendly (Zhong et al., 2010). Ning et al. (2013) also used LCA and confirmed that pyrolysis oil has a lower environmental impact compared to fossil fuels.

Fast pyrolysis has an advantage over combustion and gasification for the valorization of contaminated biomass, because the latter typically happen at higher temperatures (> 850 °C) at which metals (and especially Cd) are more easily re-released to the environment. This means that the gases resulting from combustion and gasification will contain too much heavy metals to be emitted through the chimney back in the atmosphere, so that expensive fume gas treatment is required. Moreover, in the case of gasification, part of the gases will be converted into energy by using them as a fuel for gas engines. The metals present in these gases are noxious for the engine's components, so that these gases require cleaning before they can be used as a fuel. Since pyrolysis typically happens at lower temperatures, its product gases will contain almost no metals. Experiments showed that most of the metals remain in the pyrolysis char, as long as the process temperature is below 450 °C (Stals et al., 2009). The advantage of pyrolysis thus is that the metals can be better controlled and are concentrated in a smaller volume: from the soils into the biomass and then into the char. Pyrolysis thus avoids a return of the metals in the atmosphere as long as the char is not burnt. Therefore, it has been assumed at first that the char needs to be landfilled. Furthermore, the relationship between pyrolysis and phytoextraction is actually mutual. When one wants to produce energy in a sustainable way, it is strongly encouraged to use biomass from marginal soils that cannot be used for food production (McKendry, 2002).

3.2 Main steps of the techno-economic assessment

As pyrolysis is a new technology, there are not a lot of cost data available (Rogers and Brammer, 2012). Moreover, cost data for pyrolysis plants vary significantly (Uslu et al., 2008) and the capital cost of processes that have not been built are very uncertain (Bridgwater, 2009). Therefore, existing estimates for the capital cost of a pyrolysis plant have been reviewed and integrated during a meta-analysis. Next, the results of the meta-analysis of the capital costs served as an input to a discounted cash flow model which can be used to calculate the net present value (NPV) by discounting the future yearly incoming and outgoing cash flows generated by an investment in fast pyrolysis, gasification or combustion of willow, using an appropriate discount rate (Verbrugge et al., 2008). This NPV is an indicator of the technology's profitability (Boardman et al., 2006). Another popular measure for evaluating whether an investment is financially worthwhile is the internal rate of return (IRR), which is the discount rate at which the NPV is zero. Because the IRR is a percentage it can only be used as a decision rule for selecting projects when there is only one alternative to a status quo and should certainly not be used to select one project from a group of mutually exclusive projects that differ in size (Boardman et al., 2006). Therefore, it is preferred to evaluate conversion technologies only by means of the NPV.

Because determining cash flows requires to predict the future, one is confronted with uncertainties. Decision makers want to dispose of information about the probability of a positive NPV and the crucial technical and economic parameters influencing profitability. In order to include the impact of uncertainty, sensitivity and scenario analysis have been proposed to complement the NPV analysis (Tahon, 2013). Sensitivity analysis implies varying the value of a single assumption and checking the impact on the key indicators, often without taking into account whether the change in the value of the variable is realistic. Some authors take into account real possible outcomes by determining a pessimistic, an optimistic and a most expected ("base case") scenario during scenario analysis. Though it can provide useful information on the maximal economic loss, values near the base case assumptions are often more likely to occur than values near the extremes. The analysis of economic risk can be enhanced by taking into account realistic ranges and probability distributions for the values of uncertain variables, while jointly changing them by means of Monte Carlo simulations (Hertz, 1979).

Here, the unifying approach for expressing economic risk (including Monte Carlo analysis) of Aven et al. (2004) has been applied. The NPV is identified as the overall system performance measure (step 1). The techno-economic model is the deterministic model (step 2) which links the system performance measure (i.e. the NPV) with observable quantities (i.e. prices, product yields, ...). Next, information has been collected with regard to these observable quantities by means of literature review and expert opinion. Probabilities are then used to express uncertain observable quantities (step 3). Because only literature data and expert judgments and no large datasets or historical data were available for the uncertainties, it was impossible to objectively assign probability distributions. A triangular distribution is an adequate solution when literature is insufficient for deriving probabilities (Haimes, 2004). Finally, Monte Carlo software now draws a value for each variable and calculates the corresponding NPV. This process is rehearsed 10,000 times, in order to calculate the contribution of each uncertain variable to the variance of the NPV (step 4).

The information from the Monte Carlo simulations has been taken into account when exploring a possible price range for the phytoextracting crop. First of all, the minimum price is the cultivation cost of willow which has been calculated by the levelized cost method (El Kasmioui and Ceulemans, 2012). It incorporates the costs of soil preparation, the purchase cost of the cuttings and the cost of planting them, fencing and weed killing, harvesting and removal of the stumps after seven rotations of 3 years. The maximum price is the price that an investor of a thermochemical conversion plant is willing to pay for the willow and is defined as the price guaranteeing a certainty of 95 % of a positive NPV (Kuppens et al., 2010).

After key performance indicators for economic risk have been identified during Monte Carlo simulations, companies can reduce risk by modifying the firm's operations (i.e. decreasing operational risk), by changing its capital structure, or by employing targeted financial instruments (such as insurance) (Meulbroek, 2005). Because the aim is to evaluate the economic potential of new technologies, the focus here is on the management of operational risk. The operational risk of a fast pyrolysis plant can be reduced through combining inputs: e.g. the joint pyrolysis or co-pyrolysis of biomass and biopolymers (Cornelissen et al., 2009). Co-pyrolysis can be advantageous for increasing the scale of operation so that one can benefit economies of scale, or just because other inputs are less costly (or even result in revenues by receiving a gate fee which is often the case for waste streams) and are available on a more continuous basis, or because the combination of inputs results in synergistic effects.

Operational risk can also be reduced by output optimization: i.e. by subsequent processing of your outputs so that its economic value increases or by changing process temperature so that more of the most valuable products can be produced. An example of such higher profitability is the conversion of lignocellulosic biomass cultivated on marginal land into chemicals instead of heat (Fiorentino et al., 2014). If we would be able to deal with the metals in the char, economic trade-offs exist in the joint production of oil and char as pyrolysis can be operated at different process temperatures and heating rates: low heating rates and process temperatures result in higher yields of char whereas intermediate pyrolysis temperatures and high heating rates maximize oil yields. Bridgwater et al. (1999) compiled published data from fast pyrolysis of wood which showed that the highest oil yields are obtained with short vapour residence times around 500 °C, whereas char yields increase at lower temperature and higher residence times. Stals et al. (2009) experimented with short rotation coppice from phytoremediation and found that pyrolysis oil yields reach a maximum around 450 °C, whereas lower temperatures again favour char production. In order to calculate the economic trade-off between biochar and bio-oil production from pyrolysis, Yoder et al. (2011) collected data on biochar and bio-oil yields from different feedstocks from various studies which confirm that faster heating rates lead to higher oil yields whereas slow pyrolysis results in higher yields of biochar. Yoder et al. (2011) used these data to estimate a product transformation curve (PTC) for fast pyrolysis which expresses the quantity trade-off between pyrolysis oil and char as a consequence of a change in temperature. Yoder et al. (2011) found a mean bio-oil yield of 43.56 m% which is in line with the findings of who found bio-oil yields between 40 and 50 m% for co-pyrolysis of some wood and biopolymer blends. Moreover, Lievens et al. (2009) confirm that the yield of liquid pyrolysis products of contaminated willow branches is around 40 m%. Next, the optimal process temperature for the fast pyrolysis plant can be calculated: it is where the PTC is tangent to the ratio of pyrolysis oil and char prices so that profits are maximized. A high pyrolysis oil to char price ratio will call for more oil production at the expense of char production.

However, one can hardly say that there is a real market for pyrolysis oils and chars yet. One might think of pyrolysis char and oil markets to develop in the future, but there is no way that the future prices can be equated by economic transactions made today (Lipsey and Chrystal, 2011). Basing the price on its energy content results in erroneous price estimates and hence wrong conclusions because there are many other factors (such as production costs, government policy, different elasticities of demand for biofuels compared to fossil fuels, ...) that influence the possible pyrolysis oil price. Therefore, the model of Yoder et al. (2011) has been adapted by incorporating subsequent processing of the pyrolysis products for which markets do exist: here it is assumed that pyrolysis char can be converted into activated carbon (AC), and the oil will be converted into electricity and heat. As a consequence, our model uses *net revenues* instead of *prices* for oil and char, which take into account both the gross revenue (i.e. sales price) of AC and oil and the relevant processing costs.

As a final step, a TEA can address whether the technology indeed solves the social or environmental issues it has been designed for by means of an environmental impact assessment or life cycle assessment (Barbiroli, 1997). As the economic profitability is the primary research problem, the sustainability analysis is beyond the scope of this paper.

4 RESULTS

Each of the steps that have been identified and described in the former paragraph, are now applied to the case study. The results have been reported in the following order: starting with the meta-analysis of the capital cost, moving to the results of the discounted cash flows, the Monte Carlo simulations and the exploration of a possible price range for willow, while ending with some risk reduction strategies.

4.1 Meta-analysis of the capital cost

First, a meta-analysis on existing estimates for the capital costs of pyrolysis plants has been performed. The found capital costs can be point estimates for specific case. Other authors provide equations that are a function of the plant's scale (often measured in terms of hourly throughput of dry biomass) which already aggregate existing data on capital cost estimates. The references used in the meta-analysis of capital costs can be found in table 1.

Table 1. Overview of references used in the meta-analysis of pyrolysis capital costs

Next, the equations are applied to the relevant scales of the Campine case and for each scale an average estimate has been calculated. Subsequently, a trendline has been determined for the average estimates in function of the hourly throughput of biomass. Next, the point estimates have been inventoried. Only estimates for fluid bed technology are withheld as it is believed to be the first technology to become commercially available. The point estimates have been normalized by correcting them for time by means of the Chemical Engineering Plant Cost Index (CEPCI) and for scale by means of capacity factored estimates. Not all point estimates are expressed in the same unit when it comes to scale of operation. Whenever needed, the scales have been converted in terms of hourly biomass input. Besides, some point estimates were expressed in other currencies and have been expressed in EUR by means of the exchange rate. The point estimates were then plotted and a trendline has been calculated. Finally, all data have been joint to come to the following final equation that can be used for preliminary estimates of the total plant cost (*TPC*, expressed in EUR) in function of the hourly throughput of dry biomass (ϕ, expressed in $t_{dm}\ h^{-1}$):

$$TPC = 3{,}5 \times 10^{6} \times \phi^{0.69} \qquad (1)$$

4.2 Discounted cash flow model

This equation served as an input to the discounted cash flow model (for the details we refer to former research of Kuppens and Thewys (2010) with respect to the economics of fast pyrolysis of short rotation willow from phytoextraction and Voets et al. (2011) concerning the economic comparison between pyrolysis and gasification for electricity and heat production from short rotation coppice in Flanders, and which has been updated in the TEA of fast pyrolysis for the valorisation of short rotation coppice cultivated for phytoextraction by Kuppens (2012)). The initial investment expenditure, fixed operational costs, costs for biomass purchase, pre-treatment costs, personnel costs, energy and water consumption, sales of electricity and heat, investment subsidies and exploitation subsidies, such as green power certificates (GPC) and heat and power certificates (HPC) have been calculated. In Flanders, these certificates are awarded to the producers of green power or combined heat and power. The producers can then sell these certificates to the electricity suppliers who are bound to deliver each year a minimal amount of certificates.

Table 2. Net present value of combustion, gasification and pyrolysis of contaminated willow for electricity production

From table 2 one can see that neither combustion, gasification, nor fast pyrolysis are profitable for the production of electricity only. However, pyrolysis is the least loss making conversion technology. Therefore, the profitability of fast pyrolysis for the combined production of heat and electricity (CHP) has been investigated. If one would be able to sell the heat (4.7 MW_{th}) to industrial consumers in the surroundings of the potential fast pyrolysis plant, the NPV would increase to 3.04 MEUR so that fast pyrolysis of willow for the combined production of heat and electricity becomes the only profitable conversion route.

4.3 Monte Carlo simulations

The estimation of the expenditure and revenue items (e.g. the capital cost) is highly uncertain. Table 3 summarizes the uncertainty ranges that have been found in literature or by expert judgments for some technical and economic assumptions regarding a fast pyrolysis plant in CHP mode.

Table 3. Uncertainty ranges for technical and economic assumptions regarding a fast pyrolysis plant for CHP

Next, Monte Carlo simulations have been performed. Figure 1 represents the results of the sensitivity analysis, i.e. the contribution to the variance of the NPV of the cash flows of a fast pyrolysis plant for the combined production of heat and power (CHP). A black bar indicates that an increase in the value of a variable augments the NPV. A negative contribution is indicated by the grey bars. For example, if more farmland is available, economies of scale come into play so that NPV increases. From figure 1 it can be concluded that the most important variables influencing the NPV are available farmland (i.e. the scale of operation), the willow biomass yield, the product yield (oil yield), the revenues from the green power certificates (GPC), the willow purchase cost and the electricity price. Together the uncertainty regarding the exact value of the first four variables explains more than 70 % of the total NPV variance.

Figure 1. Sensitivity analysis of the NPV of a fast pyrolysis plant for CHP

4.4 Exploration of a possible price range for willow

First of all, the cultivation cost of willow has been calculated by the levelized cost method (El Kasmioui and Ceulemans, 2012), which equals 50 EUR per tonne of dry willow and can be interpreted as the minimal price at which willow must be sold in order for a farmer to break even.

The maximum price that an investor of a thermochemical conversion plant is willing to pay for the willow is defined as the price guaranteeing a certainty of 95 % of a positive NPV (Kuppens et al., 2010), which implies that the uncertainties from table 3 need to be taken into account. With the eye on this “certainty” only investments in the production of electricity are relevant and not in CHP production, because heat sales depend on the presence of surrounding industrial consumers. Figure 2 represents the results of the calculations of these maximum attainable willow prices in function of the scale of the plant (expressed in terms of available farmland for phytoextraction).

Figure 2. Maximum attainable willow price for a thermochemical conversion plant for electricity production

From figure 2 one can see that the prices that correspond to the combustion plant are the lowest and that the prices corresponding to the fast pyrolysis plant are the highest until willow is available from 5,000 hectares of farmland (the latter is unlikely high). Fast pyrolysis is clearly the most economical technology for the potential scale of operation in the Belgian Campine (up to 2,400 hectares of farmland). At small scales, prices are negative, which implies that the investor is only willing to convert the wood if a *gate fee* is paid by the farmer to the bioenergy plant. Only when 6,000 hectares of farmland are dedicated to willow cultivation, the conversion plant's scale is large enough to recuperate the cultivation cost of 50 EUR t_{dm}^{-1}. When high amounts of biomass become available though, gasification is more economical than fast pyrolysis. This can be explained partly by the difference in capital costs which is much higher for gasification at small scales, whereas economies of scale are larger for gasification compared to pyrolysis: it can be shown that the TPC equation for gasification based on Caputo et al. (2005) has a larger investment constant and a lower investment exponent compared to the TPC for a fast pyrolysis plant. The other part of the explanation is that the electric efficiency of a biomass gasification plant is higher compared to pyrolysis, and that this efficiency even increases with electric power. The increased efficiency has been illustrated by Bridgwater (1995) for atmospheric and pressurized gasification of biomass for power generation. Also Dornburg and Faaij (2001) found increasing efficiencies with increasing scale, i.e. both increasing thermal efficiencies of installations solely for heat production and increasing electrical efficiencies for power generation technologies..

4.5 Risk reduction strategies

As stated earlier, companies can reduce risk by changing the conditions of operation, so that the NPV becomes less dependent on the main factors identified during risk analysis. Here, the impact of two possible risk reduction strategies is explored: co-pyrolysis of willow and biopolymers from the viewpoint of input optimization, and subsequent activation of the pyrolysis char from the viewpoint of output optimization.

4.5.1 Input optimization

At the input side, experimental data on fast co-pyrolysis of willow and biopolymer waste (PLA, corn starch, PHB, Biopearls, Eastar, Solanyl and potato starch) (Cornelissen et al., 2009) have been translated in economic figures by private cost benefit analysis (Kuppens et al., 2010). Co-pyrolysis of willow and biopolymer waste has several advantages:

- it is expected to decrease the water content of the pyrolysis oil;
- it can have other synergistic effects (e.g. higher calorific value);
- the economic scale of operation is increased;
- the resulting pyrolysis oil can contain special high-value chemicals;
- waste can be processed at a gate fee, so that the investor is getting paid to process the waste.

From Kuppens et al. (2010) one can conclude that fast co-pyrolysis leads to better economic results as compared to fast pyrolysis of pure willow: the NPV of cash flows has been increased. Fast co-pyrolysis of willow and PHB even increases the NPV very sharply due to the high value of crotonic acid. Except for the willow/PHB-blend, the economics however still depend largely on the revenues of green power certificates: a system which is currently changing in Flanders. Maximum prices for biopolymer waste have been calculated in the same way as this has been done for willow. If this maximum price is negative, this should be interpreted as a gate fee. If the gate fee is lower than the current disposal cost of 80 EUR per tonne for composting biopolymer waste, a realistic alternative has been found both for the owner of biopolymer waste and for the investor of a fast pyrolysis plant. This appears to be true for PLA, PHB, Biopearls, Eastar and potato starch (Kuppens et al., 2010).

4.5.2 Output optimization

As stated earlier, economic trade-offs exist in the joint production of oil and char.
The model of Yoder et al. (2011) has been adapted by calculating net revenues for subsequent processing of the pyrolysis products for which markets do exist: pyrolysis char can be converted into activated carbon (AC), and the oil will be converted into electricity and heat. Activated carbon can be used as a filter medium for the removal of heavy metals from wastewater of industrial processes (Cechinel et al., 2014), dyes removal from effluents of the textile industry by activated carbon from olive cores (Kaouah et al., 2013) or by activated carbon from agro-industrial waste jatropha curcas pods (Sathishkumar et al., 2012), purification of yellow phosphorous off-gas (Ning et al., 2011), among others. The calculations of the activation step have been based on Choy et al. (2005) for the production of activated carbon from bamboo scaffolding waste, Ko et al. (2004) for the production of activated carbons from waste tire, Lima et al. (2008) for the production of activated carbon from broiler litter and Vanreppelen et al. (2011) for the production of activated carbon from co-pyrolysis of particle board and melamine (urea) formaldehyde resin. During the activation step, heavy metals come into the flue gases so that fume gas treatment is required. Investment costs for the latter can be found in Achternbosch and Richers (2002). Combining the costs of the activation step and fume gas treatment results in the unit costs of row 8 in table 4.

The gross revenue of 1 EUR per kilogramme of char in row 10 has been based on a sales price of 2 EUR per kilogramme of activated carbon and an activated carbon yield of the activation step of 50 % of the original mass of char (Girods et al., 2009). The gross revenue of oil has been based on the revenues generated by electricity production, heat sales, green power certificates and heat and power certificates. The detailed calculations can be found in Kuppens (2012).

The resulting net revenue of one kilogramme of oil is more or less constant: it is between 0.326 and 0.330 EUR kg^{-1}, whereas the net revenue of the char declines from 0.642 EUR kg^{-1} to 0.455 EUR kg^{-1} which indicates that economies of scale are more important in char activation compared to energy production from pyrolysis oil. From the total revenues in row 15 it can be concluded that the optimal temperature is 250 °C, or that char activation is so profitable that char production instead of oil production should be favoured during the pyrolysis process.

Table 4. Calculation of the net revenue of oil and char.

One can also conclude that AC production is more beneficial than disposal of the char. The disposal cost of char in Belgium is 0.122 EUR kg^{-1} (Kuppens et al., 2011). The production cost of AC from char is higher: between 0.358 and 0.545 EUR kg^{-1} (see row 8 in table 4), though it is largely compensated by the high revenue from the sales of AC: the sales prices compensates the production cost and even results in a positive net revenue (including an expensive fume gas treatment for Cd).

5 CONCLUSION AND DISCUSSION

The main barrier in the commercialization of phytoextraction is its long time period, which can be countered by valorization of the phytoextracting crops. Especially when remediation of mainly agricultural soils is concerned, one of the main conditions is that farmers will only switch crops if they can earn a higher income during or after phytoextraction. Most often, the time required for phytoextraction is beyond the duration of the professionally active period of farmers, so that the income during phytoextraction will be a decisive parameter in the decision process of a farmer. In order to help decision makers (investors, farmers, government) in making better judgments, a methodological framework for the techno-economic assessment has been developed and applied on a case study in Belgium for fast pyrolysis of contaminated biomass that has been cultivated for phytoextraction. The TEA is a dynamic tool in which variables can change over time so that one is able to assess economic risk properly. This way, decision makers get insight in the key uncertainties, which give direction to research and development towards the most promising options.

For the operational scale of the case study in Belgium, fast pyrolysis seems more appropriate than gasification and combustion, although none of the three conversion technologies shows a positive NPV for electricity production. Only fast pyrolysis for the combined production of heat and power is expected to be a profitable conversion route for contaminated willow from the viewpoint of an investor in a thermochemical conversion plant. The profitability of the fast pyrolysis plant however stands or falls on the operational scale, i.e. the available amount of willow, and on the heat turnover, i.e. the presence of guaranteed demand for heat in the surroundings of the plant. Regarding the scale of operation, the main disadvantage of short rotation coppice is its low acceptance by farmers. Moreover, guaranteeing a sufficient heat demand is highly uncertain. As a consequence, investors will exclude their heat turnover in the determination of the price they are willing to pay for obtaining the phytoextracting crops. It has been illustrated that chances are high that the possible price range for phytoextracting willow is not able to cover cultivation costs. Unless the government is willing to compensate for the income loss of the farmers, the latter will never be prepared to switch crops.

Nevertheless, an investor can reduce economic risk by changing operations, e.g. by increasing the scale of operation using complementing feedstocks, and by subsequent processing of the char by-product into activated carbon. The results from output optimization can be considered as a preliminary feasibility study of active coal production and provide a strong recommendation to focus research on possibilities for char valorization. Some technical uncertainties though still need to be validated by experimental research in a next step: i.e. one should check the quality of char and oil when the feedstock is pyrolyzed at different temperatures. The moisture content in the oil might change at different temperatures, resulting in changing heating values and hence economics. Other quality parameters that might be impacted are bio-oil viscosity, biochar fixed carbon, targeted compounds in the bio-oil, among others. As Yoder et al. (2011) stated, their data did not allow direct estimation of these parameters. Furthermore, other valorization routes for the pyrolysis oil and char might be taken into account, such as upgrading the oil for transport fuels or chemicals and the application of pyrolysis char as a biochar for soil amendment after the metals have been removed from the char. Without the risk analysis, the opportunity of activated carbon production for the case study would not have been investigated.

Conclusively, this paper clearly illustrates the need for a uniform methodological framework for techno-economic assessments of clean technologies. In the section on the theoretical background, it is highlighted that no such standards exist for TEA that are comparable to the ISO standards for life cycle analysis (LCA). An example of the problems that can be encountered by the lack of uniform evaluations, has been illustrated by the meta-analysis of the capital costs. As a consequence, the TEA steps in this paper are recommended in order to increase the transparency of future TEAs of clean technologies.

Finally, a full techno-economic assessment should include a sustainability check. As the main objective of the current research was the economic feasibility of fast pyrolysis, this check was beyond the scope of this article. As a next step, an analysis of the external costs and benefits is recommended. For example, an external benefit of phytoextraction is the reduction of health effects. Above this, it is expected that energy production from biomass reduces greenhouse gas emissions. The latter, however, should be checked together with other environmental and social impacts during life cycle assessment. From a social welfare point of view, requiring knowledge about the external costs and benefits helps governments in determining optimal compensation programs for farmers or investors using phytoextracting crops.

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REFERENCES

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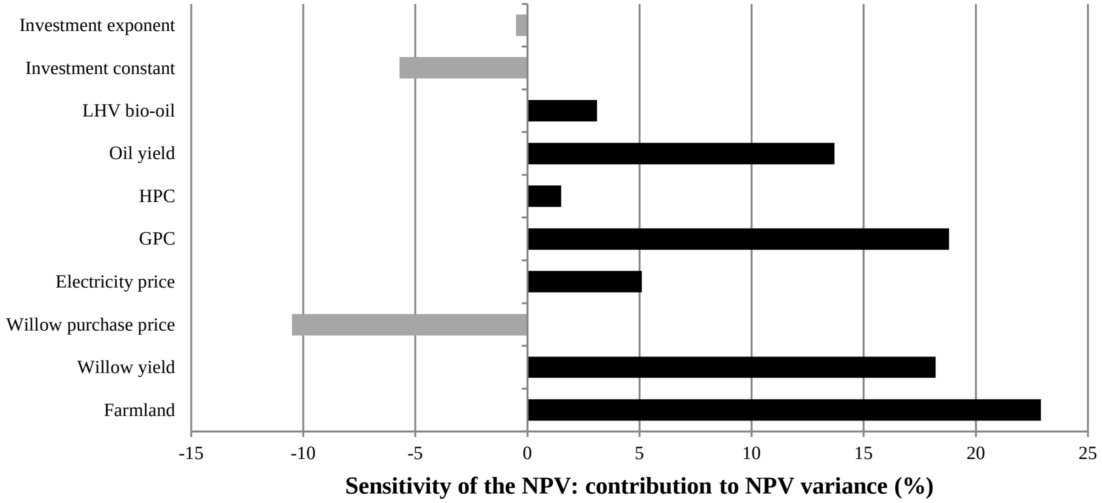
Reference	Study topic
Point estimates	
Islam and Ani (2000)	fluidized bed fast pyrolysis with and without catalytic treatment for throughputs of rice husk of 0.3, 100 and 1000 kg h^{-1}
Magalhães et al., (2009)	Dynamotive's fluidized bed reactor with a capacity of 200 t day^{-1}
Peacocke et al., (2006)	fast pyrolysis processes for plant capacities between 0.25 and 10 t h^{-1} of dry wood
Ringer et al., (2006)	prior investigations of bio-oil production costs and corresponding total capital investment for plant sizes up to 1000 t day^{-1}
Rogers (2009)	electricity generation using bio-oil produced by fast pyrolysis of energy crops in the United Kingdom
Siemons (2005)	flash pyrolysis of the most attractive biomass available in the province of Groningen in the Netherlands
Sorenson (2010)	pyrolysis system of Renewable Oil International processing 200 dry tonnes of forest biomass per day
Uslu (2005)	historic data from 1987 to 2003 regarding specific pyrolysis plant investments for thermal capacities up to 140 MW_{th} of the bio-oil
Van de Velden et al. (2008)	circulating fluid bed biomass pyrolysis reactor for an annual production of 16,320 ton bio-oil
van Stijn (2007)	personal communication about planned investments of pyrolysis reactors in Serbia
Westerhout et al. (1998)	bubbling and circulating fluidized bed, and rotating cone reactor for the pyrolysis of 50 kt of mixed plastic waste annually
Zeevalking and van Ree (2000)	pyrolysis as a possible conversion technology for the production of electricity and heat from biomass and waste
Equations as function of the plant's scale	
Bridgwater et al. (2002)	14 data points on a fast pyrolysis reactor
Bridgwater (2009)	new data from an analysis of several pyrolysis plants around the world
Bridgwater (2012)	review of the technology and economics of fast pyrolysis and the upgrading processes for its liquid product from pre-treated biomass to pyrolysis oil in storage tanks
Siemons (2002)	equation in function of the annual energetic capacity of the produced bio-oil
Brammer et al. (2005)	fluidized bed system as a function of the mass input flow of willow in kilogrammes per second
Uslu (2005)	plotting available cost estimates against the hourly feedstock flow
Rogers and Brammer (2012)	production cost of fast pyrolysis bio-oil which included the estimation of the total plant cost in function of the plant's processing capacity

Variable	Combustion	Gasification	Pyrolysis
Quantity of feedstock that requires valorisation			
Willow yield		8 t_{dm} ha^{-1} yr^{-1}	
Available farmland		2 400 ha	
Annual feedstock		19 200 t_{dm} yr^{-1}	
Technical parameters			
Electric efficiency	21 %	34 %	24 %
P_{ne} (MW_e)	2,6 MW_e	4,5 MW_e	5,1 MW_e
Operating hours	8 000 h	8 000 h	reactor 7 000 h engine 5 000 h
Economic parameters			
I_0 constant	10 941 207	12 890 503,22	4 684 181 (including engine)
I_0 exponent	0,6061	0,6773	0,7897 (including engine)
Total plant cost	18,5 MEUR	23,0 MEUR	13,7 MEUR
Net present value	**-7,22 MEUR**	**-1,66 MEUR**	**-1,07 MEUR**

Variable	***Values***		
	Minimal	***Base-case***	***Maximal***
Farmland	650 ha	2 400 ha	3 000 ha
Willow yield	5 t_{dm} ha^{-1} yr^{-1}	8 t_{dm} ha^{-1} yr^{-1}	15 t_{dm} ha^{-1} yr^{-1}
Oil yield	60 %	65 %	70 %
GPC price	80 EUR MWh_e^{-1}	100 EUR MWh_e^{-1}	120 EUR MWh_e^{-1}
HPC price	31 EUR MWh_{PEB}^{-1}	35 EUR MWh_{PEB}^{-1}	45 EUR MWh_{PEB}^{-1}
Electricity price	60 EUR MWh_e^{-1}	70 EUR MWh_e^{-1}	80 EUR MWh_e^{-1}
Willow purchase price	30 EUR t_{dm}^{-1}	50 EUR t_{dm}^{-1}	70 EUR t_{dm}^{-1}
LHV bio- oil	16 GJ t^{-1}	17 GJ t^{-1}	18 GJ t^{-1}
Investment constant	2 697 333,81	3 486 567,30	4 285 787,76
Investment exponent	0,6267	0,6914	0,7799

		Unit	(1)	(2)	(3)	(4)	(5)	(6)
(1)	**Temperature**	**°C**	250	300	350	400	450	500
(2)	**Oil Yield**	**m%**	39	43	48	51	53	54
(3)	**Char yield**	**m%**	45	40	35	30	26	22
(4)	**Total activation cost**	**MEUR/yr**	3.11	2.85	2.62	2.44	2.31	2.24
(5)	**Total CHP cost**	**MEUR/yr**	0.91	1.03	1.11	1.18	1.23	1.25
(6)	**Total char product.**	**kt/yr**	8.67	7.58	6.58	5.67	4.84	4.11
(7)	**Total oil product.**	**kt/yr**	7.41	8.42	9.22	9.83	10.23	10.43
(8)	**Unit cost char**	**EUR/kg**	0.358	0.379	0.402	0.433	0.478	0.545
(9)	**Unit cost oil**	**EUR/kg**	0.123	0.121	0.120	0.120	0.119	0.119
(10)	**Gross revenue char**	**EUR/kg**	1.000	1.000	1.000	1.000	1.000	1.000
(11)	**Gross revenue oil**	**EUR/kg**	0.449	0.449	0.449	0.449	0.449	0.449
(12)	**Net revenue char**	**EUR/kg**	0.642	0.621	0.598	0.567	0.522	0.455
(13)	**Net revenue oil**	**EUR/kg**	0.326	0.329	0.329	0.330	0.330	0.330
(14)	**Price ratio**	**-**	0.508	0.529	0.551	0.582	0.632	0.725
(15)	**Total revenue**	**MEUR/yr**	7.98	7.47	6.97	6.45	5.90	5.31


Investment exponent
Investment constant
LHV bio-oil
Oil yield
HPC
GPC
Electricity price
Willow purchase price
Willow yield
Farmland
-15
-10
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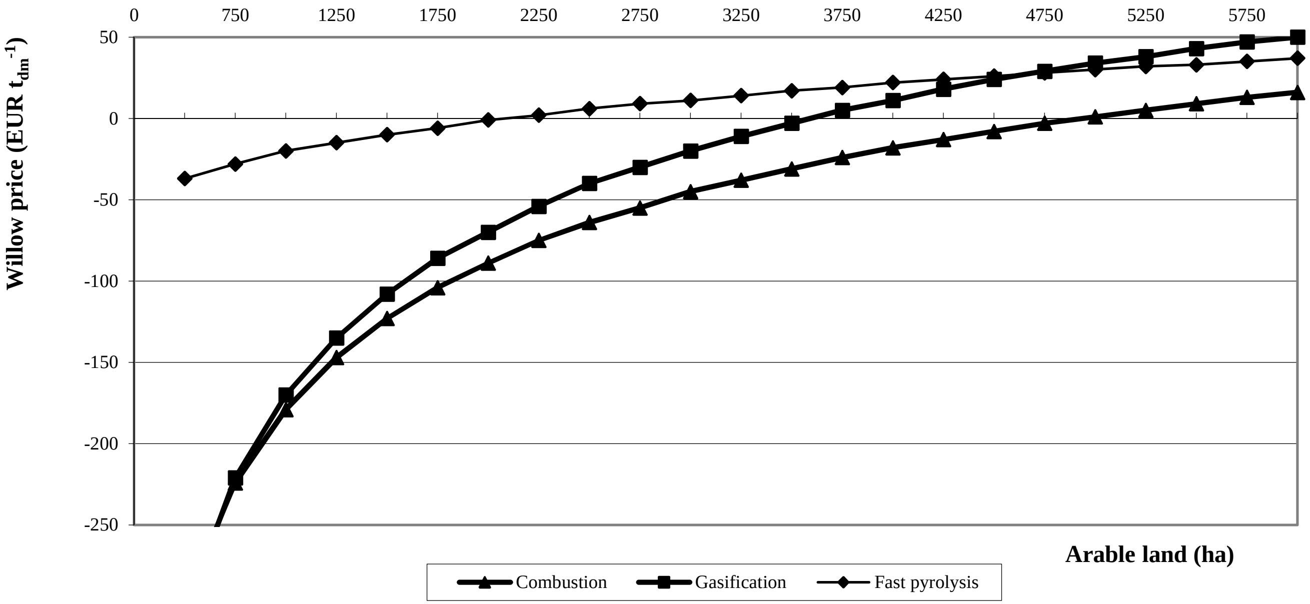
20
25
Sensitivity of the NPV: contribution to NPV variance (%)


0
750
1250
1750
2250
2750
3250
3750
4250
4750
5250
5750
50
0
-50
-100
-150
-200
-250
Willow price (EUR t_{dm}^{-1})
Arable land (ha)
Combustion
Gasification
Fast pyrolysis