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Techno-economic assessment of fast pyrolysis for the valorization of short rotation coppice cultivated for phytoextraction

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A B S T R A C T

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.

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. 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

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.

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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 Campine region in 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 life cycle. 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