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Competition between biofuels: Modeling technological learning and cost reductions over time

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ABSTRACT

A key aspect in modeling the (future) competition between biofuels is the way in which production cost developments are computed. The objective of this study was threefold: (i) to construct a (endogenous) relation between cost development and cumulative production (ii) to implement technological learning based on both engineering study insights and an experience curve approach, and (iii) to investigate the impact of different technological learning assumptions on the market diffusion patterns of different biofuels. The analysis was executed with the European biofuel model BioTrans, which computes the least cost biofuel route. The model meets an increasing demand, reaching a 25% share of biofuels of the overall European transport fuel demand by 2030. Results show that 1st generation biodiesel is the most cost competitive fuel, dominating the early market. With increasing demand, modestly productive oilseed crops become more expensive rapidly, providing opportunities for advanced biofuels to enter the market. While biodiesel supply typically remains steady until 2030, almost all additional yearly demands are delivered by advanced biofuels, supplying up to 60% of the market by 2030. Sensitivity analysis shows that (i) overall increasing investment costs favour biodiesel production, (ii) separate gasoline and diesel subtargets may diversify feedstock production and technology implementation, thus limiting the risk of failure and preventing lock-in and (iii) the moment of an advanced technology's commercial market introduction determines, to a large degree, its future chances for increasing market share.

1. Introduction

Driven by general sustainable energy targets and specific biofuel targets to curb green house gas (GHG) emissions, concerns regarding security of supply and especially in recent years rising oil prices, the production and use of biofuels have been steadily increasing globally in the last decades. The EU encourages developments to achieve an ambitious 10% share of biofuels by 2020 [1]. Driven by this target the demand for biofuels in Europe can be expected to face a strong increase compared to the current (2007) 2.6% [2]. With such turbulent short-term development comes the need for an integrated long-term vision for biofuels, as set in the REFUEL project [3]. Amongst other aspects, the role of technological learning (and associated cost reductions) is a crucial factor affecting the possible market diffusion of various 1st and 2nd generation biofuels.

Given the complex interactions between the various biofuels and fossil transportation fuels, the use of models for biofuel market penetration can be a useful tool for policy

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Nomenclature

FT	Fischer–Tropsch synthetic diesel
LE	lignocellulose ethanol
DME	dimethylether
SNG	substitute natural gas
WEC	Western European Countries
CEEC	Central and Eastern European Countries

Conversion factors

tonne	1.0 Mg
31.71 GW	1.0 EJ y^{-1}

makers, market actors and scientists. The use of energy models is not new – a wide variety of energy models have been constructed to provide policy makers with a better insight into the complexities of energy system development under various policy objectives. Many describe the complete energy system either with a technical 'bottom–up' (systems engineering) approach or with a macro-economic 'top–down' approach [4]. Specifically regarding the market penetration of biofuels, a limited number of models exist, e.g. the ESIM and LEITAP models [5], the BioTrans model [6] (used in this study) for Europe or the biodiesel model [7] for the US.

A crucial aspect of these models is how technological learning and subsequent cost reductions over time are taken into account, as these can drastically change the economic competitiveness and thus market share of a biofuel compared to other (fossil and renewable) fuels. Some energy models tend to define future cost levels ex ante, i.e. cost reductions are independent of market developments. This approach ignores demand driven market dynamics and the notion that technological learning (and subsequent cost reductions) depend on the degree to which a technology is utilized; a phenomenon which has been observed numerous times, and that can be quantified using the experience curve approach. For this reason, endogenous learning has increasingly been incorporated in many energy models but this has not been attempted for models specifically focusing on biofuels for transport.

Analysis for this study is executed with the BioTrans model, which assesses the European biofuel mix that establishes given a target-driven biofuel demand. The model fills-in the yearly demand by computing the least cost biofuel mix. The development of production cost can be modeled endogenously which makes BioTrans particularly suitable to assess the influence of specific learning parameter values on competition between fuels over time.

The objective of this study is threefold, it aims to

(i) Construct the (endogenous) relation between cumulative installed capacity and associated production cost reductions, or if this is not possible construct an (exogenous) relation following a hybrid approach, in which insights from engineering studies (mainly regarding scale effects) are combined with a scale-independent experience curve approach for both 1st and 2nd generation feedstocks and 1st and 2nd generation biomass-to-biofuel conversion technologies,
(ii) implement these relations in the BioTrans model and
(iii) illustrate the consequences of these assumptions on the rate of technological learning, its effect on market diffusion and determine the future biofuel mix as a result of the market competition.

2. Methodology

2.1. *Technological learning and cost reductions in feedstock production*

Feedstock production costs can reduce over time, mainly by gaining experience with its production. The lack of historical production cost data prohibits the possibility to model cost developments endogenously. In principle, however, feedstock production costs can be modeled endogenously, i.e. relating annual production volumes (as a proxy for gained experience) to decreasing production costs. Analyses performed for sugarcane in Brazil [8], for corn in the US [9] and for rapeseed in Germany [10] demonstrated that indeed cost reductions of (food) crops do follow an experience curve pattern. Unfortunately, for all (other) crops considered in the study, no such studies are available which could provide the necessary time series and trend lines. However, the studies mentioned show that an increase in productivity is the single-most important driver for decreasing production costs for feedstocks, contributing between 65% and 85% to total cost decline, therefore making it a suitable parameter for estimating future cost reduction potentials. Increased productivity is an important measure for cost reduction as it shows the results of improving management (e.g. adequate pest control, optimized fertilizer application etc.). Another aspect contributing to reducing costs is economies of scale in transportation, e.g. the use of larger trucks, trains or ships [8].

The productivity increase of agricultural commodity crops was modeled on the basis of a fixed annual increase, with the annual increment being developed from a time series analysis of the specific crop [11]. Despite there being a physical limit to this approach over a long duration, this trend is amply confirmed for Europe over the last four decades [12,13]. An equation

$$Y_e = f_Y \cdot t_y + b \tag{1}$$

was fitted to the historical data. The relative yield improvement (% y^{-1}) decreases over time as shown in Fig. 1. We have equated yield improvement rate to be the same as the production cost decrease during the period of our analysis from 2005 to 2030 with the initial crop production costs taken from [14].

Lignocellulosic crop productivity development curves are generally unavailable except for some experimental tree crops such as Poplar, Willow and Eucalyptus [15,16] and herbaceous species such as *Miscanthus* and Switchgrass [17,18]. Instead of fitting a curve to empirical data, literature data [19,20] have been used to project the maximum productivity (and thus cost reductions) for 2030.

2.2. *Technological learning and cost reductions for conversion technologies*

An experience (or learning) curve, as this empirical causality relation is often referred to, expresses the cost decline by