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Pareto-efficient legal regulation of the (bio)fuel market using a bi-objective optimization model

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ABSTRACT

Blending biofuels into fossil fuels allows for emission reductions in the transportation sector. However, biofuels are not yet competitive due to high production costs and investments and thus, legal requirements like blending quotas or emission thresholds must be issued if biofuels are to contribute to European CO_2-reduction goals. Thereby, the aim is to establish Pareto-efficient long-term legal requirements. Against this background, we develop an optimization model for simultaneously minimizing life cycle greenhouse gas emissions and maximizing discounted net present value in order to analyze the overall system of biomass cultivation, (bio)fuel production and blending. The applied ϵ-constraint approach allows to calculate Pareto-efficient solutions. The model is applied to the German (bio)diesel market. We show that current and past European Union directives are not Pareto-efficient and cause unintended side effects. As results, information about trade-offs between the two objectives (minimizing life cycle greenhouse gas emissions and maximizing discounted net present value) as well as recommendations on the design of the regulation is derived.

1. Introduction

The transportation sector consumes 26 percent of global delivered energy (EIA, 2013) and emits 22 percent of global CO_2 emissions, 75 percent of them resulting from road transportation (IEA, 2012). In the future, the usage of fossil fuels must be reduced in order to ensure supply security as well as projected emission savings within the transportation sector. One option for achieving these targets is the substitution of fossil fuels by biofuels (Dinh, Guo, & Mannan, 2009). Accordingly, global production of biofuels is expected to grow from 54 bln in 2005 to 222 bln of biofuels in 2021 (OECD, 2012). However, high investments are necessary, and until now production costs of biofuels (BMU, 2011) are higher than those of fossil fuels. Thus, stipulation by political regulation is necessary (as is for instance intended by the European Union Renewable Energy Directive (2009/28/EC)). Against this background, the paper focusses on the analysis and design of legal regulations for production, import and blending of biofuels for road transportation.

Each type of fossil fuel (or fuel blend) can be substituted by different kinds of biofuels. Thereby, biofuels can be classified into 1st, 2nd, and 3rd generation biofuels (IEA, 2011). Where 1st generation biofuels are mainly produced from raw materials which can also be used within the food and fodder industry like e.g. corn or sugar can, 2nd generation biofuels are mainly produced from residual materials like e.g. straw or residual wood. Biofuels of the 3rd generation on the other hand are produced from non agricultural materials like e.g. algae. Since 3rd generation biofuels are still not market-ready, they will not be discussed further. To date, political decision makers as well as investors have to decide, whether and to what extent 1st or 2nd generation biofuels should substitute fossil fuels in the future. 1st generation biofuels have disadvantages like low compatibility with engines, competition with food production and limited emission reduction potential. For 2nd generation biofuels, very high investments and production costs are needed (IEA, 2011). Production of 1st as well as 2nd generation biofuels might lead to land use change, e.g. if agricultural areas that have been used for cultivation of biomass for food or fodder are rededicated to cultivation of biomass for biofuels. Additionally, trade-offs occur with regard to life cycle emissions and costs. Thus, a thorough ex-ante analysis of the complex and interacting system of (bio)fuel production is a prerequisite for the design of long-term political regulations that are Pareto-efficient with regard to economic and environmental objectives. However, this was disregarded in the past and as a result, political regulations for the promotion of biofuels in the European Union (EU) changed repeatedly within the last years.

Thus, we conduct an ex-ante analysis of the (bio)fuel production network in order to design and evaluate Pareto-efficient legal regulations. Thereby, the complete system of biomass cultivation, biofuel production as well as import of biomass, biofuel and fossil fuels has to be regarded, and all fuels that can be blended to fulfill total fuel

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demand (fossil fuels, 1st, and 2nd generation biofuels) must be considered. Capacities of agricultural areas and potential land use change effects have to be taken into account in order to avoid unintended side effects. The system has to be evaluated regarding emission reduction and total costs simultaneously.

Against that background, we develop a bi-objective, multi-period optimization model, considering cultivation of biomass, production of biofuels, import of biofuels and biomass, as well as blending of fuels. Our aim is to identify Pareto-efficient solutions and to derive trade-off information for political decision makers regarding profit maximization and emission minimization. The paper is organized as follows. First, the planning problem is presented in Section 2, and a literature review is given in Section 3. In Section 4, the optimization model is developed, and applied to a case study in Section 5. Finally, conclusions and outlook on further research are given in Section 6.

2. Planning problem

In this section, the planning problem is characterized, followed by an overview of political regulations of the biofuel sector. Model requirements are derived as a result of this analysis.

2.1. Biofuel production system

The production system of the (bio)fuel sector (Fig. 1) consists of three phases: (1) cultivation of biomass, (2) conversion of biomass into biofuels and (3) blending of biofuels and fossil fuels into final fuel blends sold at the market.

In phase one the **cultivation of biomass** takes place. Several kinds of biomass may be used for biofuel production (IEA, 2011). These characteristics differ with regard to energy density, prices, availability, region of cultivation, and emissions during cultivation. The polluted emissions also depend on the type of land used for the cultivation, and on transportation distances between cultivation and fuel production. The capacity of the different types of agricultural land is limited. If biomass for biofuels is cultivated on land that was not used for the cultivation of energy crops so far, land use change appears (SWD(2012) 343). This results in accessory emissions that depend on the climate, soil type, land cover, and land management (2010/335/EU). However, it is still discussed how land use change can be integrated in legal regulations. If biomass is imported from other countries, emissions of biomass cultivation and land use change arising in the supplying countries must also be accounted for.

In phase two, **biomass is transformed into biofuel** using fuel-specific production technologies. These production technologies differ with regard to permitted biomass, processes, degree of centralization, economies of scale, production capacities, conversion efficiencies, resulting by-products, investments and production costs. The polluted emissions during production of biofuels vary depending on used biomass and production technology. Decentralized plant concepts convert biomass into an intermediate product in the proximity of biomass cultivation, and afterwards this intermediate is transported to a centralized synthesis facility (Trippe et al., 2013). In centralized plant concepts, all production steps are carried out within one production facility (Blades, Rudloff, & Schulze, 2005). Currently, there already exist plants for production of fossil fuels and 1st generation biofuels, whereas only pilot plants exist so far for 2nd generation biofuels (SWD(2012) 343). Biofuels and fossil fuels can also be imported from other countries, and costs, emissions as well as land use change have to be regarded for these fuels as well.

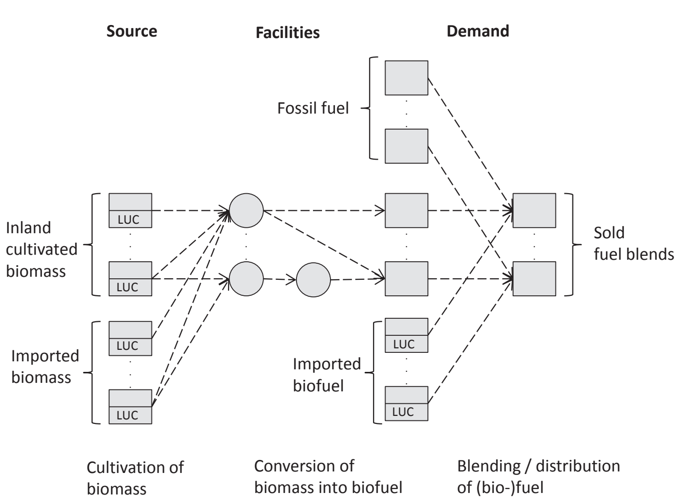

Fig. 1. Structure of the (bio)fuel sector (LUC: land use change).

Within phase three the **final blending of fuels** takes place. Thereby, the final blend depends on total demand for fuel blends, legal requirements regarding certain biofuel quotas and CO_2 reduction goals, technical blending restrictions, and production costs. The final fuel blend may be pure in quality or can be blended from different kinds of fossil fuels and biofuels. Blending of 1st generation biofuels is limited (2009/30/EC) due to restricted compatibility with car engines. Blending of 2nd generation biofuels is not restricted, since synthetic biofuels have the same (or even better) quality as fossil fuels. Besides, the specific energy contents of the fuels have to be considered in the blending process. The total life cycle emissions of the sold fuel blend correspond to the average emissions of all (bio)fuels included in the blend (2009/28/EC).

2.2. Political regulations of the fuel sector

As can be seen in Fig. 2, legal regulations may be implemented at all life cycle phases of the fuel, i.e. biomass cultivation, biofuel production, biofuel distribution or to the total biofuel life cycle.

Political instruments can be grouped into three different types of measures: a) regulatory measures (e.g. market share quotas, emission thresholds) providing specific minimum or maximum threshold values that have to be fulfilled by the market players, b) market based measures (e.g. taxes, subsidies) providing financial incentives for favorable technologies or products (or a financial burden for undesired ones), and c) suasive measures (e.g. information, promotions) aiming at a change of the behavior of the market players in a voluntary way. Legal regulations can contain only one of these political instruments (e.g. tax exactions for biofuels), but may also combine a set of different political instruments (e.g. biofuel tax exactions together with subsidies for the construction of new biofuel production plants and emission thresholds). An overview of political instruments for the (bio)fuel market applied in different countries around the world is given in Fig. 2. The different political instruments are classified regarding the three fuels' life cycle phases and types of measurement.

Fig. 3 illustrates the legal measures implemented in the EU since 1997. As can be seen, quotas for market shares for biofuels changed between 1997 and 2009. In 2009, unintended side effects like the food vs. fuel debate (OECD, 2011) and land use change effects resulted in a modification of the type of regulation, and 2nd generation biofuels were granted double to quadruple weight in the calculation of the required biofuel market share. Furthermore, minimal emission savings have to be fulfilled. Since 2009, emissions resulting from land use change are integrated in the emission calculation (2010/335/EU, 2012/0288 (COD)). A bonus that had been provided for biomass cultivated on restored degraded land (2009/28/EC) was eliminated in 2012 (COM(2012) 595).

Over time, a broad range of legal regulations for the (bio)fuel market was implemented. However, these regulations lead to unintended side effects and non-efficient results. The resulting changes of the