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Corrigendum

Corrigendum to "Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning" [Energy Convers. Manage. 149 (2017) 368–380]

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ABSTRACT

This study compares the techno-economic feasibility of five forest-based biofuel conversion pathways for road transportation in the Nordic countries with particular focus paid to feedstock cost effects on total costs in a partial equilibrium model environment. We present (I) a literature review of techno-economic estimates detailing biofuel costs at various capacities, (II) estimate a capacity-wise normalized cost-comparison of the conversion pathways, and (III) estimate the feedstock cost changes with increasing biofuel facility deployment in the Nordic forest Sector Model. The results indicate that fast pyrolysis and hydrothermal liquefaction are the most cost-competitive options among the reviewed conversion pathways. We found average costs of FASTPYR and HTL to range from 0.84 € L^{-1} to 0.91 € L^{-1} (0.93 \$ L^{-1}–1.01 \$ L^{-1}) and 0.84 € L^{-1} to 0.88 (0.93 \$ L^{-1}–0.98 \$ L^{-1}) depending on the techno-economic data used and forest biomass marked demand. Technology learning may reduce these costs further. The conversion pathways are not cost-competitive with current fossil alternatives but may be cost-competitive with current biofuel conversion pathways, given n^{th} plant cost levels. At a biofuel production level corresponding to 20% of the Nordic fossil fuel consumption for road transport, feedstock costs for biofuel producers increases 12–35%, depending on the conversion pathway and the restrictions imposed on what constitutes biofuel feedstock. This corresponds to an increase ranging from 10% to 26% on the total costs. Technology learning may outweigh the effect of feedstock cost increases on the total costs depending on the learning rate and the conversion pathway. The results of this study can potentially aid policy creation for conversion pathway evaluation and support schemes.

1. Introduction

Development of a renewable resource-based transportation sector is a global challenge, which has yet to be solved. In parallel, global demand for oil is increasing as a consequence of demand for transportation fuels [1]. Decarbonization strategies for transportation modes currently include biofuels because these, in general, can be applied in the current vehicle fleet with little modification. The Nordic countries are at a vantage point in securing investments in second-generation biofuel production facilities – they have direct access to significant amounts of forest-based feedstock and water for biofuel production and have extensive experience with forest biomass processing technologies. However, forest-based feedstock compositional complexity and variability poses challenges for biofuel refining technologies [2] and fossil fuels are considerably more cost-competitive at the current oil price. As a mitigation effort, Nordic policy makers have applied blending mandates and taxes on fossil fuel alternatives as means to promote biofuels. However, there is still a need to identify cost-competitive conversion pathways that can bridge the existing production cost-gap between fossil fuels and biofuels.

While biofuels are projected to account for more than 450PJ by 2050 in the future Nordic vehicle fleet [3], determining whether these will become cost-competitive with fossil alternatives is a cumbersome endeavor. Reviews of emerging second-generation biofuel conversion pathways demonstrate that production cost estimates differ significantly between studies [4,5]. The studies typically differ with regard to feedstock costs, capital cost assumptions and economies of scale. In addition, uncertainties related to future feedstock cost development and learning effects further complicates the assessment.

Feedstock cost uncertainties have typically been addressed using sensitivity analysis in the literature through numerous biofuel techno-economic studies. Results show that feedstock costs have a compelling

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effect on the cost-competitiveness of biofuels [e.g. 6–8]. This is especially true for forest-based feedstock, which generally displays high cost variability. The variability is, among other things, related to direct costs like harvest, forwarding and transportation, opportunity costs for forest owners as well as varying demand from the forest industry. Consequently, forest-based feedstock costs often display large local and regional variation. Techno-economic studies, which rely on localized and fixed forest-based feedstock costs, therefore often provide ambiguous biofuel cost results. In a Nordic context, forest-based feedstock costs in particular depend on demand for forest biomass from the existing forest industries and forest-based bioenergy industry. Therefore, we believe accurately estimating forest-based feedstock costs in a Nordic context and, as an extension, the total production costs, requires a coupling of conversion pathway techno-economic estimates with optimization models that cover the forest-biomass market interactions.

Using a Nordic forest sector partial equilibrium model with a biofuel facility investment module permits a more accurate estimate of feedstock costs and associated total biofuel cost, as the direct and indirect interactions with the existing forest industries and the forest-based energy sector are modelled in an encompassing way. Coupling such a model with techno-economic estimates of emerging forest-based biofuel conversion pathways, aids in determining the economic feasibility of forest-based biofuel production in the Nordic countries. In this paper, we apply the Nordic Forest Sector Model (NFSM) with an endogenous biofuel investment module to assess the economic feasibility of emerging forest-based biofuel conversion pathways in a Nordic context. We do this by (i) presenting a harmonized comparison of reviewed techno-economic estimates of identified conversion pathways and (ii) quantify feedstock market price changes with increasing demand for feedstock from biofuel facilities. Finally, we discuss (iii) what is needed in terms of learning, investment and policy mechanisms for forest-based biofuel production facilities to become cost-competitive.

2. Methods

2.1. NFSM description

NFSM is a partial equilibrium model, covering forestry, the forest industry and the bioenergy industry in the Nordic countries. The model is similar in structure to forest sector models such as the Norwegian Trade Model (NTMIII) [9]. The model is myopic; the sum of consumer and producer surplus is maximized in each period and the objective function solution provides market equilibrium prices and quantities under free competition as shown by Samuelson [10]. Conceptually, the model includes five components: (I) *timber supply* (II) *industrial production* (III) *product demand*, (IV) *interregional trade* and (V) *biofuel facility investment.*

The NFSM objective function, which is maximized, is given below while a detailed explanation of the objective function and constraints is provided in Mustapha et al. [11] and also presented in Appendix A. The data applied in the model excluding biofuel data is covered in great detail in Mustapha [12].

$$\left(\begin{array}{c} \sum_{reg,fin}\sum_{n=1}^{N} CON_{reg,fin,n} - \sum_{reg,wood}\sum_{n=1}^{N} HARVW_{reg,wood,n} \\ -\sum_{reg,rdue}\sum_{n=1}^{N} HARVR_{reg,rdue,n} \\ -\sum_{reg,tech} C_{reg,tech}PR_{reg,tech} - \sum_{reg,wtech} WL_{reg,wtech} - AN\sum_{reg,bio} CAP_{bio}INV_{reg,bio} \\ -\sum_{reg,jeg,all} TC_{reg,jreg,all}TQ_{reg,jeg,all} \end{array}\right) \tag{2.1}$$

The indexes *reg* and *jeg* refer to regions, *fin* to final products for consumers, *wood* to roundwood categories, *rdue* to harvest residues and *all* to all products (consumer products, intermediate products, roundwood and harvest residues). *tech* refers to all production technologies, while *wtech* refers to sawnwood production technologies and *bio* to biorefinery technologies. n ($n \in 1,2,\ldots,N$) is the number of linear segments. $CON_{reg,fin,n}$ is the piecewise linear approximation of the inverse demand function (A.1), $HARVW_{reg,wood,n}$ represents the piecewise linear approximation of the inverse roundwood supply function (A.4), and $HARVR_{reg,rdue,n}$ approximates the integral of the harvest residue supply function (A.6). $C_{reg,tech}$ is the unit cost, while $PR_{reg,tech}$ is the main product output variable. Capacity maintenance costs for existing and new technology are accounted for in the production costs. $C_{reg,tech}$ excludes the cost for labor in sawnwood manufacturing because this is handled in $WL_{reg,wtech}$. $WL_{reg,wtech}$ represents the cost of labor in sawnwood manufacturing and is explained in (A.7). AN is the annuity factor on the Total Project Investment (TPI), *bio* is the biofuel technology and *reg* is the region. CAP_{bio} is the TPI at minimum permitted biofuel production facility size while $INV_{reg,bio}$ is the investment variable. This term is further explained in (A.7). ($TC_{reg,jeg,all}$ is the transportation cost, while $TQ_{reg,jeg,all}$ is the transportation quantity variable.

Since demand is a core component of the objective function, we implement regional demand for biofuels to affect the allocation of the biofuel production facilities in NFSM. The allocation of the biofuel production facilities by the model also hinges on the regional demand for biofuels, which provides better estimates of the biofuel costs (including those related to distribution). While we selected horizontal demand curves for biofuels to represent the consumers' ability to shift from fossil fuels to biofuels at price-point parity it should be noted that production volumes are stipulated exogenously, so the investment module is delimited to allocation of capacity, but cannot alter the total volume installed. The total annual Nordic demand for biofuel is assumed to be 4000 million liters (ML). Demand for biofuel is distributed regionally proportionate to regional population densities and distribution costs of biofuels from facility to consumer are based on the work of Cazzola et al. [13].

2.2. Biofuel feedstock in NFSM

Forest biomass markets are closely interconnected in NFSM. While a full overview of the markets and associated interactions is too comprehensive to present here (see Mustapha [12] for a detailed overview of NFSM), we present the market interactions related to biofuel feedstock sourcing in Fig. 1. Availability of biofuel feedstock is in this study delimited to (i) Harvest residues, (ii) Pulpwood and (iii) sawmilling residuals and woodchips. Harvest residues are modelled applying regional linear supply functions as indicated in (2.1), which represent the total costs delivered at roadside. Roadside costs increase with increasing demand as collection and forwarding becomes more expensive. In-region and between region transportation costs are added to the total harvest residue costs. Harvest residue availability is a function of regional pulpwood and sawlog harvest and is affected by demand from the stationary bioenergy industry (i.e. non-transportation bioenergy industry. Pulpwood supply for biofuel production depends on availability of pulpwood, econometrically estimated supply elasticities, the reference supply levels, reference prices and transportation costs. Supply and associated prices of pulpwood changes with changing demand from the forest industries, the stationary bioenergy industry. Since pulpwood and sawlog grade wood typically grow in the same stands in the Nordic countries, pulpwood harvest also results in additional sawlog harvest because harvesting and forwarding costs are greatly reduced. Sawmilling residue supply depends on the transportation costs and the opportunity cost of the sawmills. Change in demand for sawmilling residues may change the production level of sawnwood. The potential supply of additional sawlogs will also affect the production level. Residues are used by the forest industries and the stationary bioenergy industry. Besides the competition between, and within, the forest industries and the stationary bioenergy industry for the same