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Research paper

On the macro-economic impact of bioenergy and biochemicals – Introducing advanced bioeconomy sectors into an economic modelling framework with a case study for the Netherlands

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ABSTRACT

Advanced uses of biomass for bioenergy and biochemicals are being gradually introduced and are expected to grow considerably in regional economies, thus raising questions on their mid-term macro-economic impacts. To assess these impacts, we use a computable general equilibrium model and a regional energy systems model side-by-side. The former is extended with new sectors of lignocellulosic biofuels, bioelectricity, biochemicals, lignocellulosic biomass supply and tradeable pellets. Next to 1st generation biofuels and other renewable energy supply, the economic impacts of bioeconomy are assessed for technology development and trade openness scenarios. We demonstrate the macro-economic model by assessing developments of the Dutch bioeconomy in 2030. Under rapid technical growth and trade openness, the models consistently show increased biomass consumption and supply of bioenergy and biochemicals from lignocellulose through large-scale deployment of advanced biomass conversion technologies. Traditional fossil-based sectors are replaced by biomass, which brings additional macro-economic benefits on gross domestic product (0.8 bn€ a^{-1}) and value added (0.7 bn€ a^{-1}). Furthermore, it reduces projected decline in trade balance (0.7 bn€ a^{-1}) and employment (2.5–4.5%) compared to low technology development. Extending the temporal scope to beyond 2030 may demonstrate additional macro-economic benefits of bioeconomy. This requires assessing the influence of improvements in the agricultural sector that may lower biomass prices, learning and other developments of promising biomass conversion technologies in the longer term. Uncertain fossil fuel and CO_2 price developments necessitate additional sensitivity analysis.

1. Introduction

The role of biomass in today's economies extends beyond traditional sectors such as food, feed, materials (e.g. plant fibres, lumber, paper and pulp) and traditional uses for energy (inefficient heating and cooking). While more than half of current global biomass use for energy is traditional (48–54 PJ, 76–79% in 2008), advanced and efficient supply of bioelectricity, biomass heat and biofuels is growing rapidly and is expected to continue so in the future [1]. Lignocellulosic biofuels and advanced biomaterials are being gradually introduced in some regions [2–4]. Aviation and shipping rely exclusively on biofuels to partly decarbonise their energy use [5,6]. Biochemicals and biochemical products (e.g. bioplastics) are already produced globally and consume about 4.5% of biomass used for energy and biochemicals [7]. In 2016, global production capacity of bioplastics reached 2 Mt and based on the industry's projections it is expected to quadruple before 2020 [8].

These expectations raise questions on the impacts of bioeconomy developments, possible synergies, and conflicts of biomass supply to different sectors, especially when in competition for biomass from emerging uses such as biochemicals, and on their role in climate change mitigation. Long-term projections of the global energy system simulation model TIMER show that bioenergy can contribute about 20% in emission reduction with carbon taxes above 130 \$ t CO_2^{-1} by 2100 [9]. The largest greenhouse gas (GHG) emission reductions come from

Abbreviations: BECCS, Bioenergy and Carbon Capture and Storage; CCS, Carbon Capture and Storage; CGE, Computable General Equilibrium; COP, Conference of Parties; EPPA, Emissions Prediction and Policy Analysis; EU, European Union; FT, Fischer-Tropsch; GDP, Gross Domestic Product; GHG, Greenhouse gas; Glob, Global; GTAP, Global Trade Analysis Project; HighTech, High Technology development; IEA, International Energy Agency; LowTech, Low Technology development; MAGNET, Modular Applied GeNeral Equilibrium Tool; O&M, Operation and Maintenance; PE, Polyethylene; PLA, Polylactic Acid; RED, Renewable Energy Directive; Reg, Regional; RJF, Renewable Jet Fuels; WEO, World Energy Outlook

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biofuels in road transport and bioelectricity in combination with carbon capture and storage (BECCS), whilst the emission reduction from biochemicals remains relatively small. Nevertheless, about 18% (19 EJ) of the chemical sector's secondary energy use may come from biomass in 2100 [9]. Such outcomes demonstrate the importance of bioeconomy on a global scale and in the long-term.

However, increase of biomass consumption for bioenergy and biochemicals in the mid-term may already entail large and rapid changes in the structure of regional economies with possible effects on their gross domestic product (GDP), value added and trade balance. Under this perspective, applied economics are uniquely suited to understand the impacts of various policy and technical trajectories [10]. Hoefnagels et al. [11] assessed macro-economic impacts of bioeconomy developments in the Netherlands by combining a computable general equilibrium model (CGE; LEITAP) with a bottom-up Excel tool. Hoefnagels et al. [11] demonstrated that substitution of fossil energy carriers by bioenergy and biochemicals may come with economic benefits and contribute to GHG emission reduction under preconditions of enhanced technology development and imports of sustainable biomass resources. However, as the authors indicate, their approach was faced with limitations. Firstly, LEITAP did not include a detailed representation of lignocellulosic feedstocks such as agricultural residues thereby ignoring cost-efficiency improvements that can be achieved assuming densification and trade of solid biomass (e.g. pelletisation) and the impact of by-products. The availability of low-cost biomass can be pivotal for the competitiveness of biomass conversion technologies and can also have potential impacts on other sectors and land requirements. Secondly, bio-based and fossil-based conversion technologies were aggregated at a high level. The macro-economic model could benefit by improved cost-structures, especially on capital-intensive 2nd generation technologies that utilise low-cost biomass feedstocks [11]. Thirdly, LEITAP did not include other renewable energy sources (e.g. wind, solar). Subsectoral changes, however, were found to have major influence on the macro-economic impacts [11]. Finally, the biochemical sector in LEITAP was modelled implicitly and its biochemical product portfolio was limited. Therefore, the higher level of disaggregation and improved representation of competing resources, technologies and sectors are needed to shed light on underlying elements that can be critical for the bioeconomy.

Conversion of different biomass feedstocks to an array of food, feed, material, energy and biochemicals have created complex dynamics through which biomass participates in different sectors of the economy [12]. The bioeconomy does not only affect farmers, but also material, energy and chemical industries, the well-being of consumers, balance of trade, and governmental budget. Understanding the impacts of the bioeconomy on the overall economy requires an improved modelling framework that accounts for the feedback mechanisms between bioeconomy and other markets, takes direct and indirect effects of biomass use into account and covers the global dimension of supply, trade and sustainability that are inherent to biomass. CGE analysis is considered most suitable [12,13] as partial equilibrium and input-output economic models do not capture the whole economy or include price effects, respectively. For example, CGE models have been used to address implications of biofuel policies on agricultural markets, land-use change and related emissions. This led to improved endogenous modelling of land markets in CGE models [14]. Recent efforts also focused on improving modelling of biofuels by introducing ethanol, biodiesel and their by-products [15,16], and prospective biomass feedstocks for advanced biofuels production such as corn stover, energy crops, palm oil residues [17,18]. To date, the biochemical sector is too small and there is no clear distinction in statistics and databases (e.g. Global Trade Analysis Project (GTAP)), which are used by CGE models. Furthermore, the chemical industry sector is aggregated at a high level, while in reality the sectoral flows of the industry are much more complex. As biomass conversion technologies to biochemicals may offer renewable alternatives at different levels [19], disaggregation of the chemical industry sector in CGE models is required. Choumert et al. [20] have presented a method on how to improve the oil-refining sector in the CGE model Emissions Prediction and Policy Analysis (EPPA), however, chemical products still remain at an aggregate level.

By using a global, multi-region, multi-sector CGE model, this article addresses the key limitations of the study conducted by Hoefnagels et al. [11]. To this purpose, we expanded the Modular Applied GeNeral Equilibrium Tool (MAGNET), the successor of LEITAP. MAGNET is expanded with advanced and emerging bioeconomy sectors and in particular lignocellulosic biofuels, electricity, heat and chemicals from biomass. Furthermore, we improved the representation of biomass supply including agricultural residues, forestry residues and pretreatment of those feedstocks to pellets for international solid biomass trade. We extended the model with regional renewable energy policies that are crucial for the current bioenergy developments. To overcome a key limitation of CGE models on technology representation, we improved technology details in MAGNET by collaborating with a cost-minimisation linear programming energy system model of the Netherlands (MARKAL-NL-UU). Recently, advanced biomass conversion technologies, biochemicals and renewable jet fuels (RJF), have been incorporated in MARKAL-NL-UU [19,22]. The analysis shows that renewable electricity from wind turbines, biofuels, biomass heat and carbon capture and storage (CCS and BECCS) may play a crucial role by 2030 [22]. Biochemicals are expected to become cost-competitive with fossil-based chemicals as they are produced even where no drivers such as a CO_2 emission tax are assumed (5–10% of the sector's supply) [22]. RJF, on the other hand, are produced only under specific assumptions that assume high technology development rates. Factors such as the rate of technical change, the cost-supply of biomass and fossil fuel price projections affect the level of biomass deployment in the energy system. Nonetheless, whether to meet renewable energy targets [19] or to embark on cost-efficient emission mitigation pathways [22], advanced and emerging bioeconomy uses in the Netherlands need to grow substantially, from about 140 PJ in 2015 to up to 760 PJ in 2030 [22]. Model collaboration can take place as alignment and harmonisation of input data, detailed model comparison and model linkage [21]. Following Zilberman [10], we apply a framework where the energy system model MARKAL-NL-UU [19] is used side by side with MAGNET and supplies it with insights on technology trajectories to 2030. We compare results obtained by MAGNET and MARKAL-NL-UU and highlight points of interaction that can lead to improved representation of bioeconomy in CGE models that are required to assess its macro-economic impacts.

2. Materials and methods

To improve technology details of existing sectors and expand MAGNET with new bioeconomy sectors, we develop a modelling framework in which, the cost-minimisation linear programming energy system model, MARKAL-NL-UU is also used. MAGNET is a multi-regional, recursive-dynamic, applied general equilibrium model based on neo-classical microeconomic theory [23]. MAGNET contains a number of advanced features pertinent to modelling the impact of technological and policy developments within the bioeconomy where land-use is a crucial production factor [24,25] (Supplementary material section S1). Biofuel production is included by introducing production and use of ethanol, biodiesel and their by-products [26,27]. Blending targets are included in the model via an end-user tax on road transport fuels that is used to subsidise biofuel production and stimulate production up to the level implied by the blending target. MARKAL-NL-UU is a model of the Dutch energy system that has been recently expanded to assess techno-economic impacts of bioeconomy developments in the Netherlands to 2030 [19,22]. Following a total system cost-minimisation paradigm MARKAL-NL-UU is suitable to highlight key technologies per sector under different scenarios in the mid-term [22]. An overview of MAGNET is presented in the Supplementary material (section S1). An