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Exploring path dependence, policy interactions, and actor behavior in the German biodiesel supply chain

J.A. Moncada [a,b,*], M. Junginger [b], Z. Lukszo [a], A. Faaij [c], M. Weijnen [a]

[a] Faculty of Technology, Policy, and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[c] Energy and Sustainability Research Institute, University of Groningen, Nijenborg 4, 9747 AG Groningen, The Netherlands

HIGHLIGHTS

- The effects of both agricultural and bioenergy policy interventions are explored.
- The timing of intervention of bioenergy policies determined the system's evolution.
- A lack of agents' adaptation mechanism led to a decrease in biodiesel production.
- System behavior is influenced by individual behavior which is shaped by institutions.

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ABSTRACT

Biofuel production is not cost competitive and thus requires governmental intervention. The effect of the institutional framework on the development of the biofuel sector is not yet well understood. This paper aims to analyze how biofuel production and production capacity could have evolved in Germany in the period 1992–2014. The effects of an agricultural policy intervention (liberalization of the agricultural market) and a bioenergy policy intervention (a tax on biodiesel after an initial exemption) are explored. Elements of the Modeling Agent systems based on Institutional Analysis (MAIA) framework, complex adaptive systems (CAS) theory, and Neo Institutional Economics (NIE) theory were used to conceptualize and formalize the system in an agent-based model. It was found that an early liberalization of the agricultural market led to an under-production of biodiesel; a late liberalization led to the collapse of biodiesel production. An early introduction of the biodiesel tax led to stagnation in biodiesel production and production capacity; a late introduction led to an increase in sunk costs provided that the biofuel quota is binding. Also, a lack of agents' adaptation mechanism to forecast prices led to a decrease in patterns of biodiesel production when an external shock was introduced in the system. In sum, we argue that system behavior is influenced by individual behavior which is shaped by institutions.

1. Introduction

Concern has grown in the last decades over the issue of climate change. Strategies to tackle this problem include the production of energy from solar, wind, biomass, and other renewable sources. In Europe, the production of liquid fuels from biomass has gained considerable momentum due to its potential to reduce greenhouse gas emissions, to enhance energy security through the substitution of fossil fuels, and to contribute to rural development by increasing employment opportunities[1] and diversifying the activities of farmers [2,3].

Despite the benefits of biofuels, biofuel production is not cost-competitive and thus requires governmental intervention. Policy instruments such as blending mandates, tax credits or tax exemptions, subsidies, and import tariffs are used to stimulate biofuel production and consumption in the world [4]. The literature has focused on reducing the price gap between biofuels and fossil fuels by optimizing the whole supply chain [5–8], by improving the logistics [9,10], and developing more efficient technologies [11–13]. There is clear evidence that biofuel supply chains cannot be created and developed in absence of governmental support[2] [4,15], and yet the scientific literature has focused primarily on technological developments [12,13,16,17] and their optimization [18–20].

* Corresponding author at: Faculty of Technology, Policy, and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands.
E-mail address: j.a.moncadaescudero@tudelft.nl (J.A. Moncada).

[1] Borenstein et al. [1] claims that these arguments, also used to promote renewable electricity generation, are difficult to support.

[2] As it was pointed out by van den Wall et al. [14] bioethanol production in Brazil is a unique biofuel supply chain, as it no longer receives governmental support.

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The impact of policies on biofuels production is mostly analyzed by using an equilibrium framework [6,21–23]. This approach has provided many insights by identifying promising configurations for feedstock, technology, and production capacity required to meet some policy goals. However, there is still a lack of understanding as to: what alternative stories (scenarios) could have unfolded as a result of different policy interventions; what the effects of policy interaction are on biofuel supply chain development and actors' behavior; and what strategies might steer the development of biofuel supply chains in the direction pointed to by the optimization studies.

1.1. Literature review

Support schemes to promote the production and consumption of renewable energy are a key instrument in the decarbonization of the energy mix. The most common support schemes include the competitive auctions, the feed-in tariff scheme, and tradable green certificates [24,25]. Socio-economic policies such as job creation and energy access have also influenced the deployment of renewable energy [26]. In the specific case of biofuels, policies such as: the Renewable Fuel Standard (RFS2) in the USA, the Common Agricultural Policy (CAP) and the Renewable Energy Directive (RED) in the EU have contributed to its deployment [4].

Traditionally, the analysis of the effect of policies on biofuel supply chains has been done by using an equilibrium approach. Luo and Miller [27] used game theory to model biomass and ethanol production decisions and to calculate the incentives required to drive farmers and ethanol producers to participate in cellulosic biofuel industry. Newes et al. [28] used the Biomass Scenario Model to understand the role of incentives on the evolution of the cellulosic ethanol sector. The authors found that multiple points of intervention could accelerate the expansion of that biofuel industry. Rahdar et al. [29] developed a linear programming model to study the competition between biopower generation and biofuel production under the Renewable Portfolio Standards and renewable Fuel Standard in the U.S. The authors found that cellulosic biofuel production will dominate the competition for biomass against biopower generation. Christensen and Hobbs [30] developed a mathematical model of the U.S. biofuel market. The authors argued that compliance with California biofuel policy requires rapid deployment of clean diesel fuels.

The above-mentioned studies do not completely capture the complex nature of biofuel supply chains (BSCs). BSCs are complex adaptive systems and thus they are highly non-linear, exhibit multi-scale behavior and path-dependence, evolve and self-organize making it difficult for an equation-based model to capture their characteristics [31]. By using models that lack this complexity, such as optimization models, is possible to make policy recommendations and to design optimal supply chains. But that optimality only applies in a limited context. As it was pointed out by Simon in his famous Nobel prize lecture: "*decision makers can satisfice either by finding optimum solutions for a simplified world, or by finding satisfactory solutions for a more realistic world*" [32].

Path dependence is one of the interesting properties of complex adaptive systems [33]. The concept of path dependence is defined as a self-reinforcing mechanism [34] and as an outcome (lock-in). Verne and Durand define path dependence "*as a property of a stochastic process which obtains under two conditions (contingency and self-reinforcement) and causes lock-in in the absence of exogenous shock*" [35]. As a theoretical framework, path dependence has been used to explain institutional persistence [36], governance [37], and technology outcomes [38,39]. However, as these are historical case studies it is difficult to provide strong evidence of history dependence [40].

A promising alternative to address these issues is Agent-Based Modeling (ABM). Concepts such as: emergence, adaptation, learning, and feedback mechanisms can be incorporated into ABM [41,42]. As a simulation method, ABM can be employed to "*generate multiple historical trajectories emanating from the same set of initial conditions, thus enabling them to generalize about the mechanisms and processes that produce such histories*" [43]. That is, ABM can be utilized to analyze path dependence.

ABM has been used to address the effects of policies on both agricultural and bioenergy sectors. Brady et al. [44] extended the agent-based agricultural policy simulator (AgriPoliS) to understand the impact of agricultural policies on land use, and biodiversity. Brown et al. [45] assessed the bioenergy crop uptake as a function of farmer types and policy initiatives.

Some studies specifically analyze the impact of policies on biofuel supply chain performance by using the ABM paradigm. Agusdinata et al. [46] developed an agent-based model to understand the dynamics of biofuels supply chain networks. It was found that the network behavior is very sensitive to the rate of information feedback. Shastri et al. [47] analyzed the impact of policies on the evolution of a biofuel supply chain using an agent-based modeling approach. The authors argued that regulatory mechanism such as Biomass Crop Assistance Program led to greater productivity. Other studies have used the agent-based model approach to analyze the path dependence of network industries under different policy regimes [48].

The contribution of this work is to extend the analysis of the effect of policies on the development of biofuel supply chains to account for the path dependence, policy interaction and effects on actor behavior. To achieve this goal, the German biodiesel supply chain was conceptualized and formalized by using an agent-based modeling approach. Biodiesel production in Germany was selected as a study case since it has been heavily influenced by governmental intervention [2,49] as shown in Fig. 1.

The aim of the model is to shed light on how the German biodiesel industry could have evolved under different institutional frameworks and to assess the impact of biofuel policy instruments on biodiesel production and production capacity. Specifically, the research question is: *what patterns in biodiesel production and production capacity are generated as a result of applying different policy interventions in Germany in the period 1992–2014?*

The remainder of the paper is organized as follows. Section 2 describes the development of the agent-based model and the data used in the experiments. Section 3 describes the results obtained which are discussed in Section 4. Conclusions are presented in Section 5.

2. Theory and methods

2.1. Structure of the agent-based model[3]

The construction of the agent based model starts with the formulation of the problem. The problem is formulated using the generative science approach[4], which identifies and describes the problem based on a macroscopic regularity or pattern[5] in the real world. The aim of the agent-based model is to understand how biofuel production and production capacity could have evolved as a result of different agricultural and/or bioenergy policy interventions.

[3] The model development is described in detail in Moncada et al. [50].

[4] To the generativist – concerned with formation dynamics – it does not suffice to establish that, if deposited in some macroconfiguration, the system will stay there. Rather, the generativist wants an account of the configuration's attainment by a decentralized system of heterogeneous autonomous agents [51].

[5] Patterns are defining characteristics of a system and often, therefore, indicators of essential underlying processes and structures. Patterns contain information on the internal organization of a system, but in a "coded" form [52].