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Modelling the impacts of policies on advanced biofuel feedstocks diffusion

Lauro André Ribeiro [a, *], Patrícia Pereira da Silva [b], Leila Ribeiro [c], Fernando Luís Dotti [d]

[a] School of Architecture and Urbanism, Faculdade Meridional (IMED) and INESC Coimbra, R. Sen. Pinheiro, 30, 99070-220, Passo Fundo, Brazil
[b] Faculty of Economics, University of Coimbra, INESC Coimbra, Institute for Systems Engineering and Computers at Coimbra and CeBER, Center for Business and Economics Research, Coimbra, Portugal
[c] Institute of Informatics, Federal University of Rio Grande do Sul, Brazil
[d] Computer Science Department, Pontificial Catholic University of Rio Grande do Sul, Brazil

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ABSTRACT

This paper analyzes the market share penetration of advanced biofuels and assesses the economical, political and technological factors critical to the diffusion of advanced biofuels. This study comprises economic policies, processes of technological diffusion of emerging technologies and a methodology for modelling possible transportation fuel scenarios. In order to model future scenarios, Stochastic Automata Networks (SAN) are used, a structured formalism that provides a high-level abstraction to represent continuous and discrete-time Markovian models. The results show that in order to boost development of advanced biofuels, public investment in R&D is the most important policy to be adopted. Developing strategies aimed to renewable resources; applying tax incentives and subsidies; and issuing mandatory country objectives are also encouraged.

1. Introduction

Innovative technologies and sources of energy must be developed to replace fossil fuels and contribute to the reduction of emissions of greenhouse gases associated with their use. Biofuels are particularly important as an option for displacing the use of petroleum maintaining similar vehicles that are already in use. However, alternative sources of 1st generation biofuels derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, impose pressure on food markets, contribute to water scarcity and precipitate forest devastation. In this way, the future of biofuels will depend on the development of viable, sustainable, emerging advanced technologies that do not appear to be yet commercially viable. In this perspective, various feedstocks for producing advanced biofuels are generating substantial awareness in many countries for its advantages in relation to 1st generation biofuels. In the United States, the infant advanced biofuels industry may contribute to achieve the biofuel production targets set by the Energy Independence and Security Act of 2007.

In order to boost the adoption and development of advanced biofuels, there is a strong need to influence both the speed and the direction of the innovation and technological change. With that in mind, policymakers are putting their efforts to support the development of emerging renewable biofuels, either through direct means such as government-sponsored research and development (R&D), or by enacting policies that support the production of renewable technologies.

In this context, the proposed study aims to analyze the market share penetration of advanced biofuels and assess the economical, political and technological factors critical to the diffusion of these emerging advanced biofuel feedstocks. The analysis is made based on the construction of a computational model representing the behavior of users of transportation, taking into account which kind of fuel they use and the likelihood to change this kind of fuel, as well as the impact of different policies. It is possible then to draw some insights upon which policies could be set to enhance the penetration of advanced biofuels and how they affect the overall market share of transportation fuels in the United States. The main

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* Corresponding author.
E-mail addresses: lauro.ribeiro@imed.edu.br (L.A. Ribeiro), patsilva@fe.uc.pt (P. Pereira da Silva), leila@inf.ufrgs.br (L. Ribeiro), Fernando.dotti@pucrs.br (F.L. Dotti).

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conclusion is that, without any governmental policy, the market share of advanced biofuel in the future (by 2040) will probably be very low. We note that, although the model was based on data from the USA transportation market, the conclusions may be also valid for other countries.

The structure of the paper is as follows: Section 2 presents a concise literature review on advanced biofuels; Section 3 examines the diffusion of emergent technologies and the U.S. biofuels policies are presented. In Section 4, the computational model and results are discussed. Finally, the conclusions are presented in Section 5.

2. Emerging advanced biofuels

In this section, a brief literature review of a potential feedstock being used to produce advanced biofuels is presented. There are various feedstocks that could be used to produce next generation biofuels, such as agricultural residues (e.g., corn stover, sugarcane bagasse, and sweet sorghum pulp), forestry biomass, urban waste, dedicated energy crops (e.g., switchgrass), vegetable oils, recycled oils, rendered fats and greases (U.S. EPA, 2010). Such feedstocks for producing biofuels have been developed and tested at various scales from the laboratory to demonstration plants to commercial facilities and will not be covered in this paper because the inputs and outputs vary immensely from each other and the aim here is to perform a general policy impact approach. With that in mind, this paper will focus in one potential feedstock of producing advanced biofuels: microalgae. However, as it will be shown in the next sections, this methodology could be used for multiple feedstocks for developing advanced biofuels.

Several studies have been performed on the technical feasibility of growing algae for biofuel production in the laboratory (Chisti, 2007; Brennan and Owende, 2010; Ono and Cuello, 2006; Pulz, 2001; Sheehan et al., 1998; Spolaore et al., 2006; Ugwu et al., 2008; Silva et al., 2016). The process uses the oils extracted from microalgae as the raw material to produce several types of biofuels.

Microalgae are microscopic photosynthetic organisms that can be grown in a variety of environment and conditions, including fresh, salty and brackish water. These organisms use solar energy to combine water with carbon dioxide (CO_2) and other nutrients to create biomass (Sheehan et al., 1998). Comparing to other sources of feedstock to produce biofuels, algae-based biofuels present several advantages, as demonstrated in Table 1.

After the process of extracting the oil from algae, the resulting product can be converted to biodiesel. The biodiesel produced from algal oil has physical and chemical properties similar to diesel from petroleum, to biodiesel produced from crops of 1st generation and compares favourably with the International Biodiesel Standard for Vehicles (EN14214) (Brennan and Owende, 2010).

Another possibility is the conversion of bio-oil, which could be routed via a conventional petrochemical refinery to generate various chemicals. After several hydrodeoxygenation treatment steps, the bio-oil could be transformed into a liquid hydrocarbon with properties similar to those of petroleum crude oil. Therefore, it could be refined in existing petroleum refineries, with only minor adjustments to the current petroleum industry refinery infrastructure (Naik et al., 2010).

Despite its vocation as a potential source of biofuels, many challenges have hindered the development of biofuels technology from microalgae to become commercially viable. Based on recent literature, the most important are presented on Table 2.

The current unsustainable path transportation energy resources are facing highlight the need of finding alternatives for fossil fuels. Electricity, in the long term, can be an important source of transportation energy, but for that to happen we have to replace an entire fleet of cars, ships and planes running with combustion engines used today, a restraining perspective. Therefore, a fuel that can be easily adapted to our current transportation fleet and of lower environmental impact than fossil fuels is needed.

As presented, biofuel production can be obtained from several sources. Among crops, it could be obtained from corn, sugar cane, switch grass, soybeans, rapeseed, canola, etc. Each crop has its own impacts and land-use requirements. When oil yields of different biofuel crops are compared, it becomes clear that oil crops cannot significantly contribute to replacing petroleum derived liquid fuels in the foreseeable future. For example, meeting only half the existing U.S. transport fuel needs by biodiesel would require unsustainably large cultivation areas of all major oil crops (Corn: 846% of existing US cropping area; Soybean: 326%; Palm Oil: 24%) (Chisti, 2007).

It is important to highlight that although biofuel from algae has several advantages when compared to other crops, it is not a commercial fuel in the present time. Theoretically, from the laboratory experiments, microalgae have the potential to be far more efficient than 1st generation biofuels.

Although it is scientifically and technically possible to derive energy products from several promising feedstocks, microalgae being one of them, this does not mean that large scale production is economically feasible. Thus, in the next section it is presented some basics of economics and diffusion of new technologies to draw some insights upon this new feedstock source for biofuels.

3. Economics and diffusion

Generally, economic feasibility is believed to be currently the main hurdle to overcome for new biofuel technologies, due to high costs associated to both the state of the science and technologies. On the other hand, oil prices, their main competitor, are considerably low (US$ 49.81per crude oil barrel in October 8th, 2016) (Oil Price, 2016).

In this context, taking biofuels derived from algae as an example, the current economic situation points towards large-scale production of algae biofuel not being viable as a solution to displace petroleum-based fuels (Ribeiro and Silva, 2013). The technology to efficiently produce and disseminate biofuels from microalgae is not yet competitive with more mature transportation energy options, and the high costs prevent the market diffusion of novel energy technologies.

It is widely recognized that modern economic analysis of technological innovation originates fundamentally from the work of Schumpeter (1934), who stressed the existence of three necessary conditions for the successful deployment of a new technology: invention, innovation and diffusion. Each of these keywords represents different aspects, in particular: invention includes the conception of new ideas; innovation involves the development of new ideas into marketable products and processes; and diffusion, in which the new products and processes spread across the potential market.

Emergent technologies are relatively expensive at the point of market introduction but eventually become cheaper due to mechanisms such as learning-by-doing, technological innovation and/or optimization, and economies of scale. The combined effects of these mechanisms are commonly referred to as technological learning. Over the last decades, learning theories combination with evolutionary economics have led to the innovation systems theory that expands the analysis of technological innovation, covering the entire innovation system in which a technology is embedded. In particular, “An innovation system is thereby defined as the network of institutions and actors that directly affect rate and direction of technological change in society” (Junginger et al., 2008).

In the emerging energy technologies field, there is a strong need to influence both the speed and the direction of the innovation and technological change. With that in mind, policymakers are putting their efforts on lowering the costs of renewable energy sources to support the development of renewable technologies, either through direct means such as government-sponsored research and development (R&D), or by enacting policies that support the production of renewable technologies. It is well documented (Johnstone et al., 2010) that both higher energy prices and changes in energy policies increase inventive activity on renewable energy technologies. As noted by (Popp et al., 2011), the higher costs of renewable energy technologies suggest that policy intervention is necessary to encourage investment. The impact of the lack of public policies favoring the development of renewable energy is that production costs remain too high and renewable energy does not represent an option in replacing fossil fuels.

Policies to foster innovation should not only focus on the creation and supply of new technologies and innovations, but also on the diffusion and take-up of green innovations in the market place. Such policies need to be well designed to ensure that they support and do not distort the market formation, and should be aligned with competition policies and international commitments (OECD, 2011). With this purpose, several government policies have been introduced in the energy markets worldwide in an effort to reduce costs and accelerate the market penetration of renewables (U.S. DOE, 2010). Therefore, some of the U.S. policies that could enhance the development of advanced biofuels are presented.

3.1. Biofuel policies in USA

In this section, special focus is devoted to biofuels policies, because they include major drivers for biofuel technology deployment. The U.S. policies were chosen due to the country's representative share of algal biofuel producing companies around the world. The United States shows a level of 78% of all algal biofuel producing companies around the world (Singh and Gu, 2010).

There are many objectives behind the U.S. biofuels policies (Gorter and Just, 2010). Firstly, there is a strong desire to decrease the dependence of the United States on foreign oil. The 2008 spike of fossil fuel prices is a lively reminder that fluctuations in such levels can have sizeable impacts on US welfare. In addition, there is an increasing motivation in developing alternative, environmentally friendly and more secure energy sources. The idea is that using biofuels might alleviate the environmental impacts of oil energy consumption. At last, increasing biofuels production has the added implication of increasing the demand for agricultural production and thus is consistent with a long-standing U.S. commitment to support its farm sector (Lapan and Moschini, 2012).

In order to boost the adoption and development of biofuels, the key instruments widely adopted have been mandatory blending targets, tax exemptions and subsidies. Supplementary to those, governments have intervened on the production chain by supporting intermediate inputs (feedstock crops), subsidizing value-adding factors (labour, capital, and land) or granting incentives that target end-products. Import tariffs have also played a significant role by protecting national industries from external competition (Sorda et al., 2010).

A vivid example of the utilization of these policies is the rise of the U.S. corn-based ethanol production, going from 1.62 billion gallons in 2000 to 13.31 billion gallons in 2013 (U.S. EIA, 2014). It is clear that this expansion of ethanol production owes much to the implementation of critical support policies. The corn ethanol industry has received a great share of subsidies over the past 20 years. Through federal tax credits, loan guarantees, grants and other subsidies, billions of dollars have been invested in this industry. While the biofuels industry as a whole was intended to help achieve American energy independence, reduce greenhouse gas emissions, and spur rural economic development, the corn ethanol industry has fallen short of achieving these goals and generated unintended consequences and long-term liabilities (Yang et al., 2012).

Regarding emerging biofuels, the U.S. Environmental Protection Agency suggested revisions to the National Renewable Fuel Standard program (RFS). The proposed rules intended to address changes to the RFS program as required by the Energy Independence and Security Act of 2007 (EISA). The revised statutory requirements establish new specific volume standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel that must be used in transportation fuel each year. The regulatory requirements for RFS will apply to domestic and foreign producers and importers of renewable fuel (U.S. EPA, 2010). This rule proposes to establish the revised annual renewable fuel standard (RFS2) and to make the necessary program modifications as set forth in EISA. The required volume modifications made under RFS2 are shown in Table 3, eventually reaching 36 billion gallons by 2022.

Based on Table 3 for all renewable fuel categories, the applicable standards for 2010 onwards were proposed, each representing the fraction of a refiner's or importer's gasoline and diesel volume which must be renewable fuel.

The proposed specific targets for 2016 in the U.S. include 0.128% from cellulosic biofuel, 1.59% from biomass-related diesel, 2.01% from advanced biofuel, and 10.10% from total renewable fuels.

Table 1
Advantages of using algae as feedstock to produce biofuels.

Advantages	Study
Capability of producing oil during all year long, with a fast growing potential and high oil content by weight of dry biomass (several species have 20–50%), therefore the oil yield of microalgae is much greater compared to the most efficient crops.	Chisti, 2007
Cultivation can be done using fresh, salty and brackish water and on not arable land; not affecting food supply or the use of soil for other purposes.	Searchinger et al., 2008 Chisti, 2007
Regarding air quality, production of microalgae biomass can fix carbon dioxide (1 kg of algal biomass fixes roughly 1.83 kg of CO_2).	Chisti, 2007 Cuellar-Bermudez et al., 2015
Nutrients for its cultivation (Nitrogen and Phosphorous, mainly) can be obtained from wastewater.	Cantrell et al., 2008
Growing algae do not require the use of herbicides or pesticides.	Rodolfi et al., 2008
Algae can also produce valuable co-products, as proteins and biomass after oil extraction, that can be used as animal feed, medicines or fertilizers, or fermented to produce ethanol or methane.	Spolaore et al., 2006 Brennan and Owende, 2010
Biochemical composition of algal biomass can be modulated by different growth conditions, so the oil yield can be significantly improved.	Qin, 2005
Capability of performing the photobiological production of "biohydrogen".	Ghirardi et al., 2000 Ferreira et al., 2013

Source: Authors.

Table 2
Challenges of using algae as feedstock to produce biofuels.

Challenges	Study
High cost of process technology and lack of price competitiveness of biodiesel extraction from microalgae versus petroleum diesel.	Brennan and Owende, 2010
The need to achieve greater photosynthetic efficiency through the continuous development of production systems.	Pulz and Scheinbenbogan, 1998
Develop techniques for growing a single species, reducing evaporation losses and diffusion of CO_2.	Ugwu et al., 2008
Few commercial cultivating "farms", so there is a lack of data on large-scale cultivation and there is no industry standard process.	Pulz, 2001
Impossibility of introducing flue gas at high concentrations, due to the presence of toxic compounds such as NOx and SOx.	Brown, 1996
Choosing algae strains that require fresh water to grow can be unsustainable for operations on a large scale and exacerbate fresh water scarcity.	Mcgraw, 2009
High energy consumption associated with biomass processing undermines some energy balance studies.	Clarens et al., 2010 Collet et al., 2011 Liu et al., 2013

Source: Authors.

Algae-based fuels could be considered under the advanced biofuel or bio-based diesel portion of the RFS, according to the proposed rule (U.S. EPA, 2015).

While cellulosic ethanol is expected to play a large role in meeting the 2007 Energy Independence and Security Act (EISA) goals, a number of next generation biofuels, especially those with higher-energy density than ethanol, show significant promise in helping to achieve the 36 billion gallon goal. Of these candidates, biofuels derived from algae, particularly microalgae, have the potential to help the U.S. meet the new Renewable Fuels Standard (RFS) while at the same time moving the nation ever closer to energy independence (U.S. DOE, 2010).

It is significant to highlight that although these mandates are in place, the actual produced volumes differ greatly from what was previously predicted. Regarding cellulosic biofuels, for example, the volume for 2014 established in 2010 was 1.75 billion gallons (U.S. EPA, 2010), but this amount was changed in 2013 to 17 million gallons (U.S. EPA, 2013). Thus, although the volume amounts used in this next scenario were based on that table, these amounts are probably going to be altered by the U.S. Environmental Protection Agency in the next years to values consistent with reality. Therefore, the problem with this approach is that solely mandates do not have the power to make these fuels available, and the real production is well below to what was established.

Although much more advances in this policy field in the next few years are expected, research on the welfare economics of renewable energy policy is still in its infancy and the economic effects of biofuel policies are not only complex and difficult to understand, but are ultimately ambiguous in theory (Gorter and Just, 2010). Concerning this reality, which policies are the most feasible to enhance the diffusion of advanced biofuels? To answer this question, in the next section a model of future transportation scenarios affected by different policies is presented.

4. Modelling future transportation scenarios

To analyze the impact of different policies in the transportation fuel market share, a computational model using Stochastic Automata Networks (SANs) was built. First, a basic model reflecting the scenario without policies was constructed and then different policies were added. The idea was not only to investigate the effect of each specific policy alone, but also the interplay among the different policies. The basic model is parameterized by the prices of fuels and their availability (taking into account not only the availability of the fuel itself for end-consumers, but also of cars using this fuel). The policies model is an extension of the basic model including 4 different policies: subsidy, taxes, R&D investment and mandates. Different U.S. transportation scenarios were analyzed in the period from 2010 to 2040. The analysis consists of searching for the equilibrium state (steady state) in each scenario. This equilibrium state represents the market share that results from the given parameters of the scenario.

In the following, after a short introduction to SANs, the construction of the basic and policy models is presented, and then the results of the analysis of some scenarios are discussed.

4.1. Stochastic automata network

Model-based quantitative analysis can be performed using either simulation or analytical models, or both. Simulation models are valuable when we want to express specific behaviours hardly representable with analytical modelling, for instance if the phenomenon of interest includes several kinds of stochastic processes obeying different probability distributions. On the other hand, simulation needs careful experiment conduction and result analysis to lend dependable results. To produce suitable confidence levels and intervals simulations can be computationally intensive.

Analytical models lead to high confidence results and avoid the burden related to experimentation and result production with simulation models. However, analytical models are normally nontrivial to produce since we have a reduced set of abstractions available to model the phenomena of interest. Markov Chains is a powerful abstraction to model several kinds of dynamic models (Stewart, 1994). The word 'chain' comes from the discrete state space notion. As regards time, Markov Chains can model both discrete time (i.e. state transitions occur (or not) according to certain probabilities, in given points in time) or continuous time (as time continuously passes, transitions fire with certain probability distribution of the time until the transition), originating Discrete Time and Continuous Time Markov Chains. The mathematical solution to Markov Chains relies on the fact that probability distributions are memoryless (also called Markovian property) - that is, the behavior (state transition in time) of the model depends only on its current state and not on the previous history of past states of the model. From a mathematical perspective this can be achieved with stochastic phenomena modelled with the exponential distribution or with the geometric distribution leading respectively to continuous time and discrete time chains.

Due to the generic mathematical solution to Markov Chains, one can model a system with the available abstractions and solve it mechanically, leading to exact solutions. The modeller has thus available: states, transitions, and a choice of continuous or discrete time representation. Due to its attractiveness as a method, there are applications in several different fields, such as bioinformatics, music, social sciences, queueing theory, finances, among others.

Markov Chains, however, lead to the unified representation of the phenomenon of interest in one unique chain. If we have a combination of several of such phenomena active simultaneously, limitations of Markov Chains to complex size systems emerge: one is from a modelling perspective, since the possibility of all phenomena under study has to be considered for each state of the chain, leading to fast increasing complexity while we add new stochastic phenomena to the model. Another limitation, related to the first, is the state space explosion problem, i.e. each time we consider a new aspect, the state of the system is multiplied by the new possibilities of this aspect. The system may rapidly evolve to computationally intractable models. At the same time, a mechanical partitioning of the chain to the mathematical solution is far from trivial.

Therefore, we can witness in the literature the emergence of Structured Markovian formalisms such as Stochastic Automata Networks, Stochastic Petri Nets and Stochastic Process Algebra. Besides the basic abstractions provided by Markov Chains such formalisms offer some form of modularizing models. Stochastic Automata Networks (SAN) allows to stepwise model building, adding components and keeping most of the previous model unchanged, as well as presenting considerable freedom to change the definitions of some modules while keeping the rest untouched (Plateau and Atif, 1991). There are also important approaches that take advantage of such structuring to the computational solution of complex models (Fernandes et al., 1998).

The basic idea of the SAN formalism is to represent a whole system by the composition of subsystems. Each subsystem is described as a stochastic automaton, i.e. an automaton in which transitions are labelled with events that have probability distributions according to the discrete or continuous time model. An automaton may have local events that affect transitions in only the automaton, or have synchronizing events. Different modules or automata cooperate via synchronizing events that provoke the simultaneous firing of all different transitions in different automata that area labelled with that same event. The whole network of automata gives rise to an equivalent discrete or continuous time underlying Markov chain. For further consideration we restrict the discussion to continuous time chains that will be employed in this paper.

The solution of a SAN model, as the solution of the underlying Markov chain, associates probabilities to the states of the model. Analysis can be transient of steady state. Transient analyses arrive to a probability distribution for each state of the model, once a given amount of time has passed. In this paper we focus in steady state analysis, which is the state achieved when the system has reached the equilibrium of the probability distribution of its states.

With the association of distribution probabilities to the events, it is possible to calculate the steady state probability of each state of a SAN. More concretely, to each event there is an occurrence rate associated. The inverse of the occurrence rate is the mean value of the exponential distribution function that regulates the time interval between two occurrences of the event.

4.2. Modelling transportation scenarios using SANs

The aim of the developed model is to understand the distribution of users of different energy sources depending on the following aspects: fuel price, fuel availability and car conversion price. So we model the population of users of one kind of fuel as one automaton. The state of one such automaton indicates the percentage of the population that uses this fuel. Since a user may change from one fuel to another, we synchronize the decrement in one automaton with the increment in other automaton with a synchronizing event that as a rate proportional to the possibility of its occurrence: availability of target fuel, fuel price difference, cost to convert the car to the target fuel.

The model consists of 5 automata representing the behavior of users of each considered energy source (Petrol, Gas, Electricity, Biofuels and Advanced biofuels).

Automaton ***UP*** (Users of Petrol) has 51 states, each representing a range of 2% of users. For example, if this automaton is in state 1, there are 1–2% of users of Petrol, if it is in state 49, users of Petrol are 97–98% of the total users of transport energy fuels. The increase/decrease of the number of users of Petrol occurs according to the transitions. Transitions are triggered by events. For example, in ***UP*** it is possible to change from state 0 to state 1 if one of the following events occurs: *GtoP (Gas to Petrol)*, *EtoP (Electricity to Petrol)*, *BtoP (Biofuel to Petrol)*, *AtoP (Advanced Biofuels to Petrol)* (see Fig. 1). The intuitive meaning is that there can only be an increase in the number of Petrol users if the user of some other fuel changes to Petrol. Automata representing users of other kinds of fuel are constructed analogously. Fig. 2 shows part of the automata ***UP*** and ***UG*** (Users of Gas). There we can see that the same event name is used in both automata. This means that these events are

Table 3
U.S. renewable fuel volume requirements for RFS2.

Year	Cellulosic biofuel	Biomass-based diesel	Advanced biofuel	Total renewable fuel
2008	n/a	n/a	n/a	9.0
2009	n/a	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	6.6[c]	0.80	1.35	13.95
2012	8.65[c]	1.00	2.0	15.2
2013	6.0[c]	1.28	2.75	16.55
2014	33.0[c,d]	1.63[d]	2.67[d]	16.28[d]
2015	123.0[c,d]	1.73[d]	2.88[d]	16.93[d]
2016	230[c,d]	1.90[d]	3.61[d]	18.11[d]
2017	n/a[d]	2.00[d]	n/a[d]	n/a[d]
2018	7.0	[a]	11.0	26.0
2019	8.5	[a]	13.0	28.0
2020	10.5	[a]	15.0	30.0
2021	13.5	[a]	18.0	33.0
2022	16.0	[a]	21.0	36.0
2023+	[b]	[b]	[b]	[b]

Volumes in billion gallons, unless otherwise stated.
Source: U.S. EPA, 2010.

[a] To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.

[b] To be determined by EPA through a future rulemaking.

[c] Million Gallons.

[d] Proposed Rule (U.S. EPA, 2015).

synchronized, that is, must occur at the same time, assuring that the users really move from one fuel to the other.

Each event has its own occurrence rate, which governs how often the event will happen. These rates are thus the essential component of the model, and they may be values from 0 to 1, where higher rates represent that it is more likely that the transition between the corresponding states occurs. The basic parameters (without considering policies) that are used to define the rates of transitions are, for each fuel X:

PRICE_X: price of fuel X. The price is given in Dollars per Mbtu.

AVAIL_X: the availability of fuel. This may range from 1 to 100, and is a bound limiting the number of users of fuel X (if AVAIL_X is 10, at most 10% of users may use X). We consider the value of 100 as unlimited availability.

The formula below, that gives the rate of event XtoY (changing from a fuel X to fuel Y), is basically a weighted harmonic mean. The formula should be read as: If there is still availability of fuel Y, the rate to change from X to Y is the weighted harmonic mean considering the cost of converting the car (if necessary), with weight one, the availability of Y, with weight 2 and the price difference, with weight 3. The formula itself as well as used constants were defined during the calibration of the model (they are the ones that give the best approximation to reality – see discussion about calibration below).

$$rateXY = available\_Y \times \frac{6}{\frac{1}{changeCost\_XtoY} + \frac{2}{AVAIL\_Y/100} + \frac{3}{priceDiff\_XtoY}}$$

where

available_Y: denotes whether fuel Y has not yet reached its limit. The value of this variable is zero if the number of users of this fuel is equal or greater than the availability of this resource, and one otherwise. In our model, an availability of 100 means that there is no limit, and thus, in case fuel Y has availability 100, available_Y is one.

changeCost_XtoY: this represents the cost of changing from fuel X to fuel Y regarding car adaptations that are necessary. We work with three values for this variable: 1, when no adaption is necessary; 0.2 when some adaption is necessary (like in the case of adapting a car to use gas); and 0.1 when a car change is necessary.

priceDiff_XtoY: This variable gives the distance between the prices of fuel X and Y. We use a unity-based normalization using as interval the distance between the minimum cost in all scenarios (10) and the maximum cost (50). If prices of X and Y are the same, *priceDiff_XtoY* is 0.5. If Y is cheaper than X, *priceDiff_XtoY* will be greater than 0.5 (the greater the difference in price, the more this variable approximates to 1).

Four kinds of policies were modelled: subsidy (policy 1), taxes (policy 2), mandates (policy 3) and R&D investment (policy 4). To simulate the effects of these policies in the model, the following parameters must be set for each fuel X:

Policy1_X: Subsidy is modelled by decreasing the price of a fuel by a factor (subsidy factor), ranging from 0 to 1.

Policy2_X: Taxes are modelled analogously, but with factors that are greater than 1. In this way, the price of fuel X that is considered in each model is obtained by multiplying the actual cost of X by the subsidy and tax factors.

Policy3_X: Mandates are also modelled by factors from 0 to 1 that represent the percentage of a fuel (Bio or Advanced Biofuel) in Gasoline.

R&D investment (**Policy 4**) was modelled by increasing the availability of the resource, since the expected medium to long term effect of such investment is to improve the efficiency of the technology for production and use of these biofuels.

By solving the Markov chain associated to each scenario we find the equilibrium state, that is the distribution of users in states to which the system would converge. The challenge was to calibrate this model to make it a realistic representation of the U.S. transportation market shares, such that it would be worthwhile to use it to perform analysis of future scenarios. The calibration involved the choices of harmonic mean, weights of the harmonic mean components, factors of change cost, unity based normalization for price differences, availability values of resources.

The calibration, used to validate the model, was performed in three ways: (1) by considering concrete U.S. transportation market shares data of existing years, (2) by analyzing limit situations, and (3) by analyzing a reference scenario. The years 2010 and 2013 were chosen as references and the market shares resulting from the solution of the model were very approximate to the real values of the considered years. Furthermore, the analysis of limit situations showed the robustness of the model. The model behaves as expected considering, among others, situations where all fuels had the same price and/or all the same availability. The reference scenario considered the years from 2010 to 2040 and the only policy used was 1st generation biofuels mandate, because it already affects the market share greatly. Future prices of Gasoline/Diesel, Ethanol Electricity and Natural Gas were based on EIA reference case study (U.S. EPA, 2013) in an energy-equivalent basis (MBtu per gallon). Advanced Biofuel prices stay in 50 dollars per MBtu until 2021, drop to 42 dollars in 2022 and continue dropping in a rate of 1% per year 2023 onwards. In order to represent the U.S. transportation market share, Gasoline and Diesel together represent the Petrol share. Aviation fuels and other petrol derivatives were not considered in this study. The resulting U.S. transportation market share can be seen in Fig. 3.

From this reference scenario, it is possible to notice only a minor decrease in the users of Petrol if no other policies are in effect, since the only policy used in the reference model was the 1st generation biofuels mandates. On the right (Fig. 3), there is a slight yearly increase in electricity, natural gas and advanced biofuels use. Other scenarios can be created by altering the assumed policies. This will be made in the next section.

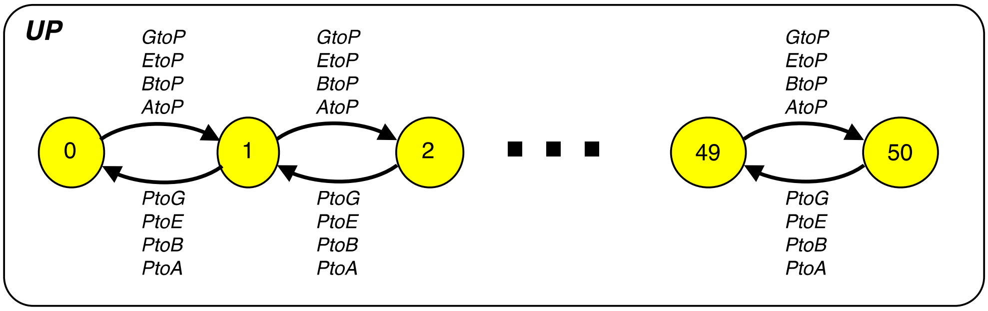
4.3. *Results and analysis*

After the steps of tuning and validating the model, many scenarios were calculated from 2010 to 2040 with different policies configurations. Table 3 presents the final results (in 2040) of Advanced Biofuels and Petrol shares in % of total U.S. transportation. This table shows the results of four different policies: Research & Development (R&D) investment in Advanced Biofuels (low, medium and high), advanced biofuels price subsidies (10%, 25%, and 50% price abatement), Petrol taxes (10%, 25%, and 50% price increase) and 1st generation biofuels mandates.

From Table 4 it is possible to realize that with low investment in R&D, no mandates nor petrol taxes and solely price subsidies, the effect on the future diffusion of Advanced Biofuels is negligible, since in the strongest 50% subsidy scenario, the Advanced Biofuels share does not reach 3% (2.8%) in the market share by 2040.

Comparing the medium and low R&D investment scenarios for Advanced Biofuels, it is possible to witness a small increase of market shares by the end of 2040 (1.4%–1.9%). In the same manner, the Petrol share decreases from 88.9% to 88.4% of the total market share in 2040.

When analyzing reference high R&D scenarios, Advanced Biofuels share is reasonably higher, achieving 3.2% of the overall U.S. transportation market share in 2040. When this higher investment in R&D is combined with price subsidies, the results of Advanced Biofuels are far more promising, reaching 13.7% of the total market



Captions: GtoP: Gas to Petrol; EtoP: Electricity to Petrol; BtoP: Biofuel to Petrol; AtoP:Advanced Biofuels to Petrol; PtoG: Petrol to Gas; PtoE: Petrol to Electricity; PtoB: Petrol to Biofuel; PtoA: Petrol to Advanced Biofuels.

Fig. 1. Automaton users of petrol.

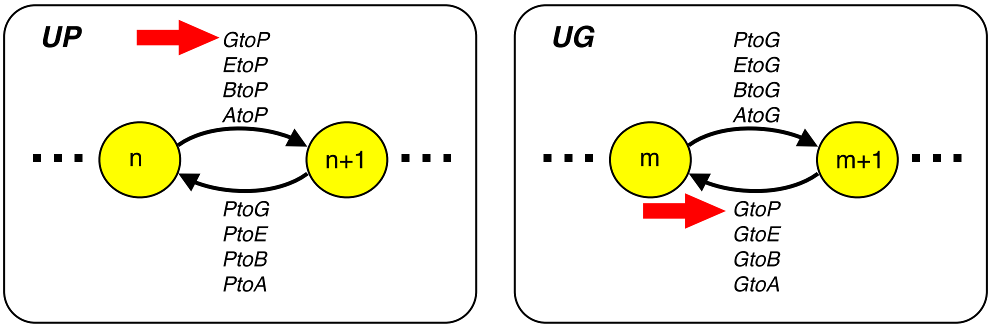


Fig. 2. Synchronized events.

share in 2040. Although it is unlikely that such a high subsidy (50%) is to be implemented by any government, it is valid to model this feature for academic purposes. On the other hand, the Petrol share decreases from 88.9% to 76.4% of U.S. transportation market share in 2040.

In the next step of modelling scenarios, price taxes on the Petrol share were applied attempting to reduce Petrol market shares. That way, not only advanced biofuels shares would rise but other sources of energy would benefit from higher prices of the Petrol share, and an increase of Natural Gas and Electricity shares were also expected.

The previous model with Advanced Biofuels price subsidies (10%, 25% and 50%) were coupled with Petrol taxes that increased the price of Petrol in 10%, 25% and 50%. These 9 scenarios were recalculated with low, medium and high R&D investments, performing a total of 27 new scenarios to be analyzed.

From these new calculations it is noteworthy the growth of advanced biofuels share and other energy sources when petrol taxes are applied. The Natural Gas share ascends from 2.9% to 21.5% in 2040 (50% petrol tax), while the Electricity share slightly climbs from 0.3% to 2.2% in this new scenario. Advanced Biofuels present a new market share of 28.2% in 2040. In these scenarios a much more balanced situation, regarding the sources of energy used in transportation, is achieved, ending with an over dependence of oil.

As commented previously, the greatest difference in final market diffusion of Advanced Biofuels depends on how intense is the R&D investment. Price subsidies also help the diffusion of Advanced Biofuels, however, with little investment in R&D the scale of production do not raise sufficiently and, consequently, a low percentage of users can change to this biofuel. Thus, a combination of investment in R&D with price subsidies showed better results.

It is important to note that with a 1% yearly decrease in Advanced Biofuels price as reference (from 2023 onwards), the final price was still more expensive than Petrol (in which gasoline prices were used) US$ 35.05 versus US$ 32.32 per MBtu in 2040. However, recognizing that it could be difficult to lower prices only due to better industry efficiency and economies of scale, the model was run another time with fixed advanced biofuels prices of US$ 42 per MBtu, in an attempt to mimic a scenario that advanced biofuels industry reaches its minimum feasible price. The results are shown in Table 5.

From the results and discussion presented some considerations can be drawn:

a) Investment in Research & Development in advanced biofuels plays a key role in the future diffusion of these fuels.
b) It is more interesting in terms of diffusion to create policies that enhance research and development of advanced biofuels that would lead to increased availability and lower future prices than to only enable subsidies to make them readily competitive with other fuels.
c) Enabling Petrol taxes not only enhances the diffusion of Advanced Biofuels but all other fuels in the market share; and if there aren't enough biofuels to fulfil the demand, natural gas and electricity become key players in the market share.
d) If no public policy is enabled to enhance the Advanced Biofuels industry, it will play a minor role in the future of energy transportation. This scenario could dramatically change depending on the policies adopted.
e) Given the uncertainty of long-term crude oil prices, the real competitive price level for advanced biofuels can be far higher.

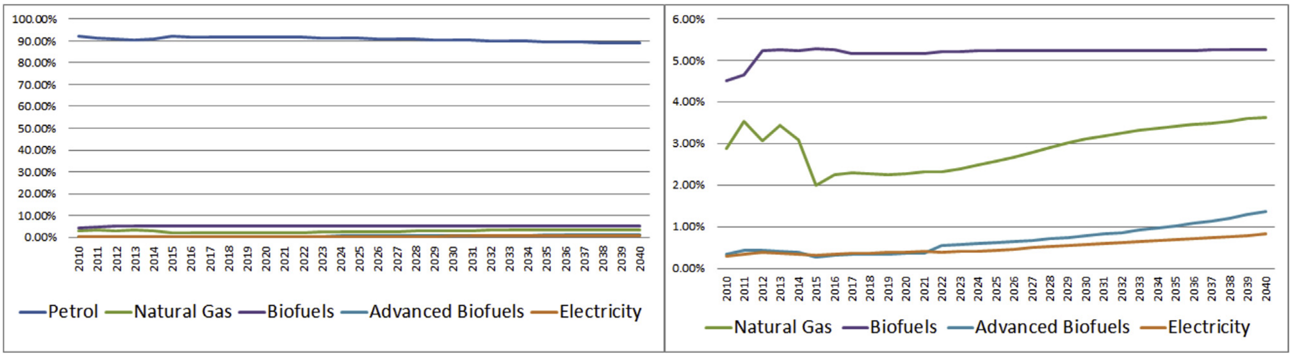


Fig. 3. U.S. Transportation market share diffusion reference scenario (left) and a graphic zoom in non-petrol fuels (right) (% of MBtu). Obs. Aviation fuels and other petrol derivatives are not accounted for.

Table 4
U.S. transportation market shares in 2040 depending on different policies.

Reference: Advanced Biofuels share				Petrol (Gasoline + Diesel) share		
R&D	Low	Med	High	Low	Med	High
Reference	1.4%	1.9%	3.2%	88.9%	88.4%	87.1%
Price subsidy 10%	1.5%	2.2%	4.1%	88,7%	88,1%	86,2%
Price subsidy 25%	1.9%	2.8%	6.1%	88,3%	87,4%	84,1%
Price subsidy 50%	2.8%	4.7%	13.7%	87,1%	85,3%	76,4%
With 10% Petrol Tax						
Price subsidy 10%	1,8%	2,6%	5,4%	87,2%	86,4%	83,6%
Price subsidy 25%	2,2%	3,5%	8,5%	86,6%	85,4%	80,3%
Price subsidy 50%	3,5%	6,1%	18,3%	84,9%	82,2%	70,2%
With 25% Petrol Tax						
Price subsidy 10%	2,4%	3,7%	9,1%	83,1%	81,8%	76,3%
Price subsidy 25%	3,1%	5,1%	14,7%	82,0%	79,9%	70,4%
Price subsidy 50%	5,2%	9,6%	24,1%	78,5%	74,0%	59,7%
With 50% Petrol Tax						
Price subsidy 10%	4,6%	8,2%	21,6%	68,3%	64,8%	51,3%
Price subsidy 25%	6,5%	11,5%	25,4%	65,6%	60,5%	46,4%
Price subsidy 50%	11,0%	16,6%	28,2%	58,7%	52,9%	41,2%

Table 5
U.S. Transportation market with fixed advanced biofuels price of U$ 42.00 per MBtu shares in 2040 depending on different policies.

Reference: Advanced Biofuels share				Petrol (Gasoline + Diesel) share		
R&D	Low	Med	High	Low	Med	High
Reference	1.1%	1.4%	2.1%	89.2%	88.8%	88.1%
Price subsidy 10%	1.2%	1.7%	2.7%	89.1%	88.6%	87.6%
Price subsidy 25%	1.5%	2.2%	4.1%	88.7%	88.1%	86.2%
Price subsidy 50%	2.3%	3.7%	9.9%	87.7%	86.3%	80.3%
With 10% Petrol Tax						
Price subsidy 10%	1.4%	1.9%	3.3%	87.6%	87.1%	85.6%
Price subsidy 25%	1.8%	2.6%	5.4%	87.2%	86.4%	83.6%
Price subsidy 50%	2.9%	4.8%	13.9%	85.7%	83.8%	74.8%
With 25% Petrol Tax						
Price subsidy 10%	1.8%	2.6%	5.1%	83.8%	83.0%	80.3%
Price subsidy 25%	2.4%	3.7%	9.1%	83.1%	81.8%	76.3%
Price subsidy 50%	4.1%	7.5%	21.0%	80.3%	76.9%	63.4%
With 50% Petrol Tax						
Price subsidy 10%	3.2%	5.2%	14.1%	70.2%	68.2%	59.3%
Price subsidy 25%	4.7%	8.2%	21.6%	68.3%	64.8%	51.2%
Price subsidy 50%	9.0%	14.9%	27.4%	61.7%	55.7%	43.0%

Although it is very unlikely to promote such taxation on Petrol derivates, it is interesting to study how strong taxation would affect the market diffusion of all fuels until 2040. Moreover, with policy support and incentives, the algal biofuels industry (and advanced biofuels) will continue to develop and assuming that this technology follows renewable energy cost trends, costs will decrease to eventual economic viability.

5. Final remarks

It is gradually becoming clearer to the society that continued use of fossil fuels for energetic purposes is unsustainable. Innovative technologies and sources of energy must be developed to replace fossil fuels. However, alternative sources of biofuel derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, inflict a lot of pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests. Besides that, many countries cannot grow most of the terrestrial crops due to climate factors or lack of fertile cultivation areas for energetic purposes. In this context that algal biofuels can really make a contribution for the future world sustainability.

Advanced biofuels technological developments in cultivation and extraction of oil should continue to move forward in the coming years with increasing investment in R&D in this area. However, as shown in this paper, many are the challenges to successful produce biofuels in an economically viable manner in the coming years with considerably low oil prices. For the establishment of a credible market, steady and with a growing demand, it needs to be stimulated as many of the implementation stages of emerging technologies can face limitations that can lower the possibility of success. In this way, modelling different types of policy support presented some interesting diffusion results.

The results of the energy used in U.S. transportation were modelled and analyzed, including overall expected evolution of each fuel until 2040. In order to boost development of advanced biofuels, public investment in R&D is the most important policy to be adopted by countries. Developing strategies aimed to renewable resources; applying tax incentives and subsidies; and issuing mandatory country objectives are also encouraged.

Modelling using SAN formalism proved to be a successful research method and provided useful future scenarios regarding advanced biofuels market. It revealed some potential diffusion pathways regarding this emerging market and allows to draw some recommendations concerning public policies. To the best of the authors knowledge, this is the first study using SAN Modelling to assess the future market penetration of advanced biofuels in the transportation sector. Although this study used U.S. data to be developed, similar calculations could be done in other regions or to assess other types of energy sources.

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