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# A dynamic programming approach for modeling low-carbon fuel technology adoption considering learning-by-doing effect

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## HIGHLIGHTS

- Dynamic programming method is used in transportation fuel portfolio planning.
- The learning effect in new fuel technology is endogenously modeled through an experience curve.
- Cellulosic biofuels play critical role in de-carbonization transport sector in near term.
- The initial 3–4 billion gallons production is critical to bring down cellulosic biofuels' cost.
- Large penetration of Zero Emission Vehicles will discourage development of cellulosic biofuels.

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## ABSTRACT

Promoting the adoption of low-carbon technologies in the transportation fuel portfolio is an effective strategy to mitigate greenhouse gas emissions from the transportation sector worldwide. However, as one of the most promising low-carbon fuels, cellulosic biofuel has not fully entered commercial production. Governments could provide guidance in developing cellulosic biofuel technologies, but no systematic approach has been proposed yet. We establish a dynamic programming framework for investigating time-dependent and adaptive decision-making processes to develop advanced fuel technologies. The learning-by-doing effect inherited in the technology development process is included in the framework. The proposed framework is applied in a case study to explore the most economical pathway for California to develop a solid cellulosic biofuel industry under its Low Carbon Fuel Standard. Our results show that cellulosic biofuel technology is playing a critical role in guaranteeing California's 10% greenhouse gas emission reduction by 2020. Three to four billion gallons of cumulative production are needed to ensure that cellulosic biofuel is cost-competitive with petroleum-based fuels or conventional biofuels. Zero emission vehicle promoting policies will discourage the development of cellulosic biofuel. The proposed framework, with small adjustments, can also be applied to study new technology development in other energy sectors.

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## 1. Introduction

The transportation sector, dominated by petroleum fuels, is a main cause of greenhouse gas (GHG) emissions worldwide. In 2014, direct combusted GHG from the transportation sector contributed to 23% of energy-related GHG emissions globally, 26% in Europe, 33% in the United States, and ranges from 15% to 40% in other major developed and developing countries [1–5]. These shares will be even larger if lifecycle GHG emissions are considered [6].

To reduce the dependency on petroleum fuels and mitigate GHG emissions from the transportation sector, governments around the world are implementing various policies and regulations [7–11]. Among these strategies, adopting low-carbon fuel technologies in current transportation fuel portfolios remains important and potentially effective. Particularly, this strategy does not require significant improvements to vehicle technologies or infrastructure. Therefore, the benefits of this strategy can be realized in a short time frame. According to the European Union's

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National Renewable Energy Action Plans, the use of renewable and low-carbon energy is targeted at 10% in the transportation sector by the year 2020 [12]. Particularly, 5% should come from advanced biofuels. In the United States, the Renewable Fuel Standard requires 36 billion gallons of renewable fuel to replace petroleum-based fuels by 2022, which equals 20% of the projected fuel consumption in transportation [13]; 21 out of the 36 billion gallons should be advanced biofuels, specifically cellulosic biofuels. Similar policies have been proposed or adopted in other major developed and developing countries with targets to be achieved in a similar timeframe, such as in Canada and United Kingdom [14,15]. The advanced biofuels, also known as second-generation biofuels, are fuels that can be manufactured from non-edible cellulosic biomass, such as woody crops, or agricultural residues. Hence, in this study, we call them cellulosic biofuels. Cellulosic ethanol is the major type of cellulosic biofuel. In comparison, first-generation biofuels are made from sugars and vegetable oils found in arable crops, which can be easily extracted using conventional technology. The cellulosic biofuels have the advantages of producing low-carbon emissions based on lifecycle assessment and of not competing with food crops for land use [16]. If all of the policies succeeded, we should expect to observe a large volume production worldwide (with a magnitude of 20–50 billion gallons per year) of cellulosic biofuels within 5–10 years. However, due to the immaturity of the technologies, only several million gallons were produced by 2014 [17,18]. Rapid technology developments in the cellulosic biofuel industry must happen in the next decade to ensure that environmental goals can be achieved [19,20].

In the energy economics field, technology advancements are usually realized as experience accumulates or through continuous production. Mathematically, it means that the unit production cost of a fuel will be gradually reduced as the cumulative production quantity increases, which is called the learning-by-doing (LBD) effect [21]. Cellulosic biofuels have had limited technology progress until now, which makes the unit production costs more expensive than that of most first-generation biofuels as well as petroleum-based fuels. As a result, private entities are reluctant to invest in this technology, and this will worsen the situation resulting in even less technological progress being made. Therefore, government guidance or even subsidies are needed to ensure that enough cellulosic biofuel is produced to develop the technology and achieve the sustainable future of the transportation fuel portfolio [22]. This creates a planning problem because governments need to know the appropriate timing and approach to economically promote cellulosic biofuels, as well as develop technology options for reducing GHG emissions before the advanced biofuels technologies are mature. It is worth noting that this technology-planning problem also exists in other energy application fields, such as solar energy adoption in the residential sector and green building in the commercial sector. To address the problem, this study establishes an analytical framework to investigate the least-cost cellulosic biofuel technologies' adoption while considering the LBD effect. Specifically, we utilize a dynamic programming approach to make sequential production decisions to cultivate a matured advanced biofuel industry. To the best of our knowledge, this is the first study of its kind to incorporate both dynamic programming and LBD modeling approaches to study transportation energy problems. We conducted a case study using California's Low Carbon Fuel Standard regulation and found the optimal technology development pattern under various government policy and fuel price scenarios. Although the results from the case study are region-specific, the established model can be applied to any region or country in the world to study low-carbon fuel technology or any type of new energy technology's adoption.The remainder of this paper is organized as follows. Section 2 presents a comprehensive literature review. In Section 3, we discuss the mathematical models and parameters. In Section 4, we describe a case study based on California's Low Carbon Fuel Standard and developed scenarios. We present the results and sensitivity analysis in Section 5. Finally, the main findings of this study are summarized and conclusions are drawn in Section 6.

## 2. Literature review

We conducted an extensive literature review to understand how new energy technology adoptions were modeled in previous studies. Particular attention is given to approaches used in transportation energy modeling studies. In summary, there are two commonly used methods to determine new technology adoption, the exogenous and the endogenous.

The exogenous approach refers to models that use externally determined parameters to represent technology evolution. Chen and Fan [23] developed a stochastic programming model to cope with the uncertainty introduced by cellulosic ethanol technology evolvement in transportation fuel portfolio design problems. A scenario tree, based on externally determined cellulosic ethanol technology evolvement possibilities, is developed to represent the uncertainties. Azar et al. [24] conducted a similar study to assess fuel choices in the transportation sector under stringent global carbon constraints. They looked into cost-effective transition pathways with a focus on biofuels. They found that biofuels will play a critical role in the transition process, but ultimately the preferred choice of fuel is hydrogen. However, the study did not consider the learning effect in biofuels, and the cost projections for biofuels were based on expert opinions. Carriquir et al. [25] studied the economic and environmental benefits of satisfying the energy demand with a portfolio of first-generation and second-generation biofuels. The economic and environmental impacts of biofuels are external parameters based on the literature or expert knowledge. They found that large uncertainties existed in second-generation biofuels, especially cellulosic ethanol, because their production costs are still very high and very limited knowledge is available to predict their future costs. Zhang et al. [26] investigated pathways to de-carbonize energy use in the transport sector in China and the US using an energy inventory model called TIMES (The Integrated Markal-EFOM System). They concluded that biofuels and electrification are important alternative fuels to facilitate the de-carbonization process in both the US and China. Similarly, Yeh et al. [27] adopted a bottom-up model called MARKet ALocation (MARKAL) and examined possible policies to reduce the transportation GHG emissions in the United States. Although bottom up models such as those of Zhang et al. [26] and Yeh et al. [27] are comprehensive, they usually rely on external parameters and the model results are sensitive to the selections of these parameters.

To sum up, the exogenous method is a solid approach to model technology development, particularly under situations when the determining factors of technology development are unclear or too much uncertainty exists. However, in reality, this is not the case for the majority of energy technologies.

The evolution of energy technologies is mainly dependent on experience with the technologies. This leads to the endogenous approach, which is an approach that has attracted more attention in recent years. Most commonly, the relationship between experience and technology evolution is modeled via an experience curve, which sets the production cost of a new technology as a function of the accumulated experience (represented by the cumulative production quantity). An important parameter in an experience curve is the progressive ratio (PR), which mathematically represents the percent reduction in cost with every doubling of the cumulative production quantity. Hettinga et al. [28] investigated the