Energy 94 (2016) 409–421

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Analysis of supply-push strategies governing the transition to biofuel vehicles in a market-oriented renewable energy system

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ARTICLE INFO

Article history:
Received 14 July 2015
Received in revised form
2 November 2015
Accepted 3 November 2015
Available online 28 November 2015

Keywords:
Biofuels
Alternative fuel vehicles
Supply-push
Energy system model
Market simulation
System-Dynamics

ABSTRACT

In this paper, the capacity expansion strategies of biofuels supply and the potential for the market development of biofuel vehicles are examined using an integrated System Dynamics model of energy and transport systems for Iceland. The biofuel markets are simulated in the context of a market-based economic system. The demand side enables an endogenous analysis of the road transport sector in which the long-term evolutions of light-duty and heavy-duty vehicle fleets are simulated through a consumer choice algorithm. Two scenarios are defined to support the fuel and infrastructure for biofuel vehicles: i) the Initial Push scenario as a tracking capacity planning strategy with an initial supply momentum, and ii) the Enthusiastic scenario as a leading capacity strategy with a continuous supply push. The results indicate that the dynamics of the bio-diesel market are not highly sensitive to the supply strategies employed. However, changing the capacity planning strategy could significantly influence the medium-term development of biogas as well as the evolution of the bio-ethanol market throughout the planning horizon until 2050. While the Initial Push scenario is less costly from a fuel supply perspective, the Enthusiastic strategy would be advantageous in terms of overall energy and transport benefits.

1. Introduction

Biofuels have been recognized as low-carbon alternative fuels that can replace fossil fuels in the short- to medium-term without major changes in the conventional existing infrastructure and vehicle fleets [1,2]. Biofuels based on waste resources and biomass residues are of specific interest due to economic and environmental advantages such as rural development [3–5], less land requirement [6], waste management, and the use of local potential [6,7]. Nevertheless, the limited biomass resource potential in some regions/countries, low efficiencies [6,8], uncertainties in the cost of distributed biomass feedstock [9], and supply chain complexities [10,11] may restrict their market development.

Iceland benefits from a renewable-based energy-system in which almost all of heat and electricity needs are met by renewable sources. However, Iceland's transport and marine sectors are heavily dependent on the imported petroleum fuels. Due to the growth of vehicles-per-capita and travel activities, GHG (greenhouse gas) emissions have been increasing during the past decade. Iceland's long-term vision includes significant reductions of net GHG emissions by 50%–75% below 1990 levels by 2050 [12]. To achieve such a deep cut in emissions, a transition to alternative fuels will be required.

In addition to the promising electricity and hydrogen transitional pathways to a low-carbon transport system in Iceland [13–15], the role of biofuels is expected to become increasingly important in both future road transport and marine sectors [16]. It has been estimated that the identified potential for the indigenous production of biogas, bio-ethanol and bio-diesel utilizing non-food

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http://dx.doi.org/10.1016/j.energy.2015.11.013
0360-5442/

and waste feedstock in Iceland could supplant at least 25% of the current petroleum fuel consumption [15,17]. The potential for the production of biofuels from energy crops and ligno-cellulosic biomass is also expected to increase as temperatures increase with climate change, making Iceland an example of a mitigation-adaptation win–win supply sector [18,19].

Recent studies on the Iceland's energy system analysis have identified the attractiveness of biogas vehicles in the medium-term [14,20,21]. Furthermore, a recent comparative analysis indicated that, compared to the hydrogen and electricity, the biofuel transition pathway could be the least-cost strategy from an overall energy supply and transport perspective [15]. However, there is no study so far which focusses specifically on the effects of supply capacity strategies on the dynamics of biofuel market in Iceland. The specific focus of this paper is on the potential market penetration of biofuels in an isolated renewable-energy-based economy as well as the nexus between capacity planning strategies, competitive market dynamics, infrastructure evolution and consumer behavior, which have not been fully explored in the literature. This study compares different capacity planning and supply infrastructure strategies aimed at stimulating the biofuel market. The main objective is to evaluate the potential impact of utilizing domestic biomass feedstock to reduce GHG emissions and to enhance energy security by diversifying fuel supply, reducing dependence on fuel imports and thereby increasing the self-sufficiency in the energy system. Biofuel markets are simulated using an integrated System Dynamics model of a market-based system that captures the interactions among supply sectors, energy prices, infrastructure and fuel demand.

This paper formulates capacity planning strategies under dynamic market conditions influenced by the complex interactions among resource supply costs, technology costs, demand patterns, and market prices. Thus, the process of biofuel market simulation and the comparative assessment between two supply push strategies, leading to either the market share expansion of biofuels or the maximum capacity utilization of individual plants, will be the principal foci of this paper.

The analysis represents an important contribution for Iceland's energy strategy to move towards a fully-renewable energy system. In addition, given the specific nature of Iceland as an isolated energy system in its infancy of indigenous biofuel production, the proposed methodology and scenario analysis can be insightful for the integrated energy and transport analysis of remote locations or island countries, with implications for emissions reduction and energy security improvement through the utilization of local resources.

2. Simulation of energy markets

The development path of the energy system and the transition towards renewable transport fuels are examined using the UniSyD_IS model of Iceland's energy system. UniSyD_IS has been already used for exploring the transition to a low-carbon transport [14], cost-effectiveness of renewable fuel support [20], economic impact of adaptation to climate change [18], and comparative analysis of AFVs (alternative fuel vehicles) in Iceland [15].

UniSyD_IS is a partial equilibrium techno-economic bottom-up System Dynamics model with a high level of resource and technology specificity in which interactions act across five key markets: electricity, hydrogen, biogas, bio-ethanol and bio-diesel. The model takes into account the entire energy system, including interactions among supply sectors, energy markets, infrastructure and fuel demand. The model encompasses conventional and alternative fuel supply pathways and the corresponding vehicle powertrains in the transport sector, simulating the interactions of around 2000 key variables up to year 2050 and beyond. Fig. 1 demonstrates the simplified structure for the short-term and long-term simulation of fuel markets with a focus on the supply and price modules. Table 1 defines the most important balancing and reinforcing feedback loops presented in Fig. 1.

2.1. Short-term energy market simulation

Generation scheduling and energy pricing are the main outputs of the short-term market simulation. The model calculates the amount of energy that would be available at the various estimated wholesale prices. The production level of each plant is determined by the following equation:

$$G_{k,t} = Min\left\{1, \left(\frac{P_{f,t}}{C_{k,t}}\right)^{w}\right\} \times H_{k,t} \qquad (1)$$

where $G_{k,t}$ is the effective production of plant k at time t, $H_{k,t}$ is the maximum production capacity, $P_{f,t}$ denotes the wholesale market price of fuel f, $C_{k,t}$ is the production cost and w is the loss willingness parameter. In the short-term, the amount of fuel supplied is determined by the market price. When offer prices are higher than the production cost, the plant will operate at full capacity. For prices lower than the cost of production, the plant will produce exponentially less, according to the loss willingness parameter, which represents the plant's tendency to sell energy below its profitability.

The model tries to minimize the wholesale price while meeting generation needs and maximizing the generator profit. It does so by testing the plants' responses to various percentage increases/decreases in the price from its value in the previous time step. The model then determines the minimum wholesale price that can provide sufficient energy (i.e., using the "Min Effective Price" substructure in Fig. 1).

If the price increase is insufficient to suppress the demand to match the production capacity, then one step increase in the price is chosen due to a production shortfall, moving the wholesale price towards the equilibrium (for a detailed description of the algorithm see Ref. [22]).

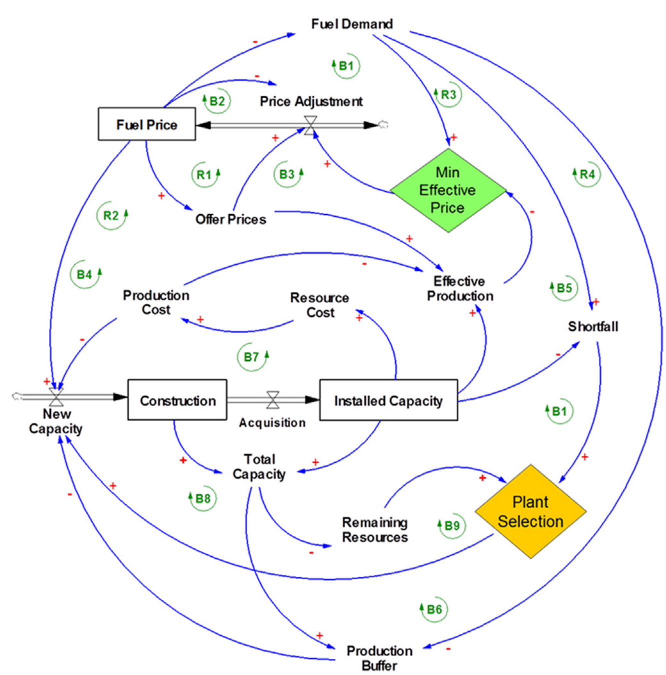

Fig. 1. Simplified stock-flow diagram for the simulation of fuel markets.