Simulation of Alternative Fuel Markets using Integrated System Dynamics Model of Energy System

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Abstract
An integrated system-dynamics model of energy systems is employed to explore the transition process towards alternative fuel markets. The model takes into account the entire energy system including interactions among supply sectors, energy prices, infrastructure and fuel demand. The paper presents the model structure and describes the algorithm for the short-term and long-term simulation of energy markets. The integrated model is applied to the renewable-based energy system of Iceland as a case study to simulate the transition path towards alternative fuel market during the time horizon of 2015-2050. The transition pathways towards hydrogen and biofuels are investigated for the numerical results. The market simulation algorithm effectively exhibits the continual transition towards equilibrium as market prices dynamically adjust to changes in supply and demand. The application of the model has potential to provide important policy insights as it can simulate the impact of different policy instruments on both supply and demand sides.

Keywords: Market Simulation, Alternative Fuels, Energy System Model, System Dynamics, Transportation

1 Introduction

The transition towards alternative fuel system is a complex process and requires effective interactions among multiple stakeholders. This process can be described by a set of nonlinear and complex equations. Nonlinearities, multiple feedback loops and time delays produce unexpected system behaviors over time. Thus, the formulation of effective policies to support the transition process requires a comprehensive analytical tool, enabling us to evaluate the interactions among...
energy markets, infrastructures and vehicle fleets. The analytical models should represent the dynamic equilibrium throughout time and contain endogenous representation of supply and demand for various fuels. System-dynamics approach satisfies these criteria as it can show a broader view of energy systems and is capable to take into account complex interdependencies and feedback structures over time. This approach looks at the process of market development as a whole and facilitates understanding the interactions of different stakeholders in complex systems.

System-dynamics approach has been widely used for studying the evolution of vehicle fleets (e.g. Janssen et al., 2006; Struben & Sterman, 2008; Leaver et al., 2009; Meyer & Winebrake, 2009; Leaver & Gillingham, 2010; Park et al., 2011; Shepherd et al., 2012; Shafiei et al., 2013). Since the transition path of energy supply and transport systems is of interest in this paper, we focus on the integrated system-dynamics model for the transition analysis as well as the interaction among various fuel suppliers and transport fleets. The integrated energy and transport modelling which assumes an endogenous demand and competitive energy markets raises the complexity of numerical simulation. Thus, the identification of the model components and the process of fuel market simulation will be the center of attention in this paper.

In Section 2, the model structure and market simulation algorithm are described. Section 3 introduces the case study for a numerical simulation. Results are presented in Section 4 and, finally, Section 5 concludes the paper.

2 Methodology

2.1 UniSyD_IS Model

UniSyD_IS is a detailed resource and technology specific model in which equilibrium interactions act across electricity, hydrogen, biogas, bioethanol and biodiesel markets. The model is composed of 60 subsectors and it is capable of simulating the interactions of around 2000 key variables up to year 2050 and beyond. The model typically takes few minutes to run over a 40-year simulation period in two-week time steps. Important outputs from the model include profiles for alternative fuels supply, co-evolution of fuel stations, GHG emissions, vehicle fleet composition, transport energy use and transition costs.

The model encompasses conventional and alternative fuel supply pathways and the corresponding vehicle powertrains in the transport sector. For a detailed description of the model see (Leaver et al., 2009; Leaver & Gillingham, 2010; Shafiei et al., 2014a; Shafiei et al., 2015). The block diagram in Figure 1 highlights the model structure, showing how different components influence each other. According to Figure 1, the model structure is divided into four main modules:

1) Energy supply: This module incorporates capacities and production costs of existing and future plants and calculates the amount of energy that can be available at the various estimated wholesale prices.

2) Energy prices: This module attempts to coordinate fuel supply and demand by adjusting the market prices. The energy market maintains one market clearing price, as all generators of all types compete in an open market.

3) Refueling infrastructure: The fuel station sector links the energy supply system to consumers and determines the station service availability as an important factor that conditions the consumer preferences toward alternative fuels.

4) Energy demand: Transport fuel use is determined using travel demand and vehicle stock. The Multinomial Logit (MNL) model gives the probability that the consumers purchase vehicles
based on their preferences toward the vehicles’ attributes including purchase price, fuel cost, maintenance cost, battery replacement cost, GHG emissions, vehicle range and fuel availability. The annual travel demand is adjusted according to changes in fuel cost per km. Transport fuel demand is then determined using travel demand and vehicle stock. Total marine fuel demand is exogenous, but the share of biodiesel in this sector is determined based on the ratio of biodiesel to diesel oil price.

Figure 1: Structure of UniSyD_IS

The model spends the bulk of its time within the confines of the energy supply and pricing modules that together pose the complexity of the energy market. The algorithm for the short-term and long-term simulation of energy market with a focus on supply and price modules are described in the following sections.

2.2 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 using the following equation:
where $G_{n,t}$ is the production of plant $n$ at time $t$, $K_{n,t}$ the maximum production capacity, $P_{f,t}$ the wholesale market price of fuel $f$, $C_{n,t}$ the production cost and $w$ the loss willingness parameter. According to the above equation, for the offer prices over 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 profitability.

Figure 2: Market simulation algorithm
Figure 2 illustrates the market simulation algorithm to equilibrate the demand with the supply curves of various plants by changing the offer price. The model tries to minimize the wholesale price while meeting generation needs and maximizing generator profit. To solve these two problems simultaneously at each time step, the model tries to make an educated guess at this optimal price. It does so by testing the plants’ responses to various percentage increases and decreases in price from the wholesale price value in the previous time step. The model then determines the minimum wholesale price that can provide the sufficient energy.

If the price increase is insufficient to suppress demand to match the production capacity, then one or more steps increase in price is chosen (i.e. the parameter \( b \) in Figure 2) due to a production shortfall. It means that the production shortfalls trigger large price increases. In this way, with each time step, the model moves the wholesale price closer towards equilibrium condition.

2.3 Long-term Evolution of Energy Market

The production costs of new constructed plants are determined by the cumulative amount of capacity constructed, plant sizes and exogenous technology learning rates. Renewable production cost is expected to increase with cumulative installed capacities due to the effects of resource supply cost and, hence, it leads to an increase in the fuel price.

In the long-term, the forecasted prices play a crucial role in building new capacity. Higher wholesale prices encourage new capacity, something that is needed to keep pace with increasing demand. Higher prices increase the potential fuel supply, which in turn leads to a negative adjustment of fuel price.

Whenever there is more demand than production capacity (i.e. shortfalls), the model must decide what type of capacity to build. The plant siting substructure of the model determines the feasible technology and plant size based on fuel shortfalls and resource availability. The least cost choice will qualify if the technology’s production cost is less than the forecasted future prices. After a predetermined amount of construction time, that amount of plant capacity will become available in the market.

3 Description of Case Study

The model is applied to simulate Iceland’s alternative fuel markets. The time horizon of the study is 2015-2050. The technologies represented in the supply side are hydropower, geothermal, wind turbine, biogas from wastes, biodiesel from vegetable oils and animal fats, bioethanol from lignocellulosic biomass and hydrogen from electrolysis (Shafiei et al., 2014a, 2014b). Wind turbine, electrolyzer and bioethanol production technologies have exogenous learning for the costs, while constant costs along the horizon are assumed for the other technologies. The future costs of hydro, geothermal and biofuel resources are modeled using supply curves in which unit generation cost is expected to increase with cumulative installed capacities. Decreasing power functions describe the economy of scale effects for the cost of different biofuel plants. The forecourt electrolysis is modeled with the capacity of 1500 kg of hydrogen per day. A linear reduction is assumed for the cost and electricity consumption of hydrogen production and delivery adopted from (NREL, 2012).

The transport fleet is divided into light (LDV) and heavy (HDV) duty vehicle fleets with the upper weight limit for LDVs being 3.5 tonnes. The vehicle technologies within each fleet are classified into four main groups: petroleum, electric, biofuel and hydrogen vehicles. We assume significant improvements in the purchase cost and fuel economy of new vehicles as described in (Shafiei et al., 2014a).
We have chosen hydrogen, biogas, biodiesel and bioethanol fuels to present the simulation results. A constant oil price of $100 per barrel is applied in the analysis and it is assumed that the carbon tax is increased from $25 in the base year to $200 per tonne in 2050.

According to Table 1, there scenarios are defined based on initial supply infrastructure. Since a biogas plant is available in Iceland, further initial supply capacity is not required for this fuel. Each hydrogen station includes one forecourt electrolyzer unit.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Number of fuel stations per year during 2018-2022 for each of LDV and HDV fleets</th>
<th>Initial production capacity in 2018 for biodiesel and bioethanol plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>one station for each of biofuels, one station for hydrogen</td>
<td>one small plant with the capacity of 2.5 million liter/year</td>
</tr>
<tr>
<td>No Supply Push</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Strong Supply Push</td>
<td>two stations for each of biofuels, two stations for hydrogen</td>
<td>one medium plant with the capacity of 5 million liter/year</td>
</tr>
</tbody>
</table>

Table 1: Scenarios for the initial introduction of supply infrastructure

4 Simulation Results

The integrated supply-demand structure of UniSyD IS, according to the algorithm presented in Section 2, determines the trend of fuel prices as depicted in Figure 3. The trend for each fuel price reflects the overall effects of technology costs, feedstock costs, resource supply curves, economy of scale and, last but not least, the market equilibrium. The fuel prices along with vehicles’ fuel economy and annual distance traveled determine the annual fuel cost, which in turn forms an important feedback that conditions the adoption of hydrogen and biofuel vehicles. The algorithm used in UniSyD IS determines the fuel prices in the market to best equilibrate supply and demand sides as illustrated in Figure 4 for the Baseline scenario.

In the Baseline scenario, the insufficient capacity to respond the increasing demand for bioethanol during 2020-2025 leads to a sharp increase in the bioethanol price. Thereafter, the higher market price and the forecasted rising demand encourage the new capacity installation for bioethanol, which in turn balances and then reduces the market price. In the same way, the inadequacies of supply capacities during 2020-2025 cause the slight growth of biogas and biodiesel prices. The growth rate of biodiesel demand due to the marine fuel use together with the effect of resource supply cost gradually increase the biodiesel price over the study period. The price of biogas, however, will remain stable in the Baseline case until 2040, where the capacity growth of biogas is saturated due to the restricted resource potential. Thereafter, the biogas price rises quickly according to the imbalance of demand and supply. The delay produced by the construction time of all biofuel plants leads to imbalance market in several time points as shown in Figure 4.
The higher stimulated demand in the Strong Supply Push scenario leads to higher market prices for biogas and biodiesel in the long-term, compared to the Baseline case. However, the larger production buffer for bioethanol in the Strong Supply Push scenario results in a lower bioethanol price. The price for bioethanol in the No Supply Push scenario reflects its production cost as no market exists.

The decreasing pattern of hydrogen price until 2025, as shown in Figure 3, is caused by the assumptions on technology improvement in terms of electrolyzer cost and energy use. The slight growth of hydrogen price after 2025 conforms to the price growth of electricity that is used in the hydrogen production process. The results in Figure 4 exhibit the same trend for both hydrogen production and demand. The reason is that the forecourt electrolyzer for hydrogen production has been considered as a must-run technology that coordinates supply and demand effectively. It leads to the same hydrogen price in different scenarios as shown in Figure 3.

**Figure 3:** Simulated market price for alternative fuels in different scenarios
5 Conclusions

An integrated system-dynamics model for the transition towards alternative fuel markets was presented. The model considers the competition between different “well-to-tank” pathways and, thus, between various fuel supply to consumers. Since the fuel demand is determined endogenously, the supply capacity is driven not by the given demands but by the demand curves. Thus, we have a system of equations for establishing the supply-demand equilibrium path. In this framework, the minimized cost of fuel supply development leads to the maximized total surplus of consumers and producers in the equilibrium condition.

We explored the transition pathways towards hydrogen and biofuel markets in Iceland with implications for fuel demand, fuel prices and required supply infrastructure. The algorithm used for the short-term and long-term simulation of fuel markets effectively reflected the continual transition towards equilibrium condition by adjusting to changes in supply and demand.

The model can show how the decisions made by energy suppliers and infrastructure owners influence the consumer behavior and, on the other hand, the impact of demand for alternative fuels on
development of energy infrastructure can be evaluated. The presented model structure enables the simulation of alternative fuel markets based on a market-oriented energy system in which fuel supply viability is determined by market clearing price and profitability. If the wholesale prices for alternative fuels are regulated by government, or energy supply infrastructure is provided by a central planner, the fuel supply decisions should be treated differently.

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References


