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Comparative analysis of hydrogen, biofuels and electricity transitional pathways to sustainable transport in a renewable-based energy system

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ABSTRACT

This paper presents a comparative analysis of electric, hydrogen and biofuel transitional pathways to a future sustainable road transport in Iceland, a country with a renewable-based energy system. The analysis is based on a system-dynamics model of Icelandic energy and transport systems (UniSyD_IS). The model is divided into four main modules: fuel supply, fuel prices, refueling stations, and fuel demand. It simulates the long-term evolutions of light and heavy-duty vehicles, taking into account the supply and utilization stages of alternative fuels. Three scenarios are defined to promote the fuel supply infrastructure for three cases of hydrogen, biofuel and electric vehicles. The simulation results for these scenarios are compared in terms of different energy, economic, and environmental indicators. The findings indicate that the electricity pathway has advantages over others in reduction of total fuel demand, mitigation cost, and profitability of fuel supply. The biofuel pathway would be the most attractive alternative in terms of emissions reduction, share of alternative fuels, and consumer economic benefits. The analysis shows that the hydrogen scenario could be advantageous in reducing fuel import and consumer fuel costs, although it has the highest cost of vehicle ownership and infrastructure development.

1. Introduction

The energy system in Iceland is characterized by an isolated energy network with over 85% of total primary energy supply from low-carbon renewable resources [1]. Iceland is a global leader in developing and utilizing renewable energy resources to generate heat and electricity. The share of geothermal resource in total primary energy has increased continuously since mid-twentieth century and it is now the largest source of primary energy in Iceland. Hydropower has also increased rapidly since the late 1960s to meet the increasing electricity demand after the establishment of aluminum industry in Iceland [1]. Nevertheless, the share of renewable energy sources in transport and fishing sectors is still negligible and all petroleum products used for these sectors are imported.

The major part of the imported gasoline and diesel fuels is used in the road transport sector. Iceland's light duty vehicle (LDV) fleet in 2011 was composed of 80% gasoline and 19% diesel internal combustion engine vehicles (ICEVs), and less than 1% alternative fuel vehicles (AFVs). AFVs mainly consist of dedicated and dual-fuel biogas, with a few hydrogen and electric vehicles [2]. Iceland does not have a rail infrastructure and, hence, heavy-duty (HDV) trucks and light commercial vehicles are used for the freight transport services on land [3]. The average annual growth rates of LDVs and HDVs during the past decade have been 4.7% and 4.1%, respectively [4].

Provision of renewable transport fuels is the most important measure to reduce both greenhouse gas (GHG) emissions and the dependence on imported fossil fuels. Recent studies have

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highlighted the importance of the transport sector to achieve a fully renewable-based energy system, e.g. Ref. [5] in Denmark, Ref. [6] in Macedonia, and Ref. [7] in Croatia. The integration of renewable transport fuels into energy system analysis has been also addressed in recent studies. Ref. [8] compared the resources, production process and costs of various renewable transport fuels in the context of a renewable-based energy system. Ref. [9] analyzed the cost of different renewable fuel pathways in a 100% renewable scenario of Denmark by focusing on the role of synthetic fuels. Ref. [10] compared three renewable energy systems including biomass, hydrogen, and electricity in Ireland through the analysis of the entire energy and transport systems.

Electricity, hydrogen and biofuels are deemed as three promising candidates that can be produced using renewable energy sources in Iceland [11]. Electricity is envisaged as an appropriate alternative fuel, since it can be generated from low cost renewable geothermal and hydro resources. Electricity can be used either directly in electric vehicles (EVs) or for hydrogen production through electrolysis. It is also possible to produce biofuels (mainly biogas, biodiesel and bioethanol) from domestic waste resources to substitute some of petroleum products used in ICE vehicles [11]. In recent years the Icelandic government has introduced incentives such as carbon and import taxes to promote the contribution of AFVs in the transport sector [12]. However, formulation of effective policies to support the sustainable transition towards AFVs in long-run requires a comprehensive analytical tool, enabling us to evaluate the interactions among energy markets, infrastructures and vehicle fleets. Previous studies have already addressed the evolution of AFVs in Iceland. The first study used an agent-based framework to predict the market share evolution of passenger EVs in Iceland [13]. The other works examined a hybrid agent-based and system-dynamics framework through a simplified test case of Iceland's energy and transport system [14,15]. More recent studies have evaluated the interactions between energy markets and AFVs using UniSyD_IS as a system-dynamics model of Iceland's energy system [4,16].

This paper contributes to the previous work [4] by extending the scope of the UniSyD_IS model through endogenous development of fuel station co-evolution. Availability of fuel supply infrastructure and development of fuel stations are critical determinants in the successful adoption of AFVs [17,18]. This has been modeled in UniSyD_IS by including fuel station provision as a function of infrastructure availability and therefore an influence on consumer choice behavior. Moreover, infrastructure co-evolution for refueling/charging stations as well as opening and exit behaviors of stations are explored in the current version of the model. The specific focus in this paper is on the comparative analysis of electric, hydrogen and biofuel vehicles and the corresponding fuel supply chains in a future sustainable road transport system. The main objective is to compare the responses to different strategies aimed at promoting fuel supply infrastructure. The findings can assist in devoting resources to strategies with superior economic and environmental benefits. The application of the UniSyD_IS model has potential to provide important insights as it enables policy analysis for entire well-to-wheel (WtW) pathways.

The model components and system-dynamics structures used in UniSyD_IS are briefly described in Section 2. Description of the Icelandic case study and the main assumptions and data sources are presented in Section 3. Scenarios are explained in Section 4, and then the simulation results are discussed in Section 5. Finally, conclusions and prospects for future research are provided in Section 6.

2. UniSyD_IS model

The system-dynamics model of Iceland's energy systems (UniSyD_IS) has been developed based on the UniSyD_NZ model of New Zealand's energy and economic systems created by the Unitec Institute of Technology in cooperation with Stanford University. The UniSyD_NZ model has been already used to evaluate the pathways to a hydrogen economy [19] as well as the impacts of hydrogen and electric vehicles on New Zealand's energy economy [20,21].

UniSyD_IS is a detailed resource and technology specific model in which equilibrium interactions act across five key markets: electricity, hydrogen, biogas, bioethanol and biodiesel. Gasoline and diesel supply sectors are exogenous. 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 to 2050 for alternative fuels supply, co-evolution of fuel stations, GHG emissions, vehicle fleet composition, transport energy use and transition costs.

In the current modeling framework, four important responsive measures of efficiency improvement, travel demand, vehicle technology shifts, and fuel switches are the taken into consideration. Other initiatives that support the sustainable transport such as shift to public and slow transport modes [22,23], changes in the use and ownership of vehicles, lifestyle changes, use of information and communication technologies, and development of the built-environment [23], are not included in the current analysis.

The model structure conceptually can be divided into four main modules: (1) fuel prices, (2) fuel supply, (3) fuel stations, and (4) fuel demand. The brief description of each substructure is presented in the following sections.

2.1. Fuel supply

Fig. 1 illustrates the key variables and the simplified structure of feedback loops for both fuel supply and fuel price modules. The energy supply sector incorporates existing plant capacities, planned and future capacities, generation cost by existing plants and the

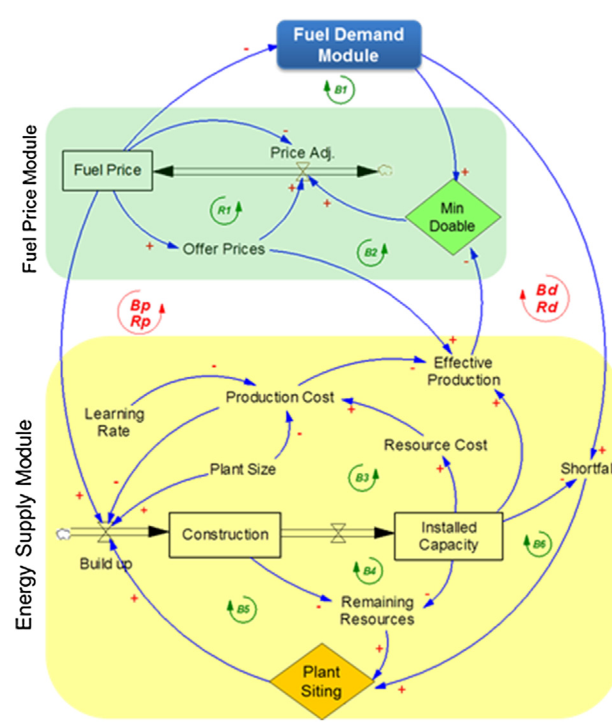

Fig. 1. Simplified structure of main feedbacks between fuel supply sector and fuel prices.