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Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity

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ABSTRACT

This study presents a simulation-based comparative analysis of hydrogen and electricity transitional pathways to a near carbon-neutral transport sector in Iceland. The development path of energy and transport sectors and the implications of transition to renewable fuels are examined using a system-dynamics model of Iceland's energy system. The model captures the interactions among fuel supply sectors, energy prices, infrastructure development and vehicle fleets. A normative approach is taken to simulate the trajectories toward feasible technological targets fulfilling a carbon-neutral transport sector. The analysis assumes an accelerated transition toward hydrogen and electric vehicles through stringent policies banning petroleum fuel vehicles from 2035. In this context, three transition pathways are compared: electricity (EV), hydrogen (H2), and mixed hydrogen–electricity (EVH2). Further sensitivity analyses are performed within each pathway to assess the impact of oil price, carbon tax, vehicle costs and the use of complementary biogas fuel. The transition pathways are compared in terms of fleet mix, energy demand, emissions reduction, transition costs/benefits and mitigation cost. The findings indicate that the electricity trajectory is advantageous in economic benefits, but it leads to a lower level of greenhouse gas mitigation.

1. Introduction

The transition process toward a carbon-neutral renewable-based transport sector is one of the major challenges in design of 100% renewable energy systems (Mathiesen et al., 2011). This process is not just a matter of technological change and, hence, broader changes are required in the economy, consumers' behaviors, and infrastructure development (van Nunen et al., 2011). To achieve a carbon-neutral transport sector, radical changes both at supply and demand sides of the integrated energy-transport system are required. These changes will have significant implications for energy-economic systems and alternative fuel markets.

Transition to renewable transport fuels is of particular interest for Iceland as an isolated energy-system and a global leader in utilizing renewable energy resources that almost all of its heat and electricity needs are generated from geothermal and hydro resources. While industrial, residential and commercial sectors are prevalent in the usage of these low-cost and low-carbon energy resources, the transport sector is still dependent on imported petroleum fuels. Long-term targets should therefore be defined for a deep reduction in petroleum fuel use in the transport sector, which contributes about 50% of total energy-related emissions (STATICE, 2016). The deep reduction in greenhouse gas (GHG) emissions requires a switch to near-fully renewable-based fuels by 2050, which

Abbreviations: AFV, alternative fuel vehicle; BEV, battery electric vehicle; EVs, electric vehicles; FCV, fuel cell vehicle; GHG, greenhouse gas; H2V, hydrogen vehicle; HDV, heavy-duty vehicle; HEV, hybrid electric vehicle; HEV_H2, hydrogen hybrid electric vehicle; ICE, internal combustion engine; ICE_H2, hydrogen internal combustion engine; km, kilometer; LDV, light-duty vehicle; MNL, multinomial logit; O&M, operating and maintenance; PHEV, plug-in hybrid electric vehicle; TtW, tank-to-wheels; WtW, well-to-wheels.

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is challenging in terms of associated costs, security of energy supply, local energy production and technological change.

There is no single solution for the implementation of a carbon-neutral transport sector (Connolly et al., 2014). Hydrogen, electricity, and biofuels are promising candidates that can be produced from renewable energy sources in Iceland. Biofuels have a limited resource potential in Iceland and hence cannot alone achieve a carbon-neutral transport system using conventional resource and technologies (Shafiei et al., 2015b, 2016). However, electricity and hydrogen may be regarded as promising carbon-neutral pathways that can be produced from renewable energy sources in Iceland. Because of a low-cost electricity generation from geothermal, hydro and wind resources in Iceland, electricity is envisaged as an appropriate alternative fuel that can be used in electric vehicles (EVs) and hydrogen production through electrolysis (Shafiei et al., 2015b).

Several previous works have addressed the evolution of alternative fuel vehicles (AFVs) in Iceland. Shafiei et al. (2012) used an agent-based model to predict the market share evolution of EVs in Iceland. Shafiei et al. (2013, 2014b) employed a hybrid agent-based and system-dynamics approach to evaluate the interactions among consumers, vehicle market and energy supply infrastructure. The authors have already developed a system dynamics model for Iceland's energy system (UniSyD_IS model) to evaluate the interactions between energy supply infrastructure and AFVs. The UniSyD_IS model has been used for exploring the transition to a low carbon transport (Shafiei et al., 2014a), cost-effectiveness of supporting renewable fuels (Shafiei et al., 2015c), economic impact of adapting to climate change (Shafiei et al., 2015d), comparative analysis of AFVs (Shafiei et al., 2015b), and transition to biofuel vehicles in Iceland (Shafiei et al., 2016).

Shafiei et al. (2014a, 2015b, 2015c) have compared the potential market share of electric, hydrogen and biofuel vehicles in response to different supply-push incentives to deal with the chicken-and-eggs problem between the vehicle adoption process and fuel availability. In contrast, the present study evaluates the transition process from a different perspective by assuming a specific time for banning petroleum fuel vehicles such that a renewable-based transport system can be achieved by 2050. Unlike the previous studies, this analysis entails changing in vehicle choice set as well as in consumer preferences through rigorous policies banning gasoline and diesel vehicles. This kind of analysis is identified as target-driven scenario analysis which assumes an accelerated transition toward hydrogen and electric vehicles as well as a rapid shift toward a carbon-neutral transport sector (Riesz et al., 2016). The main objective of the present study is therefore to evaluate the potential impact of trajectories toward feasible targets that fulfill carbon-neutrality of the energy-transport system and implications for energy security, economic costs, mitigation cost, and consumer behaviors. In other words, the conditions under which the integrated energy-transport system can meet the ambitious carbon-neutral target are identified. This analysis is not intended to forecast probable transition pathways. Instead, it is aimed at assessing the implications of transition toward a carbon-neutral transport through stringent policies supporting a rapid shift to alternative fuels. This analysis is important because it provides insights to archive a 100% renewable energy system in Iceland as an isolated renewable-based energy economy.

To evaluate how and if Iceland can achieve a near carbon-neutral transport system by 2050, a dynamic simulation-based comparative analysis of electricity and hydrogen transitional pathways is performed using the UniSyD_IS model. In Section 2, the general structure of the model, main assumptions and data sources are briefly presented. Scenarios are defined in Section 3, and then the simulation results are presented in Section 4. Finally, conclusions are provided in Section 5.

2. Modeling approach and assumptions

2.1. Transition path modeling

The development paths of the integrated energy–transport sectors and the potential impact of transition to renewable fuels are examined using the UniSyD_IS model. UniSyD_IS is a partial equilibrium system-dynamics model with a detailed representation of energy resources and technologies. It captures the interactions among supply sectors, energy prices, infrastructure development and fuel demand (Shafiei et al., 2015b, 2016).

The model comprises conventional and alternative fuel supply pathways as well as the corresponding vehicle technologies. As shown in Fig. 1, the whole model structure is divided into four main sub-modules: energy supply system, energy markets, refueling infrastructure, and consumer choice behavior. At the supply side, except for imported petroleum fuels, the fuel supply system is modeled from renewable energy sources including hydro, geothermal, wind, and waste biomass. The technologies modeled in the supply sector include hydropower, geothermal, wind turbine, hydrogen from electrolysis and different biofuel production technologies from biomass wastes. Since the main focus of this study is given to hydrogen and electricity trajectories toward a carbon-neutral transport, the following sections specifically describe these sectors in more details.

2.2. Electricity sector

2.2.1. Electricity demand and market price

The electricity market maintains one market clearing wholesale price that all generators compete in an open market. The operation of electricity sector is broken down into four steps: 1) determining the electricity demand that can be met by centralized generators, 2) associating a wholesale price with the amount of electricity demand, 3) determining post-transmission wholesale prices, and finally 4) setting retail prices. For a detailed description of the market simulation algorithm see Shafiei et al. (2015a).

The electricity demand sector is broken into two segments: a statically defined latent demand growth and the dynamic interaction of this definition with market price signals. The growth of residential and commercial electricity demand is assumed to be dependent on population growth. The growth of industrial electricity demand is linked to GDP growth. The transport electricity demand is determined based on energy use by EV fleets and electrolysis for hydrogen production.

2.2.2. Electricity generation

The electricity generation sector incorporates three key components: existing plant capacities, planned/future capacities, and generation costs by existing and future plants. The generation sector calculates the amount of electricity that can be supplied at various calculated wholesale prices. To decide on new capacity installation, first the excess electricity demand in future is estimated as the gap between the forecasted demand and total existing production capacity (including hydro, geothermal and wind power plants). Next, the capacity share of future plants to meet the excess demand is estimated as a function of production cost.

It is assumed that the existing geothermal and hydropower plants provide electricity at an average cost of 3.7 US-cent/kWh (Johannsson, 2011). The future hydro and geothermal prospects are expected to have higher supply costs, which are given by resource supply curves as illustrated in Fig. 2. Geothermal plants are assumed to emit 50 g/kWh of carbon dioxide (NEA, 2016a;