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Cost-effective energy carriers for transport – The role of the energy supply system in a carbon-constrained world

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ABSTRACT

The aim of this study is to examine how the options for producing electricity, fuels, and heat in a carbon-constrained world affect the cost-effectiveness of a range of fuels and propulsion technologies in the transportation sector. GET 7.0, a global energy system model with five end-use sectors, is used for the analysis. We find that an energy system dominated either by solar or by nuclear tends to make biofuels in plug-in hybrids cost-effective. If coal with carbon capture and storage (CCS) dominates the energy system, hydrogen cars, rather than plug-in hybrids tend to become cost-effective. Performing a Monte Carlo simulation, we then show that the general features of our results hold for a wide range of assumptions for the costs of vehicle propulsion technologies (e.g., batteries and fuel cells). However, sufficiently large changes in say the battery costs may overturn the impact of changes in the energy supply system, so that plug-in hybrid vehicles become cost-effective even if coal with CCS dominate the energy supply. We conclude that analyses of future energy carriers and propulsion technologies need to consider developments in the energy supply system.

1. Introduction

The optimal choice of transportation fuels and propulsion technology in a future CO_2-abating world is subject to debate. Three main alternatives are discussed, hydrogen, electricity, biofuels and (less frequently) synthetic fuels from coal with carbon emissions being offset through the use of biomass energy with carbon capture and storage [1,2]. These may be used in different combinations in four types of propulsion technologies, hybrids, plug-in hybrids, battery electric vehicles (BEV) and fuel cell vehicles (FCV).

Several studies have addressed the transportations fuel of the future. Jorgenson [3] and Eaves and Eaves [4] both compare electricity and hydrogen vehicles for transport, and they find electricity to be a more energy efficient option than hydrogen. However, they assume present energy supply technologies. Mierlo et al. [5], incorporate some future energy supply technologies in the analysis, and still conclude that electricity is the more efficient option. However, all hydrogen production options in the paper goes through electricity, which in the future not necessarily is true as hydrogen for instance may be produced from coal with carbon capture and storage. Further, neither of these papers makes consistent economic calculations of the different vehicles options, for this reason they cannot be used to draw any firm conclusions about the cost-effectiveness of various options.

The cost-effectiveness of future fuels and propulsion technologies will be dependent on the price of electricity, biofuels, and hydrogen, which in turn depend on the technology options available. Technology options have both a direct effect on the price, as some production technologies are cheaper than others, and an indirect effect as technologies available in the overall system affect the price of scarce resources such as biomass, oil, and natural gas. There

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are thus potentially important system interactions between the energy supply (electricity generation, fuel production, and industrial and residential heat) and the transportation sector. This is of interest since uncertainties pertain to the future technology options in the energy supply system for mitigating carbon dioxide emissions. Some uncertainties are of technical nature such as the cost of producing electricity from solar energy. Other uncertainties concern the resource base, how large are the oil and gas reserves, or how large is the carbon capture and storage potential. There are also political uncertainties. For instance, will the global society accept a large scale expansion of nuclear power, despite the risks of accidents and nuclear weapons proliferation?

A few system analyses of long-term cost-effective transportation fuels have been made. Some of these studies have, however, omitted important competing technologies. Kim and Moon [6] studied diffusion of hydrogen cars in Korea, but did not include plug-in hybrid vehicles as a competing option. van Ruijven et al. [7], made a similar global analysis, but did not include coal based liquid transportation fuels. Azar et al. [8], used an earlier version of the GET model to analyse the cost-effectiveness of biofuels compared to hydrogen in the transportation sector, but did not include plug-in hybrid vehicles. In their runs, biomass is most cost-effectively used for industrial process heat and residential heat, rather than for transportation.

Endo [9] used a MARKAL model to investigate the future role of hybrid gasoline cars and hydrogen fuel cell vehicles in Japan. He found that with a high carbon tax, hybrid gasoline cars are cost-effective in a transient phase between 2020 and 2040 and are thereafter replaced by hydrogen fuel cells cars. Similar results were obtained by Turton and Barreto [10] and Gül et al. [11], although the transition to hydrogen fuel cells takes place at the end of the 21th century. Grahn et al [12] studied cost-effective transportation fuels in an energy system model, and found the availability of carbon capture and storage and thermal solar power to have a large impact on which fuels that become cost-effective.

In this paper we analyse the long-term system effect on the road transportation sector in a carbon-constrained world using a global energy system model. The aim of this paper is to investigate how different technological options in the energy supply system affect cost-effective choices of transportation fuels and propulsion technologies.

The paper is structured as follows. Section 2 describes the model and parameters; Section 3 presents the scenarios. Section 4 contains the results and Section 5 an analysis to understand the mechanisms behind the results. In Section 6 there are wider discussions of the results, and Section 7 contains our conclusions.

2. The model

GET 7.0 is a global energy system model with five end-use sectors. The model finds the least cost solution given a carbon constraint, for the period 2000–2150, with a discount rate of 5% per year. Technology costs and performances are assumed at a mature level. Demand projections for heat and electricity are based on the MESSAGE B2 scenarios with stabilization level of 470 ppm CO_2-eq in 2100 [13], whereas the transportation demand scenarios are based on [8].

Five main energy carriers are represented in the model: petroleum based fuels such as gasoline and diesel, natural gas, synthetic fuels (synfuels) such as methanol, DME and Fischer–Tropsch diesel, hydrogen and electricity, see Fig. 1. There are four end-use stationary energy sectors with exogenous energy demand: electricity, feed-stock for chemical industry, residential and commercial heat, and industrial process heat. The transportation demand, also exogenously given, is in turn divided into different modes: rail, aviation, road, and sea, as well as into passanger and freight transport. For details about the electricity and transportation sectors, see [1,8].

In GET 7.0 we include a more detailed representation of industrial process heat, industrial feed-stock and residential heat compared to previous versions of the GET model. This influences the competition for scarce resources such as oil,

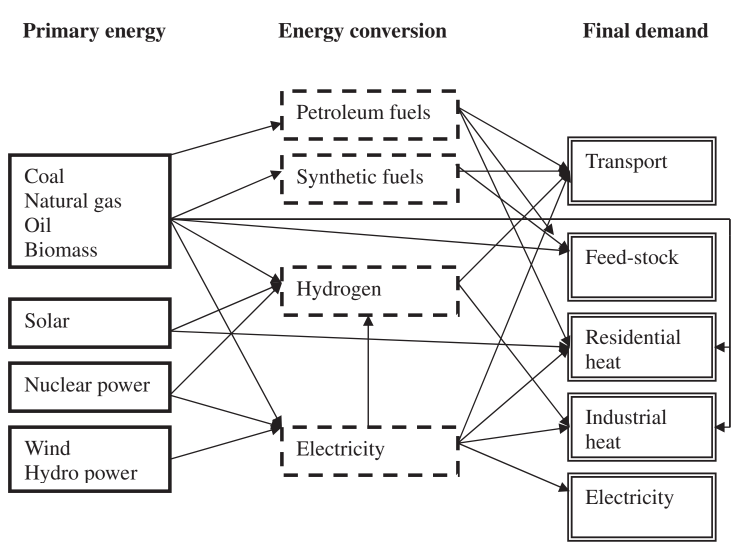

Fig. 1 – Structure of GET 7.0. Supply of primary fuels and energy carriers to end-use sectors.