Energy 34 (2009) 1423–1437

Contents lists available at ScienceDirect

Energy

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

An energy-economic scenario analysis of alternative fuels for personal transport using the Global Multi-regional MARKAL model (GMM)

Timur Gül [a,*], Socrates Kypreos [a], Hal Turton [a], Leonardo Barreto [a,b]

[a] Energy Economics Group, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
[b] Energy Economics & Policy, Austrian Energy Agency, 1150 Vienna, Austria

ARTICLE INFO

Article history:
Received 29 October 2008
Received in revised form
1 April 2009
Accepted 7 April 2009
Available online 5 July 2009

Keywords:
Hydrogen
Biofuels
Transport
Climate policy
Global Multi-regional MARKAL model

ABSTRACT

This paper deals with the long-term prospects of alternative fuels in global personal transport. It aims at assessing key drivers and key bottlenecks for their deployment, focusing particularly on the role of biofuels and hydrogen in meeting climate policy objectives. The analysis is pursued using the Global Multi-regional MARKAL model (GMM), a perfect foresight "bottom-up" model of the global energy system with a detailed representation of alternative fuel chains, linked to the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC). The analysis shows that biofuels are limited by the regional availability of low-cost biomass, but can be important for meeting mild climate policy targets. If policy-makers intend to pursue more stringent climate policy, then hydrogen becomes a competitive option. However, the analysis finds that the use of hydrogen in personal transport is restricted to very stringent climate policy, as only such policy provides enough incentive to build up the required delivery infrastructure. An analysis of costs additionally shows that "keeping the hydrogen option open" does not take considerable investments compared to the investment needs in the power sector within the next decades, but allows the use of hydrogen for the pursuit of stringent climate policy in the second half of the century.

1. Introduction

Global primary energy consumption in the year 2005 was almost 480 EJ, up from 229 EJ in the year 1971 [1]. Historically, this has been supplied primarily by fossil fuels, namely coal, oil and natural gas, which today account for approximately 81% of total primary energy supply, despite some growth in nuclear and renewables. According to the International Energy Agency (IEA) [1] as well as the US Energy Information Administration (EIA) [2], a continuation of current trends is likely to increase global primary energy demand to approximately 740 EJ by the year 2030, driven by strong growth in China and India and despite the impact of a number of policy measures expected to be taken in OECD countries.[1]

The transport sector – and in particular personal transport – plays a pivotal role in these energy consumption trends, mainly due to two key factors. First and foremost, it relies almost entirely on one fossil resource alone, i.e. petroleum and its products. Petroleum supplies 95% of the total energy used by world transport [3], and this high reliance on petroleum fuels translates into high CO_2 emissions as a result of the combustion process. The transport sector produced about 6.3 $GtCO_2$ emissions in 2005, or 23% of global energy-related CO_2 emissions [4], and the total amount of transport-related CO_2 emissions has more than doubled over the past almost 40 years (2.8 $GtCO_2$ in 1971).

The problem of CO_2 emissions from transport is likely to increase in the future as a result of the second key problem in transportation: the global demand for transport is projected to increase strongly in the decades to come as a result of economic development and growth [2,5]. Much of the growth is anticipated to take place in the developing world, notably in growing economies such as China, India or Brazil. Goldman Sachs expects China and India to emerge as the world's leading car markets, overtaking the United States in 20 (China) to 30 (India) years [6]; whereas the IEA projects that China will overtake the United States as the largest car market in the world even sooner, by 2015 [1].

The described developments are very likely to exacerbate the impacts on global climate change, as suggested by the latest report of the Intergovernmental Panel on Climate Change (IPCC) [7]. As a consequence, responding to the challenge of satisfying increased demand for energy and mobility, while at the same time combating climate change and maintaining and improving current levels of

* Corresponding author. Present address: International Energy Agency, 9, rue de la Fédération, 75015 Paris, France. Fax: +33 1 40576659.
E-mail address: timur.guel@iea.org (T. Gül).

[1] OECD = Organisation for Economic Co-operation and Development; Paris-based international organization with currently 30 mainly industrialized member countries.

0360-5442/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2009.04.010

energy security, is high on the agenda of policy-makers. As a means for tackling this challenge, alternative fuels such as hydrogen and biofuels have been advocated as potential substitutes for petroleum fuels in personal transport, but there is still a considerable need for an understanding of drivers and bottlenecks for their deployment. This paper aims at contributing to this understanding by looking into two key questions:

- What is the impact of pursuing different climate policy targets on the prospects of alternative fuels for reducing global CO_2 emissions from personal transport?
- What are key drivers and key bottlenecks for the deployment of alternative fuels, in particular for hydrogen?

The analysis is pursued using the Global Multi-regional MARKAL model (GMM), which depicts the global energy system as a whole recognising that although transport will need to play a pivotal role, energy system efforts will be needed to fully address climate change mitigation. GMM and its model features are introduced in Section 2. Section 3 presents the baseline scenario, which provides important insights regarding the extent of the challenge, and a frame of reference against which the impacts of climate policy can be assessed. In Section 4, the implications of pursuing different climate policy targets on the role of alternative fuels in personal transport are analysed. The analysis is complemented by a discussion of the sources of hydrogen production for selected scenarios, where hydrogen market penetration takes place, as well as an analysis of hydrogen delivery infrastructure as a potential bottleneck for hydrogen market penetration. Finally, Section 5 derives conclusions and policy implications.

2. Introduction to GMM

The analyses presented in this paper have been conducted using the Global Multi-regional MARKAL model (GMM), which was originally developed by Barreto [8] and has since then been enhanced and applied for numerous energy policy analyses [9–12]. GMM belongs to the MARKAL (MARKet ALlocation) family of models, i.e. a group of bottom-up, perfect foresight cost-optimization models that identify least-cost solutions for the energy system under given sets of assumptions and constraints and for a given time horizon [13–15]. For the analysis presented here, GMM was further enhanced starting from the version described in Ref. [11]. Model improvements dealt with an extension of the number of world regions (see Fig. 1), the representation of alternative fuel chains (hydrogen and biofuels) and the personal transport sector, as well as the representation of endogenous technological learning (ETL).

The reference energy system (RES) of GMM is depicted in Fig. 2 and covers the entire energy system from the extraction of resources, to conversion of primary energy carriers, to the use of final energy carriers in end-use technologies across different demand sectors. As for the latter, GMM distinguishes eight demand sectors, where personal transport is modelled in quite some detail. In the other demand sectors, a set of generic standard and advanced end-use devices is defined for each of the demand sectors (see e.g. Ref. [9]).

GMM possesses a high level of detail in the supply sector and energy conversion processes. Technology representation in electricity generation is a result of the work of Rafaj [9]; as a result of the present work, GMM additionally considers hydrogen and biofuels fuel chains as well as personal transport in much detail (see description of the hydrogen and biofuels modules below). The time horizon of GMM is 100 years divided into time steps of 10 years with the base year 2000. GMM applies a discount rate of 5% per annum in all calculations and for all technologies.

The multi-regional feature of GMM allows simulation of bi-lateral or global trade of energy or environmental commodities. Energy commodities traded in GMM include hard coal, natural gas, liquefied natural gas, oil, diesel and gasoline as well as biofuels. Energy commodity trade comes at a cost, estimated based on the latest version of the MERGE model originally developed by Manne et al. [16].

GMM is calibrated to reproduce year 2000 statistics of the IEA [17,18] on both the production and demand side. Most of the future sectoral energy demands of GMM, with the exception of transport, are based on the B2 scenario of the IPCC ("dynamics-as-usual" development) and have been taken from IIASA [19]. Future demand for personal transport is based on Ref. [20] until the year 2050. Thereafter, demand developments are based on Ref. [21]. For other transport sectors, future demand is assumed to grow at the same pace as the Gross Domestic Product (GDP) in the SRES-B2 scenario.

2.1. Resource availability

Fossil resources in GMM are based on Ref. [22] and distinguish different categories of coal, oil and natural gas. Each resource category is assigned to a price following [22], which reflect

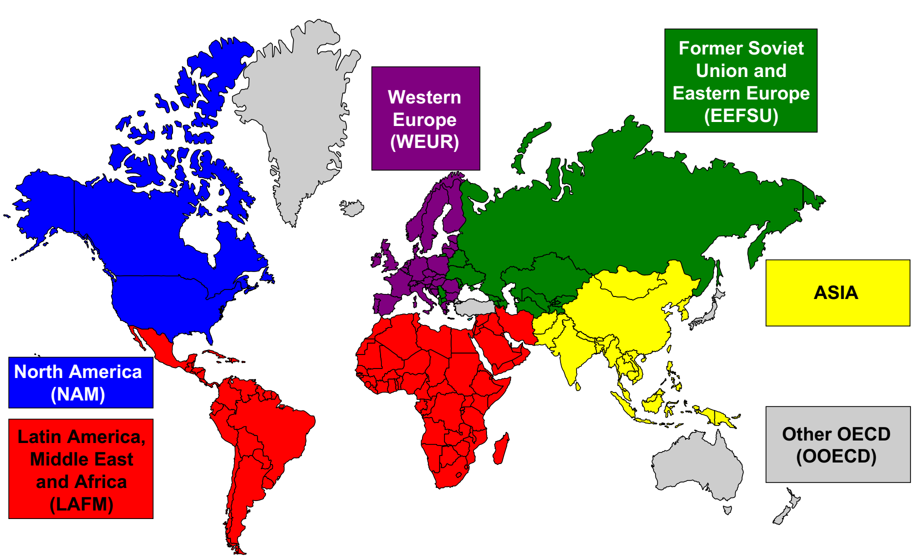

Fig. 1. The six world regions in GMM.