Energy Policy 36 (2008) 3925–3939

Contents lists available at ScienceDirect

Energy Policy

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

The role of biomass in California's hydrogen economy

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ARTICLE INFO

Article history:
Received 7 September 2007
Accepted 11 June 2008
Available online 22 August 2008

Keywords:
Biomass
Hydrogen
Supply chain optimization

ABSTRACT

This paper presents the results of a model of hydrogen production from waste biomass in California. We develop a profit-maximizing model of a biomass hydrogen industry from field to vehicle tank. This model is used to estimate the economic potential for hydrogen production from two waste biomass resources in Northern California—wheat straw and rice straw—taking into account the on the ground geographic dimensions of both biomass supply and hydrogen demand. The systems analysis approach allows for explicit consideration of the interactions between feedstock collection, hydrogen production, and hydrogen distribution in finding the optimal system design. This case study approach provides insight into both the real-world potential and the real-world cost of producing hydrogen from waste biomass. Additional context is provided through the estimation of California's total waste biomass hydrogen potential. We find that enough biomass is available from waste sources to provide up to 40% of the current California passenger car fuel demand as hydrogen. Optimized supply chains result in delivered hydrogen costing between $3/kg and $5.50/kg with one-tenth of the well-to-wheels greenhouse gas emissions of conventional gasoline-fueled vehicles.

1. Introduction

Both hydrogen and biomass-based fuels have received significant attention as future transportation fuels in recent years (IEA, 2005; NRC, 2004). The interest in these alternative fuels rests on their potential societal benefits including the possibility for deep reductions in well-to-wheels greenhouse gas emissions, and diversification of primary supply for transportation fuels away from dependence on petroleum. Hydrogen has the added benefit of zero tailpipe emissions.

Hydrogen's environmental benefits vary greatly depending on the primary energy source used to make hydrogen (IEA, 2005; Milliken et al., in press). One of the key questions is whether hydrogen can be produced at low cost with low emissions. Unfortunately, the most environmentally friendly hydrogen pathways tend to be the most expensive. Hydrogen from wind and solar could tap into vast, zero carbon resources, but are significantly more expensive than hydrogen from fossil sources (natural gas and coal), routes that, without carbon sequestration, offer modest or no benefit compared to gasoline hybrid vehicles (Milliken et al., in press; NRC, 2004). Biomass is a potentially interesting source for hydrogen as it could provide most of the environmental benefits of wind or solar hydrogen, at costs closer to those of hydrogen from natural gas or coal.

The near- and long-term outlook for biomass hydrogen is unclear. A recent study by the National Academies found that biomass hydrogen would be much more costly than hydrogen from natural gas or coal, suggesting a minor role, if any, for biomass hydrogen (NRC, 2004). Other studies suggest biomass hydrogen could be more competitive (Hake et al., 2006; Hamelinck and Faaij, 2006; Meyers et al., 2003). There is little consistency among these studies, and none have examined hydrogen in the context of the full biomass energy system. Clearly, biomass hydrogen faces several questions that need to be clarified in order to properly understand its place in the suite of future hydrogen supplies:

- Is there enough biomass to make a significant contribution toward fueling the transportation sector?
- Is biomass hydrogen economically viable? How would it compete with other near- and long-term sources of hydrogen?
- What are the environmental impacts of using biomass for hydrogen production, particularly with respect to carbon emissions?

Answering these questions in general is difficult due to the highly variable, geographically specific, nature of biomass resources. Different biomass resources are available in different regions. In addition, the density of the available feedstock can vary greatly between regions. The geographic variability is especially important due to the low energy density of both biomass and hydrogen, which leads to high transportation costs. It is, therefore,

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doi:10.1016/j.enpol.2008.06.037

crucial to consider the geographic context in making an assessment on the viability of biomass hydrogen.

The entire biomass hydrogen system, including biomass harvesting, biomass storage and transport, biomass conversion to hydrogen, and hydrogen delivery to users (see Fig. 1) must be considered in assessing biomass hydrogen. The costs of the biomass feedstock, hydrogen production and hydrogen delivery depend sensitively on scale and spatial layout (location and density of biomass resources and hydrogen users). Moreover, these costs are interdependent. For example, increasing the size of a production facility decreases the production costs through economies of scale but increases feedstock costs through increased transportation distances. Previous biomass hydrogen studies have not adequately considered the system as a whole, which has led to widely divergent delivered cost estimates for biomass hydrogen among different studies.

In this paper, we begin to tackle the questions stated above using a detailed case study of the hydrogen production potential from waste biomass in California. California is of particular interest for hydrogen research because of a wide range of policy measures encouraging low-carbon fuels in general (California Governor's Office, 2007; California State Assembly, 2006; Farrell and Sperling, 2007) and hydrogen in particular (Cal/EPA, 2005). Waste biomass resources are promising in California, especially in the near term. A recent assessment by the California Biomass Collaborative shows that biomass waste streams could be a significant resource: 24.3 million dry tons (1 ton = 1 Mg = 1000 kg = 1.102 short tons) of biomass were available in 2005 (CEC, 2004). Costs for waste biomass can be low or even negative. In addition, waste biomass resources do not pose a food versus fuel dilemma for the use of agricultural land. By contrast, the energy crops undergoing most research, switchgrass and short-rotation tree crops, are unlikely to play a major role in California (De La Torre Ugarte et al., 2003).

We explore the premise that in California, significant contributions could be made using waste biomass to fuel vehicles with hydrogen. To study biomass hydrogen systems, we have developed a mathematical model, which considers the biomass resources, hydrogen demands and prices to find the quantity of hydrogen from biomass that is likely to be made available. In the process, optimal biomass supply chains are found. Two important biomass waste feedstocks—rice straw and wheat straw—are used to demonstrate the model and give representative results for biomass hydrogen production supplies and costs.

2. Potential hydrogen production from waste biomass supply in California

Hydrogen production from California's diverse waste biomass resource base can be accomplished with two technologies, gasification and biogas reforming. Gasification produces hydrogen from dry biomass feedstocks (i.e. straws, stovers, and woody biomass). Most estimates report gasification conversion efficiency between 51% and 65% (Hamelinck and Faaij, 2002; Katofsky, 1993; Larson et al., 2005; Lau et al., 2003; Simbeck and Chang, 2002; Spath et al., 2003, 2005). To be conservative we assume 55% conversion efficiency. Biogas, a methane-rich gas, can be produced from the wet biomass feedstocks (manures, urban green waste, and food processing wastes) through anaerobic digestion. Biogas, landfill gas, and wastewater biogas are all methane-rich gases that can be converted to hydrogen through steam methane reformation. Current practice steam methane reformers achieve 70% efficiency (NRC, 2004). Biogas reformers may be less efficient; therefore, we assume 65% conversion efficiency for biogas to hydrogen.

We estimate that waste biomass resources in California could provide 335 petaJ (1 petajoule = 1 PJ = 10^{15} J) of hydrogen energy for transportation fuel. As seen in Fig. 2, the biomass in municipal solid waste represents the single largest resource available for exploitation. Waste products from various forestry operations, including forest and chaparral thinning operations for fire prevention, are the four next largest resources. Other important resources are the residues from orchards and field crops and landfill gas.

On an energy basis, the total biomass hydrogen production potential represents energy equivalent to 16% of the gasoline consumed in California in 2004 (Kavalec and Stamets, 2003). To assess biomass hydrogen's potential, the greater efficiency of

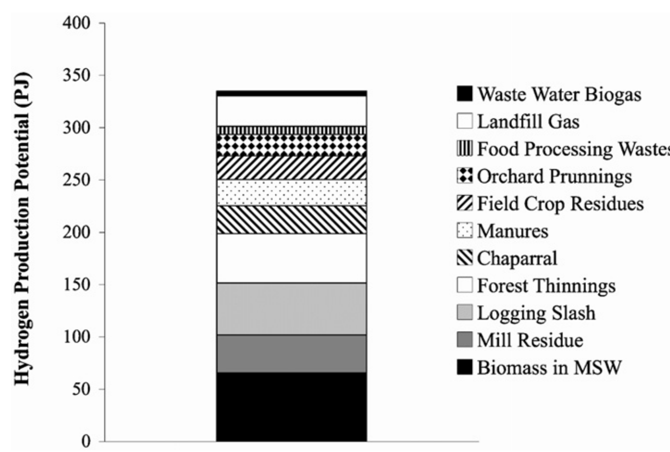

Fig. 2. Total potential hydrogen energy available from waste biomass resources in California. Biomass resource data is taken from California Energy Commission (2004). (1 PJ = 10^{15} J = approximately 7 million kg of hydrogen).

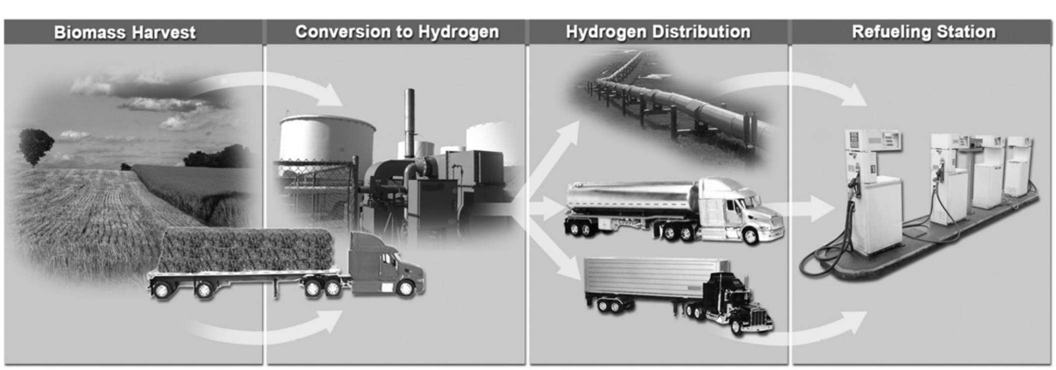

Fig. 1. Simplified picture of hydrogen production from biomass.