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Renewable and low carbon hydrogen for California – Modeling the long term evolution of fuel infrastructure using a quasi-spatial TIMES model

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ABSTRACT

This paper describes the development and use of a hydrogen infrastructure optimization model using the TIMES modeling framework, H2TIMES, to analyze hydrogen development in California to 2050. H2TIMES is a quasi-spatial model that develops the infrastructure to supply hydrogen fuel in order to meet demand in eight separate California regions in a least cost manner subject to various resource, technology and policy constraints. A *Base* case, with a suite of hydrogen policies now in effect or proposed in California (renewable hydrogen mandate, fuel carbon intensity constraint and prohibition on using coal without carbon capture and sequestration) leads to hydrogen fuel with significant reductions in carbon intensity (85% below gasoline on an efficiency-adjusted basis, 75% below on a raw energy basis) and competitive hydrogen costs (~\$4.00/kg in 2025–2050). A number of sensitivity scenarios investigate the cost and emissions implications of altering policy constraints, technology and resource availability, and modeling decisions. The availability of biomass for hydrogen production and carbon capture and sequestration are two critical factors for achieving low-cost and low-emission hydrogen.

1. Introduction, background and motivation

Hydrogen is one of the primary fuels that been identified as a means for significantly reducing greenhouse gas (GHG) emissions from the transportation sector [1–4]. While hydrogen is used quite efficiently in a fuel cell vehicle (FCV), the GHG emissions will depend on the resources and technology used to produce the hydrogen, and can vary widely. Hydrogen produced from renewables or fossil sources with carbon capture and sequestration (CCS) could lead to near zero well to wheel GHG emissions. Hydrogen has additional benefits relative to the incumbent fuel, gasoline, including significant reductions in criteria air pollutants, reduced use of imported petroleum fuels, and the ability to use a wide variety of domestic primary energy resources (including renewables).

One of the major challenges to widespread use of hydrogen as a transportation fuel is the lack of fueling infrastructure and the challenge of early station investment. Recently, a number of studies suggest that these problems could be overcome with government support for vehicle purchases and station infrastructure deployment and over time, the lifecycle cost of vehicles and fuel can be comparable or even lower cost than current gasoline vehicles [5,6].

The aggregate emissions benefits of hydrogen used as a light-duty transportation fuel will depend on the penetration of hydrogen vehicles in the light-duty vehicle market, the

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efficiency of fuel cell vehicles and the emissions associated with the production, delivery and refueling infrastructure for supplying fuel to hydrogen vehicles.

This paper describes the development and use of a modeling tool, H2TIMES, a quasi-spatial hydrogen energy system optimization model, to investigate the evolution of a low-carbon hydrogen infrastructure in California under different conditions and policy constraints. H2TIMES designs the least-cost hydrogen infrastructure (production, delivery and refueling) required to satisfy light-duty hydrogen demand and evaluates hydrogen cost, resource use, infrastructure development and emissions. The results are most interesting when seen in light of the policy constraints that are enacted to shape this transition. Specifically, the focus is on understanding how GHG constraints, renewable mandates and other "green" policies may affect the infrastructure choices and resulting emissions.

1.1. Literature review

There have been a number of analyses focused on the topic of the transition to a widespread hydrogen infrastructure. These are relevant to this study, which uses the TIMES modeling and optimization framework to develop a quasi-spatial hydrogen infrastructure transition model for California.

1.1.1. Hydrogen infrastructure component and supply chain models

A number of hydrogen studies are useful for understanding the technical and economic aspects of various technologies and specific components for producing, delivering and refueling hydrogen and vehicles. These sources include the National Research Council's hydrogen studies [1,7], the US Department of Energy's H2A project [8] and others (e.g. LBST's E3 model [9]). These analyses and technology databases are primary sources for information about hydrogen equipment and system costs and are used as the building blocks of more complex system design and optimization models.

Hydrogen supply chain (i.e. pathway) models combine the individual components into coherent pathways for producing, distributing and refueling hydrogen with the goal of understanding and comparing the costs, emissions, and resource requirements for various pathways. Yang and Ogden have developed several iterations of supply chain models using H2A and NRC data for hydrogen delivery as a function of spatial characteristics [10], a comparison tool for full pathways in seventy-three US cities [11], and to estimate costs of national infrastructure at different demand levels in the US [6,12]. Other hydrogen supply chain models have been developed at Argonne National Laboratory (H2A's HDSAM model for delivery [13]), and National Renewable Energy Lab (NREL's Macro-System Model [14]).

1.1.2. Hydrogen infrastructure transition models

There are a large number of hydrogen infrastructure transition analyses that focus on the dynamics of hydrogen energy system development. These models typically focus on hydrogen exclusively or even on specific aspects of infrastructure in a specified region in order to develop a better understanding of how these systems will work, and the best designs and pathway choices in order to minimize the cost of a transition to hydrogen fuel. These hydrogen case studies focus on the development of infrastructure with respect to the spatial characteristics of specific regions, such as Los Angeles/Southern California [15–17], Ohio [18], Beijing [19], Germany [20] and the US [5,21,22], though they often focus on different aspects of the transition.

1.1.3. Hydrogen in energy system models

A number of analyses have used energy system optimization framework (such as MARKAL/TIMES) to analyze long-term hydrogen fuel and vehicle adoption. These frameworks are used to optimize the entire energy system (i.e. identifying the resources and technologies that can meet energy demands at the lowest cost subject to various constraints). Unlike the previously described transition models which focus exclusively on hydrogen system evolution, energy system models have hydrogen as just one of many option that can be used to satisfy energy demands in the transportation sector (light-duty and sometimes other sectors like bus, rail, trucking). These models determine to what extent hydrogen can play a role within the energy system but given their size and complexity, these models tend to use a simplified representation of hydrogen infrastructure because of computational considerations.

The US Environmental Protection Agency (USEPA) incorporated hydrogen infrastructure and end-use technologies into the agency's nine-region US MARKAL model and includes two extensions of the MARKAL model [23,24]. Given the scope of a US model, the representation of hydrogen delivery is quite simplistic. Joffe et al., developed a MARKAL model of the United Kingdom (UK) and developed a Geographical Information System (GIS) based spatial model to better represent the layout of hydrogen infrastructure within the UK [25,26]. Other energy system models incorporating hydrogen include the International Energy Agency's (IEA) global Energy Technology Perspectives study which uses MARKAL [27] and USDOE's National Energy Modeling System (NEMS) [28].

1.1.4. Real-world hydrogen infrastructure

In 2012, over 200 hydrogen refueling stations were in operation in Europe, North America and Asia. An additional 200 stations are schedule to be installed by 2016. Commercialization efforts for hydrogen and fuel cell vehicles are being implemented around the world, including the European H2Mobility project (UK and Germany), Japan's hydrogen program and in California [29]. In California, the focus of this analysis, the California Fuel Cell Partnership has developed a roadmap for fuel cell vehicles and hydrogen stations [30], and there are incentives for vehicles and fueling infrastructure from state agencies (i.e. California Energy Commission and Air Resources Board).

1.2. Modeling and analysis goals for H2TIMES

The goal of the H2TIMES modeling is to develop a policy relevant, spatially-representative detailed hydrogen infrastructure transition optimization model for California. The purpose of the analysis is to understand the context and influence of different policies on the development, cost and emissions associated with hydrogen deployment in