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Greenhouse gas reduction benefits and costs of a large-scale transition to hydrogen in the USA

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ABSTRACT

Hydrogen is an energy carrier able to be produced from domestic, zero-carbon sources and consumed by zero-pollution devices. A transition to a hydrogen-based economy could therefore potentially respond to climate, air quality, and energy security concerns. In a hydrogen economy, both mobile and stationary energy needs could be met through the reaction of hydrogen (H_2) with oxygen (O_2). This study applies a full fuel cycle approach to quantify the energy, greenhouse gas emissions (GHGs), and cost implications associated with a large transition to hydrogen in the United States. It explores a national and four metropolitan area transitions in two contrasting policy contexts: a "business-as-usual" (BAU) context with continued reliance on fossil fuels, and a "GHG-constrained" context with policies aimed at reducing greenhouse gas emissions. A transition in either policy context faces serious challenges, foremost among them from the highly inertial investments over the past century or so in technology and infrastructure based on petroleum, natural gas, and coal. A hydrogen transition in the USA could contribute to an effective response to climate change by helping to achieve deep reductions in GHG emissions by mid-century across all sectors of the economy; however, these reductions depend on the use of hydrogen to exploit clean, zero-carbon energy supply options.

1. Introduction

Mounting concerns over climate change have intensified interest in hydrogen as a potential strategy to mitigate greenhouse gas emissions in the US. Over the last 10 years, technological advances in fuel cells, renewable energy and hydrogen production technologies have helped to spur the notion of a potential H_2 transition. While many analysts concede the general appeal and potential of a future hydrogen economy in the abstract, much debate focuses on whether the enormous investments required are best targeted toward other more cost-effective mitigation strategies (Eyre et al., 2002; Funk, 2001; Perry and Fuller, 2002; Romm, 2004; Rose, 2007a).

A considerable literature has emerged that has helped to shape an understanding of key elements involved in a hydrogen transition. Several "well-to-wheel" studies have focused on specific aspects of a transition and conducted comparative assessments of different feedstock's energy demands and avoided GHG emissions known (ADL, 2002; EU, 2004; Weiss et al., 2003). Mazza and Hammerschlag (2004) undertook a comparative study focused on a range of potential future systems that could meet the energy demands of either or both the electrical grid and the transportation sector while accounting for changes in greenhouse gas emissions. A central consideration of their paper was whether renewable are best employed to replace petroleum in vehicles or displace coal- and gas-generated electricity. The primary disadvantage of using H_2 technologies identified in their paper and others are the large inefficiencies associated with energy conversion. Despite the energy penalties hydrogen could play a role in transport and storage where electricity, to date, falls short (Mazza and Hammerschlag, 2004). McDowall and Eames' (2006) took a literature survey approach in which they identified various drivers for a hydrogen economy that underlie much of such research, as well as barriers, challenges, and likely characteristics of a hydrogen economy. They found that technological immaturity is a key constraint throughout the literature. Key technology improvements, for any transition pathway, are needed in fuel cell power density, longevity, economics, and fuel storage (McDowall and Eames, 2006). The analysis in our study includes the commercial scale deployment of technological pathways that

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are still being proven. The production and transmission of hydrogen has emerged as a critical element of any potential transition to hydrogen (Mazza and Hammerschlag, 2005; NRC, 2003; Brown, 2001). Centralized production facilities are more efficient, they also require storage systems, a pipeline transmission network, and pose physical energy security and environmental externality issues (Sørenson, 2005). Centralized hydrogen production could be achieved by several processes, including reforming natural gas or biomass and electrolysis from large-scale renewable installations, like solar ranches and wind farms whose generation potential are theoretically limitless (Mazza and Hammerschlag, 2004; Korpas and Greiner, 2008). Decentralized production is one way to overcome many of the infrastructural barriers to a transition (McDowell and Eames, 2006). Decentralized or on-site hydrogen production could take place in residential or commercial buildings, as could hydrogen storage for vehicles to be re-filled after daytime driving. This option could be particularly interesting as residential installation could provide residential and commercial users with their own electricity, heat and fuel for their vehicles (Rifkin, 2002; Sørenson, 2005).

Fuel cycle implications of potential hydrogen feedstocks are also an important aspect of understanding the GHG mitigation benefits of a hydrogen transition in the USA. The upstream processing to produce hydrogen affects its price, its net GHG reduction benefits, and its primary energy conversion efficiency (ADL, 2002; Lipman et al., 2004; Pembina, 2000; Ramesohl and Merten, 2006). Renewable energy-based fuel cycles have the lowest overall GHG emissions, but low-energy efficiency and high costs complicate their use. In the short-term, on-grid renewable energy yields greater emissions reductions when used to replace coal and not when used to produce hydrogen to replace gasoline in vehicles (Bossel et al., 2005; Bossel and Eliasson, 2003; Ramesohl and Merten, 2006). As such, the advancement of renewable energy-based hydrogen economy depends on a surplus of lower cost renewable energy on the grid (EU, 2004; Eyre et al., 2002; Mazza and Hammerschlag, 2004; Romm, 2004).

Until renewable sources become more abundant, reformed natural gas is the cheapest source of large-scale hydrogen—in both centralized and decentralized systems—and poses the fewest technical challenges (Eyre et al., 2002; Pembina, 2000). Bossel et al. (2005) argue that for most practical applications, natural gas can do what hydrogen does and is easier to package and distribute suggesting that merely transforming grid electricity and natural gas into hydrogen does not resolve the energy challenges we currently face. Many others argue that natural gas is best considered a transition fuel towards the ultimate goal of a renewable energy-based hydrogen economy (Dunn, 2001; EU, 2004; Weiss et al., 2000, 2003).

Demand side issues are an integral part of a transition and have been addressed in several ways. Smil (2003) argues that it will take several decades to make a transition, mostly due to the lack of infrastructure and the as yet unresolved chicken-and-egg problem (i.e., of particular concern for the transport sector, fuel cell vehicles will not be mass produced without sufficient consumer demand, which will not exist without a well-functioning hydrogen refueling infrastructure in place). Romm (2004) argues similarly, estimating that hydrogen vehicles are not likely to achieve even a 5% market penetration by 2030. A more rapid transition to hydrogen would likely only occur after strong government policy, a major shift in public's environmental values, and/or the presence of a major energy security threat. Events like these could force the necessary rapid and large shift towards domestic and renewable energy production that would enable a renewable energy-based hydrogen transition.

Other analysts have applied scenario analysis techniques to better understand the GHG reductions and cost implications of different transition strategies (Árnason et al., 2001; Bünger, 2004; Eyre et al., 2002; DOE, 2002; Shimura, 2007; Toshiaki, 2003). The US National Research Council's scenario analysis is one of the most aggressive for the introduction of fuel cell vehicles, with 40% of all vehicles in the US being FCVs by 2030, and 100% by 2038 (NRC, 2004). For the UK, Owen and Gordon (2002) analyzed a roadmap to achieving zero-carbon hydrogen powered vehicles, concluding that it would need to be implemented along with the development of a low-carbon national energy system strategy. Sweden, in working towards oil independence, has also promised sizeable investments in hydrogen research and development (Commission on Oil Independence, 2006). In Iceland, a six-phase plan for a national transition was analyzed. The final phase, slated for 2040, includes the export of hydrogen to Europe (Árnason et al., 2001; Árnason and Sigfússon, 2000).

At the policy level, debate has converged on several key obstacles and barriers (see, for instance, Solomon and Banerjee, 2006). First, the inertia of existing energy infrastructure and the large amount of investment in conventional energy resources continues to slow the transition towards less polluting energy sources. Second, much more research would be needed on the hydrogen supply chain—from well to wheels—to increase energy efficiency and cost-effectiveness; benefits of a hydrogen economy depend on how and from what sources hydrogen is produced. Third, the transportation sector, and in particular the passenger vehicle sector, is stuck in the "chicken-and-egg" problem. Some are optimistic, however, that research and development will overcome the chicken-and-egg problem. Ohi (2000) argues that "there are no technical showstoppers to implementing a near-term hydrogen fuel infrastructure for direct hydrogen fuel cell vehicles [... there are] other institutional issues to resolve, but fundamentally the technologies required are available [...the] issue here is timing and coordination of capital investments." Clearly, the chicken-and-egg problem is not unique to a hydrogen transition but applies to many other supply sources. One of the main benefits, in fact, of any fuel cell technology is the applicability of a more diverse fuel supply selection, rather than reliance on a single fuel like oil.

The current study takes the main technology and policy challenges identified in the literature review as a point of departure for a quantitative scenario analysis of how a hydrogen transition in the USA could plausibly unfold. This study explores hydrogen transitions in two contrasting policy contexts in four metropolitan areas: a "business-as-usual" (BAU) context where there is a continued reliance on fossil fuels, and a "GHG-constrained" context where the reduction of greenhouse gas emissions is a strong policy objective. The goal of the study was to understand the magnitude of the GHG reduction benefits in each metropolitan area (Boston, Denver, Houston, and Seattle) across different transition scenarios, together with the costs of the transition and the energy use implications for the study regions. The analysis applied an integrated framework linking vehicle and infrastructure technology, as well as environmental, regulatory, and economic systems in a full fuel cycle approach. For conciseness, this paper highlights results from the national transition and the case study of Boston with some cross-city comparison. Complete results from all study areas as well as a complete treatment of the fundamental calculation assumptions and technical material in support of our analysis is available in several online annexes (see Tellus, 2006).

2. Hydrogen supply

One of the primary appeals of hydrogen is that it can be produced from several energy sources and delivered in various