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Energy system analysis of the implications of hydrogen fuel cell vehicles in the Swedish road transport system

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ABSTRACT

The focus on pathways to reduce the use of fossil fuels in the transport sector is intense in many countries worldwide. Considering that biofuels have a limited technical production potential and that battery electric vehicles suffer from technical limitations that put constraints on their general use in the transport sector, hydrogen-fuelled fuel cell vehicles may become a feasible alternative. Introduction of hydrogen in the transport sector will also transform the energy sector and create new interactions. The aim of this paper is to analyse the consequences and feasibility of such an integration in Sweden. Different pathways for hydrogen, electricity and methane to the transport sector are compared with regard to system energy efficiency. The well-to-wheel energy efficiencies for hydrogen and electricity are used for estimating the energy resources needed for hydrogen production and electric vehicles for a future Swedish transport sector based on renewable fuels. The analysis reveal that the well-to-wheel system efficiencies for hydrogen fuel cell vehicles are comparable to those of methane gas vehicles, even when biomethane is the energy source. The results further indicate that an increased hydrogen demand may have a less than expected impact on the primary energy supply in Sweden.

Introduction

The Swedish road transport sector is heavily dependent on fossil energy sources and the transition to renewable or low carbon energy appears to be more difficult and costly than in the energy utility sector. In 2012, the total energy end-use in the Swedish road transport sector was 87 TWh, and 8.1% of this was biofuels (biodiesel, ethanol and biogas) [1]. In the same year, the electricity mix consisted of 48% hydropower, 4% wind power, 38% nuclear power, and the 10% combustion based combined heat and power to which 73% of the primary energy input was biomass [1]. The transition to vehicle technologies that use renewable energy sources is crucial to reduce the transport sector's impact on the global climate as well as on local air quality. Electric vehicles with energy stored in batteries or high-pressure hydrogen tanks can be a part of

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the solution for both problems. Electric vehicles with batteries are energy efficient but, with the current battery technology, limited in range, while compressed hydrogen in fuel cell electric vehicles (FCEV) provide sufficient range but infers energy losses during the production of hydrogen followed by an energy demand for compression and distribution. The advantages of both these types of electric vehicles can to some extent be combined in plug-in FCEVs, but many uncertainties remain for this type of vehicles, for example how to achieve reasonable costs [2]. Furthermore, to achieve high energy efficiency and reduce degradation in the vehicle systems, a suitable degree of hybridization and energy management strategy must be developed [2]. Vehicles fuelled by electricity or hydrogen will integrate the energy utility sector with the road transport sector with the benefits of introducing more renewable energy sources from the first to the latter while possibly providing load balancing opportunities for an increasingly complex power system. Battery electric vehicles have commonly been suggested for load balancing purposes, and so have plug-in FCEVs [2].

Both electric vehicles with batteries and FCEVs are probably necessary to achieve targets set by the European Union and the Swedish Government. Targets for the share of renewable energy, greenhouse gas emission reductions, and energy efficiency until 2020 are in place in the European Union, together with a specific target of 10% renewable energy in the transport sector [3]. As a continuation of the 2020 goals, additional binding targets until 2030 have been proposed by the European Commission: 27% renewable energy and 40% reduction of greenhouse gas emissions compared to 1990 [4]. A non-binding target for the transport sector has been set until 2050: 60% reduction of the greenhouse gas emissions in the transport sector and no conventionally fuelled vehicles in the cities [5]. According to an expert group established by the European Commission to evaluate future transport fuels, a range of technologies may be necessary to replace conventional fuels in the transport sector [6]:

- Electricity in battery electric vehicles (BEV) for short distances.
- Hydrogen and methane for medium distance.
- Liquid biofuels, synthetic fuels and liquid methane for longer transports and heavier vehicles.

The European Commission has issued a directive with the goal of providing the member countries access to infrastructure for methane, electricity and hydrogen (optional) for the transport sector [7], since the availability of such infrastructure is relatively limited in the EU when this article is written. The Swedish Government has surpassed the European Union in long-term ambition and declared a vision of a Sweden without net emissions of greenhouse gases by 2050 and, as a milestone, a fossil fuel independent road transport fleet by 2030 [8]. According to the Swedish Government's official report on the latter goal, the definition of a fossil fuel independent transport fleet is one consisting of vehicles running mainly on biofuels or electricity and the report proposes a combination of policy measures to achieve this [9].

A range of studies has compared the feasibility and consequences of new fuels and technologies considered for the transport sector. Several studies reach the conclusion that BEV are superior to hydrogen fuel cell vehicles in terms of well-to-wheel energy efficiency and emissions, at least when electricity is the energy source [10], but many of them also point out that BEV have a limited driving range and that the battery charging is time consuming [11–13]. It has been shown that in a well-to-wheel perspective it is more energy efficient to convert methane to hydrogen and use it in a FCEV instead of using methane in a vehicle with internal combustion engine (ICEV) [14], and that with methane as the primary energy source, hydrogen FCEV have the potential to achieve the highest emission reductions among the possible drivetrain alternatives (BEV was not included in this particular study) [15]. A study in the context of Switzerland concluded that with natural gas or biomass the well-to-wheel efficiency is comparable for plug-in electric vehicles and hydrogen FCEV [16], and another study reached the same conclusion, but for vehicles with a driving range above 160 km [13]. However, the Swiss study also mentioned that methane-fuelled vehicles may be an important part of a transport system based on renewable energy. Moreover, a life cycle assessment of transport solutions with wood biomass as the energy source indicated that ICEV with methane may have lower greenhouse gas emissions than a hydrogen FCEV when including the manufacturing of the car [17]. Plug-in hybrid electric vehicles fuelled with methane have also been put forward as an even further fuel resource efficient solution when natural gas and biomass are the energy sources, especially when considering range issues and infrastructure solutions [18].

Country-specific studies of the impact on greenhouse gas emissions of different hydrogen production pathways mentions the importance of considering the share of fossil fuels in the electricity production mix when producing hydrogen via electrolysis [19,20]. A study with a Norwegian perspective concluded that hydrogen has to be produced from renewable energy sources or natural gas with carbon capture and storage to achieve higher well-to-wheel energy efficiency and lower greenhouse gas emissions than hybridized diesel and gasoline vehicles [11]. In comparison, a study in a US context concluded that FCEV will reduce air pollution and greenhouse gas emissions compared to the current fossil fuelled vehicles, even if fossil energy sources are used to produce the hydrogen. In summary, most of the mentioned studies agree that it is not possible to find one optimal vehicle or fuel technology for a road transport sector based on renewable energy, but that electricity, hydrogen and methane are promising options for passenger vehicles, which also agrees with the findings of the expert group established by the European Commission [6]. In many of the studies cited in this article, the main focus of the well-to-wheel study is greenhouse gas emissions calculated in a national perspective with greenhouse gas emissions estimated from the current or near-term electricity mix. With this perspective, BEVs and FCEVs are evaluated as good options when fuelled by renewable energy sources, but the current and future electricity mix is crucial for the emissions if electricity is used directly in vehicles or for producing vehicle fuel. In an attempt to study these technologies in a slightly different future perspective, the approach used in this article is an explorative scenario, where one of the prerequisites is that only renewable energy is used in the transport sector, and

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