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The hydrogen economy – Vision or reality?[1] ☆

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ABSTRACT

When looking at future energy systems, hydrogen offers a range of benefits as a clean energy carrier, which are receiving great attention as policy priorities. This is first and foremost as an alternative fuel in the transport sector. Car makers have recently started the market introduction of fuel cell electric vehicles and are currently entering a pre-commercial phase, as they are progressing from prototype vehicles for demonstration to producing small volumes. At the same time, market development initiatives aiming at implementing hydrogen refuelling station networks are spreading in Europe, Asia, and the USA. But also in recent years, hydrogen electrolysis has gained considerable attention as a potential flexibility option to help facilitate the large-scale integration of intermittent renewable energies. Given the sustained interest in and controversial discussions on the prospects of hydrogen, this paper aims to provide a comprehensive coverage of the most relevant aspects related to the wider use of hydrogen in the energy system, including the most recent developments and insights.

Setting the context – the global energy challenge

Today's energy and transport system, which is based mainly on fossil energy carriers, can in no way be regarded as sustainable. Given the continued growth in the world's population from about 7 billion people today to over 9 billion by 2050, plus the progressive industrialisation of developing nations, particularly in Asia but likewise in South America, the global demand for energy is expected to continue to grow in the coming decades as well – by up to 50% until 2040, according to the International Energy Agency (IEA) [3] – with fossil fuels continuing to dominate global energy use. At the same time, there is a growing global consensus that greenhouse gas (GHG) emissions, which keep rising, need to be mitigated in order to prevent dangerous GHG induced climate change effects. Hence, security of supply and climate change represent two major concerns about the future of the energy sector which

☆ Note: The views expressed in this paper are those of the authors and shall not be attributable to any third-party person or organisation.

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List of abbreviations

BEV	battery electric vehicle
CGH_2	compressed gaseous hydrogen
CNG	compressed natural gas
CCS	carbon capture and storage
CTL	coal-to-liquid
DOE	(US) Department of Energy
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GTL	gas-to-liquid
HRS	hydrogen refuelling station
IEA	International Energy Agency
ICE	internal combustion engine
IGCC	integrated gasification combined cycle
ISO	International Organization for Standardization
LH_2	liquid hydrogen
LNG	liquefied natural gas
LPG	liquefied petroleum gas
NG	natural gas
PEM	polymer electrolyte/proton exchange membrane
PHEV	plug-in hybrid electric vehicle
PtG	power-to-gas
REN	renewable energies
SAE	Society of Automotive Engineers
SMR	steam methane reforming
SNG	synthetic natural gas
TWh	terawatt hour
VAT	value added tax

give rise to the challenge of finding the best way to rein in emissions while also providing the energy required to sustain economies.

The transport sector today accounts for nearly one quarter of primary energy use and related global CO_2 emissions, with the vast majority of emissions coming from road transport. Transport is also responsible for about 20% of the projected increase in both global energy demand and greenhouse gas emissions until 2040. At present, there are approximately 900 million light duty vehicles globally (not counting two- and three-wheelers), and over 2 billion vehicles are projected to be on the road by 2050, according to the IEA. Oil is still the largest primary fuel and covers more than 95% of transport energy demand. Reducing the oil dependence of the transport sector would therefore improve energy security and mitigate any anxiety about the economic and geopolitical implications of possible shortages in the supply of oil as a pillar of our globalised world based on transportation.

Transport systems perform vital societal functions, but in their present state raise a number of concerns, for instance with respect to local air pollution, climate change, congestion, land use, and noise. Local air pollution (responsible for particulate matter, ozone and acid rain), especially from road transport, is quickly becoming a major issue for urban air quality, particularly in the world's growing megacities, which calls for solutions. Greenhouse gas emissions from the transport sector and from fuel production are also increasingly subject to regulation around the world, especially in Europe, Japan and North America.

World transport energy use has doubled in the past 30 years and deep emissions' cuts will be required in the transport sector, in view of the required worldwide CO_2 emissions' reduction to combat irreversible and harmful climate change. However, mobility of people and transport of goods is one of the major drivers of economic growth and societal development. Reducing energy demand and CO_2 emissions from transport, especially from personal transport, therefore, poses a particular challenge.

The options for the road transport sector

A multitude of options exist to address needed reductions of emissions of CO_2 and air pollutants from road transport. The principal ones are demand-side measures aiming at reducing transport volume (e.g. by bringing about modal shift from private cars to public transport or by shifting freight transport from roads to rail), more efficient vehicles and cleaner fuels.

In the near and medium term, smaller cars, more lightweight and aerodynamic construction, efficiency improvements of internal combustion engines (ICEs), dieselisation[2] and hybridisation[3] can all contribute to further improvement of the fuel economy, thus helping to reduce overall fuel consumption and transport-related CO_2 emissions. But incentives need to be given likewise to car manufacturers (via emission standards) and consumers (via taxation or subsidies) to encourage the production and purchase of more low-fuel consumption vehicles. However, there is a point beyond which further improvements in CO_2 efficiency of ICE cars are limited and also increasingly costly.

To achieve a deep decarbonisation of road transport, longer term strategies must focus on developing alternative, low-carbon fuels and more efficient propulsion systems. This basically means the use of biomass-based fuels (biofuels) in ICEs and the use of electric drivetrains, which refers to a number of electric-drive vehicle options. The latter comprise

- pure *battery electric vehicles (BEV)*, using only electricity as "fuel", which is charged to the battery;
- *fuel cell electric vehicles (FCEV)*, using hydrogen as "fuel", which is stored on board the vehicle and converted to electricity by means of a fuel cell; and
- plug-in hybrid electric vehicles (PHEV), which combine a battery system with an ICE or fuel cell system.

[2] To give a theoretical example of what an improved fuel economy of vehicles could achieve: a dieselisation of the entire US light duty vehicles fleet or likewise replacing the current US gasoline vehicles fleet with more efficient European-like gasoline vehicles would result in fuel savings of as much as 2–3 million barrels of oil per day (out of a total oil consumption of about 90 million barrels per day globally).

[3] A combination of an ICE propulsion system with an electric propulsion system; there are different degrees of hybridisation, depending on battery involvement in the vehicle propulsion.