WELL-TO-WHEEL ANALYSIS FOR ELECTRIC, DIESEL AND HYDROGEN TRACTION FOR RAILWAYS

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1 ABSTRACT

This paper derives the energy efficiencies and CO_2 emissions for electric, diesel and hydrogen traction for railway vehicles on a well-to-wheel (WTW) basis, using the low heating value (LHV) and high heating value (HHV) of the enthalpy of oxidation of the fuel. The tank-to-wheel and well-to-tank efficiency are determined. Gaseous hydrogen has a WTW efficiency of 25 % LHV, if produced from methane and used in a fuel cell. This efficiency is similar to diesel traction, 26 % LHV, and electric traction in the UK 26 % LHV, USA 25 % LHV, and California 28 % LHV, considering the generation mix in 2008. A reduction of about 19 % in CO_2 is achieved when hydrogen gas is used in a fuel cell compared to diesel traction, and about 3 % reduction compared to US electricity. It has been shown that producing hydrogen from electrolysis via hydro or wind power leads to lower efficiencies than transmitting the energy through an electric grid. Further, hydrogen produced through a solar thermo-chemical process, and electricity generated from solar power, have similar efficiencies.

Keywords: well-to-wheel; railway traction; CO_2 emissions; railroad; hydrail; fuel cell

2 INTRODUCTION

Railways all over the world have to reduce their environmental impact; focus is usually given to reduce greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2). In the UK 63 % of all rail related CO_2 emissions are produced through traction, where 26 % are contributed from electric- and 37 % from diesel traction (Rail Safety and Standards Board Ltd., 2010). Autonomous vehicles have, therefore, the largest single impact on GHG emissions.

In the USA railways have the highest share of the freight transportation market with about 40 % measured in ton miles. To propel trains 3.9 billion gallons of diesel fuel are consumed annually by US railways. This represents approximately 99.5 % of their energy use for traction; the rest is electricity (U.S. Department of Transportation - RITA Bureau of Transportation Statistics, 2011).

A change in railway traction technology could have a significant impact on diesel fuel consumption and on carbon emissions. Additionally, petroleum based fuels are likely to become more expensive in the future as demand is increasing and supply decreasing, affecting railway operating costs.

Emissions and energy consumption are often measured at the point of use. This does not, however, account for the overall emissions and energy consumption. To evaluate the impact of fuels and energy carriers the whole supply chain has to be considered (Bossel, 2003; Wang, 1999). Well-to-Wheel studies have been conducted for various modes of transport, with a general focus on road transportation. Compared to other modes, railway vehicles have different duty cycles, power requirements, and useful lives. Furthermore, electricity is often used to propel railway vehicles, particularly in Europe, whereas for road vehicles this is not common, and in the air and maritime industry almost unheard of. This paper is one of the first applications of the Well-to-Wheel (WTW) methodology to the railway sector, considering the main railway fuels diesel and electricity. It, additionally, evaluates hydrogen as a potential energy carrier for railway vehicles.

This paper considers electric, diesel, hydrogen fuel cell, and hydrogen internal combustion engine (ICE) propulsion systems. Additionally, the supply chain of the fuel and its carbon content are presented. Electricity generation data are used for the United Kingdom (UK), United States of America (USA, US) and the state of California (CA). These areas have been chosen for the following reasons:

- The UK has mainline railways that have not yet been electrified, and has ambitious CO_2 reduction targets;
- The USA has very little electrification, as the distances covered by railway lines are long, making electrification less likely;
- CA has stringent emission standards, as well as a high contribution of renewable sources to the electricity generation mix (a similar level is planned to be achieved in many European countries in about 15-20 years time).

The calculations were repeated for the renewable sources: hydro, wind, and solar, to show how railways can reduce their impact and ensure their energy security.

2.1 Energy Consumption

A reduction in energy consumption of railway vehicles will lead to a lower environmental impact of the system. Cost savings for the railway operators may be possible, since the energy to propel trains has to be bought.

The energy consumption of a railway vehicle results from several factors; major elements are the efficiency of the various system components and the duty cycle. The overall energy efficiency is dependent on the vehicles drive train and the supply chain of energy, but not on the traction work provided by the vehicle, which is dependent on the physical characteristics of the vehicle, such as mass and its resistance to motion.

3 METHODOLOGY

The WTW analysis is an approach that considers the energy consumption and greenhouse gas emissions associated with production pathways and drive train systems. A WTW analysis includes the energy use and GHG emissions at every stage of the process from the original source (well) to energy delivery at the wheels (wheel). It is usually split into two stages: the well-to-tank (WTT) or fuel cycle stage, and the tank-to-wheel (TTW) or vehicle efficiency stage (TIAX LLC, 2007). This split allows the comparison of different vehicle drive trains, which are powered by the same fuel.

In contrast to heat engines, the natural form of energy to consider for electrochemical power devices, such as fuel cells, is the Gibbs free energy, ΔG. This notwithstanding, because most of the data in the literature are in terms of enthalpy, the energy calculations in this paper are based primarily on the change in enthalpy, ΔH. As indicated by the Gibbs equation, $\Delta G = \Delta H - T\Delta S$, where T is the absolute temperature at which the reaction occurs, we can calculate ΔG from ΔH if we know or can estimate the entropy.

The approach of using the low heating value (LHV) in WTW comparisons is commonly used and recommended by Wang (1999), the Department for Environment, Food and Rural Affairs (Defra), as well as the Department of Energy and Climate Change (DECC), (AEA, 2009). Calculations in LHV can lead in some instances to efficiencies above 100 %, e.g. 105 % for some condensing boilers, which is physically impossible (Bossel, 2003). The use of the high heating value (HHV) is consistent with the laws of thermodynamics and calculations have, therefore, also been presented in HHV. The conversion has been carried out on the basis that the quantity of fuel (mass, volume) does not change. The energy content of the different fuels has been taken from the U.S. Department of Energy (2008), and the carbon content of fuels has been based on information provided by the Department of Energy and Climate Change (AEA, 2009).

3.1 Assumptions

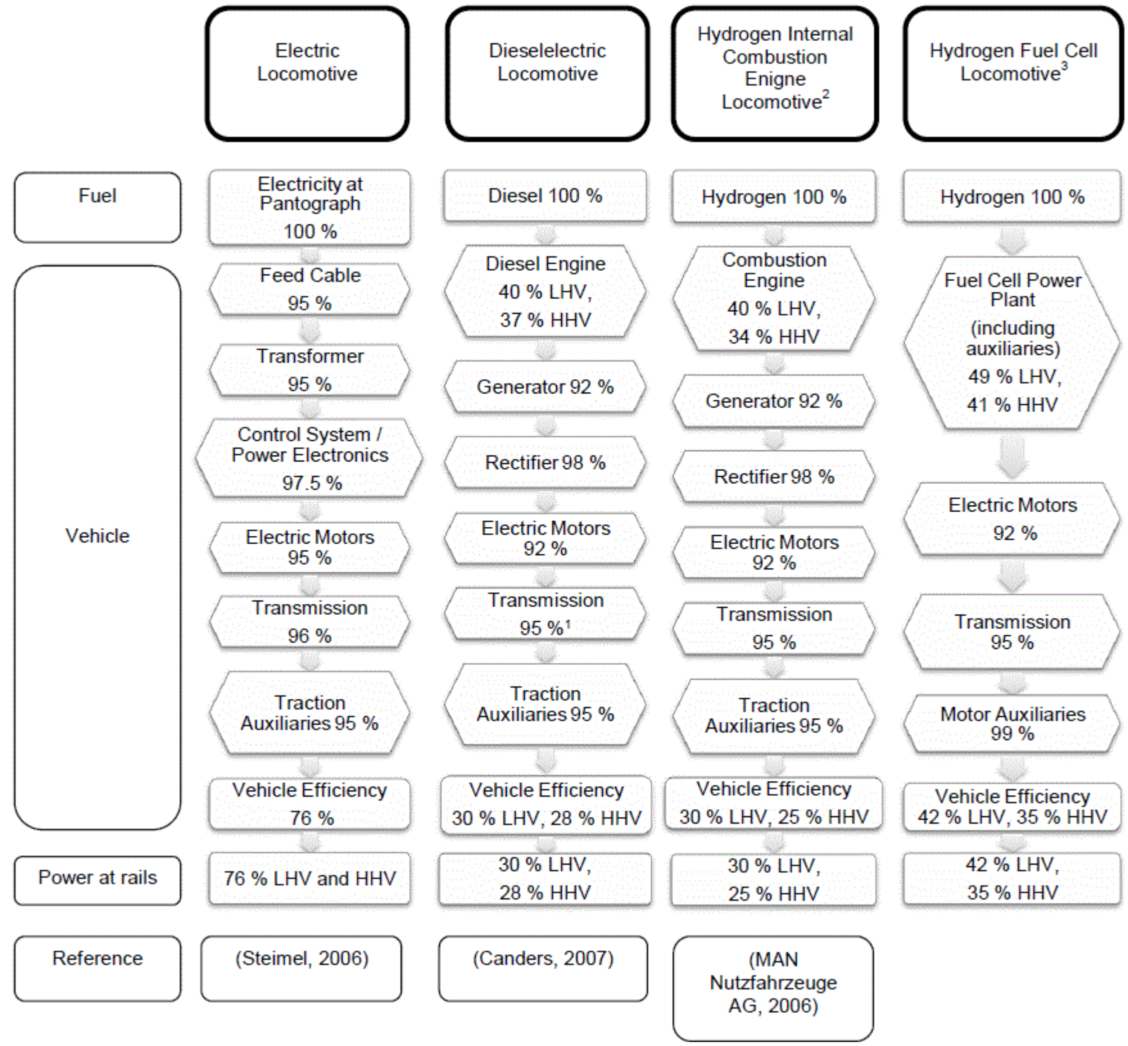
Carbon Dioxide (CO_2) emissions and high-level nuclear waste are considered emissions, any other GHG emissions are not considered. The CO_2 content of the fuels is based on UK data. It has been assumed that all regions use the same fuel types. The efficiencies of UK electricity generation power plants have been used for the USA and California. The diesel fuel cycle (WTT) and the natural gas based hydrogen cycle (WTT) are based on American data and has been used for the UK. The calculations are based on input data from various years. It is assumed that these figures are still representative. Regenerative braking is not considered, because it is not utilised widely. It could however be included by adjusting the vehicle efficiency. The vehicle efficiency for diesel and electric traction has been calculated with data obtained from literature. The ICE (diesel and hydrogen) is assumed to work at its highest efficiency. The hydrogen vehicle efficiency is based on the operational tests of the hydrogen hybrid switcher locomotive during trials in Los Angeles. The renewable mix in California is determined with the assumption that the efficiencies for biomass and geothermal power are based on the LHV. Electrical transmission losses in the power grid are based on the UK and have been used for the US and California.

4 VEHICLE EFFICIENCY

The vehicle efficiency of a traction unit is determined by how the energy that enters the vehicle is converted into traction work (TTW). Electric traction is based on an electric locomotive that is fed from a catenary line. Diesel traction is based on a diesel electric locomotive. Hydrogen can either be burned in an ICE or used in a fuel cell. Most existing rail vehicle prototypes use Proton Exchange Membranes (PEM) fuel cells (FC). Below are the vehicle efficiencies for both types. Fuel-cell traction employs fuel cells as the vehicle's prime mover. The fuel cell power plant efficiency has been established by the hydrogen hybrid switcher locomotive of Vehicle Projects Inc (Miller et al., 2010). This locomotive does not use regenerative braking, like electric and diesel traction in this paper, and has therefore been chosen. The efficiencies have been established in full service operation over a period of several months. Its power plant efficiency is 49 % LHV and 41 % HHV. Based on Gibbs free energy, the respective power plant efficiencies are 51 % and 50 %.

The company MAN built hydrogen ICEs for trucks that principally work like an Otto engine. The best efficiency of such an engine is 40 % (LHV) (MAN Nutzfahrzeuge AG, 2006). The tank-to-wheel chain is considered to be the same as for a diesel electric locomotive where the diesel engine is the prime mover. Figure 1, shows the efficiencies for electric, diesel, hydrogen fuel cell, and hydrogen ICE traction.

Figure 1: Vehicle Efficiencies



[1]Canders (2007) does not consider auxiliaries; the auxiliary value from Steimel (2006) of 95 % has been added.

[2]The Hydrogen ICE Locomotive does not exist. MAN produced a hydrogen internal combustion engine for a truck. In this comparison this engine substituted the diesel engine.

[3]For the fuel cell locomotive only the fuel cell power plant efficiency was determined. It is built from a diesel-electric locomotive, therefore, the efficiency chain from diesel has been used. Auxiliaries are already included in the power plant efficiency, so the auxiliary value at the end of the chain is motor specific.

The main conversion loss of energy occurs in the transfer from chemical energy into a different form. The vehicle efficiency of the electric locomotive is in comparison high, as the conversion from chemical to electrical energy already occurred at the electricity generation plants. The high efficiency of the fuel cell can directly be seen in the energy efficiency of the fuel cell locomotive.

5 WELL-TO-TANK ANALYSIS

The well-to-tank analysis establishes the losses from the original energy source (well) to the tank of the vehicle. The main stages in the WTT path are: (1) recovery, extraction and transport (RET); (2) refining or electricity generation; and (3) transport to the vehicle.

The WTT efficiencies in LHV, for electricity, and associated the CO_2 emissions per kWh delivered are: UK 34 %, with 0.61 kg CO_2 and 0.005 g of radioactive waste, USA 33 % with 0.648 CO_2 and 0.007 g of radioactive waste, CA 36 %, with 0.422 kg CO_2 and 0.005 g of radioactive waste. The WTT efficiencies in HHV, for electricity, and the associated CO_2 emissions per kWh delivered are: UK 32 %, with 0.61 kg CO_2 and 0.005 g of radioactive waste, USA 31 % with 0.651 CO_2 and 0.007 g of radioactive waste, CA 34 %, with 0.422 CO_2 and 0.005 g of radioactive waste. These figures have been calculated from information provided by (AEA, 2009; Barbier, 2002; Department of Energy and Climate Change, 2008a, b; E.ON AG, 2010; Evans et al., 2010; Muyeen et al., 2008; Nyberg, 2008; Seitz, 2010; U.S. Department of Energy, 2008; U.S. Energy Information Administration, 2008; Wang, 1999, 2003).

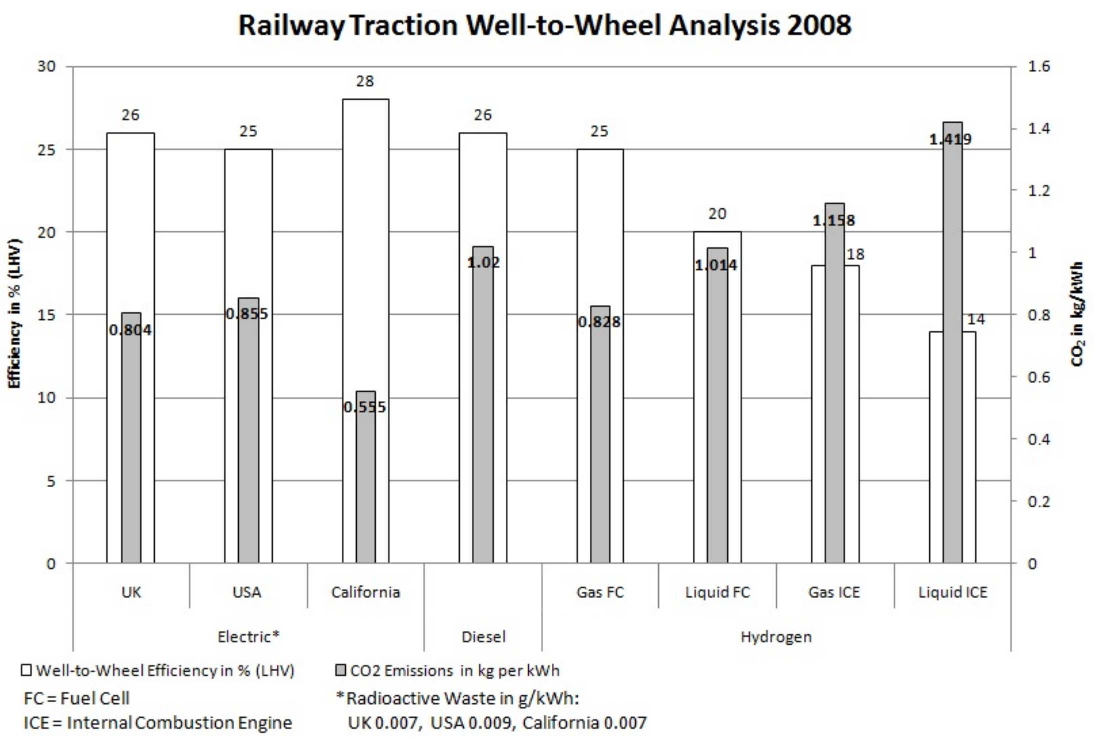
The diesel WTT efficiencies, first in LHV then in HHV, and the associated CO_2 emissions per kWh at the tank are: 86 % with 0.306 kg CO_2, and 86 % with 0.285 kg CO_2 (Wang, 1999, 2003, 2008).

The hydrogen WTT efficiencies and the associated CO_2 emissions per kWh at the tank are in LHV hydrogen as a gas 58 %, with 0.348 kg CO_2, hydrogen as a liquid 48 %, with 0.426 kg CO_2; and in HHV hydrogen as a gas 62 %, with 0.294 kg CO_2, hydrogen as a liquid 51 %, with 0.36 kg CO_2 (Wang, 1999, 2003).

6 WELL-TO-WHEEL

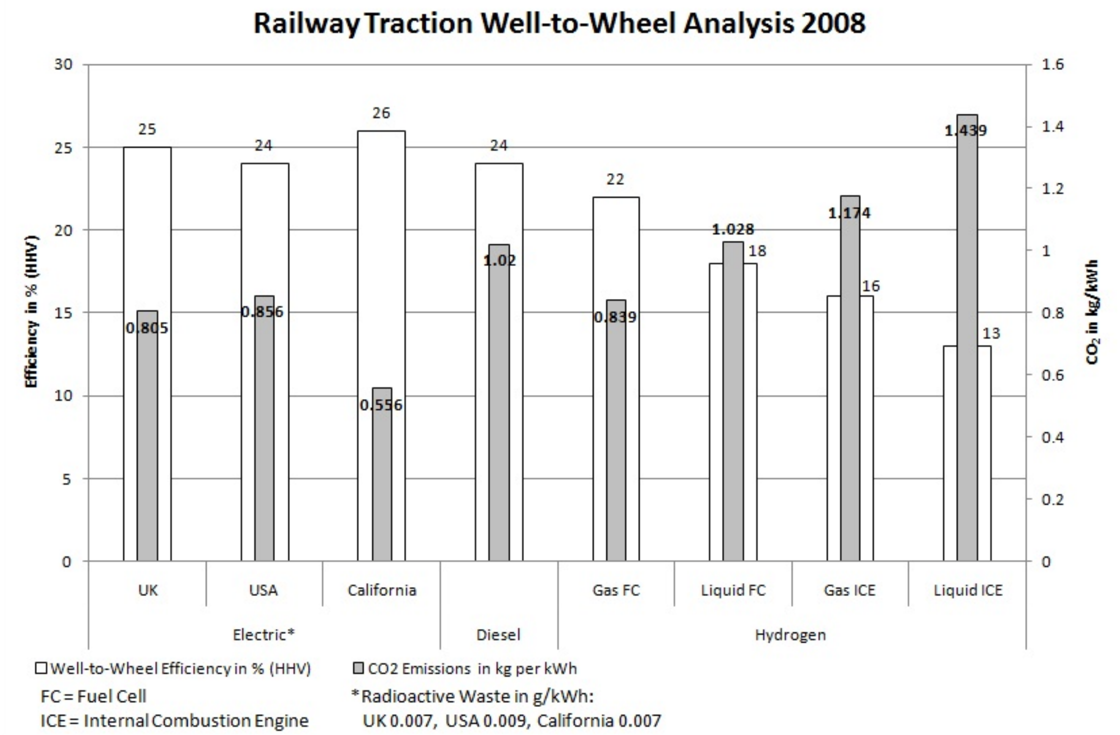
The combination of the vehicle efficiency (TTW) and the WTT figures give the WTW efficiency. Figure 2, LHV, and Figure 3, HHV, show the efficiencies and the emissions for electric, diesel and hydrogen systems, with electricity generation data from 2008.

Figure 2: Railway Traction Well-to-Wheel Analysis 2008 based on the LHV



Sources: (AEA, 2009; Barbier, 2002; Canders, 2007; Department of Energy and Climate Change, 2008a, b; E.ON AG, 2010; Evans et al., 2010; International Union of Railways and Community of European Railway and Infrastructure Companies [UIC], 2008; MAN Nutzfahrzeuge AG, 2006; Muyeen et al., 2008; Nyberg, 2008; Seitz, 2010; Steimel, 2006; U.S. Department of Energy, 2008; U.S. Energy Information Administration, 2008; Wang, 1999, 2003, 2008)

Figure 3: Railway Traction Well-to-Wheel Analysis 2008 based on the HHV



Sources: (AEA, 2009; Barbier, 2002; Canders, 2007; Department of Energy and Climate Change, 2008a, b; E.ON AG, 2010; Evans et al., 2010; International Union of Railways and Community of European Railway and Infrastructure Companies [UIC], 2008; MAN Nutzfahrzeuge AG, 2006; Muyeen et al., 2008; Nyberg, 2008; Seitz, 2010; Steimel, 2006; U.S. Department of Energy, 2008; U.S. Energy Information Administration, 2008; Wang, 1999, 2003, 2008)

The WTW efficiencies range from 14 % to 28 % (LHV), 13 % to 26 % (HHV). The 14 % and 13 % are for liquid hydrogen in an ICE and the 28 % and 26 % are achieved in California's electric system. The second highest WTW value is 26 % LHV, achieved with diesel traction and 25 % HHV is achieved with the UK electric system. The high efficiencies in California are due to the large contribution of natural gas and hydro generation. The CO_2 emissions range from 0.555 kg/kWh to 1.419 kg/kWh (LHV), 0.556 kg/kWh to 1.439 kg/kWh (HHV). The lowest CO_2 values (0.555 kg/ kWh LHV, 0.556 kg/kWh HHV) are achieved in California, due to the substantial utilisation of low and non carbons source for the electricity generation, such as large scale hydro, renewables, nuclear, and natural gas. The second lowest values (0.804 kg/ kWh LHV, 0.805 kg/kWh HHV) are achieved in the UK electric system. The high contribution of non- and low carbon sources, such as nuclear and natural gas are the reason for this. The comparison of diesel and hydrogen gas in a fuel cell, show that the WTW efficiency of diesel traction is higher but hydrogen traction would result in lower emissions. The use of ΔG for the efficiency calculations would lead to higher efficiencies and lower emissions of the hydrogen system, especially on the HHV basis. The high carbon content of a fuel is not necessarily offset by a high WTW efficiency; this can be seen in the example of diesel traction, where the WTW efficiency and the CO_2 emissions are high. The highest efficiency and lowest emissions can be achieved with electrification, if the electricity is produced with non- and low carbon sources, such as hydro, nuclear and natural gas.

Substitution of diesel traction with fuel cell vehicles using hydrogen-gas leads to a reduction of about 19 % LHV and 18 % HHV in CO_2 emissions. Hydrogen gas in a fuel cell vehicle yields a reduction in CO_2 of about 3 % LHV and 2 % HHV compared to the US electric system. The carbon reduction is, therefore, greatest in the US when the existing diesel fleet would be replaced by hydrogen gas fuel cell vehicles. In the UK the CO_2 emission of hydrogen gas fuel cell traction are about 3 % LHV and 4 % HHV higher than the electric system. In California the CO_2 emission of gaseous hydrogen in fuel cell traction would be about 30 %, LHV and HHV, higher than those in an electrified railway network. It should be recognised that this assumes that all the hydrogen is produced via steam methane reforming, whereas the electricity generation mix includes in all cases renewable and non carbon sources.

The development of more efficient fuel cells and improvements in the hydrogen supply chain, such as pressure drop pipelines, will increase the WTW efficiencies and lower the emissions of hydrogen traction.

6.1 Renewable Sources

The desire to become more independent from fossil fuels and to lower CO_2 emissions calls for renewable sources. Wind, hydro and solar sources are considered in this paper. The energy carriers investigated are hydrogen and electricity. Many renewable sources produce electricity; hydrogen can be generated with water and an electrolyser. In this paper the electrolyser efficiency is 71.5 % LHV, 84.6 % HHV (Wang, 2002).

Water flow can be used to generate electricity with an efficiency of about 90 %. These plants are an opportunity to produce hydrogen, as water and electricity for the electrolysis are present.

Wind turbines have a high theoretically efficiency, but the regularity with which the wind blows has to be considered, the load factor is 35 % (Muyeen et al., 2008).

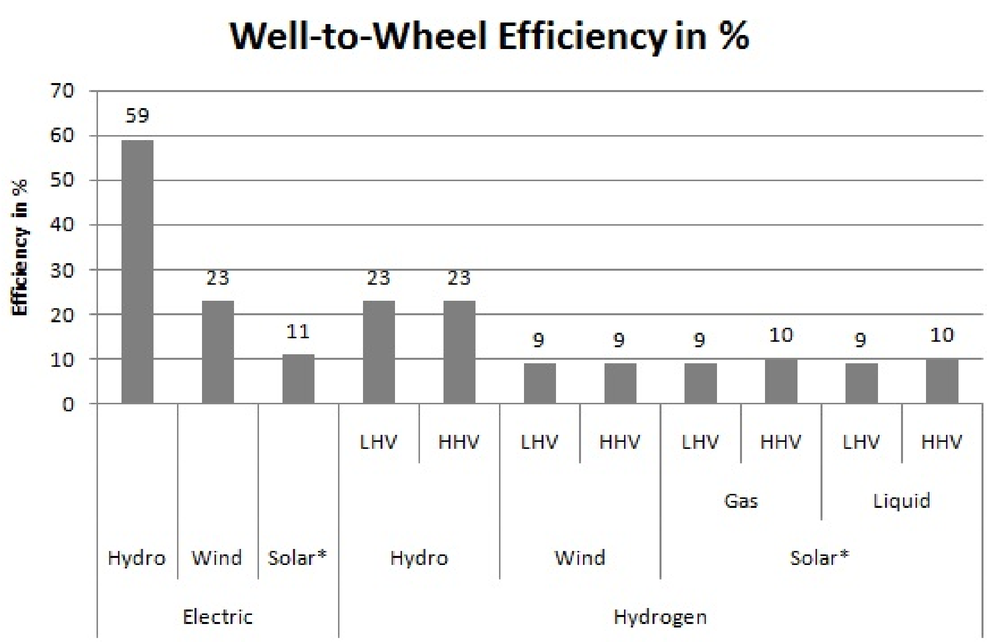
The energy return on a given piece of land is highest when the sun is directly converted into the required energy (Bossel, 2008). A 20 % conversion efficiency on about 0.1 % (approximately 500 km x 500 km) of available land, can provide the energy required by all people (Meier and Steinfeld, 2002). Solar to electricity power plants can achieve a year round efficiency of about 15 % (Solar Millennium AG, 2008). These power plants are located in Spain; sunnier areas will result in a higher efficiency, so the year round efficiency has been increased to 20 %. Large solar power plants are often not close to main demand centres, so the created electricity has to be transported. Long distances power lines, 1000 km and above, are usually HVDC to minimise losses. HVDC lines lose are about 3.5 % per 1000 km (Siemens, 2009) and losses for conversion from and back to AC are around 1.5 % (Grad, 2008).

Solar thermolysis of water will create hydrogen as an energy carrier (the necessary heat could also be provided by a nuclear reactor). A two-step thermo-chemical process using zinc and water has been developed. The conversion efficiency form sunlight to hydrogen is about 42 % (HHV). It is expected that this can be raised to 57 % (HHV) in the near future (Steinfeld and Weimer, 2010). Long distance distribution of hydrogen is likely to be by pipeline. Pumps are often installed approximately 160 km (100 miles) apart, per pump the efficiency is lowered by 1.5 % (Liu, 2003). Pipelines with pressure drops up to a distance of about 1600 km have been suggested, not requiring pumps and therefore having an efficiency of 100 %.

Liquid hydrogen distribution by ship is likely to be adopted to overcome oceans. For every 1000 km the efficiency is lowered by about 0.4 % (Wang, 1999, 2003).

Long distance overland transportation of liquid hydrogen is assumed to have a similar efficiency to ocean tankers. Figure 4 shows the WTW results for renewable sources.

Figure 4: Railway Traction Well-to-Wheel Analysis for Renewables



*The solar case includes long distance transport of 3000 km

Sources: (Canders, 2007; Department of Energy and Climate Change, 2008a; E.ON AG, 2010; Grad, 2008; International Union of Railways and Community of European Railway and Infrastructure Companies [UIC], 2008; Liu, 2003; MAN Nutzfahrzeuge AG, 2006; Muyeen et al., 2008; Siemens, 2009; Solar Millennium

AG, 2008; Steimel, 2006; Steinfeld and Weimer, 2010; U.S. Department of Energy, 2008; Wang, 1999, 2002, 2003)

In the case of hydro and wind the losses of the electric system are significantly lower than in the hydrogen system. The available areas to build new hydro power plants are limited. Hydro electricity may, therefore, not be available for electrification plans of railways. The solar efficiencies over a distance of 3000 km are similar between the electric- and the hydrogen systems.

A key issue with wind and solar power is the intermittence of solar radiation and of winds. Storage mediums can cover the fluctuations and provide dependable and uninterrupted energy output. No large scale, longer term electricity storage system, except for pumped hydro and some air pressure storage, does exist.

The current electricity production system has base load power plants that cannot react quickly to a change in demand. At low demand times, e.g. at night, production exceeds demand. The generated electricity is then often 'stored' in pumped hydro plants to be released a peak demand time. This can be utilised to balance the unpredictable power production from renewable sources, like wind and solar. The available locations for pumped hydro plants, and air pressure storage, are however limited. Hydrogen as a storage medium is for this reason very useful and is already utilised to make wind power more dependable (Aklil, 2010).

The relatively unpredictable production of electricity through wind turbines and the inflexibility of the present electricity generation can lead to electricity prices below zero, which happens frequently (Woitas, 2010), and for this reason hydrogen production to stabilise the power generation from wind turbines becomes increasingly important. The use of hydrogen as a storage medium reduces the need for backup power plants, usually gas fired, to stabilise the grid. Hydrogen has the additional advantage that it can be sold as a valuable product in its own right, e.g. as a transportation fuel; the lower overall efficiency less of a concern.

The distribution of solar hydrogen over long distance, such as 3000 km and above, may be as a liquid. Solar electric and liquid solar hydrogen distribution systems have the same efficiency between 5000 km and 7100 km, any longer and hydrogen becomes more efficient. The most efficient mode of hydrogen distribution up to a distance of 2.500 km is in gaseous form via pipelines. Pressure drop pipelines would make the solar hydrogen gas system more efficient than the solar electric version.

7 CONCLUSION

The paper shows that a high WTW efficiency reduces the amount of energy needed from the original source and that a reduction in overall emissions is possible.

The case of Diesel traction demonstrates that a high WTW efficiency does not automatically lead to lower emissions. Hydrogen as an energy carrier to provide power for railway vehicles is a suitable solution on an efficiency and emission basis, if a fuel cell is used. The WTW efficiency is similar to electric and diesel systems, but the CO_2 emissions are lower than for diesel traction. If electricity is largely produced from high carbon fuels, a reduction of CO_2 is possible through the utilisation of hydrogen when produced from natural gas; the USA case shows a reduction of 3 % in CO_2. Hydrogen production from renewables reduces the CO_2 emissions further. Compared to diesel traction the CO_2 emissions are reduced by about 19 % if hydrogen gas is produced from steam methane reforming and used in a FC vehicle.

Hydrogen can be used to ‘store’ electricity, and can therefore increase the supply dependability of renewables. The created hydrogen can be converted back into electricity or can be sold as a valuable product for direct use, e.g. as a transportation fuel. No other storage medium for electricity offers this possibility. High losses through the use of electrolysis do lower the overall efficiency and it should only be used if the main objective is electricity storage.

The WTW efficiency of sun radiation into electricity or hydrogen are similar. Liquid hydrogen becomes the most efficient on a WTW basis, compared to hydrogen gas and electric transmission, for distances longer than 7100 km. Liquefaction requires large amounts of energy and should be avoided when the distances are shorter.

In regions were large amounts of hydro power are available and the distances are short, electrification may be the preferred choice. However the large initial investment to carry out electrification may prohibit future schemes especially over long distances. Hydrogen is able to provide a sustainable alternative.

This article has not considered other benefits of hydrogen, such as lower noise levels and no particle emissions compared to diesel traction, and reduced visual impact compared to electrification. In urban areas, such as Los Angeles, these factors are significant; hydrail vehicles would contribute considerably to the improvement of local air quality, especially along busy rail corridors. Further work will be carried out in determining the most suitable railway services for hydrogen traction and the cost of implementation.

In this paper a WTW analysis for a number of different fuel and vehicle combinations has been conducted. This method is essential for meaningful comparisons. If comparative analysis does not use WTW, then there is a possibility of the not using common boundaries on the energy chain, and therefore the results may not be comparable, and bias towards specific results may be introduced. It has been demonstrated that hydrogen is a suitable energy carrier for railway vehicles on an efficiency and emission basis. These vehicles offer a reduction in GHG emissions and WTW efficiencies are similar to electric and diesel traction. Hydrail vehicles contribute, therefore, to achieving GHG reduction targets.

8 ACKNOWLEDGEMENTS

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