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Environmental benefits of transport and stationary fuel cells

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Abstract

The potential environmental benefits of using fuel cells in cars, buses and stationary combined heat and power (CHP) plants of different sizes have not been well-researched. This environmental analysis was conducted for the UK on a 'full fuel cycle' basis, encompassing all greenhouse gas and regulated pollutant emissions for the supply chain and end-use technology under consideration. Solid polymer fuel cells (SPFCs) with methanol or natural gas reformers were analysed for cars, SPFCs and phosphoric acid fuel cells (PAFCs) with on-board hydrogen for buses. CHP plants were PAFCs or solid oxide fuel cells (SOFCs). Each option was compared with one or more conventional technologies. In all cases fuel cell technologies have substantially reduced emissions in comparison with conventional technologies. Regulated emissions are lowest, by up to two orders of magnitude, and those that do occur are primarily in the fuel supply chain. The fuel cell technologies are more efficient in all cases, and carbon dioxide (CO_2) emissions are reduced broadly in line with energy savings. Methane emissions increase due to fuel switching, e.g. from petrol to natural gas powered buses, but from a very low base. The study pinpoints some areas in which alternative approaches could be made – the methods for generating and transporting hydrogen have a significant bearing on energy consumption and emissions. However, it is clear that from an overall emissions perspective the use of fuel cells in transport and power generation is highly beneficial.

Keywords: Fuel cell; Emissions; Carbon dioxide; Regulated pollutants; Hydrogen; Methanol; Cars; Buses; CHP

1. Introduction

This work attempts to model the overall amounts of pollutant emissions and energy consumption that would be caused by the widespread use of fuel cells in the UK. These are contrasted with equivalent data for conventional technologies that will be used in the near future. The emissions considered are oxides of nitrogen (NO_x), oxides of sulphur (SO_x), carbon monoxide (CO), non-methane hydrocarbons (NMHC), particulate matter (PM), CO_2 and CH_4. In addition, the model tracks the total use of primary energy in each case.

For each type of end use considered – cars, buses, CHP and power generation – the emissions and energy uses are taken into account along the entire supply chains. The result is expressed as per 'unit of end-use'. For example, the total emissions for a fuel cell car are given as grams per kilometre driven.

The different types of fuel cell systems considered in this work have many elements in common. The quantitative modelling therefore proceeds in a modular fashion in order to allow the re-use and consistency of model elements common to several applications. The modules used in the present work are schematically depicted in Fig. 1. For each type of fuel cell application, the model calculation has to start at the point of end-use, working its way backwards through the system until it encounters one or more sources of primary supply. The actual calculations are done by means of a spreadsheet programme.

The work underlying this paper was performed under contract to ETSU as part of the UK Department of Trade and Industry's Advanced Fuel Cells Programme. A report detailing that study and its conclusions is available [1]. Several parts of the supply chains in the various fuel cell applications have already been analysed in some detail in a recent investigation by ETSU [2].

These were imported as a whole into the present investigation. The elements concerned are the supply chains for conventional petrol and diesel cars; conventional diesel buses; the supply of electricity; the upstream production and refining of conventional road fuels; and the production and distribution of natural gas. These elements are marked by the shaded boxes in Fig. 1. The ETSU report [2] provides

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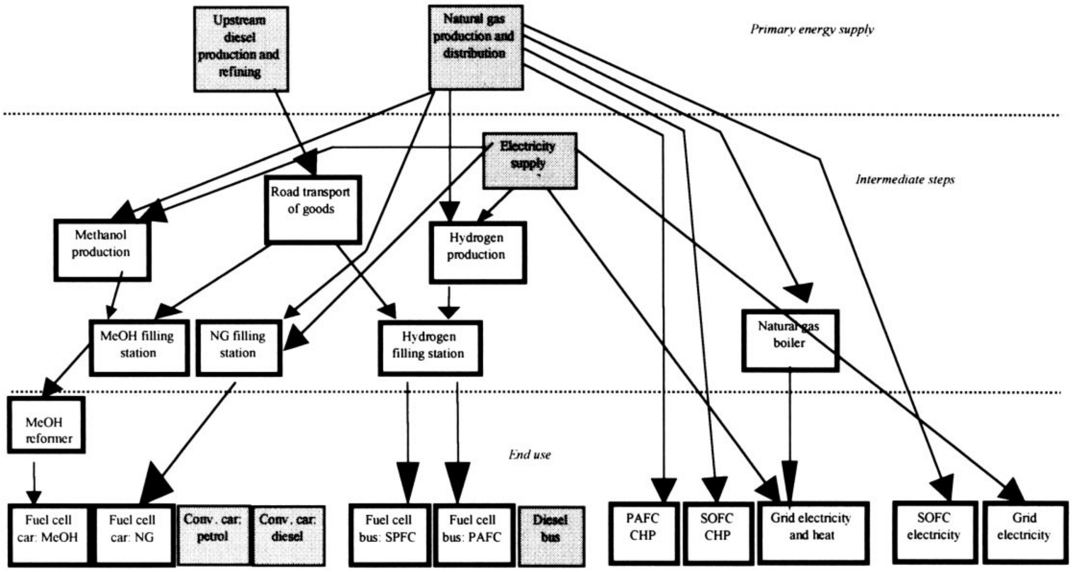

Fig. 1. An overview over the organisation of the quantitative model. See text for details.

data for the present average fleet of the UK, and it is this and the projected Euro III standards with which the fuel cell technology is compared.

2. Cars

In this section, two fuel cell applications are contrasted with two conventional technologies. In both cases, solid polymer fuel cells are considered.

2.1. Key assumptions

In the following, the major assumptions in the formulation of the model are listed. All system parameters (Table 1) have been subjected to a sensitivity analysis, described further below.

2.1.1. Fuel cell car powered by methanol

In this configuration, methanol is converted into hydrogen fuel by means of an on-board steam reformer. The methanol is produced from natural gas on an industrial scale and shipped to road-side filling stations in conventional road tankers.

2.1.2. Fuel cell car powered by natural gas

Here, natural gas is stored in pressurised form on board the car. It is processed into a hydrogen-rich gas by means of a high-temperature steam reformer. The on-board configuration for the natural gas-powered car is largely identical to the methanol-powered one, apart from the emissions of the reformer, which are assumed identical to those of a large-scale industrial reformer. This latter assumption is necessary because no on-board natural gas reformers have been built and tested.

2.1.3. Conventional cars

Both petrol and diesel powered cars have been modelled. The petrol car is considered as the base case with which all

Table 1

Key parameters for the modelling of the fuel cell car

Parameter	Value and source	Comment
Energy at the wheel: fuel cell car	0.405 MJ/km [3]	Calculated using 15% vehicle efficiency
Drive-train efficiency	0.731 [3–5]	
Fuel cell stack efficiency	0.58	Using hydrogen, drive cycle average
Fuel cell stack efficiency	0.539	Using reformate
Air compressor parasitic load	20%	Of primary power produced
Methanol reformer efficiency	0.77 [4]	
Regenerative braking	10%	Assumed energy recovery
Methanol delivery distance	450 km	Assumes two plants in UK
Natural gas compression energy	0.12 kWh/Nm^3 [6]	Compression to 250 bar

‘Energy at the wheel’ is the energy at the axle required to move the vehicle – not fuel consumption. The emissions from the on-board reformer correspond to steady-state operation [4]. They may be higher under transient conditions. The emissions in the production of methanol are assumed to arise exclusively in the burners used for process heating. Values for commercial low-NO_x burners have been used. The methanol plant is fed with natural gas from the high-pressure part of the network.

Table 2

Total systems emissions and primary energy use linked to passenger cars

Application		NO_x (g/km)	SO_x (g/km)	CO (g/km)	NMHC (g/km)	CO_2 (g/km)	CH_4 (g/km)	PM (g/km)	Energy (MJ/km)
Petrol car	Absolute values	0.26	0.2	2.3	0.77	209	0.042	0.01	3.16
Diesel car	Absolute values	0.57	0.13	0.65	0.25	154	0.03	0.05	2.36
	Relative to petrol	219%	64%	28%	33%	74%	72%	489%	74.6%
MeOH fuel cell car	Absolute values	0.04	0.006	0.014	0.047	130	0.072	0.0015	2.63
	Relative to petrol	15%	3%	0.6%	6.1%	62%	169%	14%	83.3%
Natural gas fuel cell car	Absolute values	0.024	0.0063	0.0074	0.019	83	0.059	8.5×10^{-6}	1.69
	Relative to petrol	9.1%	3.2%	0.32%	2.6%	40%	137%	0.08%	53.4%

the others are being compared. The emissions of the cars themselves are assumed to conform to the EURO III proposals. The emissions for the UK fuel supply chains are taken from [2].

2.2. Cars: results and discussion

The outcome of the model calculations is summarised in Table 2 and Fig. 2. The environmental benefit of fuel cell cars is clear: CO, SO_x, NMHC, NO_x, and PM emissions are down by one to two orders of magnitude. For the natural gas-fuelled fuel cell car, PM emissions are almost entirely absent. CO_2 emissions for the methanol car are 62% of the petrol car; 40% for the natural gas-powered fuel cell car. Methane emissions rise by around half, from a low base of 0.04 g/km. This is a fuel switching effect but is important as methane is a greenhouse gas; nevertheless reductions of up to 60% in CO_2 cause the overall global warming potential (GWP) to drop significantly [7].

Not only are emissions from fuel cell cars far lower than those of conventional cars, but a considerable part occurs away from the end user, i.e. higher up the supply chain. For the methanol-powered fuel cell car, most of the emissions of NO_x, CO, NMHC and SO_x are caused either in the natural gas extraction and processing or in methanol production and electricity generation. This suggests potentially even higher benefits of fuel cell cars, if their supply infrastructure can be made to match the cleanliness of the technology itself.

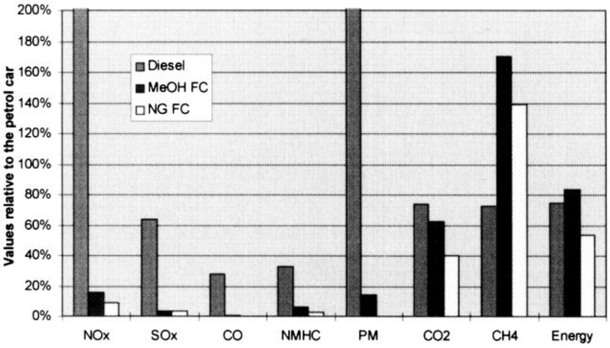

Fig. 2. System-wide emissions and energy consumption from cars. They are shown relative to those of a petrol car that conforms to the proposed EURO III standards.

The natural gas-powered fuel cell car shows the environmental performance of a technology that does not depend on road tankers (the filling stations for compressed natural gas take their feedstock from the gas grid). Its emissions are even lower than those of the methanol car, and they occur almost exclusively in the upstream part of the supply system.

Interestingly, emissions of CO_2 are reduced even more than the energy consumption. This is because using fuel cell cars implies a fuel switch from petroleum to natural gas, which is less carbon-intensive per unit of energy.

3. Buses

In this section, two types of fuel cell buses are contrasted with a conventional diesel bus.

3.1. Key assumptions

Both types of fuel cell bus are fuelled with compressed hydrogen, produced from natural gas in a large-scale steam reformer. The plant is supplied from the high-pressure natural gas grid, avoiding the leaks associated with the low-pressure part of the system. The hydrogen is then compressed and transported by road in diesel-fuelled delivery vehicles to the bus depot. This corresponds to a situation in which the small-scale production of hydrogen on-site has not become widespread.

3.1.1. Fuel cell bus

A bus with a SPFC engine can be modelled well because several such vehicles have been built and documented [8]. The main model assumptions are listed in Table 3. The PAFC bus is modelled in a fashion almost identical to the SPFC bus, the only differences being in the on-board configuration.

3.1.2. Conventional diesel bus

The emissions for the conventional diesel bus are mod-

Table 3
Key parameters for the modelling of the fuel cell bus

Parameter	Value and source	Comment
Drive train efficiency	0.88 [8]	Assuming 5% loss in traffic
Fuel cell stack efficiency (SPFC)	0.58	Using hydrogen, drive cycle average
Fuel cell stack efficiency (PAFC)	0.50 [9]	Using hydrogen, drive cycle average
Air compressor parasitic load	20% (SPFC only)	Of primary power produced
Regenerative braking	15%	Assumed energy recovery
Energy at the wheel: fuel cell bus	3.3 MJ/km [10]	Assumed from conventional buses
Hydrogen compression energy	1.29 MJ/Nm^3 [6]	Compression to 228 bar
Round trip hydrogen	200 km	Assumed
Hydrogen volume	4280 Nm^3	In pressurised cylinders

The process heat in the hydrogen production is generated using low-NO$_x$ burners which are assumed to emit zero NMHC, CH$_4$, and PM. These burners are assumed to account for all the emissions from the hydrogen production process.
The drive train efficiency for the bus is different from the car as a large diesel engine is generally more efficient than a small diesel or Otto engine.

elled after the EURO III proposals. There is no standard for CH$_4$, for which the local emissions are set to zero. SO$_2$ is calculated from the proposed EURO III average concentration of sulphur in diesel fuel, translated into grams per kilometre by using a fuel consumption of 13 MJ/km [10] and an average engine efficiency of 30%. The upstream fuel supply is modelled after Ref. [2].

3.2. Buses: results and discussion

The results of the model calculations are summarised in Fig. 3 (see Table 4 for details). The SPFC and PAFC buses are similar, and only the SPFC bus will be discussed.

The SPFC bus achieves a reduction of NO$_x$, CO, NMHC and SO$_x$ by approximately one order of magnitude, and PM by almost two orders of magnitude. Fig. 4 analyses the emissions by location. The pollutants shown have a local effect so it is important to understand the emissions location – CO$_2$ and CH$_4$ are global and have been excluded.

About one-third of the NO$_x$ and the CO, and almost all the PM, is emitted by the trucks used to ship in the hydrogen. Almost half the NO$_x$, more than half of the CO, and more than two-thirds of the SO$_x$ is produced in the generation of electricity used to compress the hydrogen (using natural gas-fuelled CCGT). Another 20% is due to trucks and their (diesel) fuel supply chain. Almost 60% of the NMHC is emitted in the upstream natural gas infrastructure (up to 8% of the raw gas is not methane). CO$_2$ emissions are down to 61% of the diesel bus, while the emissions of methane have increased by 75% compared to the conventional bus, because of the switch to natural gas as a primary fuel. Again, the GWP drops significantly. The fuel cell bus uses 80% of the primary energy of the diesel bus. Around one third of the total energy is consumed in the production and compression of the hydrogen, but 60% is used on board.

The bus itself is a true zero emission vehicle, but the use of a diesel vehicle to transport the hydrogen increases local emissions. Total emissions of NO$_x$ and CO could be reduced by one-third, and NMHC by 10%, if the hydrogen were produced by reforming natural gas on-site. Other emissions are all non-local, occurring in the electricity and upstream natural gas infrastructures. By comparison, emissions from the diesel bus are almost exclusively local, except for SO$_x$ where around three-quarters is non-local.

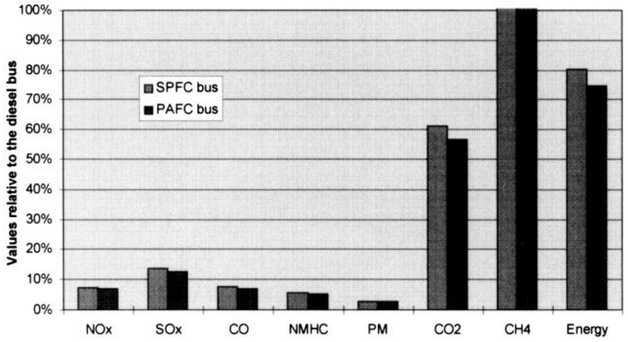

Fig. 3. System-wide emissions and energy consumption caused by buses. They are shown relative to a conventional diesel bus that conforms to the proposed EURO III standards.

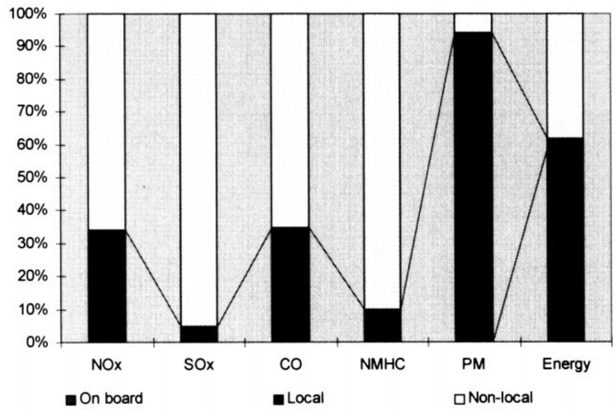

Fig. 4. Emissions and energy use caused by the operation of a bus equipped with a solid polymer fuel cell, split up by location. The lowest part shows the emissions on board, the middle one shows local emissions, and the top one those that arise non-locally (i.e. in the upstream supply infrastructure).

Table 4

Total systems emissions and primary energy use linked to buses

Application		NO_x (g/km)	SO_x (g/km)	CO (g/km)	NMHC (g/km)	CO_2 (g/km)	CH_4 (g/km)	PM (g/km)	Energy (MJ/km)
Diesel bus	Absolute values	5.8	0.78	2.2	3.2	962	0.19	0.11	14.6
SPFC bus	Absolute values	0.43	0.11	0.17	0.18	588	0.33	0.0031	11.7
	Relative to diesel	7.4%	14%	7.5%	5.5%	61%	175%	2.8%	80%
PAFC bus	Absolute values	0.40	0.97	0.16	0.17	546	0.31	0.029	10.9
	Relative to diesel	6.8%	13%	7%	5.1%	57%	162%	2.6%	74%

Table 5

Key parameters for modelling CHP

Parameter	Value and source	Comment
Heat:power ratio (fixed for all CHP)	1.85	Typical for the UK
PAFC plant efficiency	0.85	Heat plus power (LHV)
SOFC NO_x emissions	2 ppm	Internally reforming
SOFC plant efficiency	0.85	Heat plus power (LHV)
SOFC SO_x emissions	Zero	Captured in solid form
SOFC emissions: CH_4, NMHC, CO, PM	Zero	Assumption
PAFC emissions: CO_2	50 000 g/GJ [11]	
PAFC emissions: CO	2.14 g/GJ [9]	
PAFC emissions: NMHC	1.35 g/GJ [9]	
PAFC emissions: CH_4	0 g/GJ	Assumed (no data)
PAFC emissions: NO_x	2.36 g/GJ [12]	
PAFC emissions: SO_2	0.22 g/GJ	Calc. (3ppm H_2S in NG)
PAFC emissions: PM	0.77 g/GJ [12]	

The natural gas supply chain is modelled after Ref. [2]. The plant is connected to the medium pressure part of the gas grid, cutting out gas leaks in the low-pressure part. The emissions for gas-fuelled CCGT electricity generation are taken from Ref. [2]. Those for the upstream gas supply for the CCGT generation are taken from the same source. The emissions of the PAFC plant have been compiled from various publications, as none of them contained a complete set of values as considered in this work. The emissions of the natural gas boiler have been compiled from available literature. The electricity is generated by means of CCGT, fuelled with natural gas from the UK Continental shelf. The corresponding emissions are taken from Ref. [2].

4. Combined heat and power

The model configuration for fuel cells in combined heat and power (CHP) is a hotel-type environment with an electrical power load of 200 kW. The CHP plant is fuelled with natural gas and comprises a reformer which generates hydrogen on-site. Two fuel cell technologies are considered, one of them – the PAFC – being already relatively well-established, while the other one – the solid oxide fuel cell (SOFC) – is just beginning to be demonstrated. The fuel cell technologies are compared to a conventional situation in which electricity is supplied from the grid and heat from a gas boiler.

4.1. Key assumptions

Key assumptions for this area of the modelling are given in Table 5.

4.2. CHP: results and discussion

Using fuel cells for the combined supply of heat and power reduces emissions of NO_x, CO, and SO_x by approx-imately one order of magnitude, as seen in Fig. 5 and Table 6.

For an SOFC plant, CO emissions are down by almost two orders of magnitude. Reductions of NMHC emissions are to 84% (PAFC) and 76% (SOFC). Methane is down to three-quarters in both cases. Particulates are reduced by 6% for the PAFC, and entirely eliminated – within the precision of the model – by the SOFC. Both types of fuel cell plant reduce the CO_2 emissions as well as the energy consump-

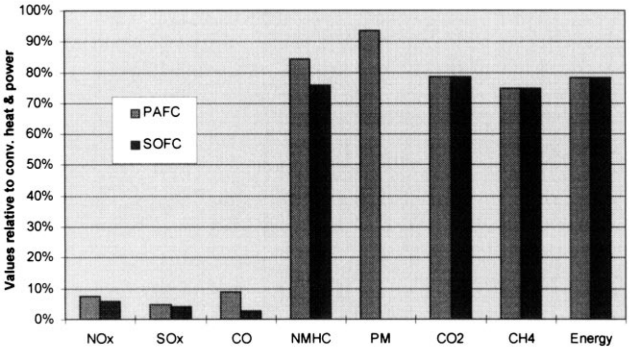

Fig. 5. System-wide emissions and energy consumption caused by large-scale (200 kW_e) combined heat and power applications. They are contrasted with those caused by conventional electricity and heat supply. They have been calculated as grams per kilowatt-hour of electrical energy generated.

Table 6

Total systems emissions and primary energy use linked to large-scale commercial CHP

Application		NO_x (g/kWhe)	SO_x (g/kWhe)	CO (g/kWhe)	NMHC (g/kWhe)	CO_2 (g/kWhe)	CH_4 (g/kWhe)	PM (g/kWhe)	Energy (MJ/kWhe)
Conventional heat/power	Absolute values	1.02	0.33	0.43	0.19	794	0.57	0.01	16
PAFC CHP	Absolute values	0.078	0.016	0.038	0.16	623	0.43	0.0093	12.6
	Relative values (%)	7.6	4.9	8.8	84	78	75	94	78
SOFC CHP	Absolute values	0.06	0.013	0.012	0.15	623	0.43	0	12.6
	Relative values (%)	5.9	4.1	2.8	76	78	75	0	78

tion to 78% of the conventional case. The two reduction rates are the same because no switching of primary fuels is involved.

The difference in energy consumption is largely due to the CHP configuration, which makes use of the heat. Thus, 'conventional' CHP may show some benefits in terms of energy consumption and CO_2 emissions, but these have not been tested.

4.2.1. Sensitivity analysis

A thorough sensitivity analysis was carried out as the model is dependent upon some assumed values and numerous other parameters. While it was noted that the precise numerical value of the result is liable to changes according to the uncertainties in the parameters, the main conclusions as discussed earlier hold firm. A more detailed discussion of the sensitivity of the results can be found in Ref. [1].

5. Conclusion

In all of the cases investigated the introduction of fuel cell technologies substantially reduces emissions in comparison with conventional technologies. Regulated emissions are lowest, by up to two orders of magnitude, with almost no emissions in the environment local to the technology – an important point for clean air zones. The use of fuel cells is more efficient than conventional technologies, and this leads to reduced carbon dioxide (CO_2) emissions. Methane emissions increase from a very low base due to fuel switching, e.g. from petrol to natural gas powered buses. However, these increased methane emissions have a minimal effect on the benefits of reducing CO_2, particularly as the fuel switch is from a high carbon content fuel (oil) to a lower one (natural gas).

In the CHP applications investigated, the energy and CO_2 savings are broadly similar to those that might be expected from a conventional CHP technology. Nevertheless, the regulated pollutant emissions are expected be lower when using fuel cells.

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