ELSEVIER

Journal of Power Sources 86 (2000) 482–494

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Assessment of the environmental benefits of transport and stationary fuel cells

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Accepted 18 October 1999

Abstract

Fuel cells (FCs) offer significant environmental benefits over competing technologies and hence the environment is a strong driving force behind the development of FC systems for transport and stationary applications. This paper provides a comprehensive comparison of FC and competing systems, and points out strengths and weaknesses of the different FC systems, suggesting areas for improvement. The results presented build on earlier work [D. Hart, G. Hörmandinger, Initial assessment of the environmental characteristics of fuel cells and competing technologies, ETSU F/02/00111/REP/1, ETSU, Harwell, UK, 1997.] and provide a detailed analysis of a wider range of systems. The analysis takes the form of a model, which compares system emissions (global, regional and local pollutants) and energy consumption on a full fuel cycle basis. It considers a variety of primary energy sources, intermediate fuel supply steps and FC systems for transport and stationary end-uses. These are compared with alternative systems for transport and stationary applications. Energy and pollutant emission reductions of FC systems compared to alternative vehicle technology vary considerably, though all FC technologies show reductions in energy use and CO_2 emissions of at least 20%; as well as reductions of several orders of magnitude in regulated pollutants compared to the base-case vehicle. The location of emissions is also of importance, with most emissions in the case of FC vehicles occurring in the fuel supply stage. The energy, CO_2 and regulated emissions advantages of FC systems for distributed and baseload electricity are more consistent than for transport applications, with reductions in regulated pollutants generally larger than one order of magnitude compared to competing technologies. For CHP applications, the advantages of FC systems with regard to regulated pollutants remain large. However, energy and CO_2 emission advantages are reduced, depending largely on the assumptions made for the heat/power ratio and system comparison. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Fuel cell; Emissions; Carbon dioxide; Cars; Buses; CHP; Electricity

1. Introduction

Reductions in emissions to the environment and in primary energy consumption, which could result from the use of fuel cell (FC) systems in transport and stationary applications, are considered and compared with alternative systems. Such discussion is of interest for business and policy decision making in the light of increasingly stringent environmental regulations and economic benefits, which could be gained from more efficient systems. Significant social benefits could result from reduced emissions.

A variety of primary energy sources, intermediate fuel supply steps and end-uses are considered. The analysis takes the form of a model, which compares system emissions and energy consumption on a full fuel cycle basis. The result is expressed as per 'unit of end-use'. For example, the total emissions for a FC car are given as grams per kilometre driven.

Transport systems considered in the analysis include solid polymer FC (SPFC), phosphoric acid FC (PAFC) and internal combustion engine (ICE) vehicles, running on different fuels, and battery-powered vehicles. The conventional petrol car and diesel bus are considered as base-case systems for transport. Stationary power systems considered include PAFC, solid oxide FC (SOFC), engine and turbine systems for combined heat and power (CHP), distributed and baseload power generation applications. The 1996 UK electricity mix and electricity from combined cycle gas turbine (CCGT) plants are considered as the base-case systems for electricity generation. Gas boilers are considered for the provision of heat.

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PII: S0378-7753(99)00445-0

The different types of FC 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 FC application, the model calculation begins at the point of end-use, working its way backward through the system to the source of primary energy. The actual calculations are carried out by means of a spreadsheet programme.

Data for parts of the systems, in particular with regard to fuel supply and conventional petrol and diesel vehicles, have been extracted from a recent investigation [3]. Data for the 1996 UK electricity mix is based on Bates [4] and Energy Trends [5]. The detailed data used in the modelling of the systems can be found in Bauen and Hart [2], and only the main assumptions and sources are given here. Also, a number of FC systems have been analysed as part of a previous study [1]. These are the FC car fuelled with methanol or natural gas, FC buses (PAFC and SPFC) fuelled with compressed hydrogen from large-scale reformers, PAFC and SOFC CHP, SOFC electricity, and CCGT electricity. The results have been included to provide a comprehensive comparison between systems.

The emissions considered are oxides of nitrogen (NO_x), oxides of sulphur (SO_x), carbon monoxide (CO), non-methane hydrocarbons (NMHC), particulate matter (PM), carbon dioxide (CO_2) and methane (CH_4). In addition, the model considers the total use of primary energy for each system.

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 [2].

2. Transport systems

2.1. Cars

A previous study [1] compared FC cars fuelled with methanol and natural gas to conventional petrol and diesel cars. To enable a wider understanding of available competing technologies, a range of alternatives has been analysed in the present study. The alternatives considered are battery-powered electric vehicles (BPEVs), internal combustion engine (ICE) vehicles fuelled with compressed natural gas (CNG) and compressed hydrogen, and FC vehicles fuelled with gasoline (using an on-board reformer) and pure compressed hydrogen. There are two models for the BPEV, one charging from a standard UK electricity mix and one from CCGT electricity only. All FC cars are assumed to be equipped with an SPFC. The petrol ICE car remains as the standard point of reference.

2.1.1. Key data

2.1.1.1. FC car fuelled with methanol. In this configuration, analysed in Ref. [1], methanol is converted into hydrogen fuel by means of an on-board steam reformer.

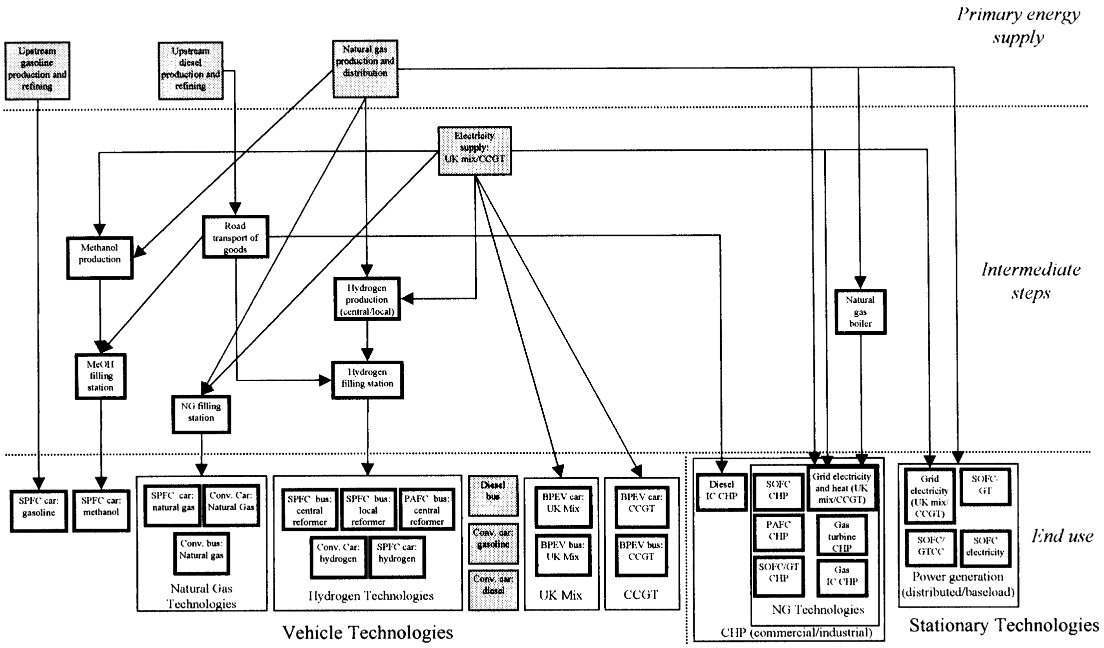

Fig. 1. An overview over the organisation of the quantitative model.

The methanol is produced from natural gas on an industrial scale and transported to road-side filling stations in conventional road tankers.

2.1.1.2. FC car fuelled with natural gas. This configuration, also analysed in Ref. [1], uses natural gas stored in pressurised form on board the car to produce a hydrogen-rich gas by means of a high-temperature steam reformer.

2.1.1.3. FC car fuelled with gasoline. The hydrogen required to feed the FC in this example is generated on board the vehicle by the use of a partial oxidation (POX) process. CO levels are reduced to below the 10 ppm threshold, above which the FC will be poisoned, in a preferential oxidation (PROX) reactor.

2.1.1.4. FC car fuelled with compressed hydrogen. In this case, hydrogen is produced at the filling station from the steam reforming of natural gas and is stored on board the vehicle as a compressed gas.

Table 1 summarises the main parameters used in modelling the FC cars.

The emissions from natural gas reforming for methanol and hydrogen production are exclusively from the burners used for process heating. Values for commercial low-NO_x burners have been used. The emissions from on-board reformers have been estimated based on discussions with industry and from the literature [2].

2.1.1.5. Battery-powered electric vehicles. The battery-powered electric vehicle has an identical drive train to the FC vehicle, except that the motive power comes from battery storage of electricity rather than from consumption of fuel on board the vehicle. In all other respects, the vehicles are identical. The analysis is based on a nickel metal hydride battery (NiMH) vehicle. Two sources of electricity are considered: the standard UK electricity mix (1996, averaged over 24 h) and electricity from CCGT plants. The emissions from the BPEV depend purely on the electricity supply and on the efficiencies of the various components in the cycle.

2.1.1.6. Spark ignition internal combustion engine fuelled with natural gas. In the case of the CNG ICE car, the efficiency of the engine is estimated to be 10% better than that of the conventional petrol car [3]. In other respects, such as the drive train, the vehicle is considered identical to the standard petrol vehicle. On-board emissions are taken from data provided by manufacturers [14].

2.1.1.7. Spark-ignition internal combustion engine fuelled with hydrogen. Hydrogen, produced from the steam reforming of natural gas at the filling station, is assumed to be stored on board the vehicle as a compressed gas. In other respects, the vehicle is again considered to be standard. In this example, the only polluting emissions from the engine will be of nitrogen oxide species formed due to the high flame temperature of the internal combustion process.

2.1.1.8. Conventional petrol and diesel cars. Both petrol and diesel ICE cars have been modelled. The petrol car is considered as the base-case with which all the others are compared. The emissions of the cars themselves are assumed to conform to the EURO III standards. 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 petrol and diesel fuel, translated into grams per kilometre by using fuel consumption and average engine efficiency. In the case of the petrol car, for which no EURO III standard exists for PM, the value corresponds to the average in the current UK national fleet [3]. The emissions for the UK fuel supply chains are taken from Ref. [3]. EURO IV standards to be implemented in 2005 envisage a halving of emissions compared to the EURO III standards. The European Union

Table 1
Key parameters for the modelling of the FC car
The ‘energy requirement at the wheel’ is the energy at the axle required to move the vehicle — NOT fuel consumption.

Parameter	Value and source	Comment
FC car energy requirement at the wheel	0.405 MJ/km [6]	Same as average requirement for petrol fuelled passenger cars
Electro-mechanical drive train efficiency	0.731 [6–8]	
FC stack efficiency	0.58	Using hydrogen, drive cycle average
FC stack efficiency	0.539 (based on Ref. [9])	Using methanol and natural gas reformate
FC stack efficiency	0.417 (based on Ref. [10])	Using gasoline reformate
Air compressor parasitic load	20%	Of primary power produced
Gasoline reformer efficiency	0.78 [11]	
Methanol reformer efficiency	0.77 [7]	
Regenerative braking	10%	Assumed energy recovery
Methanol delivery distance	450 km	Assumes two plants in UK
Natural gas compression energy	0.12 kW h/N m^3 [12]	Compression to 250 bar
Hydrogen compression energy	0.38 kW h/N m^3 [13]	Compression to 250 bar

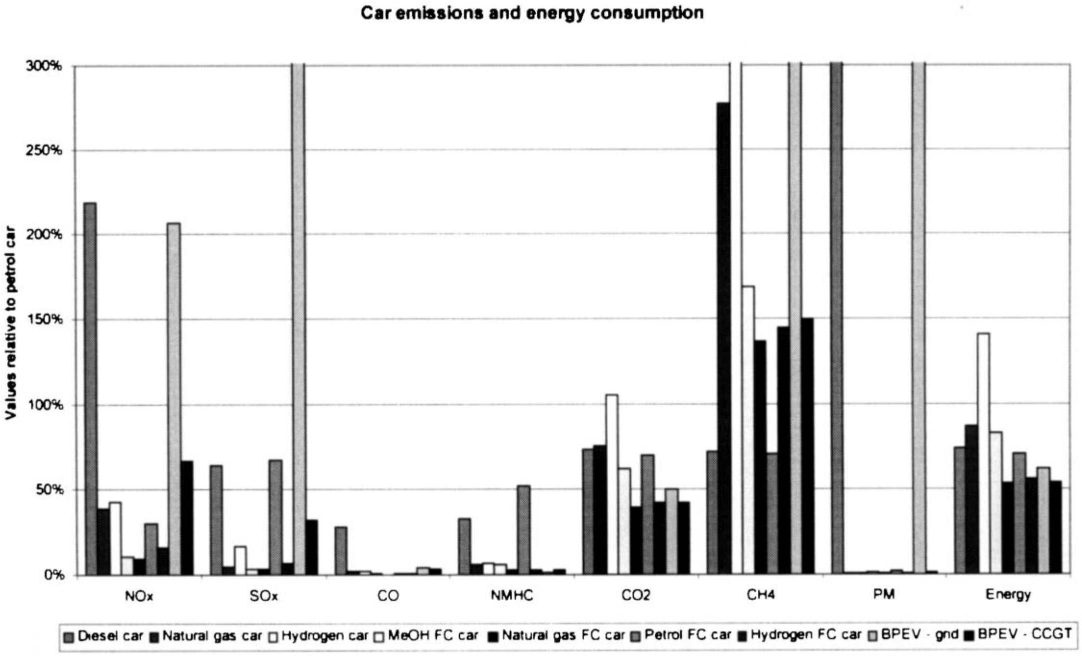

Fig. 2. Total systems emissions and primary energy use linked to passenger cars.

has been negotiating voluntary CO_2 emission limits with car manufacturers, which would reduce average on-board emissions from new car fleets to 140 g/km by 2008.

2.1.2. Results and discussion

The results on emissions and energy use are summarised in Fig. 2 and Table 2.

Emissions of pollutants other than greenhouse gases are lower for all cars, relative to those of the conventional petrol car, except for the BPEV charged with electricity from the 1996 UK electricity mix, which has higher NO_x, SO_x and PM emissions, and the diesel ICE car, which has higher NO_x and PM emissions. All the vehicles considered, apart from the hydrogen ICE car, show advantages in terms of greenhouse gas emissions compared to the conventional petrol car. Methane emissions are driven upwards by a general switch to increased natural gas use. However, methane emissions remain very low compared to

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 ICE car	Absolute values	0.26	0.2	2.3	0.77	209	0.042	0.01	3.16
Diesel ICE 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%	75%
CNG ICE car	Absolute values	0.10	0.01	0.05	0.05	158	0.12	< 0.0001	2.74
	relative to petrol	39%	5%	2%	6%	76%	277%	< 0.5%	87%
Hydrogen ICE car	Absolute values	0.11	0.03	0.04	0.05	220	0.15	0.0001	4.44
	relative to petrol	43%	17%	2%	7%	105%	364%	1%	141%
MeOH FC 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%
Natural gas FC car	Absolute values	0.024	0.0063	0.0074	0.019	83	0.059	< 0.0001	1.69
	relative to petrol	9%	3%	0.3%	3%	40%	137%	< 0.5%	53%
Petrol FC car	Absolute values	0.08	0.13	0.01	0.41	147	0.03	0.0002	2.24
	relative to petrol	30%	68%	0.4%	53%	70%	71%	2%	71%
Hydrogen FC car	Absolute values	0.04	0.01	0.02	0.02	87.6	0.06	< 0.0001	1.77
	relative to petrol	16%	7%	1%	3%	42%	145%	< 0.5%	56%
Battery car	Absolute values	0.54	0.74	0.09	0.01	104	0.30	0.05	1.98
(UK electricity mix)	relative to petrol	207%	377%	4%	1%	50%	722%	496%	63%
Battery car	Absolute values	0.17	0.06	0.08	0.02	88.1	0.06	0.0001	1.71
(CCGT electricity)	relative to petrol	67%	32%	4%	3%	42%	150%	1%	54%

CO_2 emissions and the reduction in CO_2 in all cases far outweighs the greenhouse warming potential of the increased CH_4.

The energy use of all vehicles other than the hydrogen ICE car is between 15% and 50% lower than the base-case. The hydrogen ICE car is the least efficient because of the losses in producing and compressing hydrogen and the inefficiency of the ICE. Its high energy requirement leads to overall CO_2 emissions similar to those of the conventional petrol ICE car. The CNG ICE car also suffers from using a compressed gaseous fuel without the benefits of a FC and electric motor to increase the on-board efficiency; it situates itself between the base-case and the FC vehicles. However, both vehicles have low emissions, the hydrogen ICE car in particular has very low local emissions — all zero except for a small amount of NO_x. The gasoline and methanol FC cars have a higher energy requirement than hydrogen and natural gas FC cars, situated around the benchmark for advanced diesels.

The hydrogen and natural gas FC cars are the best performers in terms of emissions and energy. Despite this, the natural gas FC car may not be a realistic technical option because of the difficulties associated with on-board storage and reforming of the natural gas. The hydrogen FC car is a true ZEV in that it has no on-board emission of pollutants. The BPEV is also a ZEV with very low energy consumption. However, BPEVs are hampered by upstream NO_x and SO_x emissions that are much higher than the FCVs, and most importantly by range. In contrast to the on-board emissions from a petrol vehicle, the emissions from BPEV occur outside an urban context. It is, therefore, difficult to compare the cases merely by examining the emissions levels. The values will also change as power generation is subjected to harsher constraints on its emissions, and with the changing UK mix over time.

The use of hydrogen-fuelled FC cars seems to be very promising if the hydrogen can be generated using local natural gas reformers at filling stations. Emissions are down by an order of magnitude in almost all cases, with negligible CO, NMHC and PM. NO_x and SO_x are below 20% (16% and 7%, respectively) of the conventional petrol car emissions, with all of these emissions upstream. CO_2 is reduced by about 60%, a reduction similar to that of battery-powered cars. The hydrogen FC vehicle appears as the most environmentally benign option, followed by the natural gas, methanol and gasoline versions, respectively.

2.2. Buses

The earlier study [1] compared SPFC and PAFC buses, fuelled with compressed hydrogen, with a conventional diesel bus. The present analysis spreads the net wider to encompass other alternative technologies, including natural gas ICE and battery-powered buses. The SPFC calculation is repeated with different supply assumptions for the hydrogen.

2.2.1. Key data

2.2.1.1. FC buses. In Ref. [1], both types of FC 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. Consideration is extended to the case where hydrogen is generated from natural gas in a local steam reformer at the bus depot. The efficiency and emissions from this reformer are considered identical to the large-scale reformer modelled in the previous analysis, but the transportation of the hydrogen is no longer a significant issue. 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.

Table 3 summarises the main parameters used in modelling the FC buses.

2.2.1.2. Natural gas ICE bus. The CNG ICE bus is very similar to the conventional diesel bus in design and operation. However, a diesel engine burning natural gas is less

Table 3
Key parameters for the modelling of the FC bus

Parameter	Value and source	Comment
FC bus energy requirement at the wheel	3.3 MJ/km [15]	Based on energy requirement of conventional diesel buses
Electro-mechanical drive train efficiency	0.88 [16]	Assuming 5% additional loss in traffic
FC stack efficiency (SPFC)	0.58	Drive cycle average using hydrogen
FC stack efficiency (PAFC)	0.50 [17]	Drive cycle average using hydrogen
Air compressor parasitic load	20% (SPFC only)	Of primary power produced
Regenerative braking	15%	Assumed energy recovery
Hydrogen compression energy	1.29 MJ/N m^3 [12]	Compression to 228 bar
Round trip hydrogen delivery distance	200 km	Assumed for central reforming
Hydrogen storage volume	4280 N m^3	In pressurised cylinders

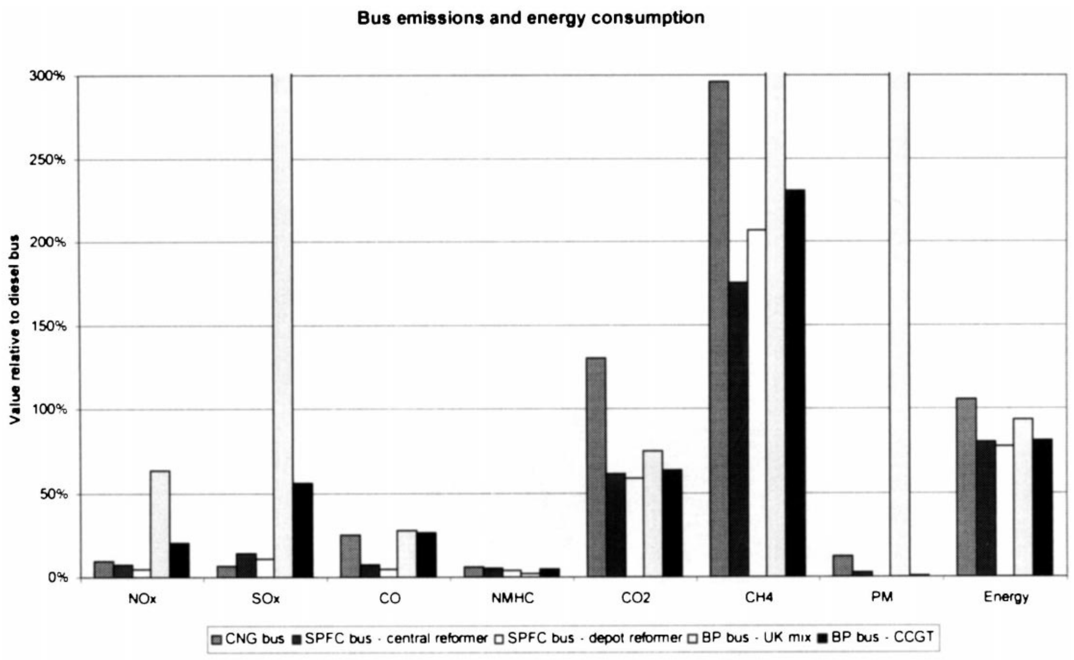

Fig. 3. Total systems emissions and primary energy use linked to buses.

efficient than one burning diesel, by approximately 6% [3,15]. Emissions from a standard driving cycle have been derived from discussions with Volvo and IVECO Ford.

2.2.1.3. Battery-powered electric buses. As with the car model, two types of BPEV bus have been modelled. In each case, the vehicle is identical but the electrical charging supply is considered to be from a different fuel mix, i.e. UK grid electricity (1996, 24-h average) and CCGT electricity. The bus itself is very similar in concept to the FC bus — the drive train, energy recovery and power electronic components are either identical or nearly so — and is assumed to use nickel metal hydride (NiMH) batteries.

2.2.1.4. Conventional diesel bus. The emissions for the conventional diesel bus are modelled after the EURO III standards. There is no standard for CH_4, for which the on board 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 [15] and an average engine efficiency of 30%.

2.2.2. Results and discussion

The outcome of the model calculations on emissions and energy use is summarised in Fig. 3 and Table 4.

FC buses are superior to all other cases analysed. The hydrogen-fuelled SPFC and PAFC buses show significant

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 (central reformer)	Absolute values	0.43	0.11	0.17	0.18	588	0.33	0.0031	11.7
	Relative to diesel	7%	14%	8%	6%	61%	175%	3%	80%
SPFC bus (depot reformer)	Absolute values	0.27	0.08	0.11	0.13	560	0.39	0.0001	11.31
	Relative to diesel	5%	10.8%	5%	4.2%	58%	206%	< 0.5%	78%
PAFC bus (central reformer)	Absolute values	0.40	0.97	0.16	0.17	546	0.31	0.029	10.9
	Relative to diesel	7%	13%	7%	5.1%	57%	162%	2.6%	74%
CNG bus	Absolute values	0.56	0.05	0.57	0.20	1250	0.56	0.01	15.38
	Relative to diesel	10%	7%	25%	6%	130%	296%	12%	105%
Battery bus (UK mix electricity)	Absolute values	3.71	5.10	0.62	0.08	721	2.10	0.35	13.6
	Relative to diesel	64%	657%	28%	2%	75%	1113%	321%	94%
Battery bus (CCGT electricity)	Absolute values	1.20	0.44	0.58	0.15	608	0.43	0.0009	11.83
	Relative to diesel	21%	56%	26%	4%	63%	231%	1%	81%

reductions in emissions and energy use compared to the conventional diesel bus. While the PAFC bus appears more energy efficient, this is directly due to the assumption that it has no parasitic compressor loads in comparison with the SPFC. Changes in technology are likely to invalidate this assumption. Hydrogen from a depot reformer as opposed to a central reformer leads to even lower emissions.

The benefits of using FC buses in terms of local air quality are compelling, with very important reductions in local pollutants compared to the conventional diesel bus. Greenhouse gas emissions are also considerably reduced. The upstream emissions from the UK electricity mix leads to significant pollution in the case of the battery-powered bus. While some emissions are reduced, there is a significant increase in SO_x, NMHC and PM emissions. However, the same conclusions apply in terms of emissions location as in the case of passenger cars. Their effect on some aspects of the environment will thus be different from that of the diesel base-case, which has largely on-board emissions. The battery-powered bus charged with CCGT electricity shows a reduction in all non-greenhouse gas emissions compared to the conventional diesel bus. While the CNG bus offers significant advantages in terms of local emissions affecting air quality compared to the conventional diesel bus, it does not appear to offer advantages in terms of energy consumption or CO_2 reductions, but results may vary for specific engines.

The energy consumption improvements are not as startling for buses. This is because the standard diesel engine is relatively efficient. The three FC buses and the battery-powered bus charged with CCGT electricity have very similar energy consumption figures at around 80% of the base-case diesel. The battery-powered bus charged with UK electricity mix still shows a 10% saving in comparison with the diesel bus. Only the CNG bus has a slightly higher energy consumption, due to the lower efficiency of the CNG diesel engine.

However, a decrease in energy use will be more significant in terms of the market for buses than for cars, as the users have different attitudes. Whereas a car purchaser is influenced strongly by the capital cost, the bus user will also take running costs into account. Reduced energy use may equate to a better pay-back for the user. It is also possible that FC buses, running for many more miles per year than cars, can contribute significantly to reduced CO_2 and urban emissions overall.

Within the error margins of the analysis, it is difficult to separate the FC buses, though the state of technology and development plans suggest that the SPFC bus with depot reformer and on-board compressed hydrogen may be the best choice, as it has lower emissions than the SPFC with a central reformer. The PAFC bus has slightly better energy consumption as it has been assumed that it has no parasitic losses, but the payload of the bus may be reduced.

3. Stationary systems

The stationary systems considered are large commercial CHP generation, industrial scale CHP generation, distributed and baseload power generation.

3.1. Large commercial CHP market

A typical capacity for large commercial CHP would be about 200 kW_e. FC CHP applications at this scale are promising, with the PAFC commercially available and the SOFC, currently at the demonstration stage, in principle also suitable for CHP. The SOFC systems in this study internally reform natural gas to a hydrogen-rich gas. The earlier study [1] assessed the environmental characteristics of these FC systems and compared them to a conventional situation in which electricity is supplied from a CCGT plant and heat from a gas boiler. FCs are likely to compete with two other systems in large commercial CHP applications: diesel-fuelled engines and natural gas-fuelled engines. These systems have therefore been added to the analysis. Engines achieve good efficiencies at the capacity considered and progress is being made in reducing their emissions.

3.1.1. Key data

The principal parameters used in the modelling of large commercial CHP systems are summarised in Table 5.

The emissions of the natural gas boiler, diesel- and natural gas-fuelled engines, PAFC and SOFC plant have been compiled from publications and industrial sources, as

Table 5
Key parameters for modelling large commercial CHP

Parameter	Value and source	Comment
Heat:power ratio (fixed for all CHP)	1.85	Typical for the UK
Diesel-fuelled engine CHP system efficiency	0.85 (0.38)	Value in parentheses gives typical electrical efficiency
Natural gas-fuelled engine CHP system efficiency	0.85 (0.36)	Value in parentheses gives typical electrical efficiency
PAFC CHP system efficiency	0.85 (0.45)	Value in parentheses gives maximum electrical efficiency
SOFC CHP system efficiency	0.85 (0.55)	Value in parentheses gives maximum electrical efficiency

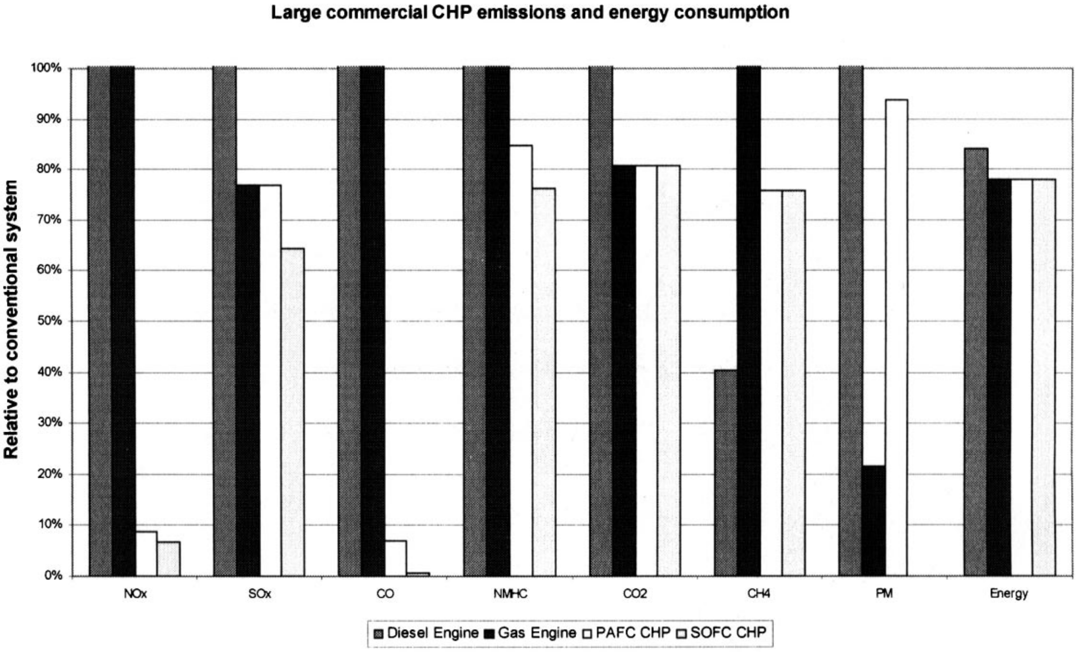

Fig. 4. Total systems emissions and primary energy use linked to large commercial CHP.

no individual source contained a complete set of values as considered in this work [2].

3.1.2. Results and discussion

The results on emissions and energy use are summarised in Fig. 4 and Table 6.

FC systems considerably reduce emissions compared to the CCGT electricity and gas boiler system. The most significant reductions are for NO_x and CO emissions, which are lower by one to two orders of magnitude compared to the base-case. Significant reductions are also achieved for the already low SO_x, NMHC, CH_4 and PM emissions. The latter are entirely eliminated, within the precision of the model, by the SOFC system. FC systems reduce the CO_2 emissions, as well as the energy consumption, to about 80% of the base-case. FCs are even more advantageous with regard to all emissions when compared to diesel-fuelled engines and with regard to NO_x, CO, NMHC and CH_4 emission when compared to natural gas-fuelled engines. CO_2 and PM emissions per unit of useful energy produced are likely to be similar for the FC and natural gas engine systems. It is important to note that use of diesel and natural gas-fuelled engines would result in an increase in local emissions of regulated pollutants compared to the base-case.

The main reason for the lower energy efficiency of the base-case system is inherent to the advantages of CHP over power only and heat only systems. In the cases considered, FC systems offer similar energy benefits to natural gas engines and greater than those of diesel engines. For lower heat to power ratios than the one considered, FC CHP systems will be even more beneficial in terms of energy consumption because of their higher electrical efficiencies.

Table 6
Total systems emissions and primary energy use linked to large commercial CHP
Emissions and energy requirement are expressed per unit of useful energy (recoverable heat plus electricity).

Application		NO_x (g/kW h)	SO_x (g/kW h)	CO (g/kW h)	NMHC (g/kW h)	CO_2 (g/kW h)	CH_4 (g/kW h)	PM (g/kW h)	Energy (MJ/kW h)
Conventional heat/power	Absolute values	0.31	0.007	0.14	0.068	270	0.20	0.003	5.7
Diesel engine	Absolute values	4.4	0.68	0.22	0.74	315	0.08	0.049	4.8
	Relative values	1432%	9443%	158%	1086%	116%	40%	1390%	84%
Gas engine	Absolute values	1.2	0.006	1.0	0.094	218	0.31	0.001	4.4
	Relative values	402%	77%	706%	139%	81%	157%	21%	78%
PAFC CHP	Absolute values	0.027	0.006	0.010	0.058	218	0.15	0.003	4.4
	Relative values	8.8%	77%	7%	85%	81%	76%	94%	78%
SOFC CHP	Absolute values	0.021	0.005	0.001	0.052	218	0.15	0	4.4
	Relative values	6.8%	64%	1%	76%	81%	76%	0%	78%

Table 7
Key parameters for modelling industrial CHP

Parameter	Value and source	Comment
Heat:power ratio (fixed for all CHP)	1	
Gas engine CHP system efficiency	0.85 (0.36)	Value in parentheses gives typical electrical efficiency
Gas turbine CHP system efficiency	0.85 (0.26)	Value in parentheses gives typical electrical efficiency
SOFC CHP system efficiency	0.85 (0.55)	Value in parentheses gives maximum electrical efficiency
SOFC/GT CHP system efficiency	0.85 (0.68)	Value in parentheses gives maximum electrical efficiency

3.2. Industrial scale CHP market

The SOFC is an interesting option for industrial scale CHP of a few megawatts capacity where high temperature heat is required. In such applications, the SOFC could be employed in a single cycle or in a combined cycle with a gas turbine (SOFC/GT). The combined cycle is best suited for an application characterised by relatively low heat to power ratios to take advantage of the high electrical power efficiency achieved by such systems. Natural gas-fuelled engines and natural gas-fuelled turbines are also options for industrial scale CHP systems. The base-case system resembles large commercial CHP where electricity is supplied by grid-connected CCGT and heat is supplied by gas boilers.

3.2.1. Key data

The principal parameters used in the modelling of industrial scale CHP systems are summarised in Table 7.

3.2.2. Results and discussion

The outcome of the model calculations on emissions and energy use is summarised in Fig. 5 and Table 8.

The smaller heat to power ratio, 1 instead of 1.85 used for large commercial CHP, results in an increase in emissions per unit of useful energy generated by the base-case system compared to the previous case. This increase is due to the greater portion of losses attributable to electrical power only generation. The energy requirement is also higher.

The emissions of the SOFC and SOFC/GT systems are again considerably lower than the base-case system, and the differences are similar to those exhibited by large commercial CHP systems. The assumption that the SOFC and SOFC/GT systems possess equal total system efficiencies implies that the SOFC/GT system has no advantage in terms of emissions per unit of useful energy compared to the SOFC system. The way emissions are allocated to the energy products is a determining factor in systems comparison. However, the SOFC/GT possesses a higher electrical efficiency and can be used in applications requiring a low heat to power ratio, which would not allow the use of single cycle SOFC. The emissions of regulated pollutants from the FC systems are also significantly lower than those from the natural gas engine and turbine systems. Based on the useful energy allocation, the engine, turbine

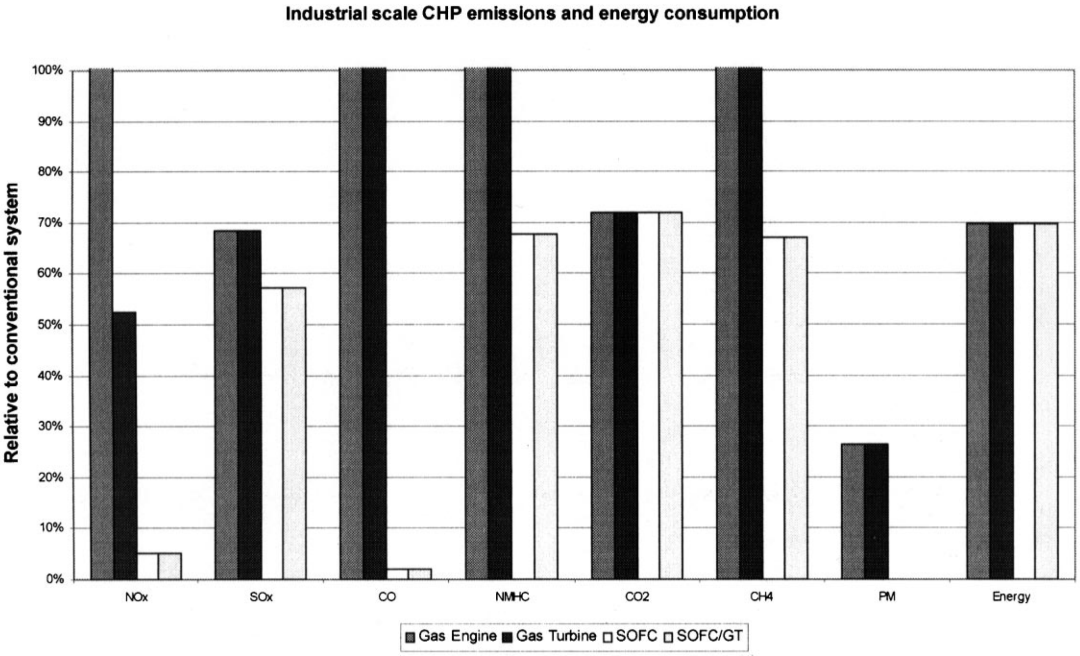

Fig. 5. Total systems emissions and primary energy use linked to industrial scale CHP.

Table 8
Total systems emissions and primary energy use linked to industrial scale CHP

Application		NO_x (g/kW h)	SO_x (g/kW h)	CO (g/kW h)	NMHC (g/kW h)	CO_2 (g/kW h)	CH_4 (g/kW h)	PM (g/kW h)	Energy (MJ/kW h)
Conventional heat/power	Absolute values	0.41	0.008	0.20	0.08	304	0.22	0.003	6.3
Gas engine	Absolute values	1.2	0.006	1.0	0.09	218	0.31	0.001	4.4
	Relative values	307%	68%	494%	124%	72%	139%	26%	70%
Gas turbine	Absolute values	0.21	0.006	0.22	0.09	218	0.31	0.001	4.4
	Relative values	52%	68%	109%	124%	72%	139%	26%	70%
SOFC CHP	Absolute values	0.021	0.005	0.004	0.052	218	0.15	0	4.4
	Relative values	5%	57%	2%	68%	72%	67%	0%	70%
SOFC/GT CHP	Absolute values	0.02	0.005	0.004	0.05	218	0.15	0	4.4
	Relative values	5%	57%	2%	68%	72%	67%	0%	70%

and FC systems all show similar energy use and reductions in greenhouse gas emissions compared to the base-case.

3.3. Distributed power generation market

The FC technology chosen for modelling a distributed power application is the SOFC. Two systems are considered: the IR-SOFC operated in single cycle mode or in combined cycle with a gas turbine. The base-case consists of grid electricity supplied by CCGT plant fuelled with natural gas assumed to originate from UK continental shelf fields.

3.3.1. Key data

For capacities typical of distributed power generation (1–10 MW_e), the electrical efficiency of an SOFC system is estimated at 55% and that of an SOFC/GT system is estimated at 70% [18].

3.3.2. Results and discussion

The outcome of the model calculations on energy use and emissions is summarised in Fig. 6 and Table 9.

Using a large SOFC plant to generate electricity rather than conventional technology reduces the emissions of NO_x and CO to almost insignificant levels — at most 4% of their previous values. SO_x emissions are reduced to at most 65% of the base-case mainly because of a reduced energy requirement, which results in lower emissions from the fuel supply chain, but also because the sulphur remaining in the natural gas is assumed to be scrubbed within the SOFC system. Particulate matter is eliminated entirely using our assumption of zero level emissions for SOFC systems, though PM emissions are also low in the case of CCGT electricity. NMHC emissions are down by a quarter, at least. CO_2 emissions are at most about 80% of the base-case. Emissions of all pollutants are reduced by a further 22% for the SOFC/GT system compared to the

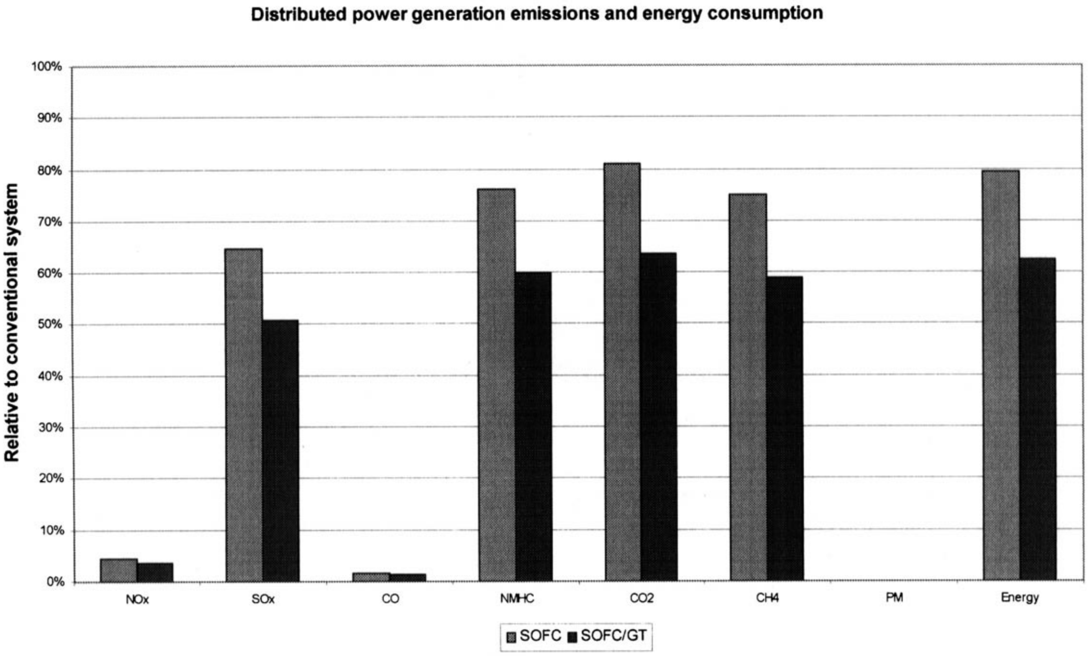

Fig. 6. Total systems emissions and primary energy use linked to distributed power generation.

Table 9
Total systems emissions and primary energy use linked to distributed power generation

Application		NO_x (g/kW h_e)	SO_x (g/kW h_e)	CO (g/kW h_e)	NMHC (g/kW h_e)	CO_2 (g/kW h_e)	CH_4 (g/kW h_e)	PM (g/kW h_e)	Energy (MJ/kW h_e)
CCGT	Absolute values	0.73	0.01	0.40	0.11	417	0.31	0.0006	8.6
SOFC	Absolute values	0.03	0.01	0.01	0.08	338	0.23	0	6.8
	Relative values	4%	65%	2%	76%	81%	75%	0%	79%
SOFC/GT	Absolute values	0.03	0.006	0.005	0.06	265	0.18	0	5.4
	Relative values	4%	51%	1%	60%	64%	59%	0%	62%

single cycle SOFC system because of its higher efficiency. The energy requirement is about 21% and 38% lower for the single cycle SOFC and SOFC/GT, respectively, relative to CCGT electricity.

3.4. Baseload power generation

SOFCs operating in combined cycle with gas turbines or in triple cycle with gas and steam turbines offer the potential for highly efficient and clean baseload electrical power. The 1996 UK electricity mix is selected as the base-case and CCGT electricity is also considered in the analysis.

3.4.1. Key data

For capacities typical of baseload power generation (100 MW_e), the electrical efficiency of an SOFC/GT system is estimated at 74% and that of an SOFC/GTCC system at 80% [18].

3.4.2. Results and discussion

Energy use and emissions are summarised in Fig. 7 and Table 10.

Emissions of NO_x and CO are reduced by practically two orders of magnitude compared to the emissions from the UK electricity mix, and by more than one order of magnitude and two orders of magnitude, respectively, compared to CCGT electricity. Full fuel cycle SO_x emissions are reduced to less than 0.14% compared to the UK electricity mix and to less than 50% compared to CCGT electricity. SO_x from the generating stage is assumed to be zero for SOFC-based systems. NMHC and CH_4 emissions are uniquely attributed to fuel supply activities in the case of the FC systems considered. NMHC emissions are generally low and are estimated to be similar for all fuel cycles considered. CH_4 emissions are significantly reduced for the CCGT and FC case compared to the UK electricity mix due, principally, to the avoided emissions associated with coal mining. The high efficiencies of the SOFC-based

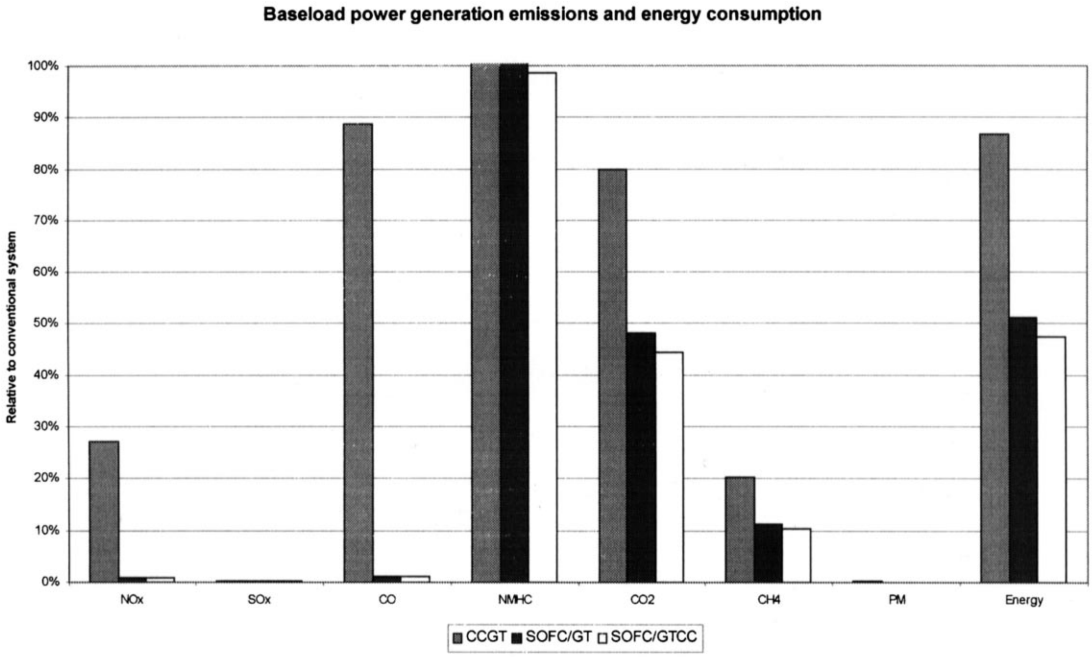

Fig. 7. Total systems emissions and primary energy use linked to baseload power generation.

Table 10
Total systems emissions and primary energy use linked to baseload power generation

Application		NO$_x$ (g/kW h$_e$)	SO$_x$ (g/kW h$_e$)	CO (g/kW h$_e$)	NMHC (g/kW h$_e$)	CO$_2$ (g/kW h$_e$)	CH$_4$ (g/kW h$_e$)	PM (g/kW h$_e$)	Energy (MJ/kW h$_e$)
UK grid	Absolute values	2.7	3.7	0.45	0.06	522	1.5	0.25	9.9
CCGT	Absolute values	0.73	0.01	0.40	0.11	417	0.31	0.0006	8.6
	Relative values	27%	0.3%	89%	188%	80%	20%	0.3%	87%
SOFC/GT	Absolute values	0.02	0.005	0.005	0.06	251	0.17	0	5.1
	Relative values	0.9%	0.1%	1.1%	107%	48%	11%	0%	51%
SOFC/GTCC	Absolute values	0.02	0.005	0.004	0.06	232	0.16	0	4.7
	Relative values	0.8%	0.1%	1.0%	99%	44%	10%	0%	47%

systems lead to important reductions in CO$_2$ emissions, which are more than halved compared to the UK mix and about 60% of those for the CCGT system.

A sensitivity analysis shows the conclusions for the transport and stationary scenarios to be stable over a wide range of variation of the model parameters. The results concerning pollutant emissions are exceptionally stable against variations in the model parameters, which are likely to account for uncertainties and possible technological improvements. While improvements in greenhouse gas emissions and energy consumption can be diminished, or in some cases even eliminated, by making very unfavourable assumptions, the general outcome is that there is very likely to be a sizeable improvement through the use of FCs.

4. Conclusion

The overall conclusions indicate that the widespread use of FCs in transport and stationary applications seems to be highly beneficial in terms of reduced energy consumption, and reduced global, regional and local pollutants.

For FC cars, there are choices to be made between the fuels, though the vehicles requiring on-board reformers will have to be judged further on the basis of the availability of fuel and on-board system complexity. The gasoline FC vehicle does not respond in modelling as well as the methanol vehicle on the basis of current data, and both are inferior to the direct hydrogen version. All FC buses have a clear advantage over the alternatives, with hydrogen produced at the depot, apparently a very efficient fuelling scenario.

FC systems offer clear advantages in stationary applications in terms of emission reductions and energy use. These benefits are particularly high for distributed and baseload power generation, where combining them with gas turbines increases the energy efficiency and reduces the CO$_2$ emissions in particular. In CHP applications, advantage should be taken of the high electrical efficiencies which can be achieved by FCs.

While there is an ongoing debate on the economic efficiency of achieving satisfactory air quality standards and greenhouse gas reductions [19], it should be noted that FCs could revolutionise both transport and stationary power sources, provide gains in efficiency and reductions in emissions beyond those envisaged from other technologies, and lead to a more diverse and possibly renewable energy future. The global social benefits, which can be reaped by the development of FC technology are indeed likely to be very considerable.

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