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Environmental impacts of energy facilities: fuel cell technology compared with coal and conventional gas technology

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Abstract

We compare the environmental side effects of power plants based on fuel cell technology with the side effects of conventional electric power plants based on coal and natural gas The environmental impact of a solid oxide fuel cell (SOFC) plant is very much less than that of a coal-fired plant (a factor of 1/300 for air pollution and a factor of 1/5 for water pollution) Compared with a conventional gas plant, impact is reduced by between 50 and 98% Damage to cultural monuments and buildings is negligible from a fuel cell plant Socioeconomic negative impacts are reduced by about 30% relative to conventional gas plants (aesthetics and noise) whereas employment is unaltered Impact on health and safety is greatly reduced compared with that from coal-fired plants and is about 70% of that from conventional gas plants Preliminary results suggest that society's willingness to pay (WTP) for clean air, and thereby better health, matches the cost of installing emission-reducing equipment on conventional power plants There is probably an additional WTP for other benefits (e g , decreased risk of global warming) Thus, the utility of very small emissions, lower CO_2 discharges, and other benefits from SOFC generators may compensate for the increased cost incurred in producing electricity by SOFC generators

Introduction

Fuel cells generate electricity and heat from gas, and they may develop as an alternative to other types of power plants, e.g , coal-fired plants and gas turbines One of the main factors which makes the fuel cell attractive is its high electrical efficiency Electrical efficiency, as higher heating value, HHV, is the ratio output power/input enthalpy of the fuel. Another factor is the low amount of unwanted side products, e g , SO_x, NO_x, and CO_2 A third important aspect of fuel cell plants is that they can conveniently be built as small (25–500 MW_e, e indicates electric power), separate modules in the region where the electric power is consumed It makes it much easier to

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TABLE 1

Fuel cells characteristics
PAFC = Phosphoric acid fuel cell, MCFA = molten carbonate fuel cell, SOFC = solid oxide fuel cell Numbers are approximations pr June 1989 Main ref , 3

Type	PAFC	MCFC	SOFC
Operating temperature (°C)	200	650	1000
Module size			
near term ($\mathrm{MW_e}$)	10	2–10	0 005–0 10
advanced ($\mathrm{MW_e}$)	25–50	100–500	25–50
Materials in the cells	Carbon, teflon[d], ceramic[d], noble metals[b]	Nickel and ceramic, stainless steel	Ceramic, nickel
Electrolyte	Phosphoric acid	Molten carbonate	Solid oxide
System efficiency (% HHV)	40–47[f]	50–57[g]	50–60
Fuel type	Hydrogen processed hydrocarbons	Nat gas, H_2, CO	H_2, CO,[a] nat gas
Cell life (yr)[d]	3	3	> 3[b]
Plant life (yr)	20	20	20
Stack power density (W $\mathrm{kg^{-1}}$)	35–86[d]		4000[e]
Key issues	Reliability, operation and maintenance cost	Reliability, durability manuf cost	Reliability, durability manuf cost

[a] Veyo [45]
[b] Lemons [22]
[c] EPRI [11]
[d] Appleby and Foulkes [2]
[e] Estimated in present work
[f] Glenn [15] quotes a value of 36%
[g] Glenn [15] quotes values of 60% for fuel cell with internal reforming, HHV = Higher heating value

adapt co-generating systems which use thermal energy for local heating purposes The present work concerns Solid Oxide Fuel Cell (SOFC) type generators It is one system in the family of advanced fuel cell generators Other system types are the Phosphoric Acid Fuel Cell (PAFC) and the Molten Carbonate Fuel Cell (MCFC) systems The generators differ in their ability to process fuel, their operating temperatures, cell materials, and electrolyte, as indicated in Table 1.

Objective

The objective of this study is to compare the impact of the side effects of SOFC power plants versus alternative power or heat generating systems

We examine the effects on the environment and on the people working at the plant or living in its vicinity. To do this we follow the schemes developed by Keeney [19] for the siting of energy facilities, and Seip *et al* [36] for environmental cost/utility calculations We identify four main groups of objectives environmental impact, impact on materials and buildings; socioeconomic impact, and health and safety impact In this work we will not address public attitude impact and only briefly discuss economic impact We emphasize environmental concern during power plant operation As far as we know there are no extra environmental loads during either construction or close down (in contrast to the situation for nuclear power plants)

We compare the environmental impact of fuel cells with that of conventional power plants fired by coal and gas Some key properties of these three power plants are shown in Table 2 We have also examined the possibility that a significant part (50%) of the waste heat from fuel cells may be utilized locally, for example, by farmers Agricultural requirements for heat in open fields in Norway are 280 kW h m^{-2} yr^{-1} for 7000 h operation period per year [14]

Fuel cell power station mass balance

The mass flow in a fuel cell power plant can be divided into two separate flows one feed and product flow path and one power plant/fuel cell material cycle The time constant for the cell material is about three years for PAFC and MCFC plants and probably more for SOFC plants Appleby and Foulkes

TABLE 2

Characteristics of power plants

Characteristics for a 200 MW_e power plant unit based on coal, natural gas (conventional plant) and fuel cells 7000 h yr^{-1} operation time

	Coal	Conventional gas	Fuel cell
Output (MW_e)	200	200	200
Efficiency (el) (%)[a]	20	40	60
Coprocessor for use of heat[b]	No	No	Yes
Fuel required (10^9 MJ yr^{-1})	25 2	12 6	8 4
Materials replaced[c] (tons yr^{-1})	Probably small	Probably small	17

[a] Recalculated from ref 14

[b] We assume that the amount of heat output from a 200 MW_e fuel cell is appropriate for local use, whereas, currently, there is no market in Norway for larger amounts of heat [14] The situation may be different in other countries

[c] Fuel cell material consumption, see text

[2] assume that operation lifetimes will be in excess of 10 000 h, 40 000 h being realistically anticipated for commercial stacks (7000 h/year) Small laboratory cells have been operated for 100 000 h In our study, we will use 3 years as the estimated SOFC stack lifetime, although this may be regarded as a very conservative estimate

To our knowledge, the materials used in the construction of a fuel-cell plant are, apart from the cell stacks, the same as those which are used for a conventional gas plant The materials used in the cell stacks depend upon the type of cells used. The main materials, plus those of greatest environmental concern, are listed in Table 1 Also, the amount of cell material varies with cell type For an SOFC generator the target for stack power density is 0 000 25 kg W^{-1} and for this type of cell 16 6 t yr^{-1} of cell stack material must be discharged (Less, if cell life is more than 3 years) The cell material in the SOFC case is mostly ceramics, which is inert and should give no significant environmental problem

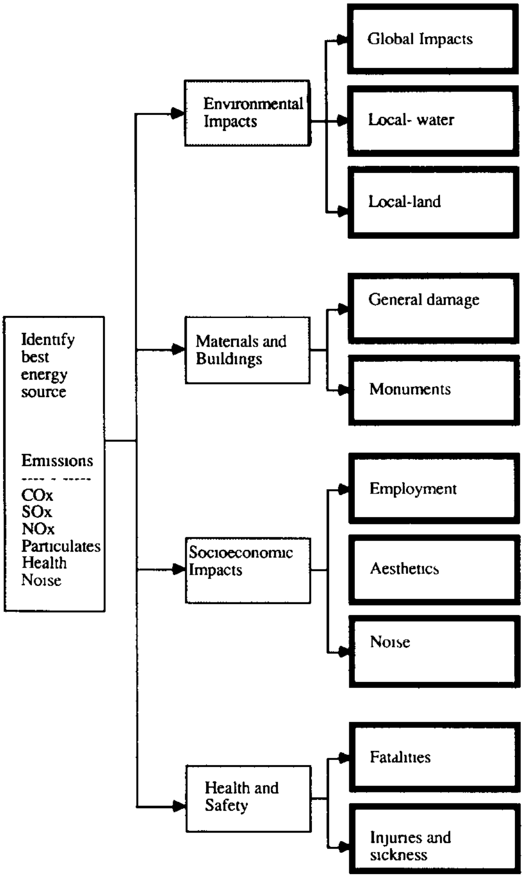

Fig 1 General objectives hierarchy for energy facilities Partly after ref 19

General objectives for environmental and socioeconomic impacts of energy facilities

A hierarchy of general objectives for an energy facility is shown in Fig 1 It consists of four main objectives divided into 10 lower level goals To obtain data for the lower level goals, we will first discuss and quantify typical pollutant emission levels from coal-fired plants, conventional gas-plants and fuel-cell plants This is done in terms of emission of NO_x, SO_x, CO_2, thermal pollution, particulates and heavy metals (lead), as illustrated in Fig 2 We then discuss each of the four main impact areas environmental impact, impact on materials and buildings, socioeconomic impact, and impact on health and safety

In this work we shall not assess the relative importance of impacts among the four groups of objectives This would be necessary to make an overall cost/benefit analysis However, we will quote studies which suggest probable costs and benefits for emission abatement measures This will give an indication of the overall benefits of converting from coal/oil or conventional gas technology to fuel-cell technology

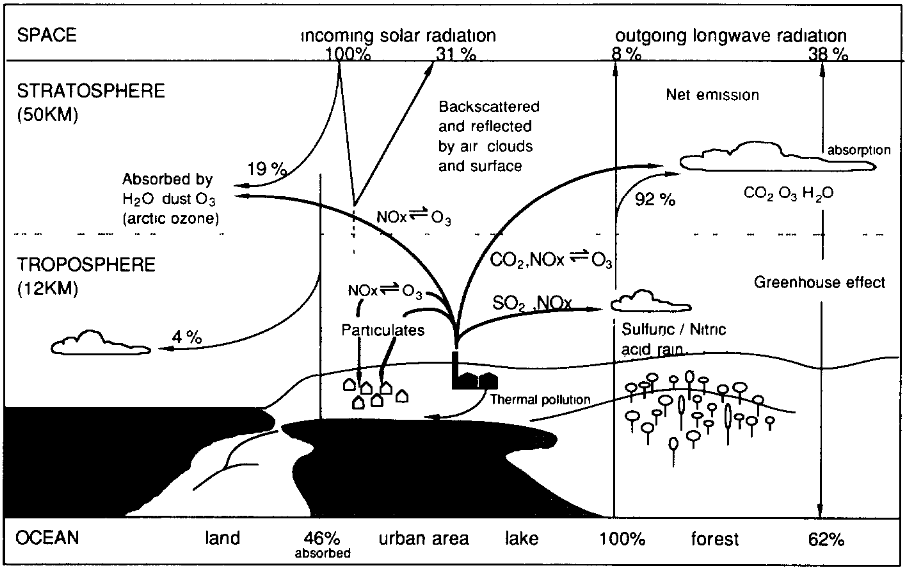

Fig 2 Emission products from electric power plants and their interaction with the environment and with processes responsible for the greenhouse effect The solar fluxes (thin lines) are shown on the left-hand side (including ultraviolet radiation) and the longwave fluxes (thermal, IR) are on the right-hand side NO_x (thick lines show transport) may, under certain conditions, form ozone, O_3, in the troposphere (where it is a toxin) and the stratosphere (where it contributes to the greenhouse effect) NO_x may also indirectly contribute to the destruction of arctic ozone (which shields against damaging ultraviolet radiation) CO_2 contributes to the greenhouse effect, SO_2 and NO_x contribute to acid rain Figure based on refs 25, 41 and 8

Pollutant emissions

To make it easier to compare emission levels we have calculated emissions from 200 MWe plants fired either with coal or natural gas Then we have compared these values with emission levels from a corresponding 200 MW_e fuel-cell plant. Data for the coal-fired plant are obtained primarily from Keeney [19], and data for the conventional gas plant from a recent feasibility study made by four electric utility industries in Norway [14], see Table 2

Pollutant discharges from a 200 MW_e power plant fired with coal and conventional gas, and a fuel-cell plant are compared The results are shown in Table 3 Data from current installations form the basis for most of the discharge values An exception is the data for fuel-cell generators, which are often based on information from target values or values extrapolated from small-scale experimental systems We have also assumed that the fuel-cell plant based on natural gas can use a co-generating system for the utilization of heat This would not be the case for coal and conventional gas plants since only small units can easily find a market for the distribution of waste heat in Norway The discharge of NO_x is very much smaller with a fuel cell than with conventional natural gas plants (of the order of 0 1 ppm of the exhaust gas) This is due to the low generator temperature of the SOFC which is below the threshold temperature for creating NO_x The only possible source of NO_x in the SOFC is in the afterburner where excess gas is burned In second generation fuel-cell systems with afterburner catalysts, NO_x emissions should be negligible With a conventional gas plant there may be an emission of SO_x 1 mg/s m^3 [14] This will give a small amount of

TABLE 3

Emissions from power plants

Emissions from 200 MW_e power generators based on coal and natural gas The gas generators are divided into two groups conventional turbine and fuel cell (SOFC) technology, respectively Sources [33, 2, 32]

Emission	Unit	Coal[b]	Natural gas	
			Conv technology	SOFC
CO_2	tons yr^{-1}	1400×10^3	695	460
NO_x	tons yr^{-1}	1500	325[a]	0 8[c]
SO_x	tons yr^{-1}	5300	10	7[d]
Particulates	tons yr^{-1}	500	3	2
Heavy metals	tons yr^{-1}	3	0	0
Heat loss	GW h yr^{-1}	5600	2100	930[e]

[a] The current value is 60 mg NO_x MJ^{-1} fuel for conventional thermomechanically generated power The Norwegian Pollution Control Authority now requires less than 26 mg NO_x MJ^{-1} fuel We have used 26 mg NO_x MJ^{-1} fuel here

[b] Weighted averages for anthracite used in Norway Lignite is not used in Norway

[c] Based on 0 1 mg NO_x MJ^{-1} in emission

[d] Based on 1 0 mg SO_x MJ^{-1} fuel

[e] SOFC with cogenerating system gives a heat loss of 465 GW h yr^{-1}

SO_x discharge from a conventional gas plant Fuel efficiency will also reduce the discharge from a fuel cell, assuming that the SOFC plant can be operated with this amount of SO_x in the gas. The amount of CO_2 discharged is reduced in a conventional gas plant relative to a coal plant as the system efficiency increases when gas is used as fuel instead of coal Similarly, decreased emission of CO_2 from fuel-cell plants is obtained compared with conventional gas plants because of the higher efficiency of the former *Particulate* discharge levels are much lower for conventional gas-fired plants than for coal-fired plants Particulates from fuel cell generators are a little less than from a conventional gas plant [31, 14]. *Heavy metals* are small in oil products other than gasoline (0 12–1 0 g t^{-1} versus 140 g t^{-1} [33]) They will probably also decrease in gasoline in the near future In gas from the North Sea the heavy-metal concentrations are negligible For example, the concentration of Hg is $(0–100)\times 10^{-9}$ g m^{-3} [14, 2] *Thermal pollution* is large from coal-fired power plants and much lower for conventional gas-fired power plants Based on the efficiency, the thermal pollution can be calculated from data in Table 2 This thermal waste is generally carried by the cooling water, some of which can be used in a co-generating system Since the power plant units are smaller for fuel-cell plants (typically 25–200 MW_e), the possibility that a market can be found in Norway for the thermal output increases (District heating, heating of office buildings, hospitals, fish farming, etc) The waste heat, i e , the thermal pollution, may be discharged to water and/ or to air [2] *Noise levels* may be about 50 dB(A) at a distance of 800 m from a conventional gas plant We do not know the noise levels from a coal plant For fuel cells, Rastler *et al* [32] give a value of 60 dB(A) at 30 m from the plant

The certainty of the emission estimates may vary widely Keeney [19] quotes 0 0, 0 16, 0 5, 0 84, and 1 0 fractiles for estimates of emission products from coal-fired plants For some of the pollutants there are several orders of magnitude between worst and best case For example, for SO_x the 0 16 fractile is only 3% of the median value. We have not reported corresponding low- and high estimates for the gas plant or for the fuel-cell plant in the present work However, a suggested domain of variation is indicated in Seip *et al* [38]

Environmental impacts

Environmental impacts are divided into global effects (contribution to greenhouse effect) and local effects close to the plant They are related to the physical disturbance of land resulting from the space occupied by the plant and its supporting facilities, and from by-product emissions The impacts can be described directly from the amount and types of organisms disturbed or from increased mortality However, this may involve complicated calculation The effects can also be described by proxy attributes that give the amount of toxic material emitted A third, indirect, measure of the effects is the amount of land with ambient concentrations of potentially toxic substances above a certain level [37] This measure is adopted in the present work

We first discuss the local impact close to the site of the energy facility, and thereafter the global impact

Local impact – land

Calculations show that the amount and distribution of smoke from a conventional gas plant may be considerable The distribution is related to the velocity of the emissions and the heat content relative to the ambient temperature Depending upon the number of exhaust and cooling towers, the exhaust may reach a height of 300 m at wind velocities of 4 m s^{-1} under neutral atmospheric conditions The effective smokestack height should be more than 50 m to avoid high exhaust concentrations in the near vicinity of the plant location [14] However, single events giving enhanced concentrations may still occur The probability of such events depends largely upon the local topography The radius for an area affected by emissions from a conventional gas plant may be about 80 km, corresponding to 2×10^6 hectares

NO_x and biota

NO_x impact the biota directly, or by contributing to the formation of ozone, which is a potent plant and microbe toxin [12] In the atmosphere, NO_x is transformed into nitrate It returns to the ground with precipitation The increased nitrate will act as a fertilizer for the soil Depending upon the buffering capacity of the soil, increased nitrogen levels in rivers and lakes also increase the acidity of the water If nitrogen is limiting algal growth, it will increase the eutrophication of waters The load of NO_x in Norway is about 220 000 tons and has increased from about 180 000 tons in 1973 The two most important sources are private and public transportation (33%) and private households (16%) Energy production accounts for less than 1% due to the very high proportion of electricity generated by hydro power in Norway NO_2 concentrations were above the lower limit for allowable daily averages (100 mg m^{-3}) at 9 out of 12 observation stations located in Norwegian cities during the winter 1988/89 [6] Table 4 summarises deposits and toxic concentrations of NO_x in Norway

SO_x

Sulfur damages vegetation and fauna Sulfur is also responsible for reduced photosynthesis and growth in large forested areas of Central Europe There is an increased die-back of silver fir (*Abies alba*) and of Norway spruce (*Picea abies*) Beech (*Fagus sylvatica*) seems to suffer from the same disease, as failing regeneration, bark necrosis, and top-dying are observed in many areas [1] However, the direct effects of increases of fluxes in sulfur and nitrogen seem, presently, primarily to be local or regional The reasons for damage to forests can be categorized in three groups (i) the direct toxicity of sulfur, (ii) deposition of acid increases net leaching of Ca and Mg, thereby increasing Mg deficiency in forest growth, (iii) at Ca/Al mol ratios below 1 0 the toxicity of Al increases Table 4, lower part, shows ambient air concentrations, and dry deposition of sulfur on European soils,

TABLE 4

Nitrogen (NO_x) and SO_2 concentrations

Total emission in Norway is about 222 000 tons NO_x and 70 000 tons SO_2 [42] NO_x values after ref 14 and SO_2 values after ref 1 except where otherwise indicated

Species	Mean annual deposits		Toxicity		
	(mg m^{-3} air)	(kg ha^{-1} yr^{-1})	(kg ha^{-1})	(mg m^{-3} air)	(mg m^{-3} soil)
Total nitrate-nitrogen					
– background	–	5	–	–	–
– wet deposit, gasplant	–	0 12	–	–	–
NO_2 Østl	15–40	–	–	100–150	–
NO_2 Roads-extreme values	222	–	–	–	–
SO_2					
Central Europe	10–25	25–100	2600	20–50	100[a]
Scandinavia	<5	1–7	2600	20–50	–

[a] Rutter [34]

compared with levels of direct toxicity of sulfur High natural acidity in many regions may give rise to concern that only a moderate increase in acidity may have adverse effects CO_2 may affect the biological impact of SO_2 CO_2 tends to reduce evapotranspiration by quicker closure of the stomata, and this also may reduce the penetration of other gases It is yet unclear whether increased CO_2 will make forests less susceptible to acid rain [18] Excess sulfur has caused severe fish fatalities in Norwegian lakes and in North America [27] The load of SO_x from Norway is about 70 000 tons annually, and has decreased from about 150 000 tons in 1973 The load from foreign sources is about 1 mill tons [6] The two most important sources in Norway are production of metals (26%) and transportation (16%) Electric power generation accounts for less than 1% SO_2 concentrations were above the lower limit (50 mg m^{-3}) during 22% of observed events in Norwegian cities during the winter 1988/89 [6] The above-limit events occurred in most cases because air parcels with high concentrations of SO_2 passed the observation station

Conclusion

Sulfur and NO_x from a 200 MW_e conventional gas plant will contribute 0 02% and 0 2%, respectively, to the total load of these products in Norway [6] Fuel cells will clearly reduce emission products considerably both relative to conventional gas-fired plants and especially to coal-fired plants The relative impact of SO_2 and NO_x in causing acidification has been determined by the Norwegian pollution control authority (SFT) as 2 45 and 0 25, respectively [44] A reduction in NO_x values must, however, be considered to be of greatest importance, because the contribution from other sources, e g , cars, push the ambient air levels close to 'critical' levels The 'critical' levels are determined by the environmental authorities If the plant is located close to areas with high SO_2 levels, the SO_2 emissions would be of greater concern (A siting close to areas with high SO_2 levels may be more likely for fuel-cell plants, because they will be sited close to highly constrained urban areas where the possibility for using excess heat is greatest)

A reduction in emission products will reduce the damaged area proportional to the volume of the emission (NO_x and SO_2, but we have chosen a conservative estimate and assigned areal values closer to the larger area corresponding to NO_x emissions) Note that the affected distance (m) from the power plant increases as the square root of the emission load

Local-impact — water

Relatively large amounts of water are discharged from conventional gas plants to an appropriate recipient The area affected by a 200 MW_e conventional gas plant is about 1 km downstream of the plant [14] i e , about 50 hectares of water will increase more than 1 °C above ambient temperature Both fresh water and saline water may be used for cooling Fuel cells are more efficient than Carnot limited power generators, especially in small units Appleby and Foulkes [2] assume that even if the waste heat from fuel cells is not utilized

TABLE 5

Cooling water requirements for power plants
Source ref 14 except for fuel cell generators where numbers are estimated in present work

Type	Size (MW$_e$)	Amount water (m^3 s^{-1})	Excess temp (°C)	Thermal cont (GW h yr^{-1})
Coal	200	>30	–	>5000
Conv gas	200	6	7 5	1000
Fuel cell	200	2 5	7 5	370[a]

[a] Thermal discharge is 115 GW h yr^{-1} if coprocessor is included

TABLE 6

Environmental impacts
Damage to the environment from a 200 MW$_e$ power plant unit based on coal, natural gas (conventional plant) and fuel cells

	Coal	Gas	
		Conventional gas	Fuel cell
Global impact (Index 1–10, 10 worst)	10	4 0	2 4
Local area – Water (ha)	>250	94	42[a]
Local area – land (ha × 10^6)	6	1 0	0 02

[a] 21 ha if coprocessor is included

in auxiliary processes or on-site heating, it can normally be rejected directly into the air rather than into a body of water However, we make the following assumptions here (i) for coal-fired plants heat is removed by water, (ii) for a conventional gas plant, 50% of the heat is discharged into water, (iii) for a fuel-cell plant 40% is discharged; (iv) for a fuel cell plant with heat utilization, 20% of the heat is discharged into water

The amounts of cooling water required for different types of power plants are shown in Table 5

Table 6 shows the resulting calculations of the effects of emission to air and water in terms of the areas affected The relatively small land area affected by discharges from fuel-cell generators reflects the much lower discharges to air of SO_2, NO_x, and particulates from such generators relative to other power generating systems

Global effects

CO_2

Carbon dioxide is largely believed to be responsible for the 'greenhouse' effect, i e , the insulation of the earth by gases trapped in the atmosphere, Fig 2 [28] Other gases which contribute to the insulating effect are methane,

NO_x, and chlorofluorocarbons (CFC). CFC is about 6000 times as efficient in increasing the global temperature as CO_2, and the other gases have intermediate efficiencies [4]. The pre-industrial atmospheric concentration of CO_2 was 230 ppm [18] and it is predicted that it will double within six decades. The world's 400 million cars contribute about 500 million tons of carbon dioxide a year to the atmosphere [10]. As atmospheric CO_2 is opaque to the earths infrared emission this disturbance is likely to cause a global temperature increase. Predictions for the doubling of CO_2 concentrations are: high emission scenario gives the year 2043, low emission scenario gives the year 2068, zero growth emission scenario gives the year 2139 [40, 18]. Predicted temperature increases caused by CO_2 doubling, range from 2.9–8.6 °C in a base scenario to 1.4–4.2 °C in a slow build up scenario [18]. Other studies reviewed by Mitchell [25] suggest increases of 2–5 °C and changes in precipitation of 7–15% depending upon geographic region.

Recent modelling experiments [46] have shown that at the end of 30 years an instantaneous doubling of CO_2 (from 330 to 660 ppm) results in an increase in the globally averaged surface-air temperature of 1.6 °C. A transient forcing case (CO_2 concentration starting at 330 ppm and increasing linearly with 1% per year until it reaches 660 ppm) gives an increase of 0.7 °C, i.e., only half of the increase caused by a sudden doubling.

The increased temperature may cause an increase in the average sea level. Thermal expansion of ocean water may cause an average increase of 7.5 cm with a 2 °C rise in temperature and a 15.5 cm increase with a temperature rise of 4 °C. The contribution due to melting of the polar caps may give rise to an increase of up to 2 m [18], however this contribution is highly uncertain and 30 cm is regarded as more probable [24, 35]. The 90% probability levels include zero rise in sea level, or a slightly lower sea level. The ramifications of the changes caused by a possible global warming are many. No country will remain unaffected, although each will have unique concerns. Most of the earth's areas will be drier, but large areas in South America, India, and Australia will be 'wetter' [40, 25]. Marine ecosystem productivity may increase [3]. However, the different regions and their ecosystems will be impacted by the temperature increase depending upon the speed of the increase [30].

There are different opinions on how far the 'greenhouse' effect has developed. It appears that a trend in global warming has continued for the last 15 years [20]. However, one of the suspected major causes for the 'greenhouse' effect, the depletion of the arctic ozone layer in the stratosphere seems not to have occurred [21]. This reference also concludes that CFC gases have, up to the summer of 1989, had a negligible influence on the arctic ozone layer. Scenarios for the 'greenhouse' effect depend upon model calculations. There are different opinions on the reliability of such calculations. Summaries are given by Moene [26], Schneider [35], and Lindzen [23]. There are other causes of climatic fluctuations [43] that may dominate the 'greenhouse' effect. However, it is almost generally agreed that the 'greenhouse' effect should not be a 'natural' experiment [29], and efforts should be initiated based on the Precautionary principle (adopted at the Second International Conference on the protection of the North Sea, November 1987 [17]) to reduce the emission of CO_2 and NO_x

We have assumed, following Washington and Meehl [46], that a rapid increase in CO_2 is worse than a corresponding slow increase Thus, a large reduction in CO_2 gives a more than proportional reduction in the effects on the global system The global impact is calculated as an index with 1 as the best and 10 as the worst $I_0 = 10$ corresponds to the continued input from coal-fired plants Our estimates of the index values for conventional gas plants and fuel-cell plants are based on reductions in NO_x and CO_2 but with emphasis on CO_2, since typical increases in nitrous oxide (from present day levels) give less relative heating ($W\ m^{-2}$) than a corresponding increase in CO_2 [46], Fig 6) Based on the above considerations, we developed the following equation to calculate the index

$$I = I_0[0\ 90(CO_{2\,\mathrm{alt}}/CO_{2\,\mathrm{coal}})^{1\ 2} + 0\ 10(NO_{x_{\mathrm{alt}}}/NO_{x_{\mathrm{coal}}})^{1\ 2}] \qquad (1)$$

where 'alt' is alternative power generation and 'coal' is power generation by coal

The greatest improvement in global impact index is the transition from coal to conventional gas-fired plants However, fuel cells reduce the impact further to less than half of this value

The load of CO_2 in Norway is about 35 mill tons per year It has increased from about 30 mill tons in 1973 The two most important sources are private households (18%) and transportation (17%) Power generation supply accounts for less than 1% [6]

Table 6 shows the results of the calculated effects of reduced emission on the global index

Impacts on materials and buildings

Emission into ambient air may degrade materials and thereby reduce the value of buildings and installations The interaction of materials with the atmosphere has recently received increased attention as a result of concern regarding the effects of acid deposition, not only on buildings and outdoor sculptures, but also on bridges and installations made of iron Carbonate rocks (marble, sandstone, limestone) are quite sensitive to SO_2 and NO_x, apparently in both gaseous and dissolved forms Significant degradation is thus observed and also anticipated in high-SO_2 environments such as fog, gas, and deposited particles Soot particles may be embedded in the surface layer of the stone and tarnish the surface Granite and slate are silicate materials and are far more resistant to degradation than carbonate rocks [16]

Often, particular details of the buildings, artworks, etc , will be especially susceptible For example, about 40% of the balconies in downtown Oslo must be repaired or replaced because of accelerated wear caused by corrosive exposure to air pollution (National Broadcast News, Nov 23, 1989) Damage has been reported more than 30 km from a source in the upwind direction

TABLE 7

Materials and buildings

Damage to materials and buildings from a 200 MW_e power plant unit based on coal, natural gas (conventional plant) and fuel cells Calculations for a Norwegian environment

	Coal	Conventional gas	Fuel cell
Damage to monuments and art works by SO_2, NO_x and particulates (no /50 yr)	4	0 02	0 01
General damage to buildings streets, etc , from SO_2, NO_x and particulates (no /50 yr)	70	0 15	0 10

A highly visible and damaging decay may take 70 years at an air concentration of 1 4 ppm SO_2 [13] We assume here that there will be potential damage corresponding to an area of 100 km^2 around a coal-fired power plant The calculations are based upon a comparison of the daily emissions of SO_2 from an oil refinery [13] of 25–30 tons and daily emissions from a coal-fired plant of 15 tons, and assuming that there are 4 monuments and art works within this area and 70 buildings of general use constructed from susceptible material that would be affected by emissions from a coal-fired plant (Such numbers would be relevant if a small Norwegian city lay within the 100 km^2 area The actual numbers depend upon the particular site chosen for the power plant) Stone and iron have a higher sensitivity to SO_x than to NO_x (sensitivity was designated by pairs of letters (H, H) and (L, N), respectively, in ref 16 (H is High, L is Low, and N is Not known) Therefore, we have assigned damage values closer to those calculated from SO_x than from those calculated from NO_x The relative damage from coal-fired plants, conventional gas plants and fuel-cell plants is shown in Table 7

The effects of degradation of materials and buildings are greatest with a transition from coal-/oil-fired plants to conventional gas plants The gain with a transition to fuel cells is probably marginal in most regions, but may be of importance in old, congested towns where concrete building are in bad condition

Socioeconomic impacts

Socioeconomic impacts generally include the impact on individuals living near a proposed facility site, exclusive of health and safety Socioeconomic impacts are felt in several ways A major effect arises from taxes and charges that any large energy facility would pay directly, or indirectly through the taxes paid by the employees A second effect is that of the boom–bust cycle associated with the rapid increase, and then decrease, of people and activity resulting from construction of the facility After the construction, a small number of employees will be working at the facility A third effect is the aesthetic impact of the facilities and their operations This includes the impact of the plant itself, cooling towers, transmission facilities, pollutants, and noise The concerns are categorized as socioeconomic as far as they impact humans (but not human health and safety)

Here, we will consider the impact of employment, aesthetics, and noise during normal operation of the plant Fiscal effects will not be discussed

Employment

The numbers of employees during operation of a conventional gas plant and a fuel-cell plant are shown in Table 8 Compared with conventional gas plants the fuel-cell plant can be operated under relatively benign conditions, they can be designed so that maintenance is required only at infrequent intervals Above all, they can be used for unmanned operation, with automatic or remote dispatch of the electricity generated It is claimed that the fuel-cell plants can be designed so that only the simplest tools and skills will be needed for maintenance activities, provided that plug-in replacement modules (e g , for the fuel cell stack) are available at short notice [2].

Although each plant may require less manpower than a corresponding conventional gas plant, a fuel-cell plant and a conventional gas plant will most probably be designed differently A fuel-cell plant will be designed as three or four separate plants located at three or four distinct locations They may require the same or more manpower per 200 MW_e output than a conventional plant We have therefore chosen to assign the same required manpower as for a conventional plant

Aesthetics

The visual impression of a fuel-cell power plant will normally show gas tanks, cooling towers, fuel-cell modules, and other industrial buildings The aesthetic impression of a large plant is then comparable with that of a gas plant or an industrial complex However, a fuel-cell power plant need not contain an industrial size smokestack and obvious cooling towers, and it can

TABLE 8

Socioeconomic impacts
Scores for 200 MW_e coal fired plant, conventional plant, and fuel cell plant

	Coal	Conventional gas	Fuel cell
Employment (man-years)[a]	Not known	27	27
Aesthetic impact (ha)[b]	30	25	5–15
Noise (dB(A))[c]	100	80	60

[a] Employment for a conventional gas plant is 150 persons during a construction period of three years Operation requires 25–30 persons assuming 5 shifts during 24 h [14]

[b] Concentrated and greenfield layout, respectively

[c] Noise level at 30 m from plant building with highest noise level 130 dB(A) is pain threshold for the ear and 50 dB(A) is noise level in living areas between 06 and 16 h recommended by the Norwegian Pollution Control Authority (A) indicates that a filter is used which simulates human hearing sensitivity

therefore probably be made aesthetically more pleasing than other power plants

Plant size and plant layout contribute to the aesthetic impact of a power plant Conventional coal-fired and gas-fired power plants will always be large and occupy an area of 10 ha or more Fuel-cell plants may be built into existing buildings because they have good efficiency as small units In this case they can be built as multi-level plants and will occupy, typically, 0.035–0 072 m^2 kW^{-1} (0 38–0 78 ft^2 kW^{-1} [32]) They may also be built as ordinary plants (unconstrained greenfield site) The area occupied is then typically ten times larger per unit power output

Noise

Since there are no moving parts in a fuel cell, ideally no noise should be generated However, noise from auxiliary equipment will be present The noise from a fuel-cell gas plant is reported to be low, so that the plant can be located quite close to living areas We do not know the noise level for conventional gas or coal-fired power plants, but present target noise levels from industrial complexes (Norsk Hydro, Porsgrunn) is 50 dB(A) at 800 m distance from the industrial site Target levels for conventional gas plants are 40 dB(A) at a distance of 100 m

Table 8 summarizes the scores for three types of power plants on socioeconomic criteria

Impact on health and safety

The health and safety concerns include mortality, morbidity, and injuries due to accidents and exposure to toxic gases during construction, normal operations, and closing down of the plant It also includes reduced well-being — appearing as extended use of non-prescription medicaments, days-off without formal sick-leave permits, etc We will, in principle, include all health impacts, also those which occur during acquisition of the fuel, transportation, and storage at the facility We also include health risks associated with waste disposal We assume, however, that for fuel-cell plants, there is no increased risk to health and safety during construction or closing down of the plant (in contrast to the situation for nuclear power stations)

NO_x, O_3 and ambient air quality

Nitrogen oxides (NO_x denotes the sum of NO and NO_2 90% of NO_x are in the form of NO) impact the ozone layer in the troposphere Tropospheric ozone, often called urban ozone, is a strong respiratory irritant and plant pathogen Ozone in the upper atmosphere (stratosphere) is beneficial because it blocks the sun's harmful ultraviolet rays Ozone is formed by photolysis of NO_2 The photolysis and oxidation of reactive (nonmethane) organic compounds (NMOC) provide a major pathway leading to the oxidation of NO without destroying ozone There is a general consensus that controlling NMOC emissions in urban areas will reduce ozone, whereas controlling NO_x may, or may not, reduce ozone, depending upon the NMOC/NO_x ratio [7]

The current ambient air quality standards for ozone specify that the average number of days with daily maximum one hour concentrations of O_3 greater than 120 ppb should not be more than one per year The proposed Norwegian heath safety limits on NO_2 concentrations are 100–150 mg m^{-3} as the average exposure during a day Local measurements close to roads with heavy traffic in Oslo have shown a value of 222 mg m^{-3} Table 4 above shows critical values for NO_x. The Norwegian Pollution Control Authorities (SFT) have assigned relative weights to the damaging effects of SO_2 (1 89), suspended particulate material (4 15), NO_x (3 77), and CO(5 66) [44].

Fatalities and diseases caused by emission of NO_x [19] are smaller from a fuel-cell plant compared with those from a conventional gas plant because the emission volume is much smaller However, since the plant probably will be located close to a densely populated center (to utilize excess heat), it is also relatively more important to discharge very small levels which do not add to high levels from road traffic

Expected annual fatalities and diseases from an 800 MW_e coal-fired plant are given by Keeney in Tables 6 5 and 6 6 of ref 19 He lists fatalities to those who are working at the plant and to the general public caused by resource recovery, processing, power generation, fuel storage, transportation, and waste management The values corresponding to a 200 MW_e plant are calculated by linear interpolation in his Table (Functional form of attribute X_1· fatalities, is linear in ref 19) Numbers for conventional gas-fired plants are found by assuming that the numbers of fatalities and diseases caused by resource recovery are one tenth the values for coal recovery, and the numbers corresponding to transportation are zero (fatalities and diseases caused by pipelines are believed to be negligible)

Numbers corresponding to fuel-cell plants are assumed to be smaller than those of a conventional gas plant because they are using dispersed power generation rather than centralized generation [2]. Moreover, fuel-cell plants will have much less moving parts, and storage capacities for explosives will be smaller

Fatalities caused by the closing down of the plant is set to zero.

A comparison of the values given to the attributes describing health and safety is given in Table 9 Conventional gas plant decreases the damage to health and safety considerably, and the transition to fuel-cell technology decreases it further

Cost/benefit considerations

We do not intend to give a full cost/benefit analysis for the reduction of emissions from power generating utilities, but we will quote some results from earlier studies. The terms we have to consider in a cost/benefit analysis can, for a certain size plant (e g , 200 MW_e), be written as.

$$C_{el} + C_{he} + C_{em} = U_{el} + U_{he} + R(U_{pl} + U_{em}) \qquad (2)$$

$$U_{em} = U_{en} + U_{mb} + U_{sc} + U_{hs} \qquad (3)$$

where

TABLE 9

Health and safety

Characteristic information for a 200 MW_e power plant unit coal, conventional gas plant, and fuel cells

	Coal[a]	Conventional gas	Fuel cells
Fatalities deaths (no /100 yr)	0 2–0 5	0 005	0 001
Injuries (no /100 yr)	38–46	2	0 5
Sickness (no /100 yr)	325–3000	1–25	1–5

[a] Keeney [19] The numbers for coal-fired plants are found by converting the annual expected fatalities (accidents) and diseases (sum of occupational and general public impacts) for an 800 MW_e coal-fired plant to 100 years of operation of a 200 MW_e coal-fired plant by linear transformations Deaths are estimated as 1–2% of injuries Calculations for conventional gas plants and fuel cells are discussed in the text

C_{el} is the cost of producing electricity (NOK yr^{-1})
C_{he} is the cost of producing heat (NOK yr^{-1})
C_{em} is the cost of reducing emission (NOK yr^{-1})
U_{el} is the utility (price) of electricity (NOK yr^{-1})
U_{he} is the utility of heat (NOK yr^{-1})
U_{em} is the utility of reducing emission products, utiles (range 0 0–1 0)
U_{pl} is the utility of not having a power station present, utiles (range 0 0–1 0)
U_{en} is the utility of reduced environmental impacts, utiles (range 0 0–1 0)
U_{mb} is the utility of reduced impacts on materials and buildings, utiles (range 0 0–1 0)
U_{sc} is the utility of reduced social impacts, utiles (range 0 0–1 0)
U_{hs} is the utility of increased health and safety, utiles (range 0 0–1 0)
R is the cost/utility ratio (NOK yr^{-1}/utiles)

For a complete analysis we would have to estimate all terms in eqns (2) and (3) Particularly, we have to determine how to convert, for example, the global index, I, into a unit which makes it comparable with the changes in health and safety Such tasks are dealt with in multi-attribute decision analysis [19, 36] This was not a task in the present analysis, but we will quote some results for the cost of reducing emissions from oil and gas generators (the third term on the left hand side of eqn (2)), and some estimates for gains in health by reduced emission (the last terms in eqn (3)) With fuel-cell technology the two first cost terms in eqn (2) will probably be greater, whereas the third cost term will be very low The last two utility terms in eqn. (2) will be higher

Gains by reduced emission are indicated in a recent study from The Netherlands by Bovy *et al.* [5] They suggest that there is a break point in acceptance by social sectors of $5000 per ton of abated emission of SO_2, NO_x, and NH_3 Suggested taxes in Sweden for emission of NO_x is 0 04 SOK g^{-1} NO_x or about $7000 per ton (Gaudernack, IFE, Kjeller, Norway) Calculations from Norway indicate that cost reductions within the health sector for reductions in SO_2 is 21 000 NOK per ton reduced emission (about \$3200), for NO_x it is \$17 000 per ton and for particulates it is \$5000 per ton The Norwegian figures have been obtained by equating the estimated cost reductions to Norwegian society in the year 2000 (e g , 67mill US\$ for SO_2) to the expected reduction (of SO_2) in that year if abatement measures are undertaken [6] The Norwegian numbers are of the same order of magnitude as those quoted in ref 5 and as those indicated by the Swedish tax proposal The implications of the Norwegian cost estimates for the three alternative power generating systems are shown in Table 10

Bovy *et al.* [5] quote a value of \$5000/ton as the general cost of reducing discharges by currently available abatement measures This estimate can be compared with the cost of reducing NO_x from diesel engines by selective catalytic reduction (SCR) The cost estimate is 0 02–0 03 NOK/kW h_e, and since the NO_x discharge is about 2 to 3 g NO_x/kW h_{el} from a diesel engine, the cost is 0 01 NOK/g NO_x or \$1700 per ton NO_x removed (Gaudernack, IFE, Kjeller, Norway). However, since this lower value only applies to NO_x from diesel engines, we have used the higher value of \$5000 per ton to calculate the annual general cost of reducing discharges from the three alternative power plant systems The values are shown at the bottom of Table 10 There are no available cost estimates for the shift in power source technology from coal or conventional gas generators to fuel-cell generators

TABLE 10

Health benefits compared with power generating costs

Characteristic information for a 200 MW_e power plant unit coal, conventional gas plant and fuel cells Tables referenced in the Source column are Tables in present work Health gains are calculated by multiplying gains per ton of gas or particulates removed with volume discharged Cost per ton pollutant removed, \$5000, is an overall cost estimate by ref 5, and does not refer to any particular technology

	Coal	Conventional gas	Fuel cells	Source
Sickness (no /100 years)	325–3000	1–25	1–5	Table 9
SO_2 (tons yr^{-1})	5300	10	7	Table 3
Health gain (\$1000 yr^{-1})	18500	35	4	
NO_x (tons yr^{-1})	1500	325	0 8	Table 3
Health gain (\$1000 yr^{-1})	25500	5525	14	
Particulates (tons yr^{-1})	500	3	2	Table 3
Health gain (\$1000 yr^{-1})	2500	15	10	
Health gain, sum (\$1000 yr^{-1})	46500	5575	48	
Health gains by transfer to fuel cell technology (\$1000 yr^{-1})	46450	5527	–	
Cost for removing emission products (\$1000 yr^{-1})	43000	2600	49	[5]

Discussion and conclusions

The environmental impact of electric power generators depends upon the technology used for each type of generator. For coal-fired and for conventional gas generators much information is available. In calculating loads from fuel cells, emission values are inferred from small-scale prototype plants or from theoretical target values, since no large commercial plant is presently operating. The information shows that emission of side products varies to a great extent, even for the same type of plant. However, if we compare emission values between plants based on the two groups of energy sources: coal and natural gas, well defined clusters appear.

The environmental impact from an SOFC plant is very much less than that for a coal-fired plant (a factor of 1/300 for air pollution and a factor of 1/5 for water pollution). Compared with a conventional gas plant, damage is reduced by between 50 and 90%. Damage to cultural monuments and buildings is negligible for a fuel-cell plant. Socioeconomic negative impacts are reduced about 30% relative to conventional gas plants (aesthetics and noise) whereas employment is unaltered. Damage to health and safety is greatly reduced compared with coal-fired plants, and is about 70% compared with conventional gas plants.

The results presented here show that fuel-cell power plants have considerably less impact on the environment than any comparable energy source based on fossil fuels. If one figure for the reduction in environmental impact relative to conventional gas technology should be given, then we suggest 60%. However, depending upon how the different goal variables are ranged in importance (see eqn. (3)), the reduction in impact relative to conventional gas plants may range from 30 to 95%. Because of the high efficiency, the discharge of CO_2 is also less than for other power plants.

The estimates of monetary gain by reducing emissions appear high. Since several independent estimates give approximately the same value, it is noticeable that the 'value' of the total discharge of NO_x in Norway of 220 000 tons (220 000 times 17 000 NOK) corresponds to about 5% of Norway's net domestic product.

The cost of reducing emission products from coal (or oil) power generators appears to be close to the willingness of Norwegian society to pay for improvements within the health sector alone. (cf. column 1 in Table 10). In addition, there will be some improvements within the other goal attributes we have defined (i.e., environment, buildings, socioeconomy).

Since SOFC power plants require no additional technology to reduce emission products, the cost of producing electricity and heat by SOFC technology can at least increase by the cost of reducing emissions from conventional technology. It is probably also cost effective to produce electricity by SOFC technology at a higher price, because only one of the four attributes adding utility to reduced emissions was included.

The emissions of SO_2, NO_x, and particulates from fuel cell plants are largely estimated or target values. But even if the values turn out to be an order of magnitude higher, the main conclusion is still valid Future improvements in conventional technology [9] may reduce the gap in the emission of unwanted side products relative to fuel cells However, risk estimates based on current 'safe' concentrations may also be decreased in the future For example, the fine fractions of particulate particles [8] and the susceptibility during pregnancy [39] may be greater than previously believed

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