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Life Cycle Air Emissions from Fuel Cells and Gas Turbines in Power Generation

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Abstract

The energy sector is responsible for a significant proportion of the emissions of the most common air pollutants. As a result, it is not surprising that cleaner and more efficient generation systems appear in the power generation market. Such is the case of fuel cell and advanced gas turbine systems, which present extremely low operational emissions as compared to other technologies based on fossil fuels.

The present study tries to assess the comparative potential contribution of fuel cell and gas turbine systems for reduction of CO_2, SO_2, NO_x, CO, and particulate emissions. A solar-hydrogen system using photovoltaic power is also analysed, given its potential use in association with fuel cells and its relevance for future energy systems.

Life cycle emissions are quantified and compared by means of a life cycle analysis methodology. This allows the inclusion in the analysis of not only the operational emissions but also the emissions associated with the manufacturing of the systems and the production and transport of hydrogen and natural gas fuels.

The results show the relative and absolute values of the specific emissions associated with the different life cycle stages of the systems. Possible ranges of variation are also identified and the influence on the results of the main system parameters and operation modes is assessed through a sensitivity analysis. The results obtained are discussed both in terms of the relative merits of fuel cell and gas turbine systems and in terms of their significance for the abatement of emissions in the more general context of other technical options.

Both fuel cells and the new generation of gas turbine systems show a similar environmental performance when working at full load, although fuel cells generally produce lower emissions. Fuel cells also present some advantages when working at partial loads. Both systems are much cleaner than older gas turbines, particularly when used in cogeneration schemes. The photovoltaic-hydrogen system emissions show a very large range of variability according to the characteristics of the manufacturing processes and the material composition of the photovoltaic modules. This system offers a clear advantage over other systems in terms of CO_2 emissions.

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Any error that may still be present in this study is responsibility of the author.

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Introduction

Fuel Cell technology was born in the last century but it is only in present years that commercialisation is slowly beginning in specific niche applications such as transport and on-site power generation.

Fuel cell modular design, high conversion efficiency, fuel flexibility, low maintenance and low operating emissions present very attractive characteristics for both applications.

In the specific case of stationary power generation, fuel cells come into play at a time when gas turbine technology is a serious contender thanks to the increase in efficiency brought about by an increase in turbine operating temperature and the use of heat recovery systems.

Based on their excellent operational performance, both systems are viewed as promising options for reduction of air emissions, particularly in sensitive areas and also with reference to the climate change issue. However, as with any emerging technology, a life cycle analysis of emissions is usually necessary to compare in a consistent way the environmental impacts of competing energy options.

This study compares low temperature fuel cells and gas turbines from an environmental point of view, quantifying the life cycle emissions of CO_2, SO_2, NOx, CO and particulates associated with different fuel cell and gas turbine systems working on natural gas and hydrogen fuel. The results can be of particular interest since some key characteristics of the systems analysed are the result of recent technological developments and no previous single study can be found covering the different aspects included in the present study.

The initial chapter gives a short review of fuel cell and gas turbine systems and their relative merits in the context of a national electricity supply network. Chapter two deals with Life Cycle Analysis (LCA) methodology and its application in this specific study. Chapter 3 presents an analysis of the systems' life cycles, including the manufacturing processes for the main components. Life cycle emissions are quantified for different generating options and a sensitivity analysis is performed to test the robustness of the results. Finally, the analysis of the results tries to put into a broader context the reduction of emissions achievable with these systems.

Objectives

The main objective of the present work is to comapre the life cycle air emissions of two modern technologies used for on-site small and medium power generation. Specifically, the aim is to see how effective fuel cell systems are in reducing the emissions of CO_2, SO_2, NO_x, CO, and particulates compared to gas turbine systems.

Taking into account that the use of clean energy technologies is only one among many ways of reducing air emissions, this work also intends to put into a broader perspective the potential contribution of the clean energy technologies related to other abatement options.

Finally, the work tries to assess the maximum reduction in emissions that may be achieved in the future by means of a clean energy chain such as PV/Hydrogen/Fuel Cell.

1. Background Information

1.1 Emissions Reductions in a broad Context

Although this study deals only with two technical options that can help reduce air emissions from power generation, there are many other levels involved in the issue of energy related emissions. Figure 1.1 shows the broad context in which the problem of emissions will be briefly discussed in this section and the relative position of the “Energy Generation” level, in which the main technical options discussed in this study are inserted..

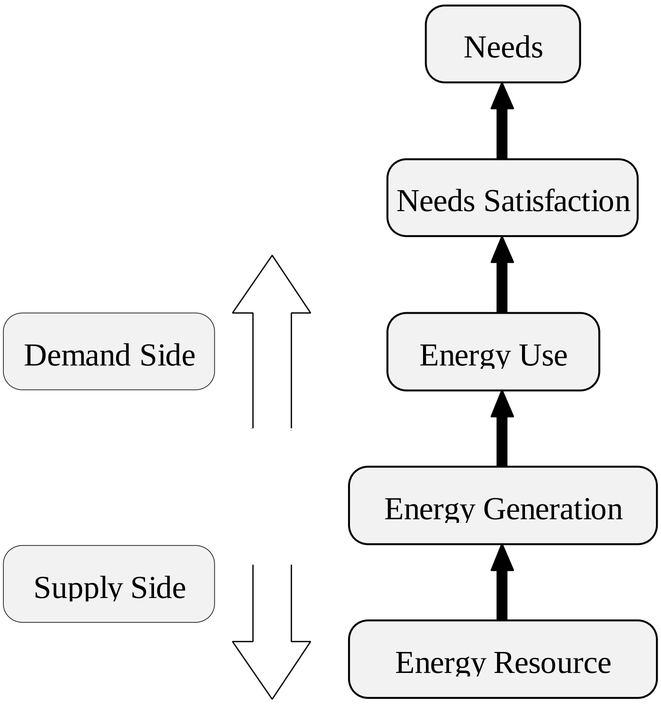


Figure 1.1 Extended energy chain

Usually the sphere of discussion on the issue of energy related emissions is restricted to the more technical aspects of energy use, transport, generation, and resource extraction. However, an important aspect of the problem that receives little attention lies outside this group and constitutes the sphere of human needs and their satisfaction, which represent the ultimate origin of the energy demand. While the solutions in the technical spheres seem to be relatively straightforward, either the philosophical and political implications of dealing with the needs issue are too high or no need is perceived for any concrete action to be taken in this area. However, in terms of efficiency in tackling the emissions problem the upper stages of the extended energy chain shown in figure 1.1 would be the best place to start. A change at these upper levels has a direct influence on all the lower levels while a change in the lower levels only represents a partial solution. Once the options at this upper level have been analysed and their feasibility assessed, one can proceed with the analysis of the next lower level and so on until reaching the energy resource level.

One can observe in later years a shift of attention towards the higher levels of the demand side of the equation and few people will deny the potential environmental benefits of transferring resources from the supply sector to the demand sector. This new approach can be observed in the transport sector where alternative ways of satisfying needs are being explored, such as in the case of the substitution of communications services for transportation services. However, the dispersed nature of the demand sector poses severe managerial problems to standard structures, which combined with capital shortage present a very difficult barrier to the practical implementation of this kind of approach (Grubb, 1991). In consequence, the traditional approach has been to focus on measures on the supply rather on the demand side of the energy chain.

The following paragraphs present some of the main technical approaches for the abatement of air emissions summarised in table 1.1. Opportunities for abatement of energy related emissions through these measures vary markedly from developed to developing countries, and particularly within the electricity sector.

The options are presented starting with the demand side and moving progressively to the supply side.

As far as possible the discussion is limited to the electricity sector but as will be obvious from the first two options the relative interchangeability between energy carriers requires the adoption of a broader perspective.

Energy Chain Stage	*Basic Issues*
Needs	Basic/Non-Basic Needs Priorities
Needs Satisfaction	Alternative Ways Material/Energy Decoupling
Energy Use	Efficiency Alternative energy carriers DSM
Energy Transport	Efficiency
Energy Generation	Efficiency Alternative fuels Renewable/Non-Renewable Centralised/Decentralised
Resource Transport	Efficiency
Energy Resource	Efficiency Alternative fuels Renewable/Non-Renewable

Table 1.1 Basic issues concerning emissions reductions in each energy chain stage.

Energy carrier switching

Some applications allow for the use of many different energy carriers by changing appliances and provision infrastructure. Matching input energy quality to end-use is one possible strategy for increasing efficiency. This means, for example, restricting electricity use to premium uses and covering the rest of the demand with other forms of energy. Although no generalisation is possible in terms of which energy carrier is optimum for a given application, the use of electricity for the provision of low grade thermal energy is highly inefficient in relation to the direct use of natural gas but it still is a quite common practice in some areas of the world. This is understandable since electricity is a preferred energy carrier thanks to its cleanliness, ease of use, and far from decreasing, its use tends to displace other energy carriers as a country develops.

Electricity use in the industrial and domestic sectors is expected to increase at the expense of other energy carriers. Although this may lead to higher use efficiency and lower local environmental impacts, the life cycle impact of such a trend is yet to be assessed.

End-Use efficiency

Compared with other stages of the energy chain, end-use efficiency is generally low, with values between 30% and 53% in developing and developed countries respectively. The highest values are those corresponding to electricity and natural gas use, the lowest to biomass use (Nakicenovic, 1993a). As a consequence, improvements in this area are to a certain extent connected with changes in energy carrier. But even in those applications where electricity is already being used as energy carrier, the increase in the efficiency of domestic and industrial appliances could help further reduce emissions.

The relative interchangeability of energy carriers discussed above means that end-use efficiency would have to improve also for non electric energy carriers to ensure an overall reduction in emissions and prevent a swapping of emissions between energy carriers.

The technical potential for energy savings in the domestic and services sectors is 30-70% for domestic appliances, 10-50% for domestic water heating, and 70-90% for buildings (IAE/OECD, 1994).

In the industrial sector the potential for savings is generally lower. Some of the options with high potential for reducing energy consumption are materials recycling, materials substitution, process integration, process change, conservation, and cogeneration. Some estimates suggest a theoretical maximum potential for energy savings in this sector of about 50% (IAE/OECD, 1994).

In some cases, huge inefficiencies arise from the way in which an energy service is provided and not from the particular conversion appliance used to provide the service. This is perceived as a priority area to make efficiency improvements (Nakicenovic, 1993a).

Finally, it should be taken into account that in a supply constrained system, increases in end-use efficiency may free supply for other uses and will not necessarily result in decreases in energy demand (Grubb, 1991).

Energy transport

The electricity transmission and distribution grids are responsible for high energy losses in some developing countries. Even excluding non technical losses, transport efficiency can be as low as 85% compared with 94% in some developed countries.

Under these circumstances, the relative advantages and disadvantages of installing centralised or decentralised systems, or making improvements in the transmission infrastructure depend to a large extent on the national or regional electricity system under analysis. For example, while the implementation of a high efficiency centralised energy system could make sense in a developed country where efficiencies downstream of power generation are near its optimum technical limit, one would question it in the case of a developing country where, for example, electricity transmission and distribution technical losses are abnormally high. In the latter case the investment in grid improvements will probably have a much greater impact on emissions, and additionally it may be more economic than a new generation plant on a saved kWh basis. Alternatively, the lack of economic resources for improvements in the transmission and distribution infrastructure could mean that the installation of high efficiency decentralised systems could be a good option, reducing emissions by bypassing an inefficient stage of the energy chain. In relation to fuel cell and advanced gas turbines this would require the reliable provision of natural gas fuel by means of pipelines or the adaptation of the systems to burn liquid fuels which can be stored more easily than natural gas. This restriction would limit the application of advanced gas technologies in isolated rural areas where topographic or distance problems prevent the reliable provision of fossil fuels. However, in new or expanding industrial areas the extension of the natural gas network may prove to be more economic than the upgrading of the electricity transmission and distribution infrastructure (Arthur D. Little, 1995).

Renewables/Nuclear

It is generally recognised that fossil fuel switching and increases in efficiency alone only represent a part of the solution to the emissions problem. Increasing the share of renewable and nuclear electricity generation is considered an effective complementary way of limiting standard air emissions.

One common concern often cited in connection with the widespread use of renewable energy systems in integrated power systems is their inherent variability and its negative influence on the system stability. However, different studies suggest that windpower could contribute between 10% and 50% to large integrated power systems without negative effects (Grubb, 1991) (Swisher, 1993). In practice, some constraints such as siting may greatly reduce their actual contribution but the most important factor affecting renewables at the moment is the question of utility regulation.

Traditional renewables such as large hydro and geothermal energy systems do not suffer from these barriers but are capital intensive.

Nuclear energy is seen by its advocates as a clean and cheap solution to the problem of common air pollutants emissions since life cycle emissions are extremely low, even for CO_2. However, its detractors present a very different view, stressing the economic and technological uncertainties plaguing the issue of radioactive waste disposal. Furthermore, many people involved in the renewable energy sector maintain that with a similar level of investment in research, development and demonstration to that spent in nuclear programs, renewable systems could offer a much better solution to our energy problems (Grubb, 1991).

Fuel switching within the electricity sector

On average coal, the less clean of the fossil fuels, represents the biggest individual contribution to electricity generation, both in developed and developing countries. Taking into account that natural gas reserves may prove to be higher than was previously thought, the room for fuel switching between coal and gas is, in principle, potentially big. Although not as geographically concentrated as oil resources, gas resources are distributed among a few key areas of the world. In these conditions, fuel switching between coal and gas, although technically possible on a global scale, could create a heavy dependence on a few production areas.

Consequently, most energy analysts consider that, in the short term, the opportunities for reducing emissions by deliberately altering the mix of supplies towards low-carbon fuels are limited (Grubb, 1991).

Alternative technologies based on fossil fuels

Some of these are covered by this study (i.e. fuel cells and gas turbines) but many other are available, particularly concerning fluidised bed coal combustion. These new technologies are much cleaner than conventional coal combustion but the emissions per unit electricity generated will still be considerably higher than those associated with natural gas systems. However, given the large share of coal fuel use in the power generation sector, the potential reductions achievable with the new combustion technologies should not be underestimated.

Estimates indicate a potential for energy savings in the power generation sector of at least 20-25%.

End of pipe control of emissions

This has been for many years the traditional way of reducing emissions but it is increasingly seen as a not very effective way of dealing with environmental problems when compared with the other options available. However, it must also be recognised that these technologies greatly reduce operational emissions relative to uncontrolled systems.

Concerning CO_2, the standard approach to emissions control may prove to be very costly relative to other alternatives, since CO_2 is the main product of thermal combustion and recovery systems are expected to lower generation efficiency by ~20% (IAE/OECD, 1994).

In relation to other standard air emissions, technologies that target one group of pollutants may have an adverse effect on other pollutants and may also decrease the system efficiency, thus increasing CO_2 emissions (e.g. catalytic converters in cars).

Non-Energy related emissions

Finally, it is worth mentioning that for some of the pollutants analysed in the present study, non energy related emissions can also contribute appreciably to total atmospheric emissions.

Further discussion on these issues can be found in (Nakicenovic, 1993b) (Gruber, 1991) (IAE/OECD, 1994)

1.2 Energy Conversion Pathways

Among all the possible options available for the reduction of energy related emissions, this study will focus on the power generation level. But even within this level the technical options available are many. Thus, this and the following section will try to fundament on efficiency and general environmental terms, the specific choice of fuel cell and gas turbine systems as the subject of this study.

Energy can take many forms, from kinetic and potential energy in water or wind, to chemical energy in fossil fuels or nuclear energy in fissile isotopes. However, it is not energy in itself that is of interest for us but its capacity to do useful work. There are two important requirements that must be fulfilled before work can be extracted from natural energy sources. Firstly, energy must be present in suitable quality and quantity at the place where the work is needed, and secondly, the energy must be released in order to do work. Energy conversion mechanisms are involved in both of these processes and thus some energy is lost in the process. In order to fulfil the first requirement it is evident that some form of concentrated “energy carrier” is needed since natural energy sources are generally too diluted to be suitable to do useful work. Thus, energy must first be converted or upgraded into an energy carrier of concentrated energy content such as electricity, or solid, liquid, or gaseous fuels. In some instances this upgrading task has already been done naturally as in the case of fossil fuels. By contrast, electrical energy is not to be found naturally stored as some kind of fuel but must be produced by man from other types of energy through relatively low efficiency processes. This represents an important difference between electricity and other common energy carriers. A second important difference involves the conversion process to do useful work. Thanks to the way in which energy is present in electricity, i.e. as potential energy of charge carriers, it can be used to perform work of a kind impossible to do with other kind of energy carriers. These two characteristics make electricity a high quality kind of energy and have pushed us into finding new conversion mechanisms in order to generate electricity more cheaply, efficiently, and cleanly.

Figure 1.2 shows some of the known energy conversion mechanisms for the production of electricity and their typical conversion efficiencies (Culp, 1979) (Kraushaar, 1993) (Nakicenovic, 1993a) (McFarland, 1994).
Each one of these conversion pathways has an inherent theoretical limit efficiency which tells us how much of the initial energy source content, be it solar radiation or chemical energy stored in a fuel, would optimally be converted into electric energy. Additionally, each has a state of the art efficiency which depends on the degree of development of the technology and which tends to grow more or less asymptotically with time towards the theoretical limit.

Some important inferences can be drawn from a comparison of the conversion efficiencies of different systems:

- In general terms we can see that renewable conversion energy systems have a relatively low conversion efficiency compared with conversion systems based on the combustion of a non-renewable energy source such as natural gas, oil, or coal.

- Within the energy systems that "burn" fossil fuels, although thermal combustion systems are the most widely used at the present moment, they are not the ones that present the best potential conversion efficiency. For example, fuel cell systems using chemical oxidation have higher theoretical conversion efficiency.

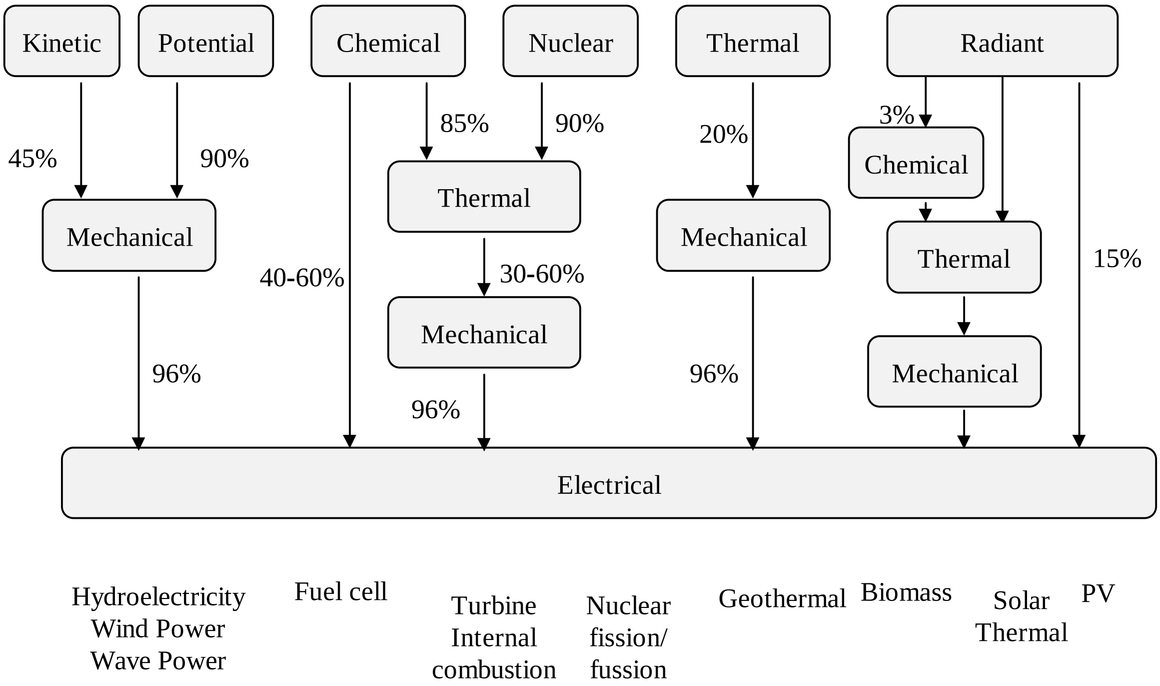


Figure 1.2 Energy conversion mechanisms for the generation of electric power.

The restrictions imposed by thermodynamic laws are manifested in a more or less general rule concerning energy conversion systems: the more diluted an energy source is, the more material, energy, and land resources will be necessary to produce a unit of useful power. Thus, one can expect renewable energy systems to be more resource and energy intensive during the manufacturing processes, reflecting the large (per unit power generated) and/or complex systems required for energy conversion (e.g. hydro, wind, photovoltaic and biomass conversion systems). The converse is generally true for conventional combustion energy systems, for which manufacturing processes are quite straightforward and where the concentrated nature of the energy source manifests itself in a compact energy conversion system. However, in this last case resource extraction can account for the disruption of large areas (e.g. open cast coal mining), whereas the occupation of land by some renewable systems, though large, may be compatible with other productive uses.

The relatively high intensity of use of resources during renewable system manufacture will manifest itself as pollution produced along the life cycle of the systems rather than specifically during the operational stage. However, this pollution tends to be different both in quality and quantity from that produced by conventional systems. For standard air pollutants, emissions associated with renewable energy systems tend to be much lower that those associated with conventional systems, even considering the whole life cycle of the systems.

Fuel cell systems that use natural gas as an energy source stand between these two extremes. They are not a renewable energy system in the sense that they still "burn" a fossil fuel, but they are not a conventional energy system either since the energy conversion mechanism is not thermal combustion but electrochemical conversion. In this sense they may be put in a different class jointly with nuclear energy but without all the environmental and political issues associated with radiation. Additionally, fuel cell systems have a higher conversion efficiency than conventional systems and are particularly good at burning non-carbon fuels such as hydrogen. On the down side, gas fuelled fuel cell systems still use conventional combustion processes during the reformation of natural gas and consequently they emit some conventional air pollutants during the operation of the system. However, the combustion temperature tends to be lower than in standard burners and fuel is not 100% natural gas but a mixture of natural gas and hydrogen, which produces lower emissions. This has no effect on CO_2 emissions, which can only be reduced by increases in overall system efficiency.

All the above mentioned characteristics make fuel cell systems an interesting area for a comparative life cycle environmental assessment.

Anticipating some of the results one would expect that given that fuel cells systems "burn" a concentrated energy source such as natural gas, hydrogen, or methanol, the material and energy consumption during manufacturing will be much lower than for, for example, photovoltaic systems which exploit a more diluted energy resource, but higher than for conventional systems. The latter is due in part to the different degree of development of each technology and also to the inherent complexity of each conversion system.

For a fuel cell system operating on natural gas one would expect much lower overall emissions than for a conventional system (except for CO_2) but still higher than those from renewable systems due to the natural gas chain emissions and the operation of the reformer. However, significant differences may exist in the emissions of non-standard pollutants, as occurs for photovoltaic and wind energy systems.

1.3 Power Generation Schemes

This section will try to identify the specific way in which the conversion systems selected for this study are inserted into broader energy chains, going from the extraction of the energy resource to the delivery of electric power. This will help define some of the important parameters of the study, such as the power range of each system, and the overall energy conversion efficiency of the energy chains and their estimated variation ranges.

When considering the provision of electricity at a national scale one can broadly distinguish between four basic power generation modalities:

1) Generation near the primary energy source and electricity transport through the grid.

For some systems there is no other alternative since the energy source cannot be transported (Hydroelectric power, PV). For fossil fuel systems, although this option is rather inefficient in terms of energy conversion, it can present certain economic advantages for medium power systems.

2) Centralised generation near the load. This is the conventional scheme adopted for large fossil fuel systems. Large conventional power stations located near the largest population or industrial centres in order to minimise losses during electricity transport.

3) On-site generation with grid interconnection. In this approach the generating system is physically located next to the individual consumer. Any excess power is fed into the grid and conversely, any deficit in power is compensated by the grid.

4) On-site isolated systems. These systems are also located next to the individual consumer but they don't rely on the grid to compensate for fluctuations in demand or supply of power. Some renewable systems cope with this disadvantage by coupling with a conventional generator while others store the energy in chemical or electrochemical form.

Table 1.2 summarises the characteristics of each group.

By far the archetypal scheme that has been followed in many countries included types 1) and 2) systems, interconnected by a national or regional electricity grids. These schemes are generally medium to high power systems in order to take advantage of certain economies of scale. Regretfully, this leads to big environmental disruptions and their presence near populated or important natural areas is being increasingly questioned both in environmental and health & safety terms.

Type of System	**Remarks**
Generation near energy source with grid connection	Large Hydropower. Photovoltaic. Wind. Some fossil fuel systems. Large power transmission losses over long transport distances.
Centralised generation near load	Large power fossil power stations. Nuclear. Concerns about environmental impact.
On-site grid connected generation	Renewables (specially wind,PV). Fuel cells. Medium/Low power fossil fuel systems. Specially suitable for commercial and industrial applications. Cost of system relatively high. Impact of conventional systems in sensitive locations
On-site isolated generation	Renewables. Fuel cells. Medium/Low power fossil fuel systems. Systems working on a fossil fuel depend on its reliable transport. Renewables may need batteries if not in a hybrid system. Power supply may be of low quality (variability, reliability,etc) Cost of system is usually high but lower than grid extension.

Table 1.2 Main electricity generation schemes.

Types 3) and 4) share a relatively small proportion of the electricity supply and initially entered the market in specific niche applications such as industrial generation using by-product gases, provision of electricity in areas isolated from the grid, or in portable energy systems. The inherent advantage of renewable energy systems was immediately recognised in this area but power reliability and variability problems still present some barriers to widespread use. For this reason small power conventional generating sets are also widely used in this kind of applications. However, the same environmental pressures affecting type 2) systems mentioned above also affect conventional systems in these two medium and low power categories, particularly when used in densely populated areas. Consequently, the market is moving towards low or zero emissions technologies but seems to be still doubtful of the reliability, variability, and overall quality of renewable systems power for commercial and industrial applications. On-site grid-connected applications can be considered a niche market for fuel cells. A modular technology, with very low operational emissions (except CO_2) when working on natural gas, low maintenance and relying on a chemical fuel that can be easily stored.

Another relative advantage of big centralised systems often cited its the lower maintenance requirements compared to several on-site units. On the other hand a decentralised system may help minimise transmission and distribution losses and increase the reliability of the electricity network.

Efficiency comparison

Among the many conventional systems available, natural gas systems have been chosen for the analysis thanks to their many environmental and maintenance advantages compared with oil or coal systems. Their only disadvantages may be the bulkiness of natural gas compared to the other fossil fuels and the relative cost of the fuel. The first can be a problem where no good pipeline transmission and distribution networks are in place.

Several conversion technologies are available which burn natural gas to generate electricity. Due to technological and siting characteristics these technologies can present a wide range of conversion efficiencies when taking into account the whole energy chain, from the extraction of the natural gas to the delivery of electricity. Such variation in system efficiency is quantified in figure 1.3, which shows the life cycle efficiencies of several energy systems working on natural gas and hydrogen. Figures include energy consumption and losses during natural gas extraction, processing, transport, distribution, and conversion in the turbine or fuel cell. Data used for the calculation of these figures is included in Appendix 1.

The main source of variability for the systems working on natural gas is the variability in the conversion efficiency of the power generating system itself, mainly due to differences between old and new technologies.

All the efficiencies presented in figure 1.3 show some degree of variability according to technological factors and uncertainty in the data. All but the three last columns shown in figure 1.3 represent systems working on natural gas. The last three systems work on hydrogen fuel. Among these last columns, the first one includes all the conversion losses from a photovoltaic/electrolysis system used to produce the hydrogen while the remaining systems ignore these losses and start computing losses from the processing of the hydrogen fuel. This allows making a more fair comparison between the systems working on natural gas and hydrogen.

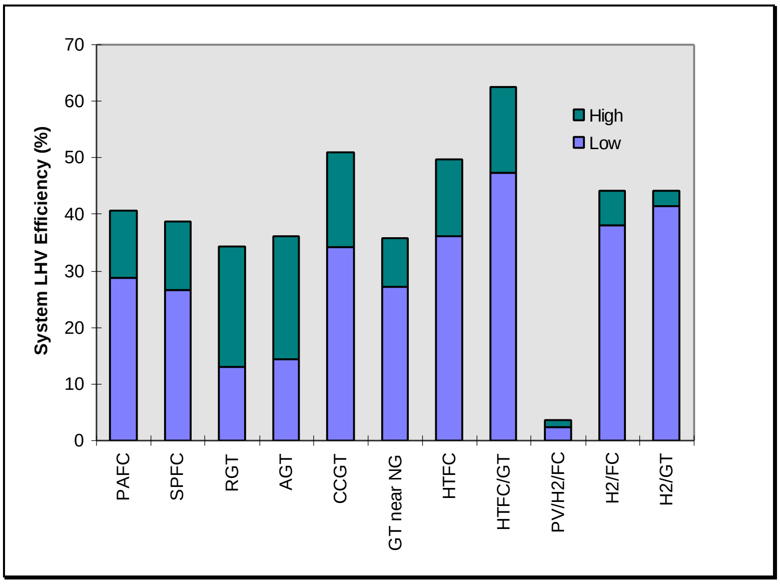


Figure 1.3. Efficiency comparison between different power generating systems[†].

(PAFC=phosphoric acid fuel cell, SPFC=solid polymer fuel cell, RGT=radial gas turbine, AGT=axial gas turbine, CCGT=combined cycle gas turbine, NG=natural gas source, HTFC=high temperature fuel cells, PV=photovoltaic, H_2=hydrogen)

When analysing these data it has to be taken in mind that some of these technologies are not yet commercially available or are even in early stages of development while others have been in the market for several. The first columns from “PAFC” to “GT near NG” can be considered commercial or pre-commercial technologies (with the exception of advanced low power gas turbines which are yet under development), while the rest of the columns are in different stages of research and development.

PAFC, SPFC, RGT, AGT, HTFC, H_2/FC, H_2/GT figures are computed for on-site systems and thus they avoid energy losses during electricity transmission and distribution. CCGT and HTFC/GT systems are considered in centralised power generation and their ranges of variation include maximum and minimum technical losses in power distribution in electricity grids. However, they do not account for abnormally high power losses, as those that can be found in several developing countries, and that generally have a non-technical origin. The same is valid for the system “GT near NG” but in this case transmission losses are included while natural gas transport losses are excluded.

Concerning the systems working on natural gas, there is no big difference between fuel cells and top performing simple cycle gas turbines. CCGT have a clear advantage over other systems thanks to the high conversion efficiency attained by this technology, even when considering energy losses during electricity distribution. The worst performers are old on-site radial or axial turbines due to their very low conversion efficiency.

Hydrogen energy chain efficiency is lower than that of natural gas even excluding hydrogen generation efficiency and when storage is mainly as compressed gas and only a minor part as liquefied hydrogen. This is due in part to the lower density of H_2, which increases leaks and energy consumption for compression. Low generation efficiencies due to the use of renewable energy systems can not be easily related to emissions as with conventional systems as will be shown in sections 3.5 and 3.6 (main results and sensitivity analysis).

[†] For a description of the systems mentioned in this figure see sections 1.4 to 1.7.

The calculations shown in figure 1.3 assume fuel cell and gas turbine system efficiencies when working at 100% rated power. However, it is also interesting to analyse how these systems perform at partial loads. Figure 1.4 shows such a dependence with load for both types of systems.

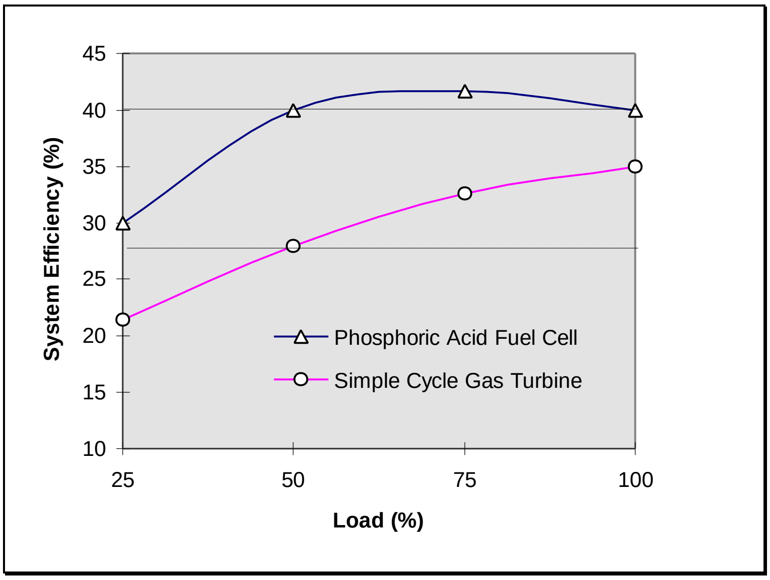


Figure 1.4 PAFC and simple cycle gas turbine system efficiencies as a function of load when working on natural gas.

For fuel cell systems with external reforming the efficiency curve remains at or above rated power efficiency up to 50% load and then it drops abruptly at 25% (NYSERDA, 1997) (Satomi, 1997). Gas turbines are less efficient than fuel cells when working at partial loads (Cohen, 1996), particularly in the case of simple cycle systems. Under certain circumstances, this fact has a big influence on specific emissions as will be discussed in section 3.6 (sensitivity analysis).

1.4 Fuel Cell Systems and Technology

General

There exist five broad types of fuel cells identified by the type of electrolyte used: alkaline (AFC), phosphoric acid (PAFC), solid polymer (SPFC) (also called proton exchange membrane, PEMFC), molten carbonate (MCFC), and solid oxide (SOFC).

AFC, PAFC, and SPFC work at low temperatures and are generically denominated low temperature fuel cells (LTFC). Conversely, MCFC and SOFC work at high temperatures and are known as high temperature fuel cells (HTFC).

PAFC and SPFC are the two technologies that are closest to commercialisation and consequently are the two selected for analysis in the present study (Hart, 1995). Although some of the other technologies offer better potential conversion efficiency than PAFC, they are still in the development/demonstration stage and some material degradation problems remain to be solved. In the case of SPFC, this technology is particularly attractive thanks to its low specific weight and simplicity.

Fuel cells can work on a variety of fuels, among them hydrogen, methanol, and natural gas. However, there is an efficiency loss when burning natural gas or methanol due to the energy consumption for the production of hydrogen (see fuel processing section).

A summary of some characteristics of the different fuel cell technologies is shown in Table 1.3.

Fuel Cell Type	**LHV[‡] Efficiency (%)**	**Remarks**
Alkaline	50-65% (H_2)	Stationary, Transport, Aerospace applications Low Temperature (100 °C-200°C) Precious/Non-precious catalyst Research/Demonstration Stage Successfully used in space missions for many years
Molten Carbonate	50% -55% (NG)*	Stationary applications High Temperature (650°C) Problems with materials corrosion. Short cell life Research/Demonstration Stage
Phosphoric Acid	40% (NG, atmospheric) 45% (NG, pressurised)	Stationary applications Low Temperature (200°C) Platinum catalyst Commercialisation Stage
Solid Oxide	50%-55% (NG)	Stationary applications High Temperature (800°C -1000°C) Tolerant to impure fuel Problems with materials/high temperature Research/Demonstration Stage
Solid Polymer	40% (NG,present) 43% (NG, short term) 55%-60% (H_2)	Stationary and Transport applications Low Temperature (80°C -110°C) Platinum catalyst Sensitive to fuel impurities Demonstration/Commercialisation Stage

Table 1.3. Main Characteristics of Fuel cell types.

[‡] LHV = low heating value efficiency, i.e. the efficiency calculated on the basis of the low heating value of a fuel

* (NG) = Natural Gas

Components and Operation

PAFC and SPFC systems working on natural gas can be broadly divided into 4 main subsystems as shown in figure 1.5.

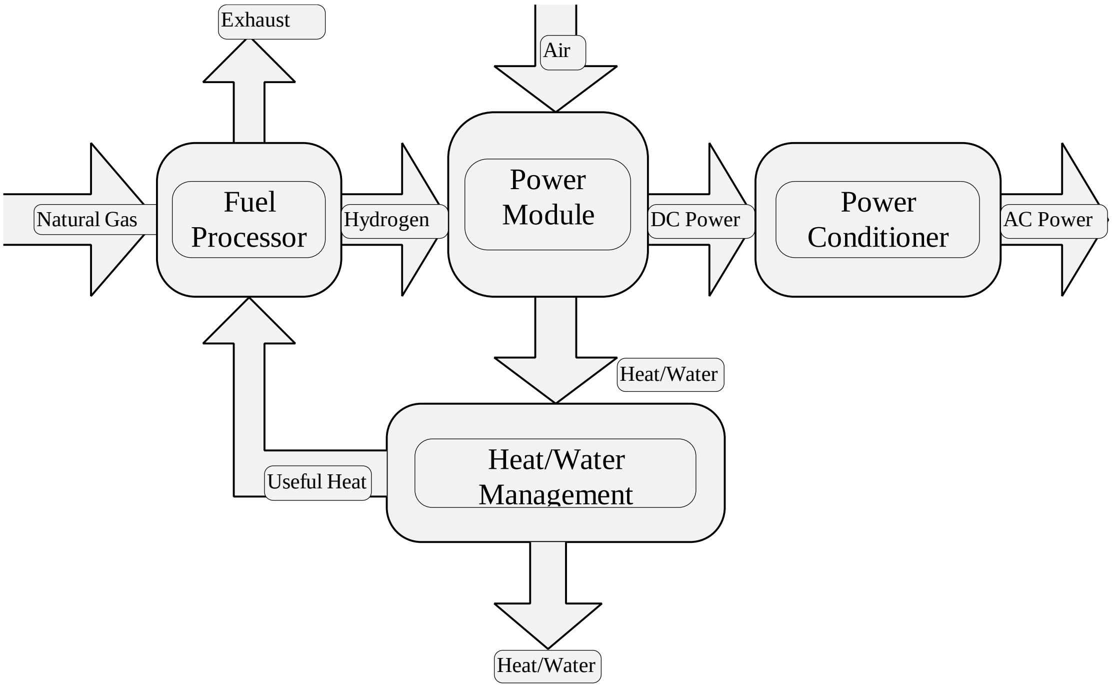


Figure 1.5 Fuel Cell system main components.

Fuel processing

When consuming natural gas, fuel cell (FC) systems must first reform the fuel to produce hydrogen. This is because the energy conversion mechanism is sensitive to carbon poisoning, which makes the FC very inefficient and shortens its lifetime when working directly on natural gas. Thus, not only the H_2 gas must be produced but its content of residual CO gas must be low enough to avoid poisoning the cells. All these operations are accomplished in the fuel processing subsystem. The subsystem consists of a fuel reformer to produce the H_2, CO shift oxidisers to convert CO into CO_2, and an optional desulfurizer.

Many types of natural gas reforming technologies are available. Steam reforming is the most common method, using a burner working at temperatures above ~650 °C and producing a mix of 80% H_2 and 20% CO_2 at an efficiency of ~80%. For PAFC systems, optimised steam reforming is usually adopted since part of the heat energy in the steam produced in the operation of the fuel cell can be used in the reforming process, reducing the need for additional fuel. For SPFC systems the option is not so clear since the working temperature is not high enough to produce steam. However, steam reforming can still be used and the surplus heat could be used to do some work. Alternatively, a method called partial oxidation can be used. This method involves heating the natural gas in an atmosphere poor in oxygen and works at much lower temperatures than steam reforming (~350 °C), but only produces 50% H_2. Finally, a method called autothermal reforming, combining steam and partial reforming, seems particularly suitable for SPFC systems. This technology takes advantage of the fact that partial oxidation is an exothermic reaction and the heat produced can be used in steam reforming which is an endothermic[§] reaction.

Both steam reforming and partial oxidation use catalysts to promote the reaction. These catalysts are usually pellets made from copper/nickel oxide supported over some temperature resistant substrate such as alumina, magnesia, or mixed ceramics.

The fuel processing subsystem is the source of the system emissions through the burning of fuel in order to reform natural gas. However, two main differences separate this type of burner from a conventional natural gas burner. Burner temperatures are considerably lower than in conventional systems, thus reducing NO_x emissions. Additionally, the excess hydrogen and heat from the stack reduce natural gas fuel requirements. Since H_2 fuel contains no carbon or sulphur, emissions of most common pollutants such as SO_2, CO, and particulates are lower when burning the H_2/natural gas mix.

[§] An exothermic reaction produces heat while and endothermic reaction consumes it.

Power module (includes fuel cell stack)

This can be considered the heart of the system, the place where the energy is converted from chemical to electrical form in one single stage without the need of a generator as in conventional systems. The power module consists of many cells connected together in what is called the fuel cell stack. Each cell is a square or rectangle of ~0.5 cm thickness and its composition is similar to that found in conventional electrochemical batteries, with an anode, a cathode, and an electrolyte. However, the important difference between the technologies is that in the fuel cell the energy is externally provided through the H_2 gas instead of being stored in the system as in a battery.

Both PAFC and SPFC work in exactly the same simple way. As shown in figures 1.6 and 1.7 the incoming H_2 gas molecules are dissociated in the anode in the presence of a platinum catalyst, producing two H^+ ions and two electrons. The H^+ ions are transported through the electrolyte (which is a poor electronic conductor) while the electrons are transported from the anode to the cathode through the load, closing the circuit. The electrons, once in the cathode, recombine with the H^+ ions in the presence of oxygen and a platinum catalyst producing water. The interface region where the electrocatalyst, the gases and the electrolyte are in contact is where the reaction takes place.

Summarising, the reactions are:

Anode	$2H_2 \Rightarrow 2H^+ + 4e^-$
Cathode	$O_2 + 2H^+ + 4e^- \Rightarrow 2(H_2O)$
Overall Reaction	$2H_2 + O_2 \Rightarrow 2(H_2O)$

Usually, the voltage across a single cell is too low for practical applications and consequently the cells are connected in series conforming a stack. The anode of one cell provides the electrons for the cathode of the adjacent cell. For a given cell design, the stack current can be controlled by adjusting the cell area.

The specific cell geometry and type of materials used are detailed in figures 1.6 and 1.7 for PAFC and SPFC respectively.

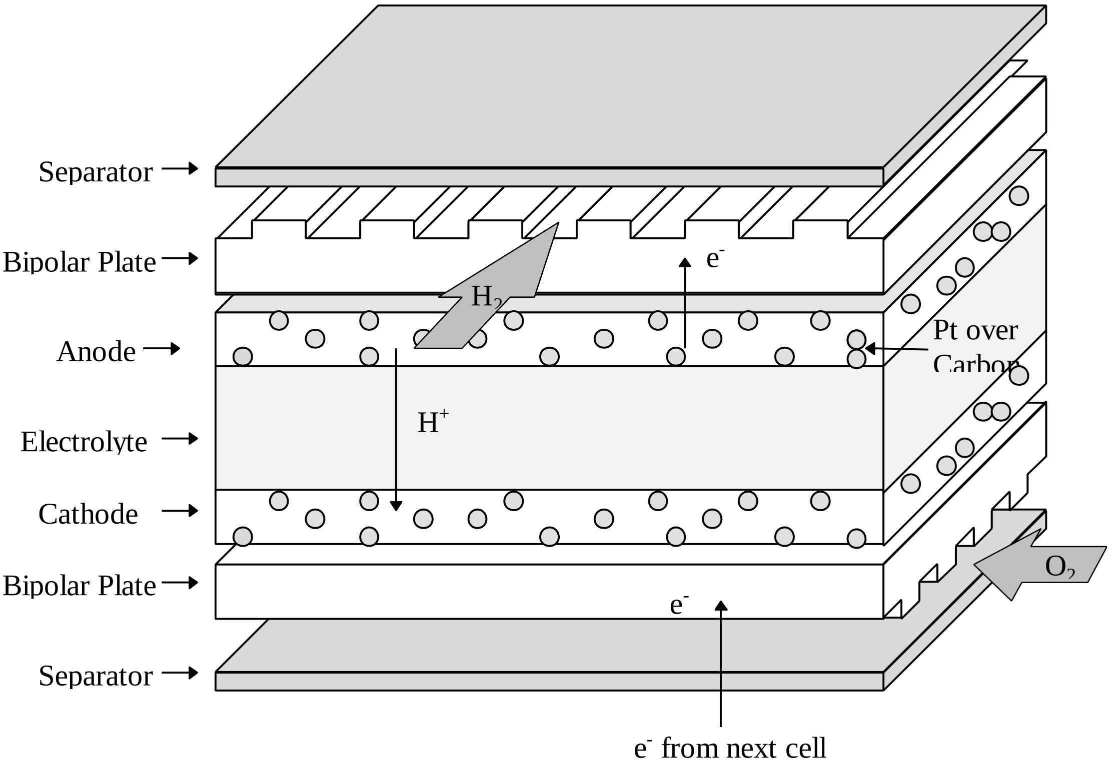


Figure 1.6 Cell design for Phosphoric Acid Fuel Cell .

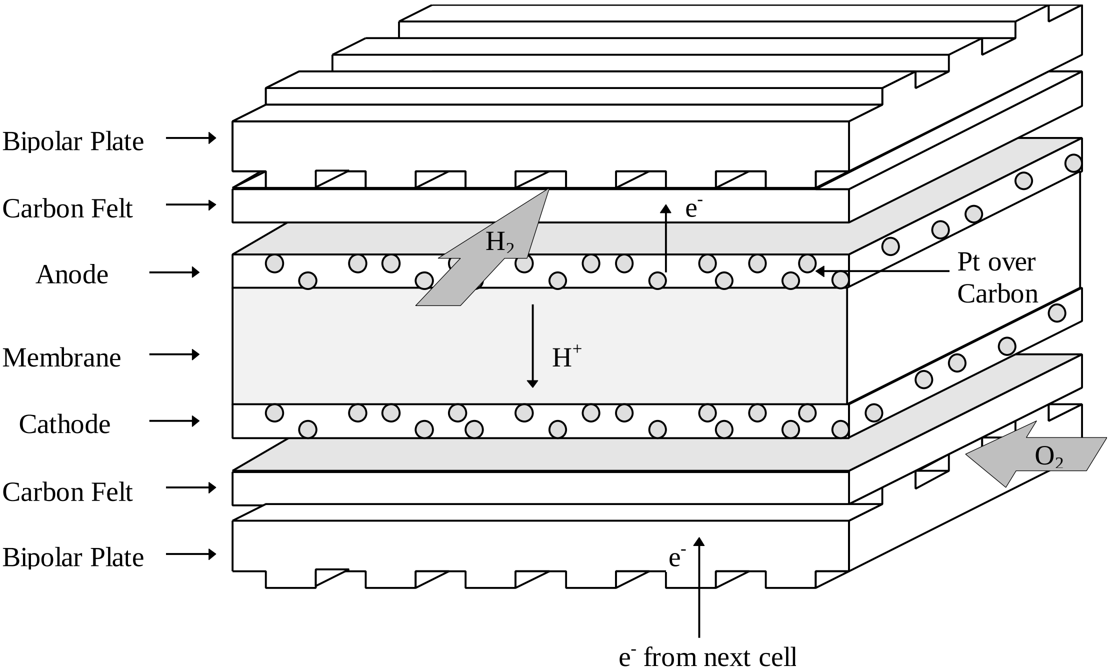


Figure 1.7 Cell design for Solid Polymer Fuel Cell

In both types of cell the anode and cathode are made from graphite materials, which have an excellent electric performance and suitable corrosion resistance at the operating temperatures.

As shown in figures 1.6 and 1.7 graphite plates (usually called bipolar plates) provide a support for the electrocatalyst. Many designs exist for the bipolar plates but all of them must contain channels through which both the H_2 and the O_2 gases enter the reaction zone. The geometries shown in figures 1.6 and 1.7 are the ones that have been adopted for the present analysis. In the case of the PAFC the porous bipolar plate allows storage of the liquid electrolyte, thus extending the useful lifetime of the cell. Additionally, the contact surface between gas and electrocatalyst is increased in relation to the design in figure 1.7 since the gas channels are on the other side of the plate. However, the use of a porous plate means that an impervious graphite separator must be used to prevent the mix of H_2 and O_2 from adjacent cells, increasing the weight of the stack. In SPFC systems where no electrolyte needs to be stored the simplicity of an impervious bipolar plate is a definite advantage, mainly in terms of volume and weight.

The electrocatalyst is of the same type in both technologies, only the amount of catalyst used per cm^2 of cell varies. It consists of Platinum (Pt) deposited over carbon black particles and mixed with polytetrafluoroethylene (PTFE) polymer. Carbon black is used as support for the Pt thanks to its high surface area, corrosion resistance, and good electrical properties while the PTFE is a highly corrosion resistant polymer that provides hydrophobicity to the mixture.

In PAFC systems the electrolyte is liquid phosphoric acid at ~200 °C in a matrix of silicon carbide ceramic material (SiC). In SPFC it is a solid membrane made on a material based on PTFE and sulphonic acid groups. Due to the presence of an acid electrolyte, material degradation is more of a concern in PAFC systems than in SPFC systems. As a consequence, graphite quality needs to be higher in PAFC. This has manufacturing implications as will be explained in section 3.2.

As mentioned above, the ensemble of cells is connected in series simply by clamps that press one cell against the other. This guarantees a good electric contact between cells and helps minimise gas leakages.

Gas can be introduced into the electrodes by means of external manifolds connected to the sides of the stack as in PAFC or internal manifolds running perpendicular to the cell area. In both cases a set of conducts feeds the gases and another set collects the unreacted surplus. The water produced in the cathode is evacuated with the excess gases.

Usually some method of stack cooling is necessary in PAFC to eliminate excess heat. One common option is to place a cooling plate every 5 cells. Some cooling fluid (air, water or water/glycol mix) circulates through the cooling plate and a heat exchanger is used to recover some of the energy for the fuel reformer and other applications.

Power Conditioner

The fuel cell stack produces DC power which must be converted to AC power by means of an inverter. If necessary, voltage may be adjusted using a transformer. This subsystem may also include special connections to feed surplus electricity to the electric grid.

Heat/Water management

Excess heat and water must be removed from the stack to prevent overheating and flooding that could impair cell performance. In PAFC the operating temperature is high enough to produce steam/hot water which can be used in commercial and industrial applications. A heat exchanger is used to extract the heat from the cooling fluid circulating through the stack. In SPFC no steam is produced unless steam reforming is used since the cell operating temperature is 80-110 °C. Some hot water is produced which could be used for domestic applications. However, no useful work can be extracted from it for commercial or industrial applications.

For more information on fuel cell systems see (Appleby, 1996) (Appleby, 1989) (Blomen, 1993) (Hart, 1995) (Kordesch, 1996) (Penner, 1995).

1.5 Gas Turbine Systems and Technology

General

As in the case of the fuel cells there exist many different types of gas turbine systems for stationary applications. Broadly speaking the most common ones are radial gas turbines (RGT) and axial gas turbines (AGT), which differ in the way they impart kinetic energy to the gases in the compressor or to the blades in the turbine. RGT are most commonly used for low power systems while AGT are better for medium and high power systems. Within AGT we can distinguish between standard gas turbines and more complex systems working with both steam and natural gas.

Table 1.4 shows some of the characteristics of these systems. In the present work and due to the power range analysed (< 1MW), the two technologies under study are RGT and open simple cycle AGT. In closed or semiclosed systems the exhaust gases are recycled and used again as working fluid as opposed to open cycles where they are discarded to the atmosphere. In combined cycle gas turbines the exhaust gases of a turbine are recovered and used to drive another power cycle, most commonly a steam turbine. Some results are also presented for these type of systems given their high performance.

Many of these systems have some sort of heat recovery subsystem (regenerator, recuperator, etc.) that helps improve the overall efficiency of the system. Consequently, the conversion efficiency can vary greatly between systems according to the specific heat recovery scheme utilised as shown in table 1.4.

Gas Turbine Type	**System Efficiency (%) LHV**	**Remarks**
Axial Open Simple Cycle	20% -40% 47% target for 1-25MW (*)	Medium-High power range Simpler than closed or semiclosed systems Corrosion problems with bad fuel
Axial Closed Cycle	≥ open cycle	High power range Clean working fluid Constant efficiency over wide load range High Cost and Size
Axial Combined Cycle	47-57 %	Medium/High Power Range High efficiency
Radial	9-18% without heat recovery 26%-30% recuperated system 38% ceramic turbine	Low power range (<500 kW) Simple system

Table 1.4 Main Characteristics of different Gas Turbine types.

(McDonald, 1996), (Barker, 1996a), (Barker, 1996b), (Stambler, 1996), (Ohhashi, 1995) (Fulton, 1994)
(*) (Stambler, 1995)

Simple cycle efficiency target for both large and small systems is around 40% and 38% respectively. Large systems have already attained this level and are being commercialised while small systems still need further development and are not commercially available.

CCGT systems are breaking the barrier of 60% thermal efficiency, the optimum efficiency for the Brayton/Rankine cycle (Johansson, 1996). The smallest CCGT systems is around 20MW while the highest efficiencies are attained by systems >300 MW (Barker, 1996b).

A further type of combined cycle gas turbine system that can be found is the Integrated Gasification Combined Cycle (IGCC). This system uses the gas produced from coal gasification to drive a gas turbine. Although it presents many environmental advantages compared with conventional coal combustion this system will not be dealt with here because the input fuel is not natural gas but coal.

High power gas turbine systems in general can achieve higher efficiencies than low power systems. One reason for this is that when scaling-up a system the power of the system increases as the square of the scaling factor while the mechanical losses increase in a linear way. The other reason is that larger systems can operate at lower speeds and thus can avoid the gear losses due to speed conversion between the turbine and the generator.

Components and Operation

Gas turbines work on the principle of a simple thermodynamic cycle, compressing air, then heating it through the combustion of natural gas and finally expanding the hot gases through a turbine to produce mechanical work which is then transformed into electrical energy by means of a generator. The components of a simple open cycle gas turbine are shown schematically in figure 1.8.

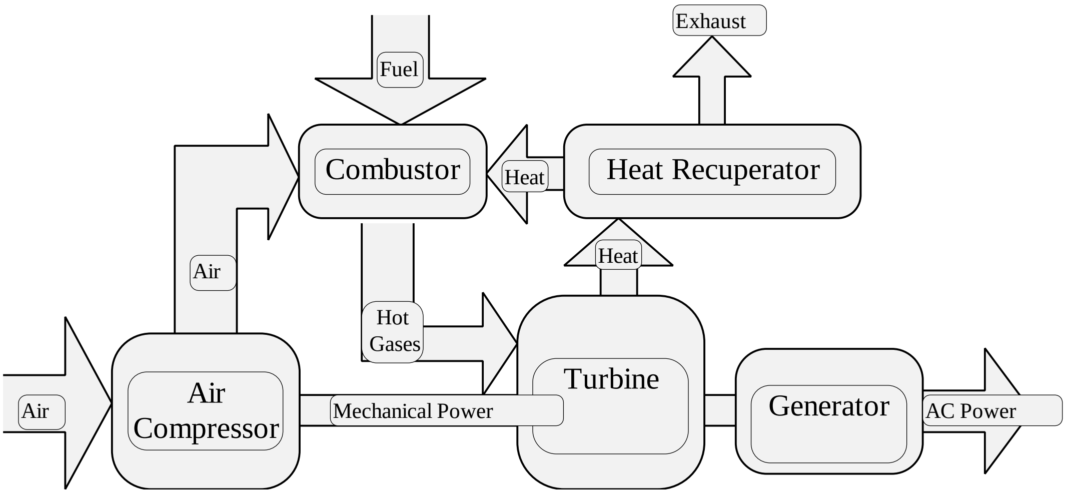


Figure 1.8 Simple Cycle Gas Turbine system main components

Basically the system is symmetric since the turbine performs the reverse work done by the compressor and actually both are similar in design. Useful work can be extracted from such a system since the compressed air is heated in between the compression and expansion stages so that a thermodynamic cycle can operate based on the temperature difference thus created. Both the compressor and the turbine consist of a series of blades which can impart kinetic energy to a gas or take it away from it to convert it into mechanical energy.

Several compression and turbine stages can be connected in series to increase the compression ratio and the power output of the system.

The turbine, compressor, and generator can be mounted on the same or on two different shafts. In both cases a part of the turbine mechanical energy drives the compressor and the rest drives the generator.

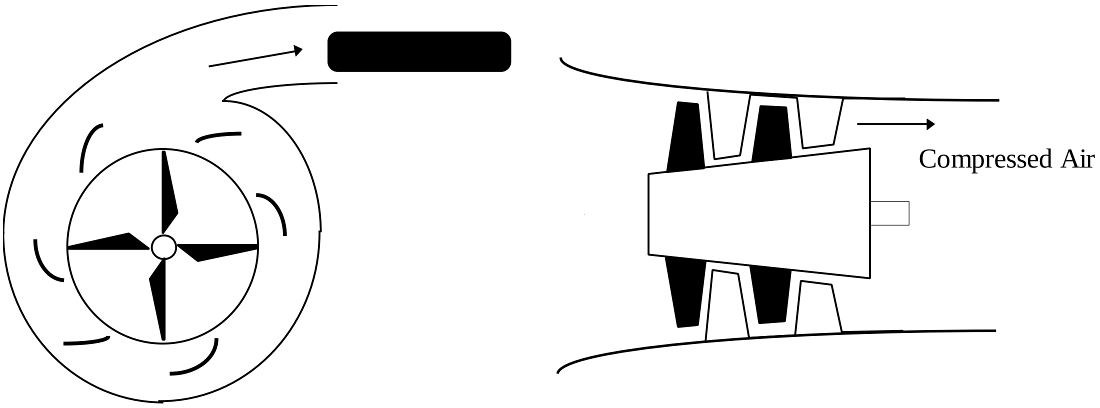
Generally speaking the higher the combustion temperature the higher the overall efficiency of the system. Increasing the turbine inlet temperature from 1000 °F to 2000 °F can increase the system efficiency by 15% units (Parker, 1997). Thus, turbine cooling, the development of coatings and high temperature materials for some of the system components (combustion chamber, exhaust vanes, turbine blades, etc.) , and advanced manufacturing processes are helping to markedly increase the performance of the systems.

Compressor

Two types of compressors are available: radial and axial (see figure 1.9). In the radial type the blades accelerate the air outwards from the centre of the compressor where the gas kinetic energy is converted into pressure energy. This type of system is very simple but becomes very bulky when a high compression ratio is required since the latter depends on the compressor’s diameter. A solution would be to use several compression stages but unfortunately the fact that the gas must enter the compressor at the centre and leave at the border makes this design too complex. However, radial compressors present the advantage of simplicity in small and very small power systems (<500 kW).

Axial compressors accelerate and compress the air in the direction of the axis of the system and thus several stages can be used to achieve high pressure ratios without increasing the compressor diameter. This type of compressor is particularly suitable for medium and large power systems.

Compressor parts are not subjected to high temperature stresses as other components of the GT systems and consequently the only requirement is that blades and other parts must be made of high quality steels. However, some special coating is needed to ensure good sealing between the blades and the compressor case while controlling abrasion at the same time.



Radial Compressor
Front View

Axial Compressor
Side View

Figure 1.9 Radial and Axial compressors.

<u>Combustor</u>

The compressed air is used as the oxidiser in the combustion of the natural gas fuel in one annular or several individual combustion chambers located around the main shaft. This is one of the high temperature areas of the system and in high efficiency systems special nickel alloys must be used instead of steel. The temperatures attained are generally between 1100 and 1400 °C.

The geometry and type of combustor has a direct influence on NOx emissions through the gas residence time and the temperature. In modern combustors of annular geometry residence times are reduced and emissions are lower.

<u>Turbine</u>

As in the case of the compressor, two types of turbines are available, radial and axial. The same considerations are valid here concerning the simplicity of radial turbines in low power systems. The only difference are the material requirements for the turbine blades due to the high temperature of the combustion gases. The blades in axial turbines are usually made of nickel/chromium alloys and have some type of cooling to prevent overheating.

Generator

The generator generates electricity simply by inducing an electric current in a rotating coil in the presence of a magnetic field produced by another coil or a permanent magnet. In all but extremely small systems, generators use copper or copper-silver windings to produce the inducing magnetic field. In large systems generators can be coupled directly to the turbine but in small ones a gear box is needed since the turbine works at higher speed than the generator. This means that generator efficiency at rated power decreases from ~96% in large systems to ~90% in small ones (<200kVA) (Evett, 1995). High speed generators are being developed and will help reduce energy losses in small systems (Pullen, 1991).

Exhaust/Recuperator

When the combustion gases leave the last turbine stage they are collected by an annular chamber and either discarded or used to improve the overall efficiency of the system by recovering part of the useful heat energy. This latter option is becoming particularly important in modern gas turbines and can lead to much higher efficiencies compared to systems without heat recover. One such system for heat recover is a recuperator, composed by a system of thin walled ducts where heat from the exhaust gases is transferred to the incoming compressed air. Another design is a regenerator. In this type of system a large chamber is heated with exhaust gases and then cooler compressed air is circulated through it while a second chamber is heated.

For more information on Gas Turbine Systems see (Considine, 1977) (Wilbur, 1985) (Kirk-Othmer, 1996b)

1.6 PV/Hydrogen Systems

This energy system substitutes the gas energy chain present in the two systems discussed in sections 1.4 and 1.5 by a hydrogen fuel chain including photovoltaic generation (PV) and water electrolysis as shown in figure 1.10.

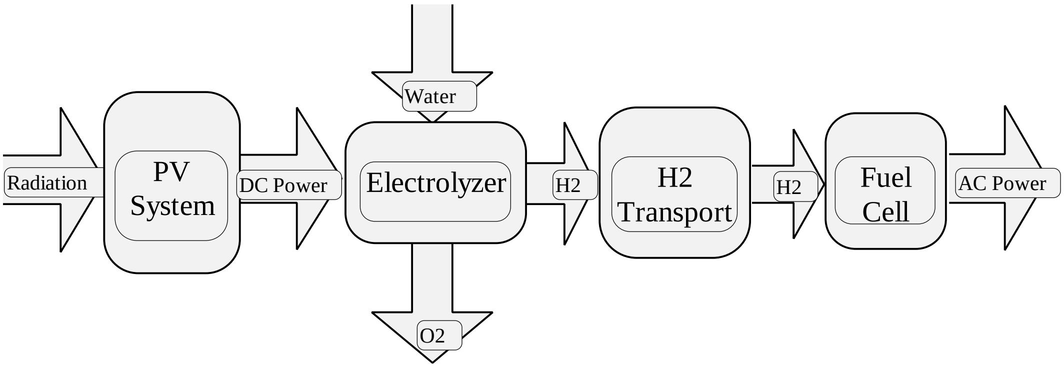


Figure 1.10 Main components of a PV/Hydrogen/FC system

This system “sacrifices” overall conversion efficiency for the flexibility of dealing with an energy carrier in chemical form instead of as electricity.

Photovoltaic subsystem

The PV subsystem is used to convert the incident solar radiation into DC electricity to power the electrolysis subsystem. Being dependent on solar radiation, the power output of the system has both daily and seasonal cycles and varies markedly with location. The PV modules can be connected in series and parallel in such a way as to match the load as close as possible.

Commercial photovoltaic cells are usually composed of two layers of Silicon (Si) semiconductor material. The upper and lower layers differ only by the fact that one of them is doped with boron or phosphorous. When an incident photon of suitable energy excites an electron in a Si atom, this jumps to a new energy level where it can travel freely along the Si crystal lattice. The doping of Si mentioned above creates an intrinsic potential difference between the two Si layers which makes the charge carriers flow in the same direction, and thus creates an electric current. The charges are collected by metallic fingers on the surface of the cell and by a conductive layer at the back of it.

The degree of order and purity of the Si crystal structure has a marked influence on the energy conversion efficiency of the process since the presence of impurities and crystal boundaries can make the energy carriers to go back to their original locked state in a Si atom. The material in the cells can vary from a single crystal structure (monocrystalline Si) to an amorphous one (amorphous Si), and the efficiency varies accordingly. It has also a marked influence on the manufacturing process and the cost of the cell. Production of monocrystalline Si cells is highly energy intensive in comparison with production of amorphous cells.

Electrolyzer

This subsystem splits water molecules into its atomic components, producing H_2 and O_2 gases. Conventional electrolyzers use an alkaline electrolyte and a porous asbestos diaphragm to separate the product gases, H_2 and O_2. However, there are other designs which present better prospects for future use thanks to their higher efficiency. These are the zero gap cell geometry electrolyzer (an advanced version of the alkaline design), the solid polymer electrolyzer (SPE), and the steam electrolyzer. Here we will only deal with solid polymer electrolyzers, which are based on the same technology as solid polymer fuel cells but operate in the opposite sense. Instead of consuming H_2 and O_2 to produce electricity and water, the SPE consumes water and electricity to produce H_2 and O_2. This electrolyzer has a better potential efficiency than advanced alkaline electrolyzers but lower than steam electrolyzers. However, steam electrolyzers are still in the development stage while SPEs have been in the market for some years (Winter, 1988). Power consumption is between 172-196 MJ/kg H_2 for conventional electrolyzers, between 152-160 MJ/kg H_2 for SPE, 152-170 MJ/kg H_2 for advanced alkaline electrolyzers, and 128-140 MJ/kg H_2 for steam electrolysis (Coluccia, 1994).

After production, the H_2 and O_2 gases are purified to separate residual water vapour and compressed for storage or transport. As in the case of fuel cells, some electrolyzer designs work under pressure and this saves part of the energy cost for compressing the hydrogen.

H_2 transport, storage, and distribution

Once purified, the H_2 gas may be transported under pressure in pipelines similar to those used for natural gas. In principle, H_2 may be transported in the same pipelines used at the present moment. Steel embrittlement when transporting H_2 at high pressure only becomes critical when dealing with high purity hydrogen (>99.5%) as that used in the petrochemical industry, but this is not the case for energy applications (Yurum, 1995). However, auxiliary equipment used to compress the gas and pipeline sections sensitive to metal fatigue will have to be changed to provide suitable handling and prevent metal embrittlement (Mohitpour, 1990). Additionally, having hydrogen a much lower density than natural gas, transport and storage efficiencies tend to be lower than for natural gas due to the increase in losses and the energy requirement for gas compression. Sealing systems must be improved to avoid high gas losses.

Short term storage of hydrogen gas (daily variations in production) can be done in pressurised vessels or in the pipelines themselves, while for long term storage (seasonal variations in production) liquefaction is more suitable because of its lower losses (Winter, 1988). Distribution can also be done through pipeline systems similar to those used for natural gas.

1.7 Highly Efficient Systems

Two types of system have the potential to achieve extremely high conversion efficiencies: a gas turbine combined cycle working on hydrogen (Kobayashi, 1997) and a high temperature fuel cell/gas turbine hybrid working on natural gas (Appleby, 1996).

The first type of system includes a regenerator for heat recovery and turbine blades made of carbon fibre composite. The thermal efficiency of the combined cycle is 64% (LHV) based on semiempirical parameters (~60% electrical).

The second type of system combines a high temperature fuel cell (MCFC or SOFC) and a turbine that works on the excess heat from the fuel cell operation. Its conversion efficiency would be between 65% and 70% (LHV) (Appleby, 1996) (Fry, 1997).
These are mainly research systems due in part to their high capital costs.

Finally, the US Department of Energy has underway an Advanced Gas Turbine Program which, by the year 2000 intends to help commercialise combined cycles with LHV efficiencies in excess of 60% when working on natural gas (Bannister, 1995).

2. Methodology

The present study used a life cycle analysis (LCA) methodology to quantify air emissions from the different life cycle stages of the systems analysed. This chapter will describe the broad characteristics of this methodology and its application in the context of this specific study.

2.1 LCA methodology

LCA analysis comprise three broad stages: scoping, inventory and impact assessment. The scoping stage helps identify the objectives of the study, the environmental issues to be studied, the limits of the systems to be analysed, and the important processes and parameters that should be taken into account when collecting the information for the quantitative analysis. Some of these tasks require performing a preliminary analysis of the processes associated with the system under study. This helps identify important areas and set the system boundaries. Although the are no general rules for the selection of the boundaries of a system, with the exception of the inclusion of the main processes, its influence on the results can be quite marked. Thus, a LCA report should include a list of the processes analysed in order to assess the possible limitations of the study and facilitate comparison with results from other studies. Luckily, the relative contribution of a given process to the overall emissions tends to decrease the further away from the centre of the analysis the process is. This guarantees that, if the system boundaries are well chosen, their expansion will only add a marginal contribution to the total emissions.

Once the limits of the system are identified, quantitative information must be collected on each of the processes in such a way as to be compatible with the objectives of the study. This may involve the quantification of the energy and material fluxes associated with many industrial processes and assigning emission factors for each of these processes. The product of the emission factors and the fluxes gives the total emissions for each process.

Within LCA studies the quantification of life cycle air emissions can be done by slightly different ways depending on the degree of precision required and the reliability of the available data. The bigger the system boundaries the larger the amount of processes that will be involved in the analysis. Consequently, the analysis of complex systems may require quantifying a very large number of interactions between those processes. This problem can handled with precision employing matrices with coefficients modelling such interactions. However, when analysing a generic process or technology where there is a big variability range compared with the marginal contributions accounted for in the matrix method, a simple enumeration of processes is enough to obtain a picture of absolute and comparative emissions. Such is the method employed in this study.

In order to compare the emissions from a series of energy systems, the sum of the contributions from the different processes over the system life cycle is divided by the total energy delivered. This gives an indicator of the specific emissions associated with the system, for example grams of CO_2 per unit kWh of electricity delivered by a fuel cell. These environmental indicators or interventions are thus calculated on a common basis for all the systems and can be used in disaggregated or aggregated form to make a quantitative comparison of the systems environmental performance.

Usually aggregated figures are presented but the analysis of the disaggregated data provides a better idea of the origin of the emissions. This is particularly critical for local pollutants where aggregated figures can give only a very poor idea of the environmental impact of multiple emission sources.

Once the environmental indicators are quantified, the associated environmental impacts must be assessed.

In many cases several environmental impacts are associated with each system analysed and these may vary from system to system. Under these circumstances no clear ranking of the environmental performance of the systems can be derived without the inclusion of some subjective considerations to assign relative weights to the impacts. The different impacts can be aggregated in a common indicator by many different methods but all of them run the risk of losing important information originally present in the disaggregated data. However, this aggregation process is usually performed to facilitate the drawing of practical recommendations.

2.2 Scope of the Study

The present study is limited both in time and resources and consequently it does not involve a full life cycle analysis (LCA) of fuel cells and gas turbine systems. The analysis includes the scoping and inventory stages of a LCA and only a limited amount of environmental indicators are quantified. These are :

- CO_2
- *CO*
- SO_2
- *NOx*
- *Particulates*

All of these indicators habe been quantified per unit kWhe delivered by the energy systems.

The air emissions figures shown in the results section are mainly derived from energy related pollution due to the lack of data concerning non-energy related emissions. Only very little information is provided on non-energetic pollution and in some cases the impact and its source are identified but not quantified.

Other common air pollutants such as methane (CH_4), hydrocarbons (HC), and volatile organic compounds (VOC) were not included in the analysis due to the lack of a consistent classification along the many emission factor sources consulted. This is due to the overlapping between some of these classifications. For example CH_4 can be present as CH_4, HC, or VOC depending on the specific study consulted.

In general terms all the processes and materials directly involved in the final composition or operation of the energy systems have been analysed. Upstream processes reach up to the extraction of raw materials while downstream processes go up to the decommissioning stage. Only qualitative information is available on the decommissioning of the new technologies due to lack of practical experience. Auxiliary

equipment and materials used along the different manufacturing processes are not included in the analysis except through their energy consumption during operation.
In some cases direct information on a process or material was not available and surrogate information has been used whenever possible to avoid assigning a zero value.

Given the air emission indicators chosen for the analysis, the inclusion of the above mentioned processes is considered to be enough to give an adequate idea of the range of specific emission values that might be expected from each system. The limitations will be analysed to a certain extent through a series of sensitivity analyses (see section 3.6).
As far as possible, all the calculations include a range of variation in the data. In some cases extreme values have been adopted to represent the state of the art and future technologies.

The analysis is performed on the specific technologies that are considered to be representative both at the moment of writing and in the short term. For this reason some of the results may be extremely sensitive to technological advances and this will be analysed to some extent in section 3.6 (sensitivity analysis). Furthermore, for some of the components, alternative manufacturing processes exist which are not analysed here and may produce different results from those shown.

The list of processes included in the analysis of each system is presented in appendix 7.

2.3 Study Limitations

This is a preliminary study and the results presented are only intended as a guidance as what life cycle air emissions may be expected from the specific systems analysed. This study needs to be verified by more detailed analysis and could be complemented by an economic assessment of the options presented.

Further refinements in the analysis can be included in future studies when more quantitative information about manufacturing processes is available. However, it seems that given the characteristics of the fuel cell and gas turbine systems and their reliance in a concentrated chemical fuel, manufacturing emissions will remain extremely low as long as the system does not include a renewable energy conversion component.
The situation may be very different for pollutants not included in this study and this is clearly an area for further research where a detailed analysis of some manufacturing processes may be necessary. The discussion and conclusions refer only to the environmental indicators analysed in the present study and any generalisation to other pollutants must be avoided. Similarly, the results apply only to the systems analysed and the factors mentioned in the sensitivity analysis may change results considerably.

Among the data that need to be refined, verified, or added are those corresponding to platinum production, assembly processes, systems installation, and fuel cell electrode manufacturing. The operational emission factors for radial, CCGT, and AGT need verification. Particularly those for RGT which were set equal to those from AGT due to lack of data. The same is true for SPFC, whose emissions factors are taken from PAFC systems.

Non-energy related emissions can be relatively important for some of the pollutants studied and some of the conclusions presented should be viewed in the light of this broader context. Non energetic emissions associated with the production and processing of carbonaceous materials (volatiles) and resins (styrene) may be of particular relevance for future studies.

3. Analysis

3.1 System Specifications

Tables with the general specifications of the systems analysed are presented in appendix 2.

Phosphoric Acid Fuel Cell System

The PAFC system analysed is a 1 MWe power plant working at atmospheric pressure on natural gas fuel. It has an external multitube reformer to convert the natural gas into hydrogen. Most of the general specifications for this system have been taken from the published literature but some of them are assumptions based on other systems. Such is the case with useful lifetimes both of the cells and the plant. Cells have been assumed to have a lifetime of 40000 hr and plant of 20 yr. These assumptions are tested in the sensitivity analysis.

This system is quite bulky in terms of weight if one compares it with a scaled up version of smaller plants (see (ONSI, 1996) and appendix 2).

Solid Polymer Fuel Cell System

This is a very compact 250 kWe system working on natural gas. It has been necessary to make more assumptions about this system since in this case there is only one prototype of this type of system and detailed information is not available. Specifications are based on data from SPFC systems working on hydrogen and PAFC systems of a similar power output. As before, cell and plant lifetimes have been assumed to be 40000 hr. and 20 yr. respectively. The influence of this parameters will be tested in the sensitivity analysis.

Axial Gas Turbine System

The specifications for this system do not correspond to any particular plant but are an average for plants of this size. The system is 1 MWe net power with both multistage axial compressor and turbine. Some of the more important specifications such as the efficiency are not fixed but have been assigned a range of variation to account for different technologies, from old systems without energy recovery to modern systems with hot end components and heat recuperator or regenerator.

Radial Gas Turbine System

The same is valid here as in the previous case. This system is 250 kWe net power with a single stage radial compressor and turbine. However, in this case the technology corresponding to the upper end of the efficiency range of variation is not yet commercially available.

Photovoltaic/H_2/Fuel Cell System

This system is 100 MWe net power. Power is first generated in a monocrystalline photovoltaic plant located in a region with good annual solar radiation (5 kWh/m^2.day annual average). H_2 gas is produced by solid polymer electrolyzers and transported via long distance pipeline to a distribution centre. Water is considered to be available nearby. Some of the hydrogen is liquefied to absorb seasonal variations in the production rate and some of it is stored under pressure to absorb short term variations. The pipeline can also be used for daily pressurised storage. H_2 gas is distributed via pipeline to dispersed SPFC fuel cell generators which convert it into electricity. Compression energy for pipeline transport is obtained by burning H_2. Energy for liquefaction and pressurised storage is taken from the electricity grid.

This system is completely hypothetical since no plant of this size has been actually built. However, the system components are available and have been tested separately at different power ranges. Specifications in some cases can be considered as realistic/optimistic assumptions in relation to present values in order to assess the maximum potential for the reduction of emissions presented by this energy option. It is also to account for technological developments that may take place in the next few years.

Other systems

Other systems such as high temperature fuel cells (HTFC), combined cycle gas turbines (CCGT), and medium power axial gas turbines (AGT) have been also included in the analysis. Specifications are based on the available commercial and scientific literature.

3.2 Production Processes

This section briefly discuss some of the general characteristics of the production processes of the different systems. Schematic diagrams of the processes have been included in appendix 3. Material inputs for system manufacturing are given in appendix 4.

In the cases of Photovoltaic Cells and Fuel cells, there exist alternative methods of production. Even for gas turbine manufacturing new production processes and materials are appearing pushing the limits towards higher operating temperatures. Only very broad aspects will be discussed here and generally those corresponding to the most representative technology.

It will be assumed that the production processes for the Solid Polymer Electrolyzer are similar to those for the Solid Polymer fuel cell and consequently they are not discussed.

Fuel cell

As already mentioned, the heart of the fuel cell system is the stack and being also the most non-standard part of the system, its production will be analysed here in more detail. Figure 3.1 shows the basic components of the PAFC system life cycle.

Both in PAFC and SPFC the main stack materials in terms of weight, besides steel, are carbon and graphite materials. Graphite is basically derived from carbon material through a high temperature process that increases the order of the crystallographic structure, giving it better thermal, electric, and corrosion resistant properties than carbon (Kirk-Othmer, 1996a). It exists both in natural and synthetic forms. This last type is produced by subjecting a mixture of carbonaceous materials (petroleum coke, carbon black, coal) and binder materials (coal tar, petroleum pitch) to temperatures between 2400-3000 °C. The raw materials are usually by-products of petroleum refining and coal-tar distillation. The quality of the graphite obtained depends on the quality and the heat treatment received by the raw materials. Graphite bipolar plates for PAFC are produced by cutting and machining solid graphite blocks.

Sometimes synthetic resins are used to produce impervious products such as glassy carbon or impermeabilised graphite used in cell separators for PAFC. Resin carbonises directly but can not be converted into graphite, thus lowering the quality of the end product. This has special interest for fuel cell applications where graphite quality is important. Specifically, PAFC must use high quality graphite due to the highly corrosive environment and the electric conductivity restrictions presented by the thickness of the plates. By contrast, SPFC can do well with lower quality materials which can be more easily produced by composite technology from carbon fibres and synthetic resins because they work at lower temperature, they do not use an acid electrolyte and the plates are thinner.

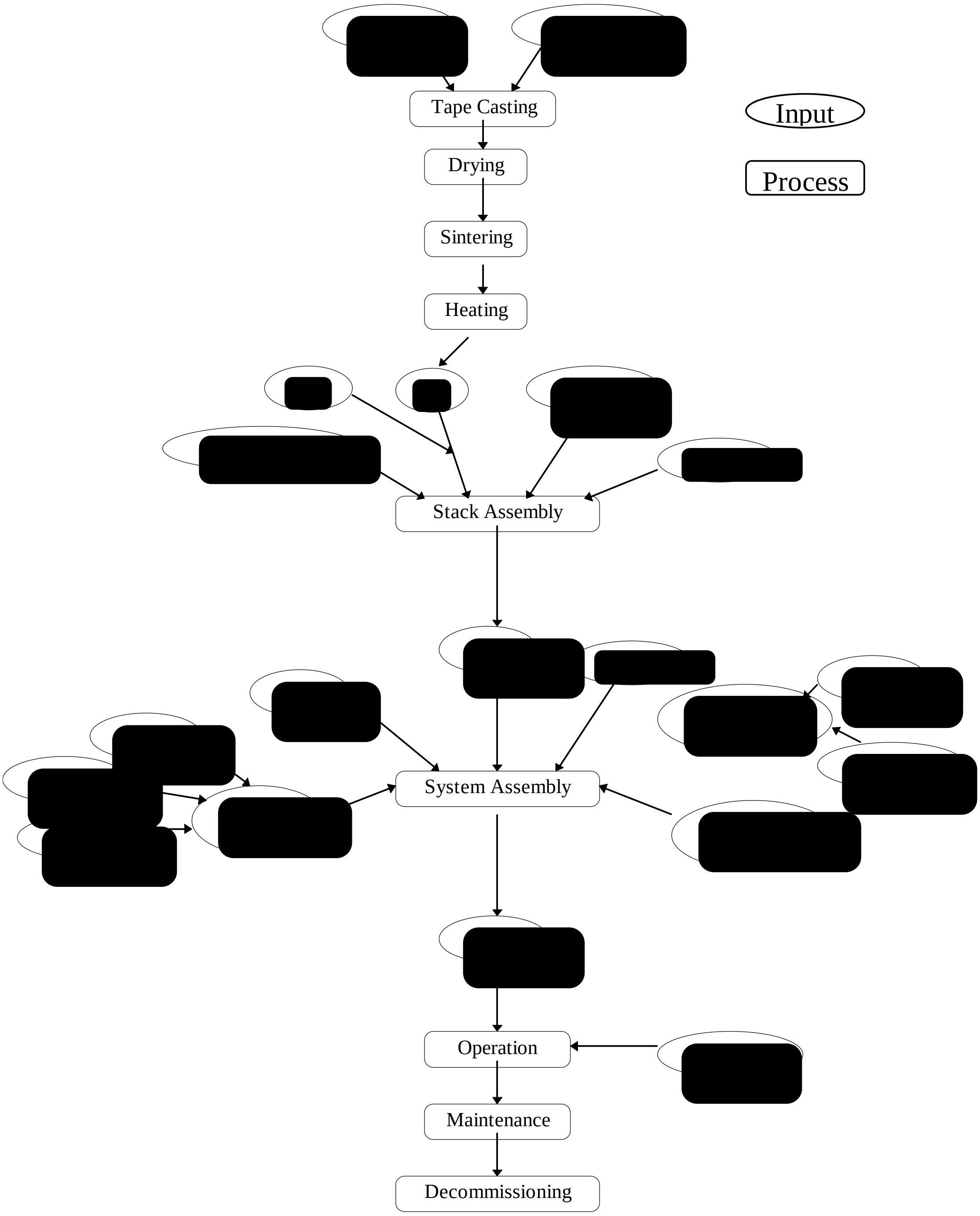


Figure 3.1. Schematic view of the life cycle of a PAFC system

Carbon fibres are produced by the same high temperature treatment as graphite but starting from pitch or polyacrylonitrile (PAN). Graphite fibres are mixed with phenolic resin and the composite thus produced is heated and moulded to produce impervious bipolar plates for SPFC. Machining is not necessary in this case since the gas channels are included in the mould. This process is both simpler and cheaper than cutting plates from a solid block.

Carbon Black is another of the carbonaceous materials used in fuel cells. There exist several types of carbon blacks obtained by slightly different processes that involve the reaction of a hydrocarbon fuel in an oxygen limited atmosphere at temperatures between 1320 and 1540 °C. High quality carbon blacks are commonly obtained using acetylene or natural gas as raw material. When the quality of the carbon black is not high enough for fuel cell applications it can be treated at high temperatures (1200-2500 °C) to improve its corrosion resistance (USEPA, 1995) (Appleby, 1989).

Carbon black is the preferred support for the Platinum catalyst, a precious metal that is usually recovered from the extraction of other minerals (Gold, Iron, Silver, Copper, Nickel, and Cobalt) and is generally found in association with Palladium, Rhodium, Ruthenium, Iridium, and Osmium. By far the most common source of Pt are sulphide ores of Ni and Cu. After electrorefining of Ni or Cu the remaining metal concentrate is treated as shown in appendix 3 (figure A3.7) in order to separate the Pt, Au, and related minerals. The process may be repeated to increase the purity (Ammen, 1984).

The electrocatalyst paste is formed from Pt, Carbon black, and PTFE, as shown schematically in appendix 3 (figure A3.1) and is commonly applied over carbon felt (SPFC) or the bipolar plate (PAFC) using rolling or tape casting techniques.

In the case of PAFC the electrolyte matrix is a ceramic material produced by the method described in appendix 3 (figure A3.10) and is filled with phosphoric acid electrolyte after different parts of the cell are assembled. In SPFC the thin film electrolyte is produced from polymer granules as shown in appendix 3 (figure A3.9).

The ensemble of bipolar plate, separator, electrocatalyst and electrolyte matrix or membrane is hot pressed to obtain one cell.

The rest of the components of the fuel cell system are mainly metallic, principally steel and other ferrous materials. The manufacturing process for these ferrous materials depends on the working conditions that the final component has to withstand. The

various processes involved are schematically described in appendix 3 (figure A3.14). Broadly speaking the higher the quality required the more steps are necessary to guarantee a suitable alloy composition and the more energy is consumed in the process. Once this is obtained the components may be formed by different techniques as will be discussed the following section (gas turbine manufacturing).
For further information on fuel cell manufacturing processes see (Appleby, 1989) (Kordesch, 1996) (Blomen, 1993).

Gas Turbine

Gas turbines may involve a big variety of steel and nickel alloy components designed to withstand the different mechanical and thermal stresses along the system. Nickel alloys are produced by similar processes to high quality steel alloys. Once the suitable alloy composition is obtained the different components are produced by forging, casting and rolling techniques. Forging is generally used for components with simple geometry as a turbine rotor while casting is reserved for more complex forms as in turbine blades with built-in cooling channels. In casting, the melted alloy is poured into a mould with the shape of the component where it solidifies. Casting can be performed in an inert or vacuum atmosphere to improve the quality of the end product and the solidification process can be thermally controlled in such a way as to reduce to a minimum the defects in the metal structure of turbine blades. These processes can increase the energy consumption for the production of blades.

The components must undergo a series of conditioning treatments. One of these, coating, is of special importance for turbine operation since it prepares surfaces for withstanding abrasion in a controlled way and preventing fluid leaks at the same time. Finally, individual components are joined into larger ones by welding, or by brazing when alloys are not compatible for welding (Meetham, 1981) (Taplin, 1989).

Photovoltaic Cells

Commercial photovoltaic cells are produced from Silica (SiO_2), the principal component of common sands. This starting material must be refined to a degree in accordance with the type of cell to be produced, monocrystalline cells requiring the highest quality and amorphous the lowest.

A schematic view of the monocrystalline cell production process is shown in appendix 3 (figure A3.15). After two initial refining processes (Carbothermic reduction and Siemens process), the Silicon (Si) is grown into a monocrystalline crystal of about 13 cm diameter in a process that is highly energy intensive. Alternatively, in the production of semicrystalline or polycrystalline Si cells, an ingot is melted from the purified silicon material and a controlled thermal process produces monocrystalline areas perpendicular to the cell surface. In both cases cells must be cut from the solidified block and as a consequence much of the material is lost. A series of processes follow where the different Si layers must be formed and the delicate metallic contacts printed onto the cell surface.

As an alternative to starting from raw SiO_2, the photovoltaic industry has been using Si material that is rejected from the microelectronics industry but that has enough quality to be used in photovoltaic applications. Some companies are working on Si refining processes that are cheaper than the standard processes, originally developed for the electronics industry. The solar silicon thus produced will be specifically designed for photovoltaic applications.

Amorphous cell production takes a very different approach, using a relatively cheap process well suited for mass production. This is at the price of lower efficiency and a reduced useful lifetime.

Natural Gas

The production of natural gas is schematically shown in figure 3.2. This involves the exploration, extraction, processing, and transport of the fuel up to the point of consumption. These group of processes will be briefly denoted as precombustion processes.

Processing of the gas extracted is necessary to separate impurities such as CO_2 and H_2S, and to prepare the gas for transport. The amount of these impurity gases that is produced depends on the specific composition of the gas resource. Transport is generally done by long distance pipelines but can also be done in liquefied form at the expense of a much higher energy consumption. If the gas is transported by pipelines, compression stations located along it maintain the gas flowing at a suitable pressure. This stations are fuelled with the gas transported. Gas is commonly stored under pressure and distributed by local pipeline networks.

Although this is a well known technology, variations in the location and characteristics of the resource affect the actual operating parameters (Knoepfel, 1994).

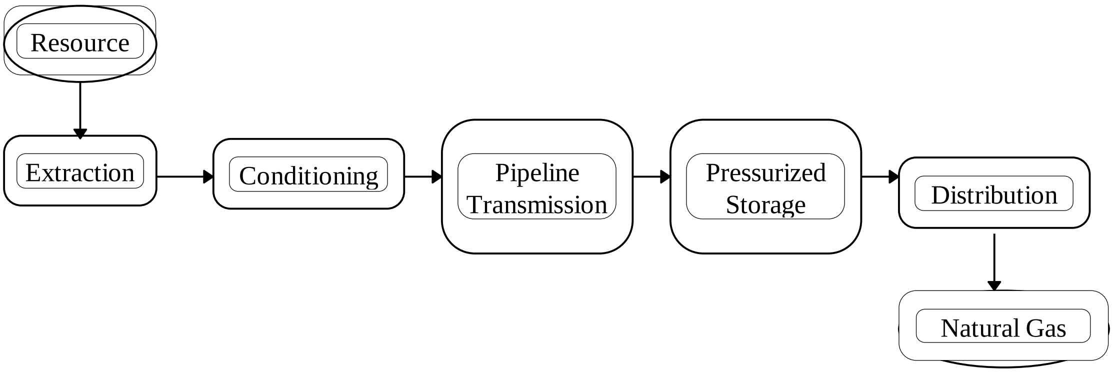


Figure 3.2. Natural Gas precombustion processes

3.3 System Operation and Maintenance

Fuel Cells

Before start-up, fuel cell systems must be purged with an inert gas such as nitrogen to prevent problems due to the initial phases of hydrogen production from the reformer. The systems can reach rated power in a few hours, the time that takes the reformer to reach a steady state of hydrogen production.

In PAFC the phosphoric acid electrolyte is solid at ambient temperature and consequently it must be stored under special conditions to prevent damaging the cells. During the periods when the system is not operating, energy must be provided to the stack to prevent the solidification of the electrolyte.

Once in operation, the systems respond in a matter of seconds to load changes.

The only inputs required for operation are natural gas and air, though water may be needed occasionally for steam production for the reformer. Availabilities of >90% have been recorded, which compare favourably with an average of 85% for gas fired generators. Maintenance is required annually in order to replace water treatment filters, air filters, and check critical components. Forced shutdowns in modern units are generally caused by problems in peripheral systems such as the water treatment system, thermal management system and power distribution system. Some external power must be provided during system maintenance of PAFC in order to avoid electrolyte solidification.

A scheduled shutdown is required every 5-10 years for stack and fuel processor overhaul due mainly to catalyst degradation (ONSI, 1996) (Hojo, 1996).

Fuel cell systems are considered a very low maintenance technology and can be designed for unattended automatic operation and remote monitoring.

Gas Turbines

As in the case of fuel cells, gas turbines also require relatively clean fuel in order to work properly and to prevent the useful lifetime shortening. Maximum content of sulphur in fuel is generally specified by the manufacturer.

Gas Turbines require the provision of lubricating oil for their operation. This they consume at a rate of ~0.1 g/kWh. In general no water is needed since the turbines are usually air cooled.

Originally, gas turbines were primarily used for peaking and emergency applications and consequently their availability used to be relatively low. Now, gas turbines are also used for base generation and availabilities of >80% are common.

The turbines are generally designed for approximately 100000 hr of operation without undergoing a major overhaul. Maintenance includes the change of air filters and replacement of lubricant.

Gas turbines derived from air turbine technology can achieve starting times from cold as low as two minutes, but thermal shock would reduce the time between overhauls. Heavy duty gas turbines can start in less than ten minutes but usually require 30 minutes.

Photovoltaic/H_2/Fuel Cell

Photovoltaic systems without battery storage require very little maintenance except for the cleaning of the modules surfaces to prevent dust accumulation.

The handling of hydrogen requires special safety measures but not much more complex than those taken for other highly flammable fuels.

3.4 System Decommissioning

Although energy systems are usually given a lifetime between 20-30 years, it is often the case, particularly in developing countries, that their useful lifetime extends much beyond this limit and that the systems undergo several overhauls before being decommissioned. Parts of a system subjected to different stresses have different rates of degradation and may have to be replaced or repaired many times along the system lifetime. It is not until the cost of repairing the systems compares unfavourably with the cost of alternative options for the provision of power, that the system is finally decommissioned. Once this time comes, some parts may still be in good working order and may be used as spares for similar systems. Other parts may have more value as scrap metal. Only very general options will be discussed here for the main components of the systems under analysis. For some of the systems there has not been actual experience in system decommissioning and so only some potential alternatives are given.

Fuel Cells

Most parts of the fuel cell system are made from ferrous metals and it should be possible to recycle them or in some cases use them as spare parts.
Given the relatively short lifetime of the cells compared to that of the entire system the question of the recyclability of the graphite materials and the Platinum catalyst is of special interest because of their economic value. ONSI corporation reclaims the catalyst in used stacks and when they replace a stack they offer a rebuilt stack that reuses a lot of the original components (Hawkins, 1997).

Gas Turbines

In this case the useful lifetime of the turbine will depend to a large extent on the operating conditions. Short starting times and the generation of peak power will reduce time between overhauls. The critical components are the blades and discs of the turbine itself. Life cycle in well designed machines may be in excess of 50 years (Wilbur, 1985).

As in the case of fuel cells, the metallic components, which in this case represent the vast majority of the system, can be recycled as scrap metal or reused when in proper order condition. The high quality alloys used for some of the components should have a good value as scrap metal.

Photovoltaic Modules

The frames made of aluminium and the support structure made of steel or iron should be easily recycled. The bulk of the module, composed by the glass/plastic/silicon assembly can be incinerated or used for landfilling (Häne, 1991). However, if the modules are incinerated, some of the plastics can emit toxic compounds.

3.5 Air Emissions

This section presents the aggregated air emissions associated with the life cycles of the systems studied. The results shown include emissions from fuel production and system manufacturing and operation.

Figures 3.3 to 3.7 show the total specific emissions of CO_2, SOx, NOx, CO, and particulates for each of the systems analysed. For gas turbines and fuel cell systems the ranges of variation shown represent mainly variations in operational efficiency and emission factors. For the PV/H_2/FC system the range of variation represents the use of clean electricity in the PV module manufacturing process. A more detailed analysis of the factors that influence emissions is included in section 3.6 (sensitivity analysis) where it is shown that the ranges of variation can be larger than those shown here.

The grid values included in the following figures are shown as reference values and correspond to the emissions associated with the generation of 1 kWhe in an electricity grid. The lower values correspond to Switzerland’s supply mix in 1988 (38% nuclear and 62% hydro), while the higher values correspond to a supply mix based mainly on fossil fuels (48% coal and 40% gas/fuel oil) (Haberstatter, 1991). These two types of supply mix represent extreme cases in terms of standard air emissions.

The specific system parameters for the low and high emission scenarios shown are included in appendix 6 jointly with disaggregated emission data. Emission coefficients for the production of materials is included in appendix 5.

Only CO_2 emissions are presented for some of the systems due to lack of emission coefficients and information about their manufacturing processes (e.g. High Temperature Fuel Cells (HTFC)). It is assumed that manufacturing processes contribute marginally to the total CO_2 emissions associated with these systems and consequently they are included in figure 3.3

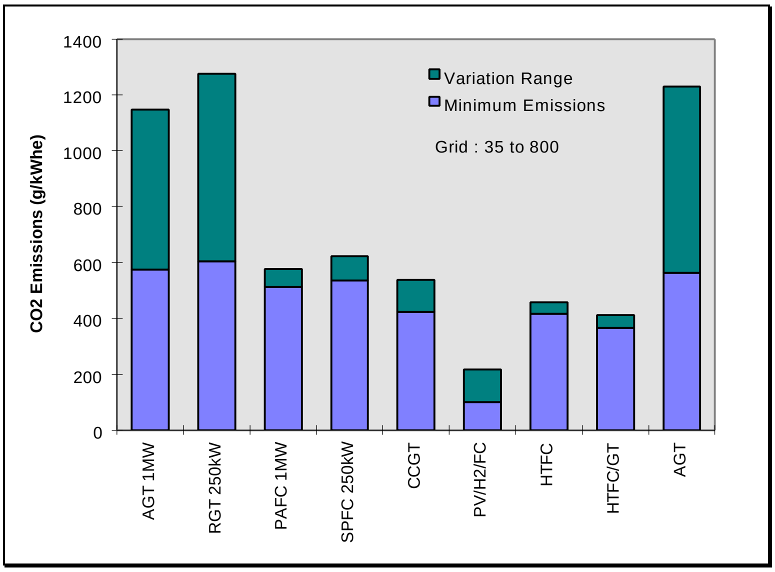


Figure 3.3 CO_2 life cycle emissions

(AGT 1MW =Axial Gas Turbine On-Site, RGT=Radial Gas Turbine On-Site, HTFC=High Temperature Fuel Cell, AGT= Axial Gas Turbine near gas extraction)

Grid values represent extreme cases of specific air emissions in g/kWhe from two actual electricity grids (low: Switzerland, high: mainly fossil fuels).

Simple cycle gas turbines and LTFC systems shown are on-site systems while CCGT systems are centralised

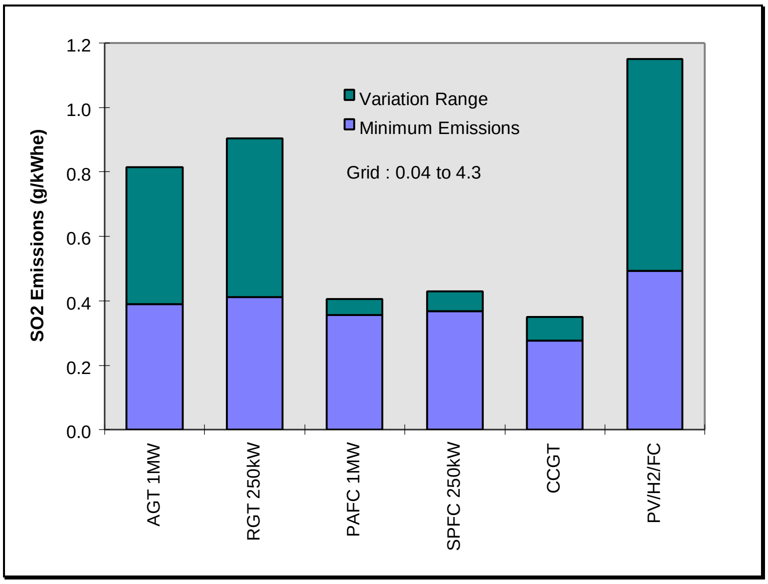


Figure 3.4 SO_2 life cycle systems emissions

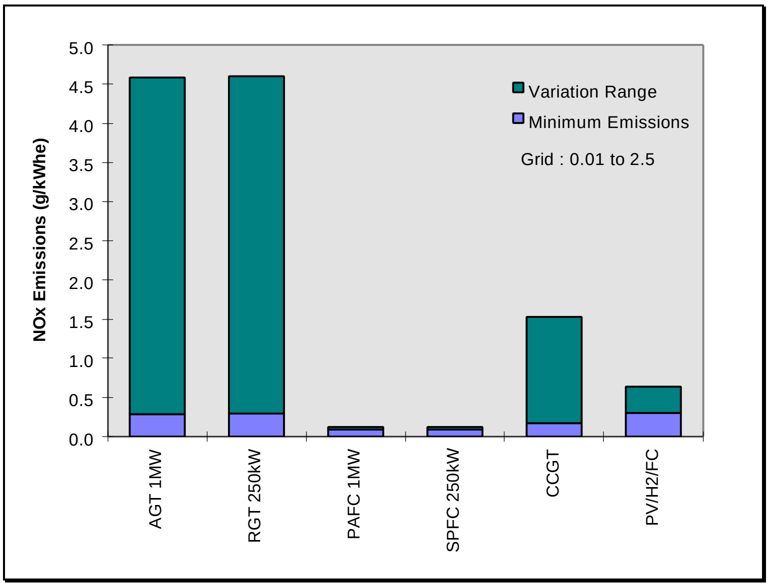


Figure 3.5 NOx life cycle systems emissions

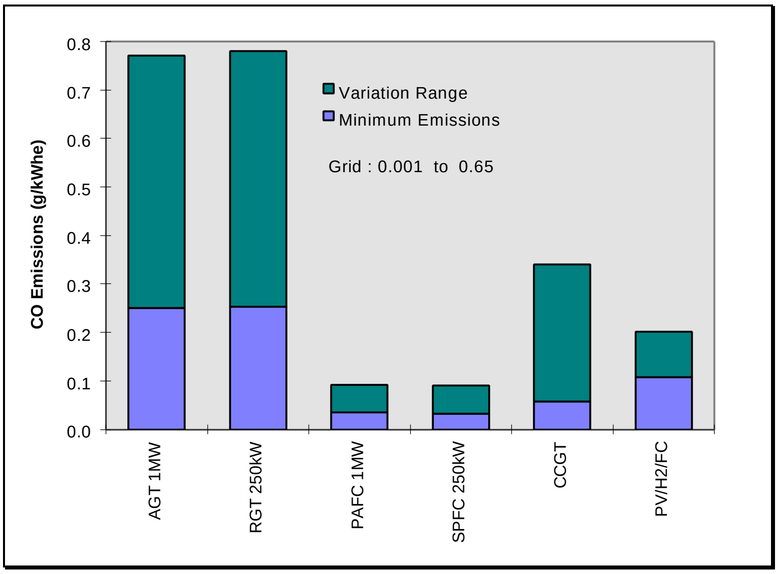


Figure 3.6 CO life cycle systems emissions

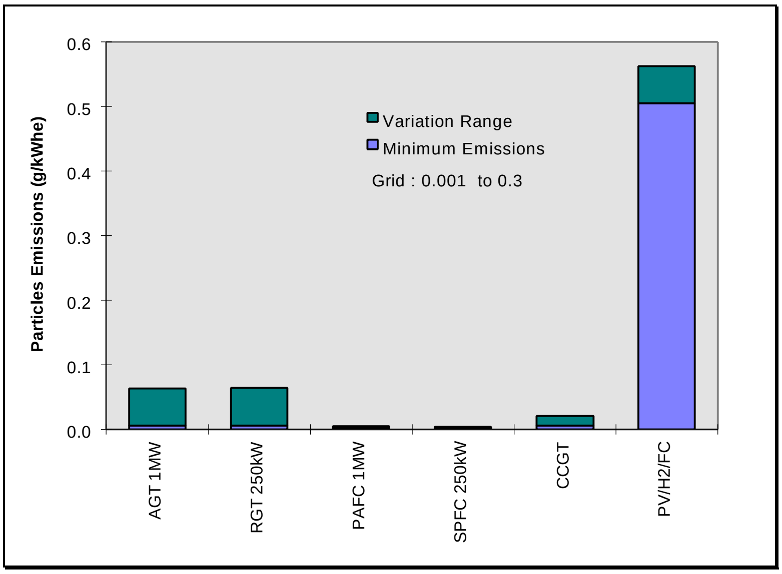


Figure 3.7 Particulate life cycle systems emissions

Figures 3.8 to 3.13 show the relative contribution of manufacturing processes, gas natural precombustion and system operation to the total specific emissions

High and low emissions scenarios are shown in these figures, representing the maximum and minimum emissions shown in figures 3.3 to 3.7. Detailed values for all the systems are shown in appendices 6 and 7.

Both in the case of gas turbines and fuel cells, the operation of the systems generates air emissions. The production of natural gas also is responsible for some emissions. The corresponding emissions factors for these processes are given in appendix 5.

Process emissions during natural gas precombustion are mainly due to natural gas extraction and natural gas conditioning. Energy related emissions represent a big part of the total precombustion emissions, except perhaps for SO_2 emissions where gas conditioning can contribute quite a large amount depending on the efficiency of sulphur removal and the characteristics of the fuel.

The variations observed for Gas Turbine systems are the result of the combined effect of operational efficiency and emission factors variation.

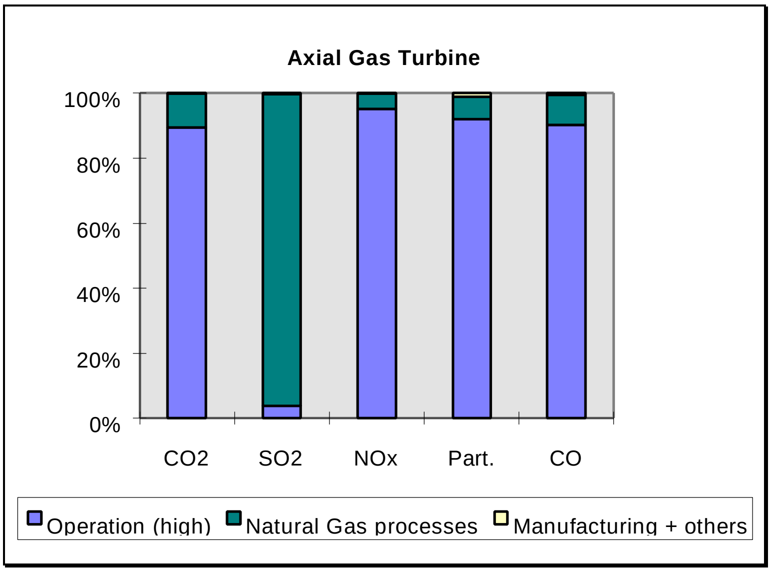


Figure 3.8 Axial Gas Turbine disaggregated emissions (high scenario)

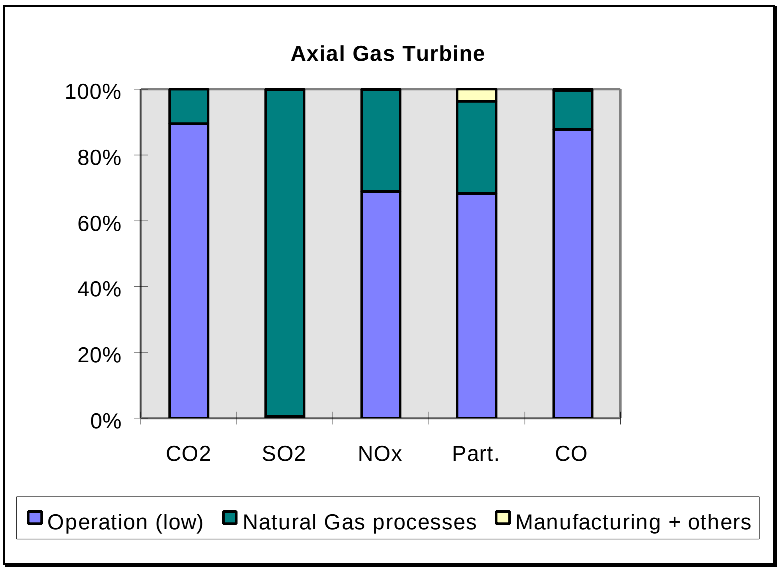


Figure 3.9 Axial Gas Turbine disaggregated emissions (low scenario)

In the case of fuel cells, the variations observed are mainly the result of variations in the operational emission factors.

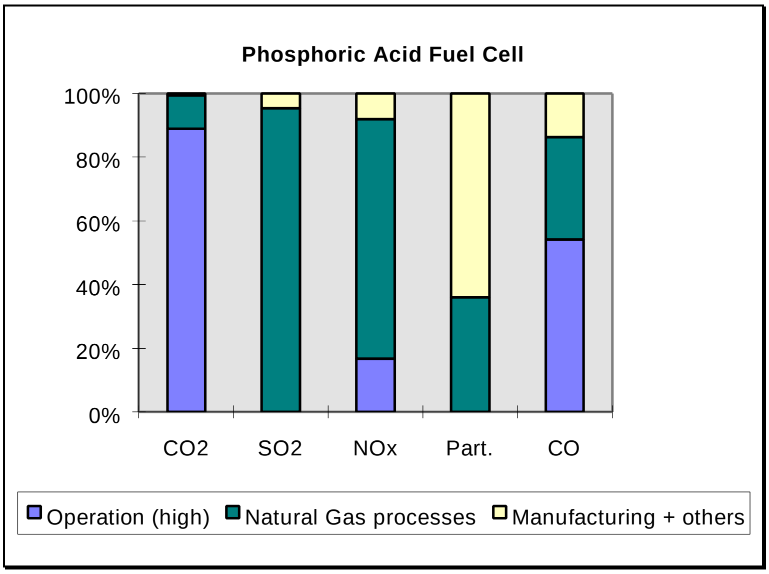


Figure 3.10 PAFC system disaggregated emissions (high scenario)

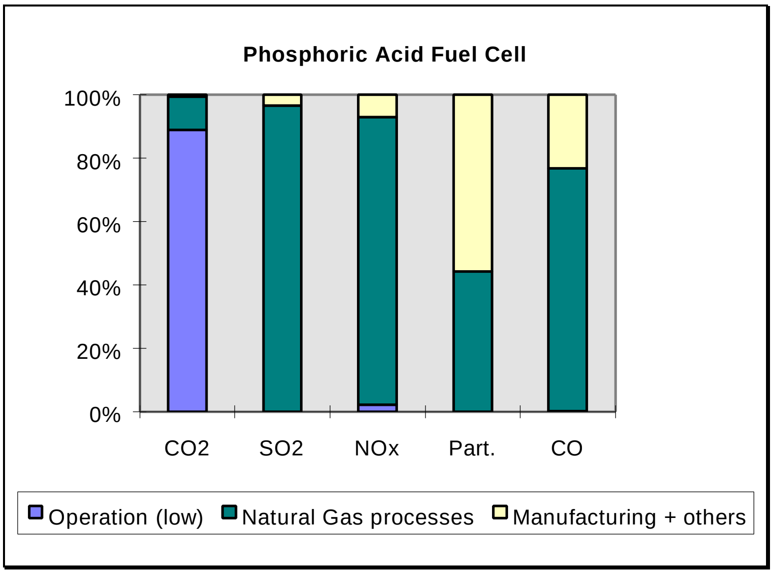


Figure 3.11 PAFC system disaggregated emissions (low scenario)

For the PV/H_2/FC system the operational emissions are associated with energy consumption during hydrogen transport and storage. No air emissions are produced during operation either by the PV modules or by the fuel cells working on hydrogen. However, some emissions are produced during the long distance transport of hydrogen and its storage due to energy consumption.

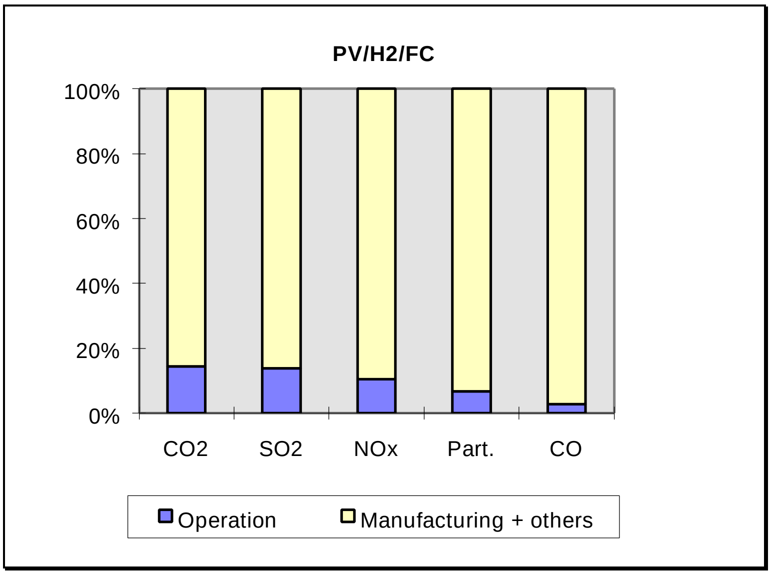


Figure 3.12 PV/H_2/FC system disaggregated emissions (high scenario)

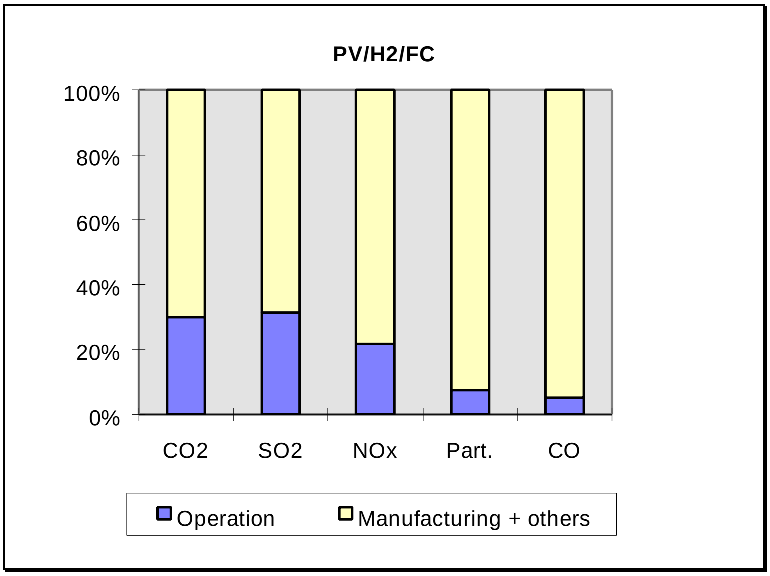


Figure 3.13 PV/H_2/FC system disaggregated emissions (low scenario)

3.6 Sensitivity Analysis

Some of the figures presented in section 3.5 (main results) display minimum and maximum values for each of the systems analysed, providing an idea of the range of emissions to be expected with varying system characteristics. As already shown in figures 3.3 to 3.7, the overall emissions from Gas Turbine Systems are extremely sensitive to the specific type of turbine mainly due to variations in operational emissions through efficiency, emission control measures, and general design of the combustion process. The specific effect of system efficiency on CO_2 emissions is shown in figure 3.14 for phosphoric acid fuel cells and axial gas turbines.

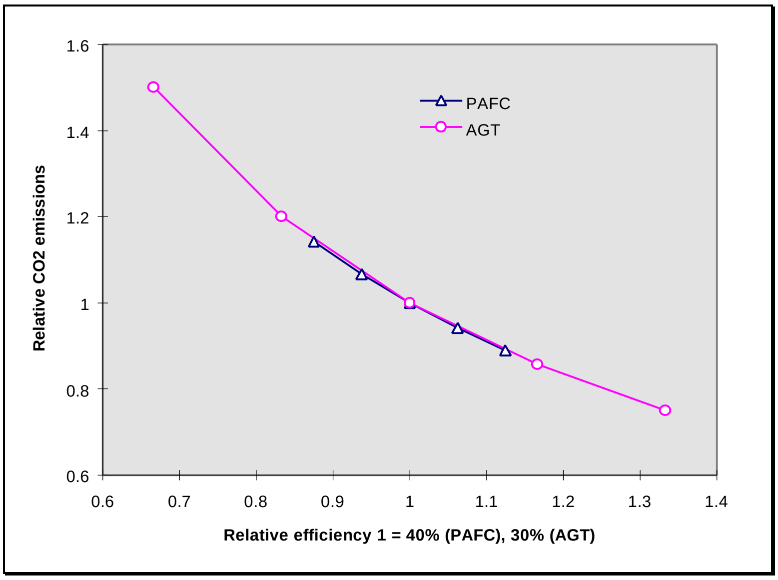


Figure 3.14 Effect of system efficiency on CO_2 specific emissions from PAFC and AGT.

However, there exist other sources of variability not included in the calculation of the values presented in section 3.5 and they will be discussed in this section.

Natural Gas Precombustion

Natural Gas precombustion processes represent a large proportion of the total emissions from gas turbine systems, particularly when operational emissions are low and for some pollutants as SO_2. The only exception seems to be CO_2 because of the uncontrolled emissions during combustion.

Emission coefficients for the extraction/conditioning/transport stages of the natural gas energy chain can vary considerably as a function of fuel composition, transport distances, characteristics of the infrastructure, etc. SO_2 emissions during natural gas conditioning can vary up to an order of magnitude due to sulphur content in fuel and efficiency in its removal. The values shown in section 3.5 are calculations based on average figures and consequently SO_2 emissions could be much higher in specific situations. In the cases of CO_2, NOx, CO, and particulate emissions are mainly related to energy consumption along the precombustion processes.

The influence of natural gas precombustion processes over fuel cell emissions is much more marked than for gas turbines since operational emissions are extremely low for fuel cells (except for CO_2).

Figures 3.15 to 3.17 show SO_2, NOx and CO overall emissions under a high precombustion emissions scenario. These figures can be compared with those presented in section 3.5 (main results).

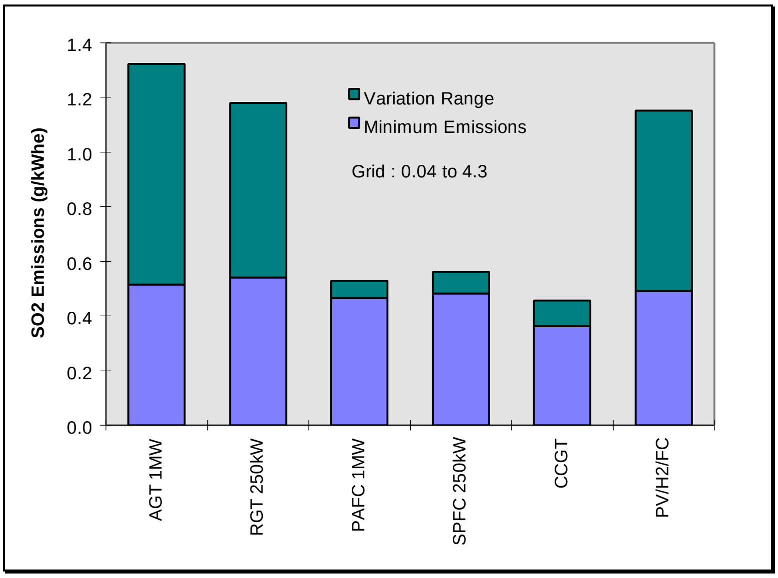


Figure 3.15 SO_2 emissions under a high precombustion emissions scenario.

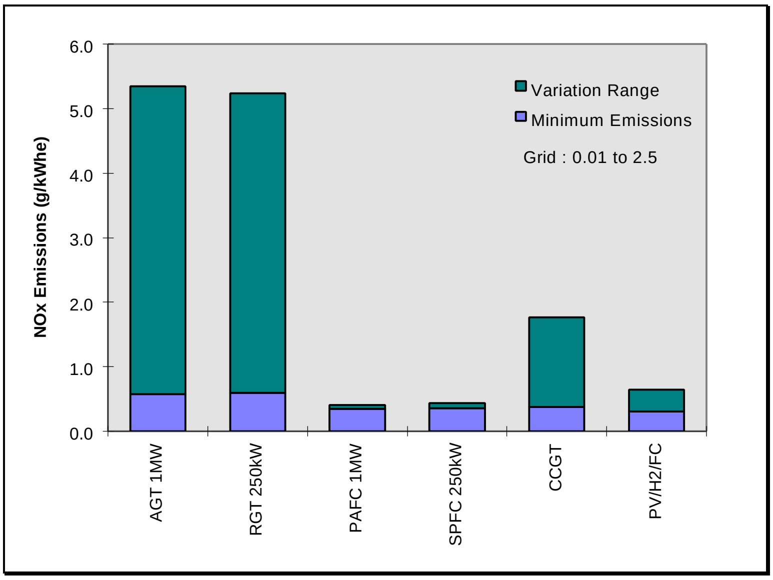


Figure 3.16 NOx emissions under a high precombustion emissions scenario

For the three pollutants shown in figures 3.15 to 3.17 the effect on gas fuelled systems is large enough so as to increase their emissions markedly in relation to those from PV/H_2/FC systems.

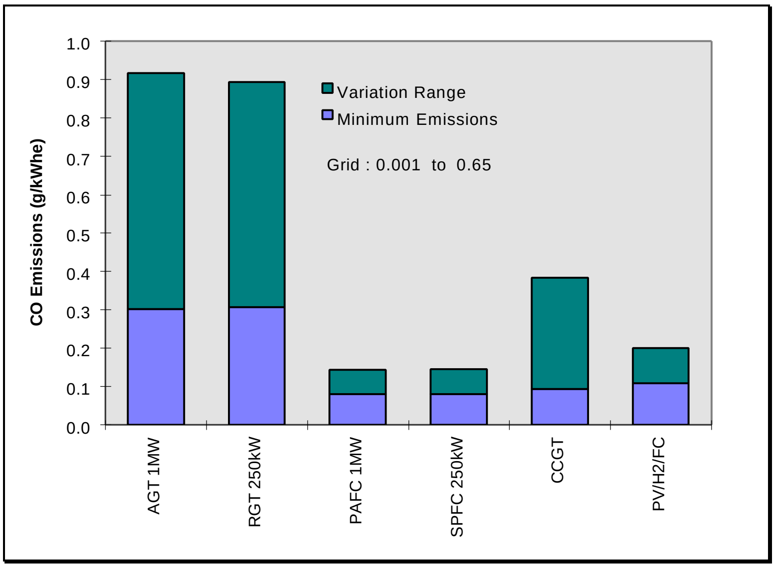


Figure 3.17 CO emissions under a high precombustion emissions scenario

Manufacturing/System Lifetime/Solar resource

For GT systems the contribution of manufacturing emissions to total emissions is extremely low even when operational emissions are lowest. Consequently, sensitivity to variations in material composition and manufacturing processes is low. Even a 10 fold increase in installation energy or doubling the ferrous material composition adds little to the overall emissions. This also means that system lifetime has little influence on emissions, except through a decrease in conversion efficiency.

In the case of fuel cells, only CO and Particulates are sensitive to changes in the material composition and manufacturing processes. These pollutants are not strongly affected by energy consumption during manufacturing or assembly but a 50% increase in ferrous metals composition increases total emissions in the low emissions scenario by ~15%.

Variations of the system lifetime affect total emissions through metal composition. Both variations in system and stack lifetime affect manufacturing emissions, mainly associated with ferrous metals, graphite and phosphoric acid production. However, for the last two products this effect has little influence on total emissions.

The figures presented in section 3.5 (main results) include variations in the system useful lifetime for all the systems except for PV/H_2/FC where a fixed 30 years lifetime was adopted.

A similar behaviour to that corresponding to fuel cells can be observed, although in a more marked way, in PV/H_2/FC systems, where energy and material intensities during manufacturing are high, accounting for >75% of the total emissions. The emissions are particularly sensitive to the PV subsystem useful lifetime (see figure 3.20), the degree of recycling of the materials used and to the energy mix used to produce grid electricity. It has already been shown in the results that the type of electricity used in the production processes has a large influence on the total emissions. Particulates and SO_2 emissions from manufacturing could decrease ~40% and ~16% respectively using recycled materials (Nadal, 1995), and could be further reduced by using less or alternative materials.

Finally, the quality of the solar resource has a marked effect on PV/H_2/FC emissions. The influence on total emissions is similar to that produced by variations in system lifetime, affecting emissions through a reduction of the total electricity produced in a given period of time. Figures 3.18 and 3.19 show specific emissions under 6 kWh/m^2.day average solar radiation as compared to 5 kWh/m^2.day used in the calculations shown in the figures in section 3.5 (main results) (6 kWh/m^2.day is a typical insolation value for very good solar resource areas).

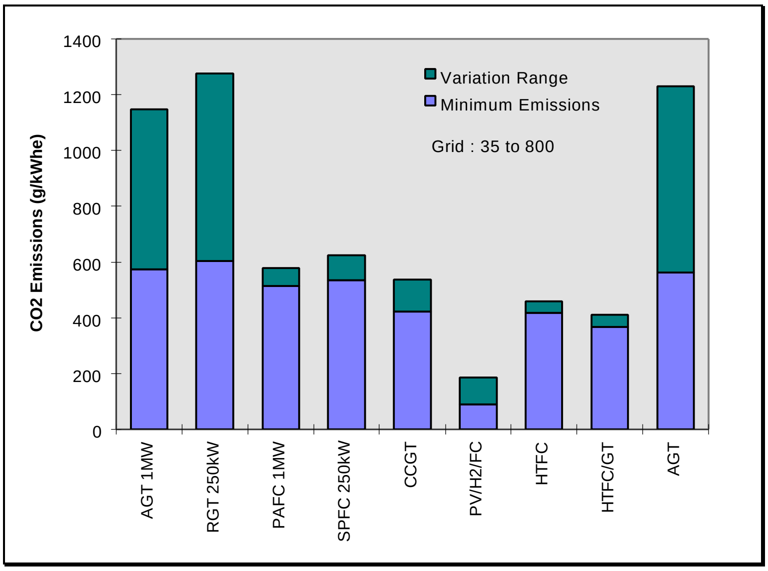


Figure 3.18 CO_2 life cycle system emissions (solar resource 6 kWh/m^2.day)

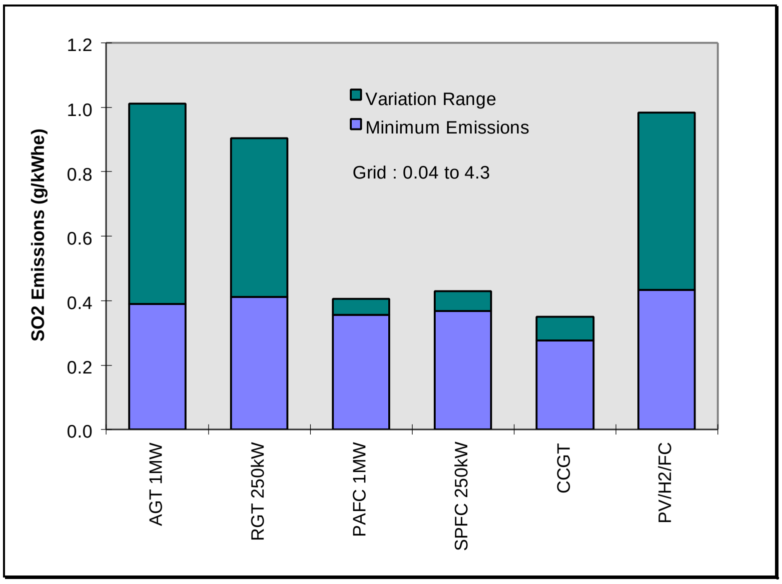


Figure 3.19 SO_2 life cycle system emissions (solar resource 6 kWh/m^2.day)

Finally, figure 3.20 shows in a different way how large is the effect of the quality of the solar resource and the useful lifetime of the PV modules on CO_2 specific emissions

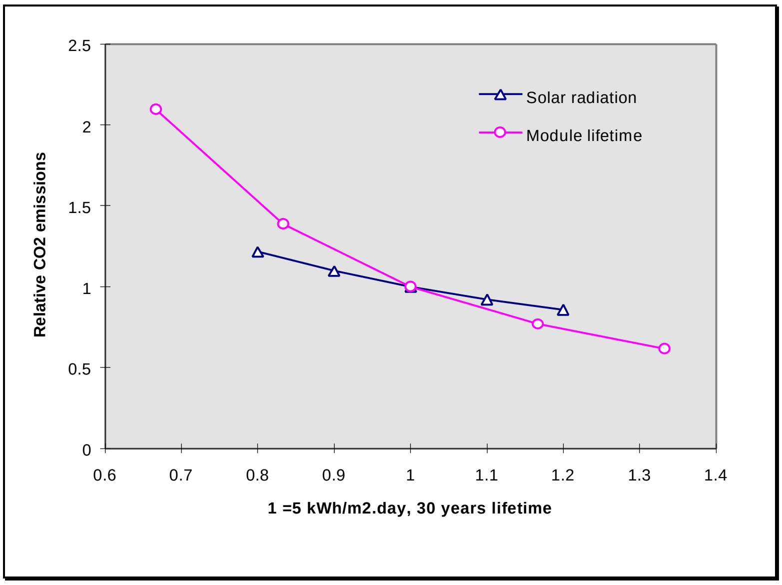


Figure 3.20 Effect of solar resource quality and PV module useful lifetime on CO2 specific emissions.

Partial Load Efficiency

For gas turbines, as shown in figure 1.4, efficiency drops markedly when working at partial loads. All the results presented so far assume that the systems are operated at rated power. Although this is generally the case for large power systems, it is interesting to see how the results change if the system is working half of the time at 50% of rated power. Figure 3.21 shows the results of such an analysis, assuming that the useful lifetime remains the same and that the drops in efficiency at 50% rated power are 0% and 7% for fuel cell and gas turbine systems respectively.

As can be seen the percentage increase in CO_2 and SO_2 emissions is generally lower for fuel cell systems, because these pollutants are more related to system operation or natural gas processes than to manufacturing. Conversely, increases in Particulate and CO emissions are higher for fuel cell systems as an indirect effect of the manufacturing processes and the reduction in the amount of electricity generated during the system lifetime.

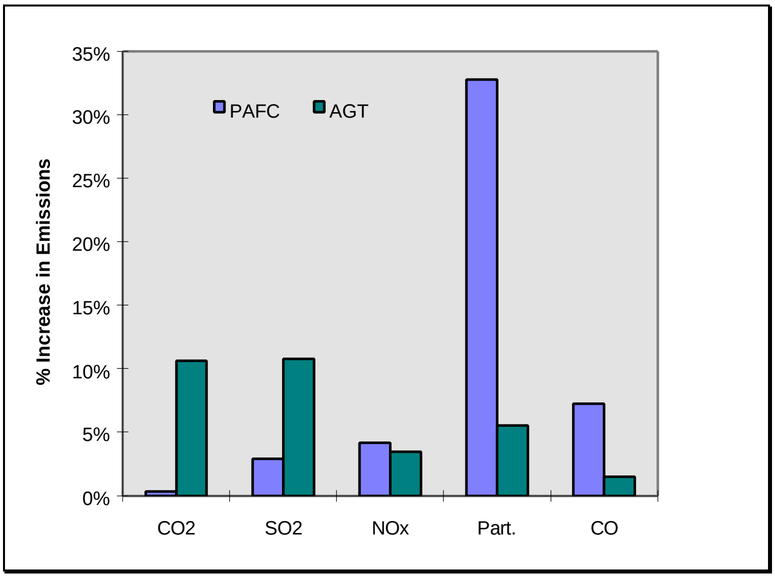


Figure 3.21 Increase in emissions from partial load working cycles

The observed variations are due exclusively to a reduction in electric energy output through efficiency and load changes. The direct effect on operational emission coefficients of fuel cell and gas turbine burners working at less than rated power has not been considered and may alter these results.

Cogeneration

The results shown in section 3.5 (main results) do not consider the emissions that are avoided by the use of the excess heat produced by PAFC systems (low temperature heat, ~60 °C). The thermal efficiency of the PAFC system is around 40%. According to economic evaluations performed by New York State Energy Research and Development Authority (NYSERDA, 1997), approximately 1.3 MJ of natural gas is displaced per MJ thermal energy produced by the PAFC system or equivalently ~4 MJ of natural gas per kWhe produced, or ~0.4 MJ of gas saved per MJ of gas consumed by the PAFC system. If we consider combustion in a standard boiler this gives the results shown in figure 3.22, where the standard system specific emissions are compared to the emissions avoided (on a kWhe basis).

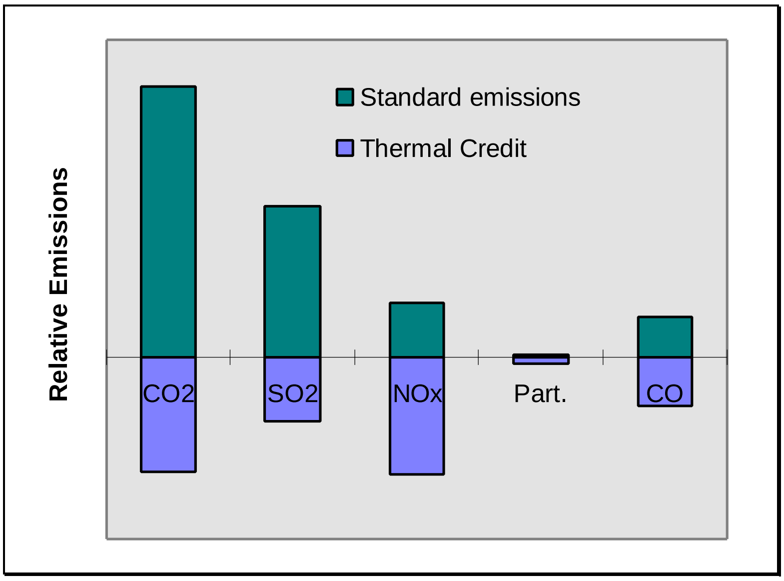


Figure 3.22 Emissions credit for thermal energy use in PAFC relative to electricity emissions.

This simple calculation shows the great potential for reduction in emissions when the system is used as a cogeneration unit instead as a simple power generation unit.
Although the figures shown are based on actual data, they can be considered optimistic since they correspond to the biggest fuel savings that have been achieved among a range of cases (NYSERDA, 1997). The magnitude of the emissions avoided varies from case to case depending on the emission coefficients from the alternative boiler and the efficiency with which the thermal load can be matched with the thermal output from the fuel cell. Furthermore, the greater the requirement for high temperature heat the lower will be the emissions savings.

Gas fired systems are also very suitable for use in cogeneration schemes thanks to the high heat value of the exhaust gases. While simple cycle gas turbines require additional equipment for the generation of steam (additional boiler), CCGT can use the steam from the steam turbine cycle.
According to one report (DOE, 1994), a 1MW CHP system based on a gas turbine can produce fuel savings in the order of ~4.2 MJ/kWhe, or 0.19 MJ of gas saved per MJ of gas consumed by the CHP system. This represents half the amount of fuel savings per unit of primary energy consumption compared to PAFC systems. However, the figures

from PAFC and gas turbine systems are not strictly comparable since they come from different applications that produce different amounts of electricity and heat, and the temperature of the heat produced is also different. Taking into account that the heat produced by the CHP gas turbine system is of higher temperature than that from the PAFC system, the emissions avoided per unit work produced should be similar for both systems (Kordesch, 1996).

4. Discussion of Results

In general terms there is not much difference between the emissions of the fuel cell systems and the top performing gas turbines, particularly CCGT. Not even high temperature fuel cells (HTFC) or HTFC/gas turbine hybrid systems seem to offer a clear advantage over CCGT in terms of CO_2 emissions. However, due to the great range of variation in turbine technology and the lower efficiency when working at partial loads, gas turbines can produce much higher emissions than fuel cells. Furthermore, depending on the specific system used to control emissions from gas turbines, lowering the emissions of one pollutant may have the effect of increasing the emissions of other pollutants (Cohen, 1996).

For gas turbine systems manufacturing related emissions are extremely low but the contribution of some processes, such as installation processes, to the total emissions may have been grossly underestimated. The use of highly energy intensive methods for casting turbine blades, such as equiaxial blade casting, may need to be further analysed but as explained in the sensitivity analysis and given the weight represented by the turbine blades related to the whole system the results are not expected to change considerably.

For fuel cell systems manufacturing emissions are also fairly low, higher than for gas turbines but certainly much lower than for PV systems. These emissions are mainly related to the high use of steel in the systems.

For both top performing gas turbines and fuel cell systems, a very high proportion of the emissions (with the exception of those corresponding to CO_2) are related to the processes of extraction, conditioning and transport of natural gas. Given that these emissions vary markedly from region to region with the specific natural gas system characteristics, this is a big source of variability in the total specific emissions. The cleanup of these operations would greatly reduce the emissions associated with both systems.

PV/H_2/FC systems show very different behaviour from other systems since their emissions are mainly associated with the manufacturing processes. Although these systems produce a marked reduction in CO_2 emissions relative to conventional systems, the results for other pollutants are no better and in some cases worse than for other top performing gas technologies. As already mentioned this odd behaviour is related to the high energy intensity during photovoltaic cell manufacture and the high material intensity for the production of the PV system, combined with the extremely low efficiency of the PV/H_2/FC energy chain (see figure 1.3).

However, thanks to their abnormal origin these emissions could be greatly reduced by using “clean” electricity in the manufacturing process and using recycled materials or redesigning the systems so as to avoid the use of large quantities of aluminium and steel per kW installed. A reduction in manufacturing energy intensity would also help but it would have to be attained without a proportional reduction in the efficiency of the PV modules, since a lower energy output will increase the specific emissions. Another alternative would be to use less energy and material intensive renewable systems than PV, such as wind energy converters, for the generation of power.

Notwithstanding the advantage of producing a flexible energy carrier such as hydrogen, in the context of a mainly conventional electricity grid the PV/H_2/FC system analysed is at a disadvantage with respect to grid connected renewable systems located near the load such as PV and wind energy turbines. Although the emissions from the PV modules will still be the same, the location near the load greatly increases the efficiency of the system and thus reduces the specific emissions. The same applies to wind converters, with the additional advantage that the emissions from the manufacturing process are much lower than for PV modules. In both cases the interconnection with the grid would offer a similar degree of reliability to that provided by the storage of a chemical fuel.

A PV/H_2/FC system could make much more sense in the absence of a reliable electricity grid, located as near as possible to the load, avoiding liquefaction, and if possible using wind energy turbines, small hydroelectricity or improved PV modules so as to minimise manufacturing related emissions.

For stationary applications, the low efficiency involved in long distance hydrogen transport may mean that locating the fuel cell systems near the electrolyzer plant and transmitting the electric power along highly efficient power lines could be a more efficient option. Although this system would have the advantage of energy storage in chemical form it would not be able to provide H_2 for transportation applications, and would only be justified where the grid system maximum capacity for variable source generation had been surpassed.

Two important factors discussed in the sensitivity analysis may substantially alter the results of this study and therefore its conclusions. Firstly, although only the provision of electricity is analysed here, some of the systems (e.g. PAFC, HTFC and gas turbines) are able to provide useful thermal energy as well. Consequently, overall emissions for these systems would be lower if this energy were calculated alongside electricity when calculating the specific emissions. Such a calculation could be done in terms of the exergy[**] value of the electric and thermal energy components (Kordesch, 1996), or simply by calculating the emissions avoided using the savings in natural gas (see sensitivity analysis). Both types of systems can achieve marked reductions in all emissions when used in cogeneration schemes.

Secondly, due to the fact that the specific emissions are calculated taking into account the efficiency of the system working at rated power, overall emissions for a non flat load curve will be different. This is particularly critical for gas turbine systems since, as shown in figure 1.4, system efficiency drops quite markedly below rated power. Fuel cell systems are not affected as long as the load remains above 50% of rated power since the efficiency is almost constant in this power range. As shown in section 1.3, when working at partial loads fuel cell systems offer a considerable advantage over gas turbines in terms of CO_2 and SO_2 emissions. Particulate and CO emissions increase more for fuel cells than for gas turbines since gains in terms of efficiency are offset by a fixed contribution from manufacturing which increases the specific emissions as the energy output decreases. However, even accounting for these increases the overall specific emissions of CO and particulates are generally lower for fuel cell than for radial or simple cycle axial gas turbine systems.

[**] Exergy can be defined as the actual available work that can be extracted from a given energy form

In grid isolated systems with strong load variations, fuel cells would have some advantages over gas turbines but the requirement of a relatively reliable gas supply is a strong constraint since in developing countries there are still many areas isolated both from the electric grid and the natural gas network. In these cases it could be easier to find finance for the expansion of the natural gas infrastructure than for the power infrastructure (Dunkerley, 1995). However, for areas far away from existing energy networks, renewable systems with storage or conventional backup would probably offer a more economic alternative.

In some systems where energy losses during electric power transport and distribution are very high, the installation of decentralised fuel cell or advanced gas turbine systems could be an efficient way of lowering emissions. However, this would have to occur on a massive scale to have a noticeable effect.

The potential contribution of fuel cells and advanced gas turbines to the abatement of energy related air emissions depends to a large extent on the growth of natural gas share in the electricity mix supply, on the growth of electricity demand relative to other energy sources, and on the sources that it displaces as a consequence of these increases. As mentioned in section 1.1, the global technical potential for coal displacement by natural gas seems to be high but the constraints may prove to be too large.

According to one study (IAE/OECD, 1994), in OECD countries gas share in electricity supply mix was around 10% in 1991 and is expected to double by 2010. Primary energy for electricity represented ~40% of total primary energy demand and is expected to grow to 45% by 2010. Thus, natural gas use for electricity generation represented ~4% of primary energy demand in 1991 and is expected to grow to ~8% by 2010. Even if gas share growth is produced through coal displacement, given the small share of gas used for power generation in total primary energy demand, the contribution to emission reductions from this displacement seems to be much lower than the potential contribution from savings in energy end-use cited in section 1.1.

If fuel cell systems displace other gas technologies rather than coal technologies, the effectiveness will depend to a large extent on the technology to be replaced. In this context fuel cells can make a big contribution when displacing old gas systems but only a marginal one when competing with top performance gas cycles.
Overall, given the still high share of coal (~45%) in electricity production in OECD countries, the individual reductions achievable through new gas technologies seem to be much lower than those from other options, particularly end-use energy savings (including the ways in which energy services are provided) and new coal technologies.

In contrast with the analysis above for the OECD region, marked reductions could be achieved in countries with a high gas share in the electricity supply mix where old gas technology is replaced for new gas technology, be it CCGT or fuel cells. A similar situation would be observed in countries or areas with a large potential for coal displacement by new gas technologies. But even in these cases reductions will depend on electricity demand relative to other sources and savings in energy end-use will probably still have a bigger potential for the reduction of emissions.

5. Conclusions

The following are the main conclusions of the present study referring to the provision of electric power for stationary applications:

- On a LCA basis and when working at full load, PAFC and SPFC offer a slight environmental advantage over the new generation of gas turbines.

- On a life cycle basis and when working at partial loads up to 50% rated power, PAFC and SPFC present lower emissions of CO_2 and SO_2 than advanced gas turbines.

- The use of PAFC and gas turbine systems in combined heat and power schemes can reduce emissions markedly by decreasing fuel requirements between 30% and 15% relative to standard installations.

- Emissions from gas turbine systems present variations bigger than a factor of two depending on the age and type of technology analysed.

- In a PV/H_2/FC system, efficiency losses along the hydrogen energy chain amplify emissions associated with photovoltaic systems. Unless these efficiencies are improved, PV emissions are lowered, or alternative renewables are used to generate the electricity, this system offers only a marginal advantage over advanced gas technologies in terms of standard air emissions. The only exception is CO_2 specific emissions, which in this case are much lower.

- Low temperature fuel cell and advanced gas turbine systems, if widely applied and under favourable circumstances, may help reduce emissions in the short term in energy systems where electricity transportation and distribution losses are high.

- In electricity systems with low transmission and distribution losses, centralised new generation CCGT systems may be easier to implement than numerous PAFC or SPFC systems and they offer similar environmental advantages.

- New gas technologies for electricity generation seem to offer only a partial solution to the issue of energy related air emissions. On a global scale, only an approach that prioritises policies that target the end-use level but at the same time combines reductions at all levels of the energy chain seems to have the potential for achieving a substantial reduction in emissions.

There are areas that need to be analysed further. These include refining and completing the present analysis following the points mentioned in sections 2.2 and 3.6, and performing similar environmental studies in the following areas:

- High temperature fuel cells for power generation.
- PAFC and high temperature fuel cell systems for the combined production of heat and power compared with other CHP schemes.
- Hydrogen energy chains based on other renewable systems for the generation of power.

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