SIXTH FRAMEWORK PROGRAMME

Project no: **502687**
NEEDS
New Energy Externalities Developments for Sustainability

INTEGRATED PROJECT

Priority 6.1: Sustainable Energy Systems and, more specifically,
Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.

Deliverable n° 9.2 - RS 1a
"Final report on technical data, costs and life cycle inventories of fuel cells"

Due date of paper: 28.02.2008
Actual submission date: 13.06.2008

Start date of project: 1 September 2004 Duration: 48 months

Organisation name for this paper: POLITO, IFEU, DLR
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Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)

Dissemination Level

PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary

List of abbreviations

BAU – Business as Usual

BoP – Balance of Plant

CCS – Carbon Capture and Sequestration

CHP – Combined Heat and Power

FC – Fuel Cell

FCH JTI – Fuel Cell and Hydrogen Joint Technology Initiative

GHG – Greenhouse Gas

HFP – Hydrogen and Fuel Cell Technology Platform

HHV – Higher Heating Value

HVAC – Heating, Ventilating and Cooling

IEC – International Electrochemical Commission

LCA – Life Cycle Assessment

MCFC – Molten Carbonate Fuel Cell

MEA – Membrane Electrode Assembly

NG – natural Gas

PAFC – Phosphoric Acid Fuel Cell

PE - Pessimistic

PEMFC – Polymer Electrolyte Membrane Fuel Cell

Ren - Renewables

RO – Optimistic Realistic

SOFC – Solid Oxide Fuel Cell

UPS – Uninterruptible Power System

VO – Very Optimistic

WG – Wood Gas

WP – Work Package

YZS – Yttria-stabilized Zirconia

Abstract

The fuel cell technology is one of the most investigated options for future stationary supply of energy, both in the residential and in the industrial sector.

The report presents current technological achievements and the future development pathway in the next four decades of fuel cell power plants.

A special focus is set on the technology hot spots, both at a general level and at the specific fuel cell type level. Current industrial and research developers are mentioned, but information are based on current available data and do not pretend to be an exhaustive and ever-updated list as fuel cell developers have a continuous and intense activity and fluidity in research targets and financial assets.

The cost issue is assessed outlining the present status and the future figures according to forecasted installed capacity and assumed learning curves based on progress ratios.

In the specification of future technology configurations, three scenarios are envisaged where favourable, neutral and unfavourable conditions apply for the technology to penetrate the market and to reach performance targets. For each scenario technical and cost data related to each specific technology are provided.

Finally, for each scenario a life cycle inventory analysis has been performed in order to evaluate emissions and land use due to the four phases (construction, fuel supply, operation and dismantling) of the life of a fuel cell system.

Structure

The report is composed of five chapters.

Chapter 1 introduces the type of technology.

Chapter 2 is devoted to the detailed description of all the fuel cell power plants that will be assessed under the technological, economical and environmental point of view.

Chapter 3 presents the possible development pathway for the technology and for the costs.

Chapter 4 details the features of the selected future specifications of fuel cells systems.

Chapter 5 contains all the relevant data that were used for the inventory analysis and the results of the analysis itself.

Chapter 6 presents the conclusions of the work.

1 Introduction

A fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidant, both externally supplied, to electrical energy and by-products including heat.

Fuel cells are generally connected in series to achieve the desired power output. The assembly of several cells together with the necessary equipment (separators, cooling plates, manifolds and supporting structure) is called fuel cell stack. When one or more stacks are assembled together then a fuel cell module is obtained.

In this Report, fuel cell power systems (or power plants) are addressed: they are generator systems that use a fuel cell module to convert the chemical energy of reactants by an electrochemical process to electric energy (direct current or alternate current electricity) and thermal energy.

Fuel cell systems can be used in portable, transport and stationary applications but according to the purposes of the NEEDS project, this WP addresses only the stationary application.

In March 2005, the International Electrochemical Commission (IEC) has issued its first standard on Fuel Cell Technologies. According to standard 62282-1 (Terminology) a fuel cell system for stationary application is comprised of the parts depicted in Figure 1.1.

As for what concerns the net power output of a fuel cell power plant, the classification proposed in this Report is:

Small Fuel Cells Power Plant: ≤ 10 kW

Large Fuel Cells Power Plant: > 10 kW.

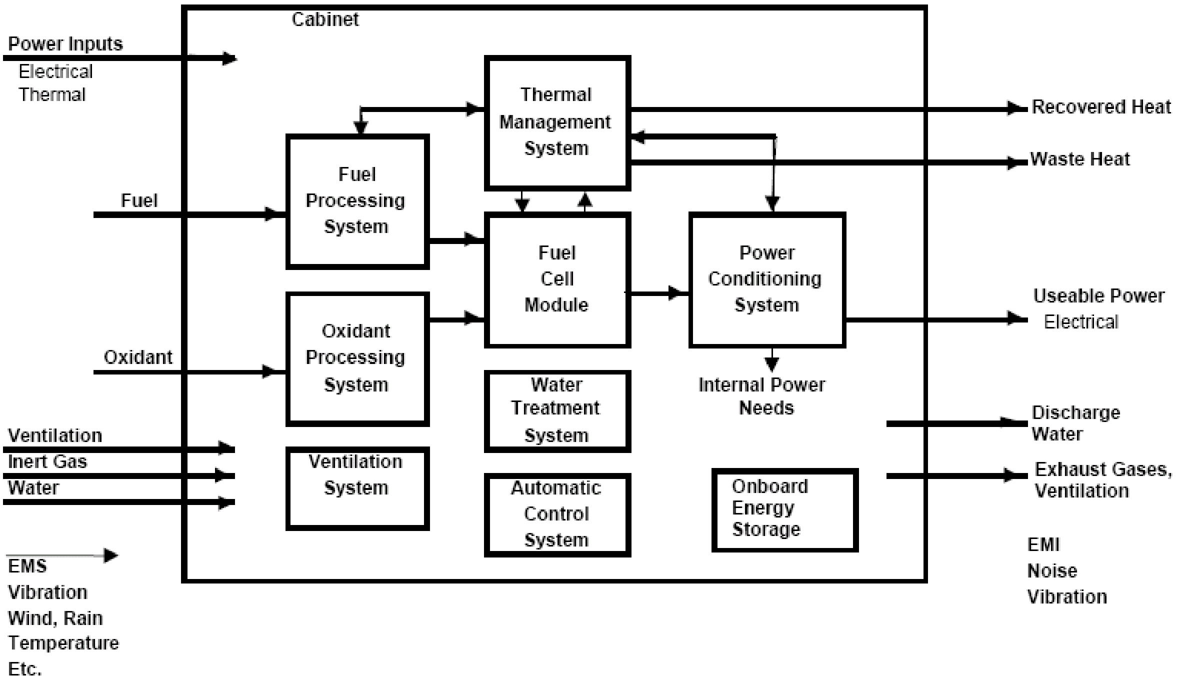


Figure 1.1 - Fuel cell system scheme according to IEC 62282-1 [25]

Fuel cells exist in different types, distinguished mainly by the electrolyte and the corresponding operating temperature. For stationary applications, the most important fuel cell types are:

- PEMFC – Polymer Electrolyte (or Proton Exchange Membrane) Fuel cells
- PAFC – Phosphoric Acid Fuel Cells
- MCFC – Molten Carbonate Fuel Cells
- SOFC – Solid Oxide Fuel Cells

Fuel cells may be supplied with fossil fuels (mainly natural gas, but also gasoline) or directly with pure hydrogen (in the case of PEM fuel cells). One further option is to supply fuel cells with wood gas: this solution, together with the possibility of supplying hydrogen produced via electrolysis (with electricity derived from renewable sources), stresses the capability of fuel cells to be a viable solution for a sustainable electricity and heat production in the future energy mix.

2 Fuel cell power plants today

2.1 Technology options

2.1.1 PEMFC

The Proton Exchange Membrane Fuel Cell (PEMFC) takes its name from the special plastic membrane used as the electrolyte. The most common material for this membrane is Nafion, a perfluorinated sulphonic acid polymer. The membrane is comprised between the two porous carbon electrodes coated with a minimum amount of platinum catalyst. Platinum is essential for the reaction to take place, due to the low operating temperature of PEMFC, and it is highly sensible to any CO content in the fuel which may poison the catalyst in a short time.

The assembly (membrane and the electrodes) is called membrane electrode assembly (MEA). The fuel gas (hydrogen) an the oxidant (air or oxygen) are supplied to the MEA passing through a series of plates which have the purpose to diffuse them in the most uniform way to the two membrane sides (see Figure 2.1 for an exploded view of the core of a PEMFC).

A stack is composed by a series of single cells separated by bipolar plates with integrated gas flow channels. Bipolar plates may be either metallic of made of carbon composite.

When supplied with fuel and air, the cell generates electric power at cell voltages around 0.7 V and power densities of up to about 1 W/cm^2 electrode area. The products of the reaction are water and heat which have to be removed. The removal of heat is favoured by a cooling circuit where air or water is circulated. The membrane relies on the presence of liquid water to be able to conduct protons effectively, and this limits the temperature up to which a PEMFC can be operated.

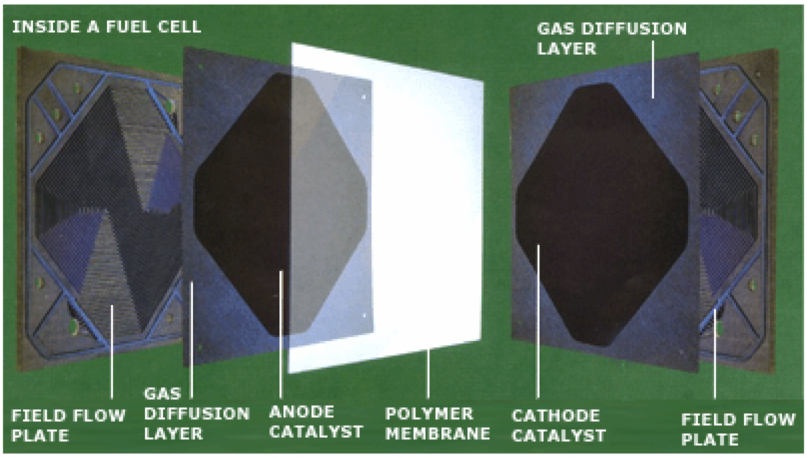


Figure 2.1 - MEA structure [www.FuelCellToday.com]

The reactions involved in a PEMFC are:

$$H_2 \Rightarrow 2H^+ + 2e^- \qquad \text{(Anode)}$$

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \Rightarrow H_2O \qquad \text{(Cathode)}$$

The stack has to be connected to a power conditioning system to obtain AC electricity to be used in households.

The PEMFC is operated with pure hydrogen. In a fuel cell power plant, hydrogen can be either supplied directly or, as in the case of the here assessed systems, it is produced in a fuel processor installed within the plant. Thus the fuel supplied can be natural gas or other hydrocarbons.

2.1.2 SOFC

Solid Oxide Fuel Cells (SOFC) belong to the group of high-temperature fuel cells. They are operated at temperatures up to 1,000 °C and are of high interest because of their specific properties, especially the fuel utilization: they are able to work with a great variety of fuels (gaseous hydrogen or hydrocarbons like gasoline, diesel, kerosene, heavy oil, natural gas, or even biogas) while needing only a relatively low demand for cleaning, in particular concerning sulphur, and reforming of these fuels. In contrast to low-temperature fuel cells where CO is a severe catalyst poison, the CO can be used also as a fuel and reacts to CO_2 in the conversion process.

Another advantage is that the SOFC generates a certain amount of heat. Because of its high temperature level it can be efficiently used also for a lot of subsequent tasks which increase the overall efficiency and economy. The highest electrical as well as overall efficiency can be reached by coupling the SOFC with a micro gas turbine using the high temperature “waste heat” for generating electricity (hybrid concept).

The SOFC major components include the anode, the cathode, and the electrolyte. Fuel cell stacks contain electrical interconnects - the so called bi-polar plates - which link individual cells together in series. In its electrochemical active parts, the SOFC consists mainly of ceramic materials. In general two productions methods exist: the well known wet powder processing with subsequent sintering steps and different plasma spraying processes, currently under development [25].

The two electrode reactions are expressed as:

$$H_2 + O^{2-} \Rightarrow H_2O + 2e^-$$

$$½O_2 + 2e^- \Rightarrow O^{2-}$$

At the cathode side molecular oxygen is dissociated; the resulting oxygen atoms are reduced to O^{2-} combining with two electrons each. These ions migrate via the electrolyte to the anode. There, the oxygen-ions combine with hydrogen and produce water vapour and complete the reaction by releasing two electrons to the external circuit. The electrons, freed during this process, return via an external load to the cathode side starting again the described process. It generates an open circuit voltage of about 1.1 V. During cell operation generating power, values between 0.5 and 1 V per cell can be obtained. Current densities amount to values between 0.5 and 1 A/cm^2 [25].

The anode is mostly built as a cermet, which is a mixtures of ceramics and metals, e.g. NiO and zirconia, and is fired at a temperature similar to that of the electrolyte. The electrolyte is a semipermeable membrane through which the O^{2-} ions can pass. As electrolyte material, typically stabilized zirconia doped with yttrium oxide (YSZ) configured to achieve near-zero porosity is used. It is typically fired at a temperature between 1350° and 1500°C, depending on particle size distribution and composition [51].

The cathode layer is a perovskite-like mix of conducting oxides, e.g. $La_{0.8}Sr_{0.2}MnO_3$ (LSM), which is fired at a lower temperature to minimize the development of secondary phases with the zirconia electrolyte. These secondary phases increase electrical resistance at the interface.

SOFC technology uses two basic designs: planar and tubular (see Figure 2.2).

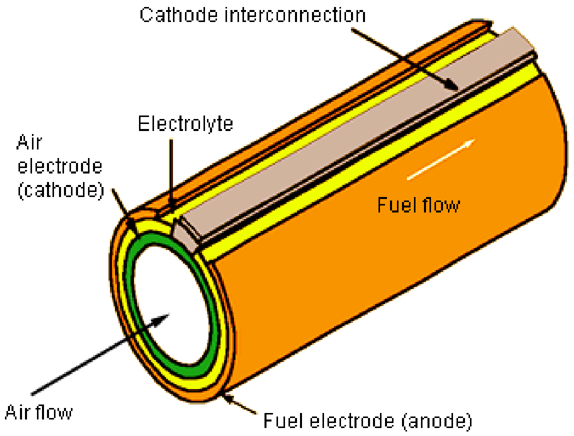


Figure 2.2 - Siemens cylindrical-tube SOFC technology

2.1.3 MCFC

The Molten Carbonate Fuel Cell (MCFC) belongs to the high-temperature fuel cells. In the MCFC, carbonates (Li_2CO_3, K_2CO_3) are used as electrolyte. It is operated at 650 °C. The electrodes consist of nickel materials.

In the MCFC, carbonate ions which are produced at the cathode are conducted through the electrolyte:

$$CO_2 + \frac{1}{2} O_2 + 2e^- \quad \Rightarrow CO_3^{2-} \qquad \text{(cathode).}$$

At the anode, the H_2 reduces these ions to CO_2:

$$H_2 + CO_3^{2-} \quad \Rightarrow H_2O + CO_2 + 2e^- \qquad \text{(anode).}$$

To supply the CO_2 required at the cathode, the CO_2 from the anode off gas is fed back.

MCFC offer the advantage of high (electrical and thermal) efficiencies, high temperature of the exhaust heat (which makes the production of steam feasible) and the straight-forward use of carbon containing synthesis gases. Correspondingly, MCFC are developed for use of different fuels. Whereas most developers have demonstrated systems using natural gas, biogas from agricultural residues, wastewater treatment and waste treatment plants as well as gasified coal are included in the development activities.

Also, due to the relatively high operating temperature, expensive catalysts are not required, whereas compared to the SOFC, which operates at even higher temperatures, expensive ceramics can be avoided.

2.1.4 PAFC

Phosphoric Acid Fuel Cells (PAFC) use an electrolyte that is a relatively concentrated solution of phosphoric acid absorbed in a silica carbide matrix. The electrodes are constituted by a graphite support treated with small quantities of platinum as a catalyser. They work at a temperature of about 200°C and can be classified as medium temperature fuel cells.

PAFC represent the most mature technology and several units have already been delivered and installed worldwide mainly for backup purposes. Nevertheless, important and thorough studies [46] have envisaged a possible or promising future as alternative stationary Combined Heat and Power (CHP) technologies particularly for PEMFC, SOFC and MCFC. UTC Fuel Cells, a US based company, is the most important developer and seller of PAFC as it has already delivered more than 200 units; in the last two years it has decided to continue selling the optimised PAFC unit as is, and to turn its interest on R&D of PEMFC.

In addition, LCA data for PAFC are difficult to obtain. These are the main reasons for this Report and all the assessment made within this WP to be focused on PEMFC, SOFC and MCFC.

2.1.5 Summary

Table 2.1 presents typical values for fuel cells features.

Table 2.1 - Fuel cells main features

Electrolyte	Transferred ions	Average operating temperature (°C)	Electrical efficiency (%)	Residual heat temperature (°C)
PEM	H^+	80-120	40	60-80
PAFC	H^+	180-200	40	70-80
MCFC	$CO_3^=$	630-670	50-55 (60-65)	600-700
SOFC	$O^=$	800-1000	50-55 (60-65)	700-1000

2.2 Current market penetration and main developers

2.2.1 Market surveys

Fuel cell systems for stationary applications are under development since many decades although it is not until recently that a certain amount of interesting results have been obtained from the key developers, thanks also to the huge funding from the governments and to the experience gained in the past tests. Notwithstanding the early discovery of their fundamental operation principles, fuel cells are still a young technology and can get a decisive element of learning from the amount of hours of continuous operation of its systems.

The market is growing with different patterns, according to the category of the fuel cell system analysed.

The small systems have seen a continuous increase in the number of units delivered per year. It should be remembered that both UPS and CHP systems belong to the small systems group and that in this report we consider only the CHP subgroup.

There is a sort of "geographic" split between the two subgroup diffusion: UPS units are mostly developed and installed in North America, while CHP units are preferably manufactured and operated in Asia (namely in Japan, thanks to the Large Stationary Demonstration Programme). Figure 2.3 shows the present split of the manufacturing capability in the world with reference to the small systems.

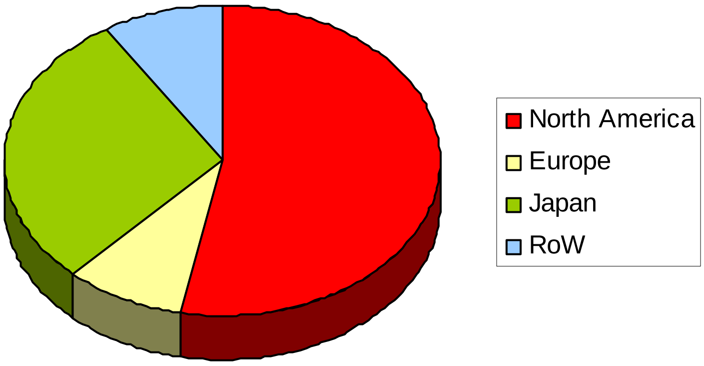


Figure 2.3 – Split of manufacturing capability in the world (small systems) [1]

The trend of annual new units delivered is pictured in Figure 2.4 and it is consistent with many of the forecasts studies produced in the past.

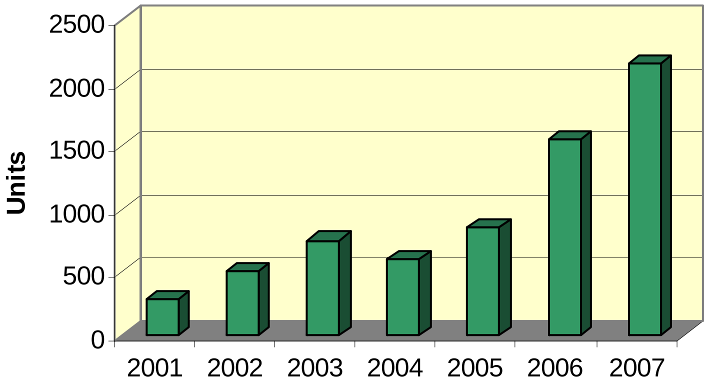


Figure 2.4 – Number of new annual small stationary units installed [1]

The small systems, then, are mainly powered by two types of fuel cells, PEMFC and SOFC (Figure 2.5).

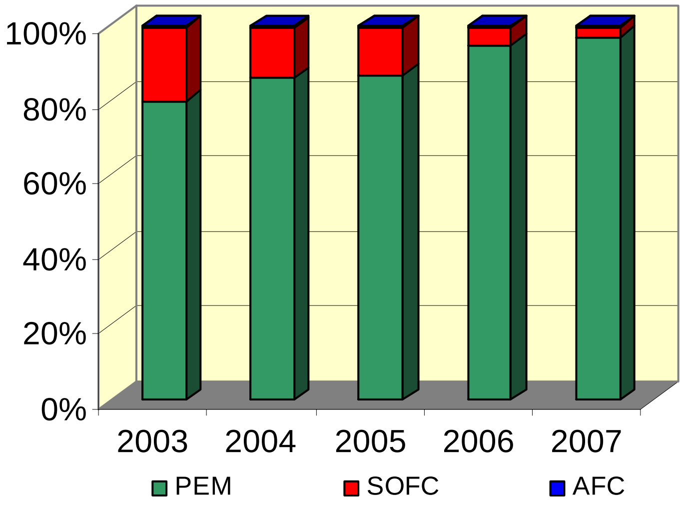


Figure 2.5 – Shares of type of technologies per year [1]

Concerning the large fuel cell systems, in Figure 2.6 the number of installed units is represented per annum.

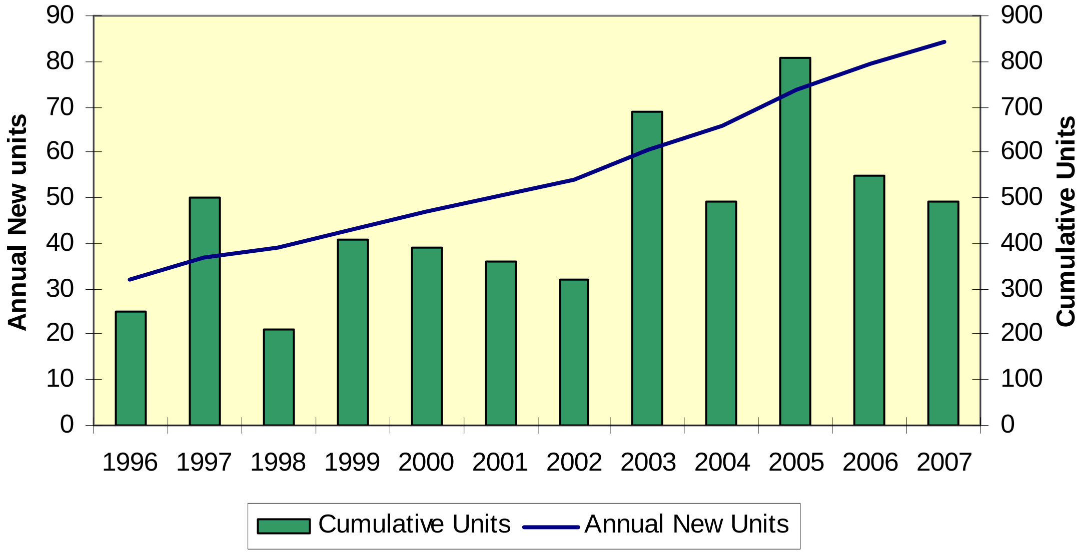


Figure 2.6 - New and cumulative installed large fuel cell units [2]

The trend seems to show a decrease in the delivery rate, but in fact, it depicts the actual philosophy of large fuel cells systems developers, that is to build less units but bigger. This idea is also clearly show in Figure 2.6: the annual number of new units decreases but the cumulated capacity rises and, more interestingly, annual amount of MW installed makes a jump onward (Figure 2.7).

Finally, Figure 2.8 shows the share per type of technology when large systems are concerned. The choice of the type of technology depends on several aspects and opportunity reasons: just to cite one of them, the availability of the kind of fuel is a key factor for choosing which of the technology is to be installed and where.

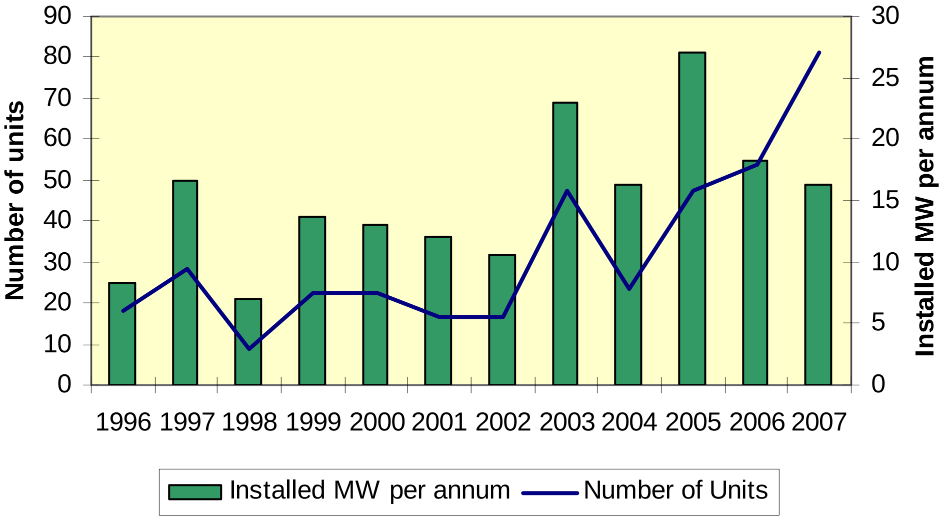


Figure 2.7 - Annual number of Units and MW installed [2]

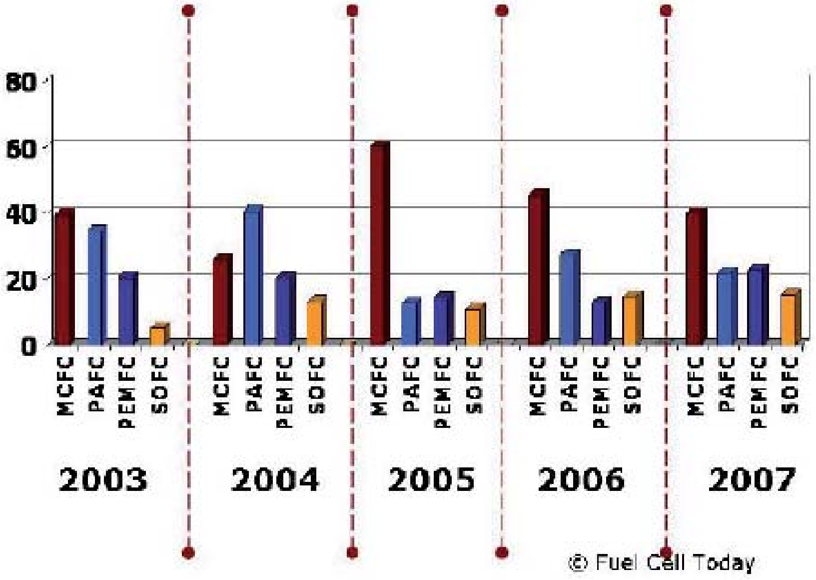


Figure 2.8 - Technology per type and per percentage [2]

2.2.2 Current developers

2.2.2.1 PEMFC

PEMFC are consistently developed worldwide for transport application: huge funding is dedicated to the R&D of systems suitable for automotive installations. Nevertheless, some important companies are focusing (also) on small and large stationary units especially in Japan.

Concerning small PEMFC power plants, Ballard, which is very active in the transport application field, in conjunction with its joint venture company Ebara Ballard (J), focuses also on the development and commercialisation of Ballard 1 kW CHP stack for residential applications. Ebara has the exclusive in Japan, while Ballard holds the rights in the rest of the world. Other stack developers which develop and produce stacks and systems for residential CHP applications are European Fuel Cells (D), Hydrogenics (CAN), Nuvera (USA/Italy) and Shanghai-Shen Li (China). In Japan, Fuji Electric Advanced technology, Hokkaido Gas, Matsushita Electric Industrial, Mitsubishi Heavy Industries, Sanyo Electric, Toyota Motor

Company and Toshiba Fuel Cell Power Systems are all directly engaged in the development of proprietary fuel cells, generally in the size of 1 kW for small residential applications [4].

A side quote is for developers of Uninterruptible Power Systems (UPS): P21 (Germany) CellKraft (S), Electro Power Systems (I), New Japan Eco Systems (J), Plug Power (USA), Alternergy (USA) and ReliOn (USA).

Concerning large stationary systems, fewer companies seem to have an interest in developing systems: NedStack (NL, which has developed also small systems), Electrocell (Brazil), Hydrogenics (CAN) and Nuvera Fuel Cells (USA/Italy).

It has to be underlined that the list of PEMFC developers is very fluid, with some new companies which appear on the scene and some others which change name after relaunch operation, re-organisation and merge with other companies. Also, some companies are responsible for developing the auxiliary equipment and adopt fuel cells from other providers. Under these assumptions, the above list of developers is not intended to be exhaustive and it is only a picture of the moment when this report is prepared.

2.2.2.2 SOFC

Low power range (1-10 kW)

Hexis Ltd. (former Sulzer Hexis, Switzerland) is one of the leading European companies in the fuel cell industry and it is the leading developer of residential fuel cell systems based on planar SOFC technology. Over the past couple of years it has undertaken extensive field testing of its pre-commercial “Galileo 1000 N” micro-CHP (1 kW electrical and 2.5 kW thermal power).

Another developer is Ceramic Fuel Cells in Australia. Its products are SOFC stacks sized at 1 kW to 2 kW each. The current focus of Ceramic is Residential Micro CHP, in the range of 500 watts to 10 kW, and remote power.

Mitsubishi Materials (Japan) is working on a joint project funded by NEDO with Kansai Electric (Japan) to develop a 10 kW system using a lanthanum gallate cell to be operated at lower temperature below 800°C. They have already developed 3 kW power generation modules consisting of three SOFC stacks which are operated at an intermediate temperature. They have confirmed stable operation and attained a power generation efficiency of 55% (DC, LHV base). [6]

Not only in the automotive sector, but also for aircraft SOFC are being in development. The main aircraft manufacturers Boeing and Airbus are involved in the development if APUs (Auxiliary Power Units). [25]

Medium sized power ranges (100 – 500 kW)

Siemens-Westinghouse Power Corporation (SWPC) is currently the most advanced developer of SOFC in the range between 100 and 250 kW electric power, with optional use of high-temperature steam. SWPC [53] originally worked on a tubular design of SOFC. The new development is a flattened tubular design providing higher power density by about 30-40% as well as still avoiding the sealing problems of planar fuel cells. New designs named HPD (high power density) and Delta are under development [21].

The largest atmospheric pressure SOFC system ever built, a 250 kW CHP system, began operation in 2003 in Toronto. As of 2004 the system has operated for more than 1,100 hours.

A 100 kW SOFC cogeneration system supplied by Siemens Power Generation (PG) successfully operated in the Netherlands. This system was supplied to EDB/Elsam, where it operated for 16,667 hours at a peak power of about 140 kW. It fed 109 kW into the local grid and 64 kW of hot water into the local district heating system. It operated consistently at an electrical efficiency of 46%. In March 2001 the system was moved from the Netherlands to a site in Essen, where it was operated by RWE for additional 3,700 hours, for a total over 20,000 hours. After that it was operated in Turin and reached 36,900 hours in July 2007. [54]

The first SOFC hybrid system (in combination with a gas turbine) was installed at the National Fuel Cell Research Centre at the University of California, Irvine, in conjunction with the utility company, Southern California Edison. This module incorporated a micro turbine produced by Ingersoll-Rand Energy Systems and had a total output of 220 kW, with 200 kW from the SOFC and 20 kW from the micro turbine. As a proof of concept demonstration, it succeeded in demonstrating the concept and the operating characteristics and parameters of pressurised hybrids. It operated for nearly 3,400 hours and achieved an electrical efficiency of about 53%. This is the highest known electrical efficiency achieved by any large-scale fuel cell system. [55]

Mitsubishi Heavy Industries (Japan) is working on Solid Oxide Fuel Cells and Proton Exchange Membrane Fuel Cells. The development is focused on two solutions, for medium-scale distributed generation and for alternate thermal systems in large-scale SOFCs [3].

The first one is the development of a 200 kW cogeneration system using planar cells called MOLB (Mono-Block Layer Built) together with Chubu Electric Power. Initially, the product is expected to be priced at several hundred million yen. MHI forecasts that the cost can be reduced down to around 500,000 yen/kW (3,700€/kW) with the expansion of the market by 2008 - 2009.

The second project is technology development for a 350 kW system combined with micro gas turbine in cooperation with Chubu Electric Power. They have succeeded in operating of pressurised 10 kW modules for 7,000 hours in 1998 and also succeeded continuous operation of 10 kW pressurised internal reforming systems for 750 hours.

Large power range (500 kW – 2 MW)

Siemens Power Generation (PG) together with the German utility Energie Baden-Württemberg (EnBW) announced in autumn 2006 to build a fuel cell power plant in the range of 2-4 megawatt in 2012 with an electrical efficiency of 70 %. This will be reached by use of a pressurised hybrid version which is a SOFC combined with a micro gas turbine. In a co-operation with DLR Stuttgart and the University of Stuttgart the basic research is planned to be finished until end of 2008 [53]. With exploring this large power range, Siemens PG is focused on the industrial and dispersed markets [25].

In competition with Siemens PG, the company Rolls Royce develops its own large (1 MW) SOFC. It uses ceramic tubes of rectangular cross section on which the cell components are put as planar strips. [57]

2.2.2.3 MCFC

A number of MCFC systems have been realized worldwide. In fact, MCFC belong to the most advanced fuel cell types in the large stationary sector. Among the fuel cell technologies being commissioned in 2006, MCFC dominate with more than 50 % of the recent installations.

Among the market leaders, FuelCell Energy develop products with nominal ratings of 250 kW_{el}, 1 and 2 MW_{el}. FuelCell Energy also released a hybrid system coupling a gas turbine to the fuel cells. Munich based mtu CFC solutions develops in co-operation with FuelCell Energy the HotModule, a 250 kW_{el} cogeneration unit, which has been installed at some 35 locations mainly in Germany. Recently, CFC solutions announced the new generation hot module with 345 kW_{el} and 250 kW_{th}. Further system designs with 400 or 500 kW are in the planning stage.

Ansaldo Fuel Cells (AFCo) develops systems with power outputs ranging from 500 kW to 5 MW. Three of the Series 2TW systems with 500 kW have been in operation or planning in the last year.

Various other companies pursue the production of MCFC systems, such as US based GenCell, developing smaller systems of 40 to 100 kW_{el}. In Japan, several companies work on the development of MCFC, including Mitsubishi Electric Corporation, KEPRI from Korea, Ishikawajima - Harima Heavy Industries Co. Ltd. (IHI), who concentrate on coal-fueled larger power plants, Hitachi Works Ltd. and Toshiba.

2.3 Current technological status

2.3.1 PEMFC

Typical referred efficiencies of small PEMFC for domestic CHP systems are around 28% (electrical efficiency) and 50-52% (thermal efficiency), even if some producers claim slightly different figures especially for electric efficiencies (e.g. Fuji refers of $35\%_{el}$ LLV and $51\%_{th}$ LLV) [4].

As for the lifetime, current technologies show stacks which can last for longer periods than in the past: Ballard Mark 1030 V3 unit is already designed to meet the Japanese government target of durability set at 40,000 hours for residential systems, and the same is for Fuji fuel cells [4]. Matsushita Electric Industrial has a short term target of 10 years endurance per stack, which, again, corresponds to about 40,000 hours in Japanese utilisation pattern of the technology.

2.3.2 SOFC

To update the current technology status of the SOFC development, four different levels of power ranges are considered. Parts of the overview are taken from [25].

Very low power range: in this range small tubular cells are in development. Encouraging results of R&D in this field were reported in [58] and [60].

Low power range (1-5 kW): in this range mostly planar cells are under development together with some activities using tubular cells.

A *portable* 1 kW SOFC generator with methanol was recently described in [23].

In the field of *small stationary systems,* the Hexis has undertaken extensive field tests to develop the “Galileo 1000 N” micro-CHP system, operating on natural gas and generating 1 kW electrical and 2.5 thermal power. The integrated gas burner of 20 kW delivers additional thermal power if needed, which results in a unit covering the basic electricity needs and the entire heat requirements of a typical family home. (The former activities of the Canadian company Fuel Cell Technology, FCT, in this field have meanwhile been stopped).

Regarding the *transport sector,* APUs (Auxiliary Power Units) seem to be very attractive since they are able to operate with standard car fuels (or kerosene in case of aircraft) needing only a relatively low effort for cleaning and reforming these fuels. As an example for the aims of car manufacturers the target values of BMW are given ([35], [59]): SOFC system power of 6 kW, power density of the cells >0,5 W/cm^2, over 5,000 full load hours, systems costs of <500 €/kW.

Medium sized power ranges (100 – 500 kW): Siemens PG’s first pre-commercial product will be the tubular SFC-200. This is a 125 kW SOFC cogeneration system, operating on natural gas at atmospheric pressure. It reaches an electrical efficiency of 44-47% at full load. An overall system energy efficiency of more than 80% is expected, assuming steam/hot water or other cogeneration [55]. In 2007 three of these systems started their operation in Hannover, Tokyo, and Fairbanks, Alaska. In 2008 a power plant of the next generation shall be installed at the Siemens daughter TurboCare in Turin, Italy. Using a new material with a higher conductivity, a load of 150 kW and an electrical efficiency of 47 % is announced. [54]

Large power range (500 kW – 2 MW): in this range no SOFC system is operating yet.

2.3.3 MCFC

As MCFC manufacturing involves mainly well-known manufacturing processes [17], most of the developers have demonstrated large-area stacks. FuelCell Energy has 50 MW/year manufacturing capacity.

At present, the typical Molten Carbonate Fuel Cell systems have electrical capacities of 40 to 500 kW_{el}. Electrical efficiencies of the mature systems without hybridisation (e. g. coupled with a gas or steam turbine) are between 45 and 47 % at start-up. The Hot Module, for instance, exhibits an initial 47 % electrical efficiency in full load, with a slight decrease in partial load. With time, this efficiency is significantly reduced in a number of systems. FuelCell Energy claims that for their system without turbine, 57 % at product maturity could be achieved [13]. For a hybrid system with an unfired gas turbine, FuelCell Energy claims to have reached 56 % over 800 hours.

However, today, these system efficiencies are only achieved at start-up, with significant degradation over time. Total efficiencies reach up to 80 to 85 %, depending on the thermal integration of the system (e. g. return temperature, use of steam or hot water) and other parameters.

Current capital costs are strongly dominated by the high R&D cost at present. Whereas many companies do not publish cost data, MTU CFC Solutions currently states that their capital cost is below 9,000 €/kW. FuelCell Energy announced that for their 300 kW system DFC3000, soon capital cost will be US$ 3,200 to 3,500/kW whereas current cost for larger units it is still around US$ 4,300 to 4,600/kW .

2.4 Present reference technology systems

As reference technology systems the following have been chosen:

- SOFC stationary fuel cell power plant: 1 kW_{el}
- SOFC CHP stationary fuel cell power plant: 250 kW_{el}
- PEMFC power plant: 2 kW_{el}
- MCFC power plant: 250 kW_{el}

Table 2.2 and Table 2.3 show technical and cost data of the reference technologies.

Table 2.2 - Technical data of reference fuel cell power plants (efficiencies based on HHV)

		SOFC	SOFC CHP	PEMFC	MCFC
max. net el. power (busbar)	kW	1	250	2	250
net el. power at el. peak load	kW	1	250	2	250
net thermal power at thermal peak load	kW	2	176	3,7	212
el. efficiency at el. peak load	%	27.1	47	28	46
thermal efficiency at thermal peak load	%	50.3	33	52	39
technical life time	a	8	8	6	8
full load hours	h/a	5,000	5,000	5,000	5,000

Table 2.3 - Cost data of reference fuel cell power plants

		SOFC	SOFC CHP	PEMFC	MCFC
spec. Investment costs (overnight capital costs)	€/kW	>10,000	10,000-25,000	4,000 - 10,000	4,200 - 9,000
fixed costs of operation	€/kW/yr	200-500	200-1250	80-200	84-450
Source		[34]	[34]	[52]	[32]

3 Fuel cell technology development pathways

3.1 Fuel cell power systems hot spots (general)

In the following paragraphs, a list of strong and weak points of the fuel cell technology have been listed and briefly commented.

Table 3.1 - Weak and strong point of the fuel cell technology

Weak points/barriers	Strong points/ diffusion factors
High cost	High electric efficiency
Lifetime, degradation	Use of existing natural gas infrastructure
Reliability	Energy security
Many competitors	Low criteria pollutant emissions
	Reduced noise and vibration
	High power to heat ratio

High cost

Fuel cell power systems for stationary application have still a too high cost per kW installed (see Paragraph 2.4). Interestingly, it is not only the cost for the fuel cell stack, which in many cases causes less than one third of the total capital cost. Rather, a large portion of the cost is caused by the reformer and other balance of plant components.

It is likely to be reduced in the next years thanks to the next phases of the technology evolution and to the scale up of the production processes (technology learning). Beside reducing cost, the efficiencies, durability and technical performance must be enhanced.

Reaching these goals simultaneously presents a major challenge for fuel cell developers. Of primary concern is the establishment of a stable system with high life-time and decent performance. Even though degradation rates have decreased considerably in the past years, the life time of the systems still needs to be further enhanced.

Lifetime / Reliability

Due to the early phase of development, fuel cell systems have not had time to prove their reliability and the full length of their life span. However, this is one of the most important points for public acceptance of the new technology and for economically attractive performance. A reasonable target for stationary fuel cell stacks could be comprised between 5 and 8 years, while tests have demonstrated only for some technologies (e.g. SOFC) a durability over 20,000 hours.

The poor lifetime is partly due to material science issues, such as degradation, diffusion, decomposition or crystallisation processes inside the stack, etc.

Many competitors

In the same segment of the energy systems where stationary fuel cells are set, there are many valid competitors (each with their strong and weak points). Concerning large power plants, natural competitor is the large scale electrification based on coal with a CO_2 capture system, nuclear and renewable sources. On the smaller scale, micro-turbines, reciprocating, steam and Stirling engines can also offer a valid alternative, while, at the root of the problem, a higher heating insulation of buildings, either as a rule for new constructions or as a result of retrofitting of existing houses, can decrease the heat demand thus reducing the need for stationary CHP systems.

Electric Efficiency

Undoubtedly one of the most important features of fuel cell systems is the potentially high electric efficiency which is – for each power range – higher than that of the competitors if the target values of the manufacturers will be achieved over the full life-time of the system. The total (i.e. electric plus thermal) efficiency of the CHP systems, however, depends on the system design and is in many cases not higher, or even lower, than that of, e. g., reciprocating engines (which can be well above 90 %). This is due to the fact that in fuel cell systems, heat from a number of smaller heat sources must be captured whereas in reciprocating engines, only three main heat sources provide the heat to the heat exchanger.

Energy security

The adoption of fuel cell stationary systems may, due to the higher electric efficiency foster the reduction of fossil fuel dependency of our society even if fuel cells will continue to be fuelled with natural gas thus not completely disconnected from the fossil fuels group. An option, which will be assessed for the future fuel cell systems is the possibility to supply MCFC and SOFC with biogene gas, for instance biogas from anaerobic digestion or synthesis gas from the gasification of solid biomass (thus a renewable source). Whereas for mobile applications, hydrogen produced from renewable energy is a possible fuel even in the earlier phases of market development, for stationary applications, within the time frame of this project, the use of hydrogen is reduced to niche applications such as island systems or storage devices.

Use of existing natural gas infrastructure

The diffusion of domestic PEMFC and SOFC systems and of centralised MCFC and SOFC systems is supported by the great advantage of not needing a dedicated new infrastructure. The existing natural gas grid may efficiently supply fuel either to the residential or the industrial application of the technology. However, this is also valid for the competing technologies.

Low pollutant emissions

Fuel cell systems have a low emission level. Whereas the carbon dioxide emissions are lowered due to the higher efficiency, particularly the pollutant emissions, such as NO_x or CO, are very low. In hydrogen operation these are zero. When reforming natural gas or other fossil fuels, they are extremely low due to the comparatively low temperatures involved and the requirement to clean up impurities such as sulphur and CO.

3.2 Fuel cell specific hot spots

3.2.1 PEMFC

PEMFC are particularly affected by the inlet fuel purity. The perfect application of PEMFC would be with hydrogen as a fuel, but this would lead to a series of side-effects to the market penetration mechanism (first of all a lack of hydrogen infrastructure). PEMFC catalysts are easily poisoned by CO and sensibly reduce their lifetime, thus also the fuel processor included in the fuel cell system has to be extremely efficient.

Although PEMFC employ noble metals as catalysts, studies [46] demonstrated the higher contribution to the total cost of the stack is given by the bipolar plates and the electrodes. The reason for this is that PEMFC are still manually manufactured. Thus a large-scale production may give a consistent cut to PEMFC costs. A positive spill-over effect could also come from the development and diffusion of fuel cells for automotive applications: huge investments are dedicated to this research field and several prototypes have already been positively tested, thus the commercialisation phase seems to be nearer in the transport than in the stationary sector.

3.2.2 SOFC

An important weak point is the problem in the choice of materials in SOFC stacks under varying operating conditions (e.g. variety of fuels). Whereas the engineering problems of designing and producing SOFC systems for small and medium scale CHP plants appear generally not un-solvable (as in the SOFC Hexis development), the materials problems at the basis of the degradation mechanisms still constitute a dramatic threat to the feasibility of SOFC technology as a whole. Not meeting the aim of securing 10,000 to 40,000 hours of operating time would in the medium term eliminate any chance of market access for SOFC technology in stationary applications.

SOFC are capable of internal reforming thus making direct use of methane (natural gas) as well as hydrogen. SOFC therefore could form a link between today's gas supply infrastructure and a future hydrogen economy. To get a more efficient operation with natural gas and higher hydrocarbons new materials have to be developed to minimise coking problems. Efforts have to be made to improve the redox and sulphur tolerance of fuel electrodes. Doing this would make SOFC highly flexible in the way of fuels (hydrogen, natural gas, biogas, biomass gasification syngas, liquid hydrocarbon reformats etc). [50]

3.2.3 MCFC

Most of the MCFC companies are at a pilot and demonstration project phase. Nevertheless, beside cost reduction, which is an issue for each fuel cell type, MCFC suffer particularly from degradation issues. This is due to the fact that the materials employed in an SOFC must withstand 40.000 hours at 650 °C in the presence of a molten salt under reducing or oxidising conditions. In addition, the electrodes degrade because the nickel from the electrodes enters the melt (metallic nickel precipitation into the electrolyte matrix) and causes short circuits, making advances in life time and degradation necessary.

However, improvements have been achieved. For example, some MTU CFC Solutions systems have been operated for considerably more than 20'000 hours. In some of the projects, the stack will be replaced, re-using the balance of plant of the systems.

3.3 Main drivers influencing future technology development

Given many aspects with respect to the general framework, techno-economic factors and social/institutional prerequisites, a mid-/long-term projection of market perspectives is not trivial at all. Although fuel cells in general offer a convincing growth perspective, a closer look, e. g. to the field of household energy supply, reveals some open questions and uncertainties. Due to interdependencies between competing technologies and trends (Figure 3.1), currently seen comparative advantages of fuel cells might lose relevance if in the future frame conditions will change. On the other hand, new opportunities may emerge that call for adaptation of products and applications [49]. Major **general framework aspects** include:

- Ultra-efficient building concepts (e. g. "passive house") together with renewable energy supply options such as solar-thermal heating gain increasing importance, so that the demand for conventional space heating and warm water will drop dramatically.
- Energy saving efforts will effect the heat demand of the existing building stock, too, so that the size of the future heat market in general is likely to decrease.

- Competition from increasingly efficient and clean conventional technologies put fuel cells under cost and performance pressure. The relative ecological performance of fuel cell CHP will be affected by a changing environment, e.g. in terms of decreasing specific GHG emissions of the public power generation that will build more and more on renewables.

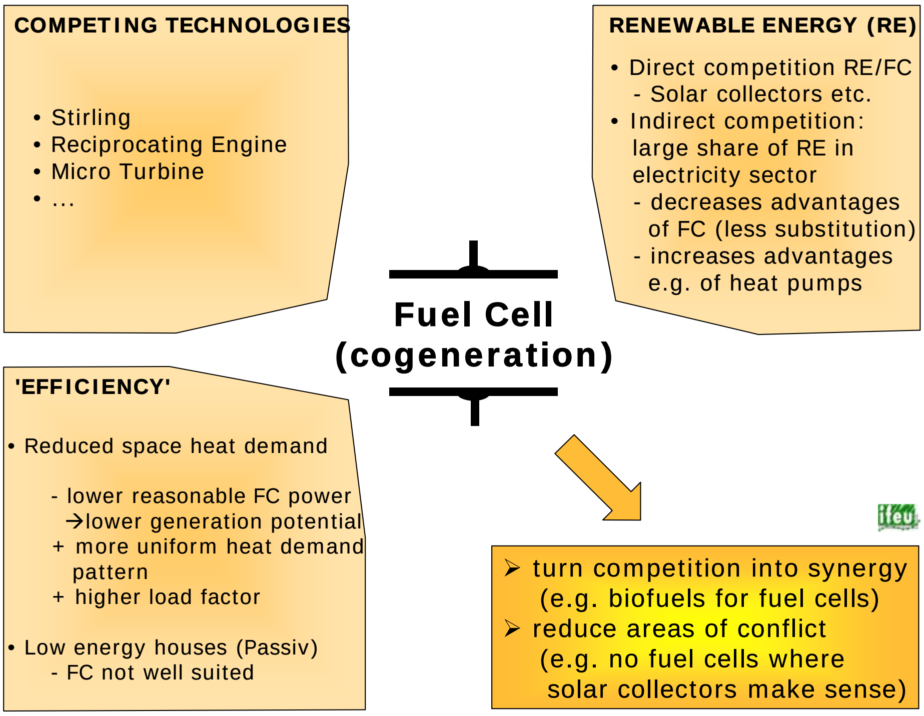


Figure 3.1 - Potential areas of conflict for fuel cells [49]

- On the other side, fuel cells benefit from a European policy framework which, principally, supports CHP, measures to increase energy security and efficiency and CO_2 reduction targets.

- The power plant replacement, which allows new technologies to enter the stage, is determined by the vintage pattern of the existing European power park, by political decisions (e.g. phase-out of nuclear power plants in several EU member states), and other aspects.

- A likely increase in electricity and gas costs will make efficient technologies and electricity feed-in more attractive; higher gas costs, however, shift the economic advantages towards renewable energy carriers.

- At the same time, however, new business opportunities and markets may emerge, e. g. in terms of grid-oriented strategies in decentralised energy systems or the use of biogen fuels. In addition, small fuel cells might open up a completely new market, that of domestic CHP.

The speed of market penetration also depends on **techno-economic factors**. Here, the time-scale is determined especially by the availability of reliable technologies, including degradation and balance-of-plant components and achieving performance targets (see chapter “hot spots”) and a significant decrease in capital costs.

It is evident, that in general a technologically reliable and economically attractive option will hardly succeed on the market if other obstacles prevent a diffusion of the technology. In parallel to the technical progress, therefore, a co-evolution of **socio-economic and**

institutional prerequisites has to take place to pave the way for a smooth market introduction. These prerequisites were outlined in [49] and include

- cost-efficient and consumer friendly standardisation of power plant systems;
- timely qualification of installation contractors and other market actors involved;
- information and promotion activities that enable the end-user to take investment decisions in a new technology area;
- a further dissemination of integral planning techniques for buildings that – from the very beginning – combine efficiency aspects with regard to the building shell, the HVAC technologies and the energy supply solution within a holistic optimisation;
- smooth and non-discriminating grid interconnection of distributed generation technologies in general;
- a fair grid access and a level playing field for market entry of fuel cell generation capacity;
- development of appropriate rules and balance and settlement systems for integrating smaller scale power generation into the energy markets, e.g. in terms of back up power.

In this context the European Hydrogen and Fuel Cell Technology Platform (HFP Europe) should be mentioned. It facilitates and accelerates the development and deployment of cost-competitive, world class European hydrogen and fuel cell based energy systems and component technologies for applications in transport, stationary and portable power [28].

Furthermore, recently (May 2008) the European Parliament has set up the Fuel Cells and Hydrogen (FCH) Joint Technology Initiative (JTI) which was proposed by the European Commission in autumn 2007. Between 2008 and 2017, the FCH JTI will have a budget of EUR 1 billion. The investment will be shared by its two founding members, the European Commission and the European Fuel Cell and Hydrogen Joint Technology Initiative Industry Grouping, a non-profit organisation uniting the sector's key players. The aim is to bringing together the research, development and deployment programme to bring fuel cells and hydrogen technologies to the European market [17].

3.4 The potential role of fuel cells in a future energy supply system

In IEA [46] a scenario study has been performed taking into account several key drivers. The scenario study is called ESTEC from the first letter of the 5 dimensions analysed: Environment, Supply security, Technological progress, Economic conditions, Competing options. Each dimension of each scenario is associated with a plus (+), minus (–) or neutral (0) symbol in series following the acronym indicating that a set of parameters for that dimension have a positive, negative or neutral effect on the potential use of hydrogen and fuel cells. For instance, a higher incentive to reduce CO_2 emissions would be characterised by a plus sign as the first sign in a list following ESTEC. The parameters that are considered in these scenarios are those that were previously identified to be of high importance a sensitivity analysis included in the report [46].

Environmental policies (E) are represented through CO_2 reduction incentives that can vary in level, coverage and timing. The CO_2 reduction incentive is a way of representing the combined impact of policies, regulations, subsidies, taxes, etc., that have the effect of reducing emissions and enhancing energy security.

Explicit energy-security policies (S) are represented through targets to reduce oil import dependency and through taxation policies that favour the use of alternative fuels over conventional oil.

Technology advances (T) in hydrogen and fuel cells are modelled through three sets of variables: the cost of the fuel cell vehicle (FCV) drive system, the efficiency of the FCVs and a gradual transition from distributed to centralised hydrogen production. This last model characterisation is intended to represent the additional effort needed to overcome transition and infrastructure barriers, such as the chicken-or-egg problem.

Economic conditions (the second E) are modelled through oil and gas price assumptions, as well as the discount rates in the transport, service and residential sectors.

Finally, the prospects for competing options (C) includes a set of assumptions for alternative technologies, transportation fuels, CO2-free electricity production from nuclear and renewable energy, and fossil fuels with CO2 Capture & Storage (CCS).

Four scenarios, then, have been analysed:

Scenario A – ESTEC --++- → Weak CO_2 policies, liberalised markets and market-driven technological development

Scenario B – ESTEC 0+++- → Strong new CO_2 policies in Kyoto countries and rapid technological development

Scenario C - ESTEC 0+--- → Strong new CO_2 policies in Kyoto countries, but technological development lags

Scenario D – ESTEC +++++ → Strong new CO_2 policies worldwide, with rapid technological development.

According to this study the stationary fuel cell capacity installed has been evaluated until year 2050 and is shown in Figure 3.2.

To meet the structure of the NEEDS project, three alternative technology development scenarios may be envisaged and derived from the ESTEC study:

- the “very optimistic” scenario, coincident with Scenario D
- the “optimistic-realistic” scenario, coincident with Scenario C
- the “pessimistic scenario”, where no fuel cell affirmation takes place.

The very optimistic scenario sees, as a result, the diffusion of stationary fuel cells up to 300 GW. The scenario is driven by a worldwide consciousness of the importance of abating CO_2 emissions and by the fluctuations of oil price, thus forcing to have a strong position in terms of energy supply security. The technology development is assumed to grow rapidly while competitors are set aside by lack of governmental support for further R&D.

The optimistic-realistic scenario considers still a bold position only of Kyoto countries about the reduction of CO_2 emissions. Oil prices and availability is a concern while technology development is not as rapid as desired and competitors grow stronger.

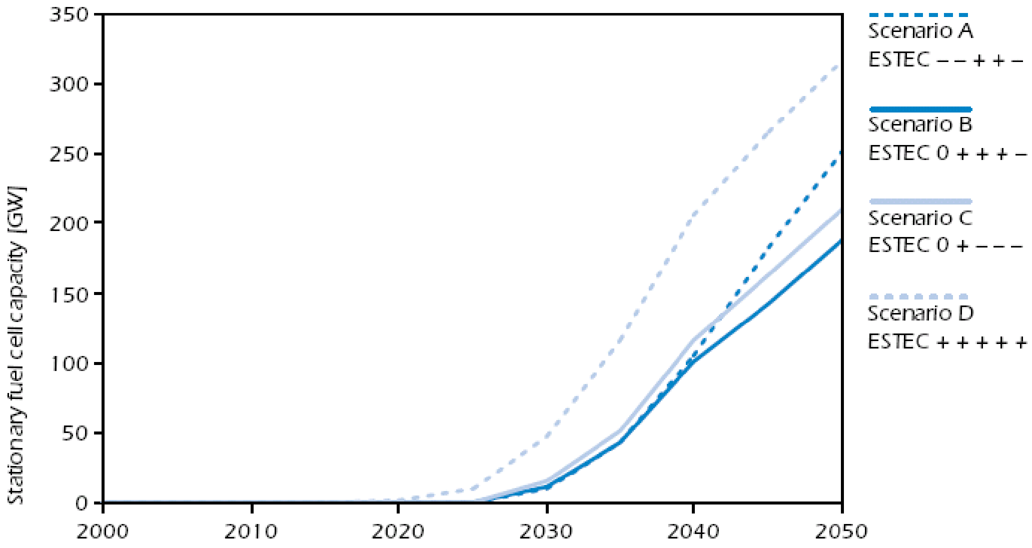


Figure 3.2 - Global stationary fuel cell use in the ESTEC scenarios [46]

Table 3.2 shows the figures used for the different time horizons:

Table 3.2 - Fuel cell capacity installed in 2005, 2025, and 2050 under the different technology development scenarios

Technology Development Scenario		**2005**	**2025**	**2050**
Very optimistic	GW	0.1	10	320
Optimistic realistic	GW		0.5	200
Pessimistic	GW		0.1	0.1

3.5 Technology development perspectives

3.5.1 PEMFC

New materials for the membrane are being investigated for use in high temperature PEMFC. Nafion has the disadvantage of being expensive and, at temperatures above 80 °C, it presents a loss of proton conductivity due to dehydration. This is particularly important because there is a distinct advantage to run PEMFC at higher temperatures: the poisoning effect of carbon monoxide (commonly present as an impurity in H_2) on the catalyst is reduced. Among the new materials a family of new high performance high temperature thermoplastics known as polyphthalazinones are now being produced commercially in China by Dalian New Polymer Material Co. and a series of novel polymers are being designed and fabricated: hydrophobic rigid thermoplastic polymer main chains for mechanical and chemical stability combined with more flexible sulfonated graft chains [44].

Concerning the catalyst, the present amount of about 1.4 g Pt/kW [46] could be reduced in high temperature fuel cells at an amount as low as 0.2 g Pt/kW. However, reducing the amount of platinum at the cathode with the current Pt/C catalyst system, results in cell voltage losses and in efficiency losses of 2-4% [21]. To increase the power density, and reduce the platinum load accordingly, improved efficiency of the mass transport, the diffusion media and the electrode structures are necessary. New electrode production technologies such as gas diffusion layer technology can also reduce the platinum needs, because a larger share of the Pt surface area is available for the electrochemical reaction, enhancing the catalyst activity by up to 50% [15]. New, more active Pt-alloys with cobalt and chromium appear capable of a three-fold activity increase in the mass activity [6].

Bipolar plates see carbon-polymer composites or coated-steel as the best materials candidates. Bipolar plates are currently made from milled graphite or gold-coated stainless steel. Ongoing R&D is aiming to replace these materials with polymers (plastics) or low-cost steel alloys [12][23][27]. The use of plastics would allow the use of low-cost injection-moulding production techniques.

Simplification of the system, particularly the balance of plant, e. g. better matching of BoP and cell conditions, adapting the media supply to the cell requirements (e. g. with respect to purity), etc. Several studies, besides, are aimed at optimising the self-humidified membrane solution: this improvement could greatly simplify the BoP. One of the proposed solutions is a membrane composed of two outer layers of plain Nafion and a middle layer of Pt/carbon nanotubes (Pt/CNTs) dispersed Nafion. The Pt/CNTs present in the membrane provides the sites for the catalytic recombination of H_2 and O_2 permeating through the membrane from the anode and cathode to produce water [38].

Cost reduction The current cost of the Nafion-type membranes can be up to US$ 800/m^2, which translates into US$ 250-300/kW [8]. Alternative materials such as organically modified silicates (ORMOSILs) which promise a factor 10-20 cost reduction [38] are not yet commercially ready. In the case of electrodes, their cost depends on the production technology used and the production volume. Automated production on a large-scale may lower the electrode cost from US$ 1,500-2,000/m^2 to US$ 150/m^2.

Porvair, a component producer, claims that its carbon/carbon bipolar plates can be produced for US$ 250/kW, if the production volume were 10,000 units per year, and that the cost might drop to US$ 25/kW for 1 million plates per year [23]. A Ni-Cr alloy cladded steel bipolar plate would cost US$ 80/m^2 [12]. Given a power density of 2-6 kW/m^2, this translates into US$ 13-40 /kW. Achieving higher power densities will be essential to r-+educing the cost of bipolar plates.

The use of plastics would allow the use of low-cost injection-moulding production techniques for the production of bipolar plates.

3.5.2 SOFC

Cost reduction. The costs for the 100 kW Siemens-Westinghouse demonstration plant which was put into operation in the Netherlands in 1998 were estimated to about 100,000 €/kW$_{el}$. Investment costs for a today's demonstration plant are estimated by Siemens to 10,000 to 25,000 $/kW. Costs for a first commercial market introduction shall be reduced to 6,000 $/kW. The costs for the stack are estimated to about 25 to 50 % of the total system costs, while the share of the gas turbine is about 35 %.

For planar concepts, prices for electrolyte-supported cells produced in batch wise series are in the range of 2,500 to 5,000 $/kW, whereas the prices of prototypes of anode-supported cells are in the order of 12,000 $/kW. It is obvious that an order of magnitude cost reduction is still required to achieve commercially acceptable prices for the cells. Hexis expects to reduce costs for the 1 kW$_{el}$ HXS Premiere system to 3,600 CHF until 2010s [34]. The Solid State Energy Conversion Alliance's ultimate cost goal for 5kW planar solid oxide module (mass produced at 100,000 units per year) is approximately US$400/kW. This target also represents about an order of magnitude cost reduction over current systems. Several developers have operated single cells for 40,000 hours and several small stacks (~2kW) have been operated for more than 1000 hours. Technology improvement with the aim to achieve 40,000 hours life time and $400/kW by 2010 represent significant challenges. [47]

Long term target costs has been estimated to 1000 US$/kW for CPH units and 500 US$/kW for small scale systems [28]. However, [34] find the long term target figures extremely optimistic. The SOFC will be able to operate at high temperatures which will eliminate the fuel reformer and give a competitive (cost) advantage. An alternative key issue for cost reduction of SOFC is to realize operation at lower temperatures, temperatures of 750-850 °C rather than 950-1000 °C. This would allow the deposition of very thin (5 to 10 micron) electrolyte layers because YSZ electrolyte conductivity drops dramatically with decreasing temperature. The benefits of low-temperature operation are the use of lower-cost stainless steel materials, for example for the cell separators, and probably largely improved stability towards thermal cycling

Moreover, the material cost of the tubular cells is high. The cost of the tubular cells produced by Siemens-Westinghouse could be reduced by half by developing new tubes with alternative material [34]. The manufacturing cost could be reduced considerable by replacing the present process of depositing the thin electrode and electrolyte layers (i.e. an electrochemical vapour deposition) with a plasma spraying process. For planar cells the material cost is already low, but could be reduced further if cheaper material is used [34]. No figures on estimated cost reductions are to be found in the literature [43].

Finally, considerable work has to be done and a considerable amount of money to be invested to reach a mass production of cells as a precondition for industrialisation. This is necessary for serious market entrance and for entering the learning curve described later. Concerning this it has also to be evaluated whether production by batch processing or by continuous manufacturing of the different cell layers represents the more promising way [25].

Efficiencies. The development target of the Hexis cells is to achieve an electrical efficiency > 30 %, so that we assume a 32 % net electrical efficiency and a 90 % overall efficiency as a long term development perspective.

According to information from Siemens, a stack lifetime of more than 80,000 hours seems to be achievable already now with the Siemens-Westinghouse tubular stack concept (as a conservative estimate, we assume a stack lifetime of 40,000 hours for current state-of-the-art).

Regarding the hybrid system it is expected that hybrid systems with a capacity of 1 MW can achieve an electrical capacity of 60 % using simple small gas turbines. At the 2 to 3 MW capacity level with larger, more sophisticated gas turbines analysis indicates that electrical efficiencies of 70 % or more are possible.

Research & development in general. Since 2005 fuel cells (and hydrogen for the energy economy) are main parts of the German 5th Energy Research Programme under the motto “Innovation and New Energy Technologies”. Concerning further development, priorities have been predetermined based on the general benefits of fuel cells:

- high electric efficiency thanks to the direct conversion of fuel,
- suitability for combined heat and power and thus high exploitation of the primary energy,
- potential zero-emission operation.

The fuel cell is considered to be a key technology of a sustainable energy supply. In spite of its broad application potential it has to prevail over fully developed and established technologies, such as batteries, combustion engines and conventional combined heat and power plants in all fields of application. Strategic considerations concerning a successful market implementation has to orientate towards 1,000 – 1,500 €/kW as cost objectives for stationary fuel cells. Substantial cost reductions are thus necessary and they cannot simply be achieved through mass production. Instead, considerable R&D efforts are needed. Top priorities are the *prolongation of the durability of fuel cells* and a *substantial reduction of system costs*. [41]

Degradation process and new materials. Along the integrated project Real-SOFC (which runs from 2004 to 2008 and involves the European fuel cell industry and a number research institutions) it is the aim to improve the control of durability in SOFC stacks by supplying a broad understanding of degradation processes and from this developing a range of new materials and protective measures for enhanced lifetime. There are essential properties of SOFC materials to be improved:

- development of new cathode and electrolyte materials to increase power density > 0.6 W/cm^2 cell area at 700 °C
- development of new cell and interconnect materials as well as protective coatings to enable an operation time of 10,000 hours, degradation of smaller than 0.5 % / 1,000 hours at operating temperatures of 800 °C, and thermal cycling up to 100 cycles
- improve the resistance of anodes against fuel gas impurities (working towards the aim of operation with biogeneous fuels, unprocessed natural gas and reformats)
- increase the sulphur tolerance > 10 ppm by developing new fuel stack and stack materials, including coatings
- low cost standard materials and processing to enable stack costs < 2,500 €/kW at 800 °C
- new and novel materials and processing routes
- quality assurance and standardisation as tools for cost reduction in industrial-scale manufacturing
- life cycle analysis as a comprehensive tool on environmental hazard analysis

3.5.3 MCFC

Future development of MCFC will combine developments on different levels:

Technological innovations from materials science and engineering, such as the search for alternative cathode materials and electrolytes [19]. As this research is still at a very early stage of materials screening, different materials cannot be modelled using LCA. However, generally, the production phase within the overall life-cycle of fuel cells has a relatively low contribution to total impacts [48]; nevertheless, some materials, such as Nickel, do show in the overall life-cycle results of the system.

Another example of such incremental innovation is a new mechanical layout of the cells, reducing the material demand and associated cost [27].

Simplification of the system, particularly the balance of plant, e. g. better matching of BoP and cell conditions, adapting the media supply to the cell requirements (e. g. with respect to purity), etc. In our LCA, this effect will be modelled by assuming a reduced specific amount of BoP materials required.

Coupling MCFC with downstream devices such as an unfired gas turbine or steam turbine systems which use the exhaust heat to enhance electrical efficiencies. FuelCell Energy investigates, for instance, using the Brayton cycle for that purpose, allowing the fuel cell operation at ambient pressure independent of the gas turbine cycle pressure ratio [19]. MTU estimates that efficiencies of up to 55 % can be achieved in such hybrid systems [9]. FuelCell Energy estimates that for larger systems (40 MW) in the very long-term, rated efficiencies of up to 70 % could be achieved. However, the total efficiency (electrical plus thermal efficiency) remains the same, so that the question arises whether this more complex system is worth the effort.

In principle, various other combinations could be possible, such as coupling high and low temperature fuel cells etc.

Switching fuels. Another line of future development, which depends on the realisation of a reliable natural gas-based product, includes the development of systems running on other fuels such as other liquid hydro carbons, bio fuels, bio/ sewage/digester gas. First systems running on methanol and biogas have been realised. Here, MCFC offer the advantage that a higher CO_2 content in the fuel, as is the case for biogas, does not necessarily lead to an energy penalty because the fuel cell requires CO_2.

Thus, MCFCs are possible future technologies promoting a switch to renewable fuels. In co-operation with WP 13, the use of synthesis gas from biomass in a MCFC is investigated.

Cost reduction. While increasing performance and life-time, significant cost reduction will be necessary to become competitive with fuel cells. The mid-term cost target of the MTU Hot Module (250 kW_{el}) is 1200 to 1500 €/kW_{el} [11]. This target, however, has not yet been met by the manufacturers. In contrast, current 250 kW HotModule systems cost about 9,000 €/kW_{el}. The goal is to decrease system costs by approx. 100 to 200 k€ per year. As quoted above, FuelCell Energy announced that for their 300 kW system DFC3000, that capital cost will be US$ 3,200 to 3,500/kW in near-future systems.

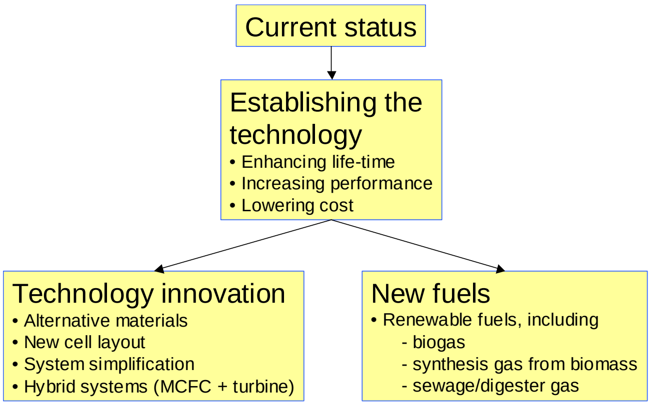


Figure 3.3 - Future development of MCFC

To further approach this goal, various measures have to be taken. For instance, in 2004, FuelCell Energy has reduced cost by 27 % through qualifying multiple vendors, negotiating discounts, materials substitution and others [35]. Series production, with its simplified production processes and economy of scale effects, will therefore significantly contribute to cost reduction. Substantial reduction potential lies also in a simplified system design, production processes with lower numbers of process steps, and design for manufacturability to decrease labour cost [13].

3.6 Development of costs

Several studies have been performed to analyse the future cost reduction trend of fuel cells.

In general, there is little information about fuel cells, and progress ratios for this technology is calculated or evaluated based on a very short history and on very few installed units. Thus, according to “Experience curves for energy technology policy” [45] progress ratios of 92% were considered reasonable range for the experience curve. In [37], authors discuss cost and prices of fuel cells; they apply a range of assumed progress ratios (75%-85%), but only if learning investments up to 50 GW really are made. The fuel-cell technologies are to be considered modular technology, which, compared to other types of experience curves indicate a progress ratio of 70-95% [42]. The technology will be either small (<5kW) or medium sized (200kW-5MW). Experience curves with a progress ratio of 70% and 95% have only been seen for a relatively modest number of technologies: more likely will be progress ratios of 75-90%. Experience curves with progress ratios ranging form 75% to 85% can be reasonable.

For our study, an average 80% of progress ratio is considered for all the three technology development scenarios [43]. In Figure 3.4 an actual development of specific costs for some types of fuel cells [34] is shown, while in Figure 3.5 leaning curves for power generation technologies up to 2030 are shown [16]. It is to be noted that for SOFC fuel cell systems the progress ratio is about 80% also according to this WETO study.

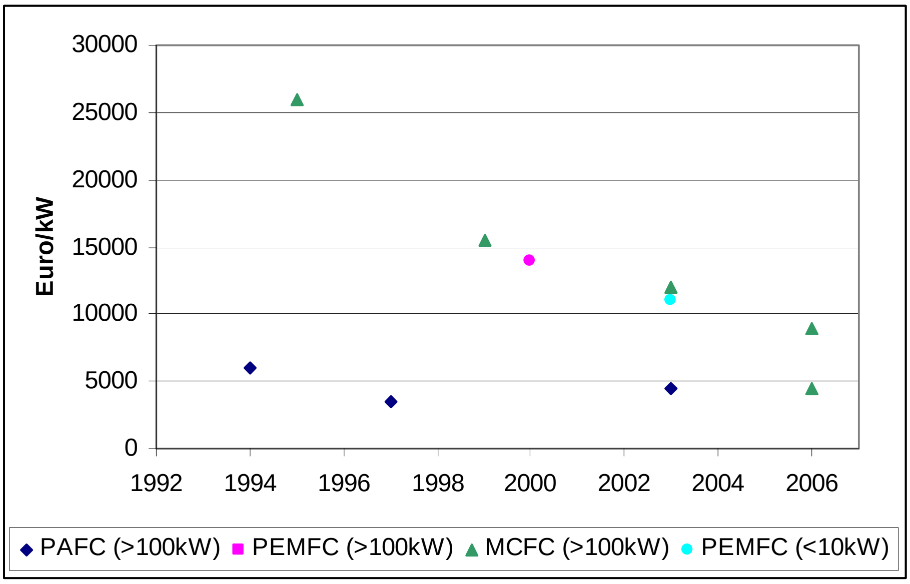


Figure 3.4 - Development of specific fuel cell production costs (excluding SOFC) [34].

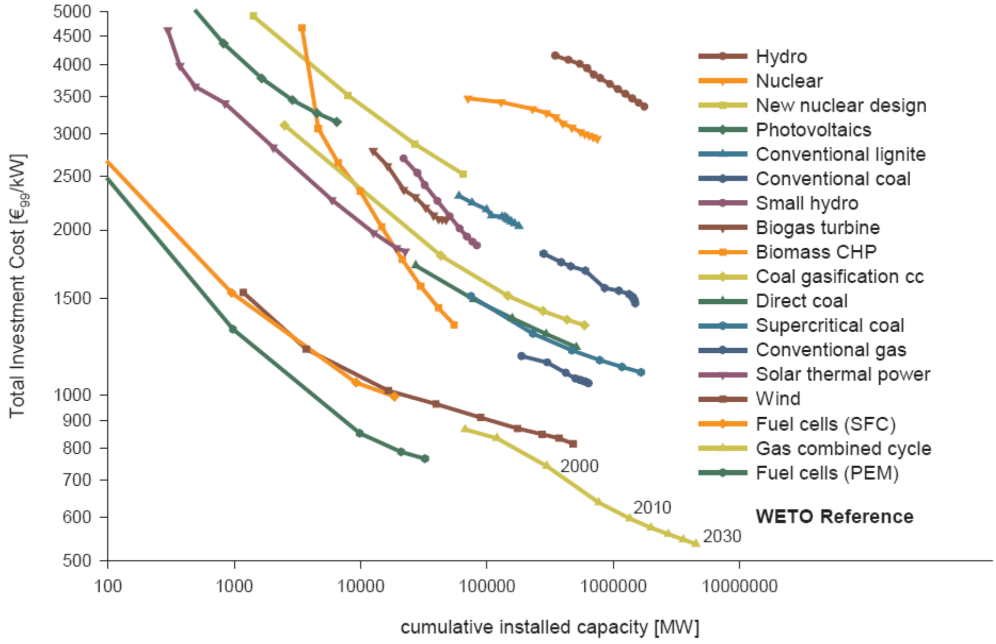


Figure 3.5 - Learning curves for power generation technologies up to 2030 (a point every 5 years) [16]

Key sources of cost reduction for fuel cells are:

- Material costs for stack production, i.e. production and supply of platinum group metals, graphite and membranes in the case of the PEMFC.
- The fuel stack lifetime is too short and results in a high cost. The fuel stack lifetime is approximately 20.000 hours with target around 30,000 to 40,000 hours [14]. According to Siemens-Westinghouse a stack lifetime of more than 80,000 hours seems to be achievable with the tubular stack concept. For the state-of- the-art 40,000 hours are estimated [28].
- The cost of the power electronics is too high and needs to be reduced.
- The overall integration of the separate pieces (the reformer, the fuel cell stack and the power electronics) needs to be optimised.
- The production cost is too high. Cost reduction will be required in both the production of single parts (automation) and in the assembling process. The production capacity can be increased by at least triple or quadruple in the near future [52]. This will make cost reductions possible.

Material availability may also be a restriction to cost reduction in the future. The large scale production of fuel cells may lead to constraints in material in the future: such materials may be platinum group metals used in PEMFC, lithium and nickel used in MCFC. However, recycling could be limiting cost increase in the future [32].

Table 3.3 - Generic learning curve for fuel cells used in the different technology development scenarios

Very optimistic				
		Current	**2025**	**2050**
Capacity	GW	0.10	10	300
Investment cost				
Progress ratio: f=0.8	€/kW	10,000	2,271	760
Progress ratio: f=0.7	€/kW		935	395
Progress ratio: f=0.9	€/kW		4,966	1,354
Optimistic realistic				
		Current	**2025**	**2050**
Capacity	GW	0.10	0.50	200
Investment cost				
Progress ratio: f=0.8	€/kW	10,000	5,956	866
Progress ratio: f=0.7	€/kW		4,368	273
Progress ratio: f=0.9	€/kW		7,830	2,396
Pessimistic				
		Current	**2025**	**2050**
Capacity	GW	0.10	0.10	0.10
Investment cost				
Progress ratio: f=0.8	€/kW	10,000	10,000	10,000
Progress ratio: f=0.7	€/kW		10,000	10,000
Progress ratio: f=0.9	€/kW		10,000	10,000

For the application of the learning rate we generate a generic learning curve for all fuel cell types. We start with initial values of 10,000 €/kW as an average value for both small and for CHP systems. The following table illustrates the cost development until 2050 depending on the installed capacity taken from the chosen scenarios and the learning rate of 20 % (progress ratio of f = 0.8). A sensitivity analysis for learning rates of 10 % (f = 0.9) and 30 % (f = 0.7) is shown in Table 3.3.

Concerning the SOFC CHP system we introduce floor costs of 1,000 €/kW for 2050 to meet the already very optimistic target costs reported in chapter 3.5.2. For the MCFC and PEMFC we also use target costs for 2050 as floor costs.

Regarding the wood gas fired MCFC and SOFC we add an extra charge of 10% to the investment cost to include the additional cost of the gas purification unit.

4 Specification of future technology configurations

4.1 Overview

Following the scenario choice explained in Paragraph 3.4 and taking into account the large uncertainties of future development and the limited benefit of an exaggerated number of systems to be assessed, the scheme in Table 4.1 is proposed for describing the future technological specifications of fuel cell technologies.

Table 4.1 – Technology development scenarios and technology development matrix

	2025	2050
Very optimistic scenario	FC development stage 1	FC development stage 2
Optimistic realistic scenario	FC development stage 1	FC development stage 1
Pessimistic scenario	No fuel cell development	No fuel cell development

To simplify, the technologies are assumed to have two-stages evolution.

In the pessimistic scenario (PE), it is assumed that no evolution nor affirmation of the fuel cell technology take place, while for the optimistic realistic (RO) scenario it is assumed that the first stage of the development will last for the entire time horizon of the study. Finally, in the very optimistic scenario (VO), the development of the technology will see both the stages, in temporal sequence.

Several technology solutions are considered according to the scenario envisaged: SOFC and MCFC foresee a hybrid solution in all future cases, except for the pessimistic case. Furthermore, their "large" versions see a possibility in the supply of wood gas to their systems. In Table 4.2, Table 4.5 and Table 4.8 is the summary of the technology options for all the scenarios.

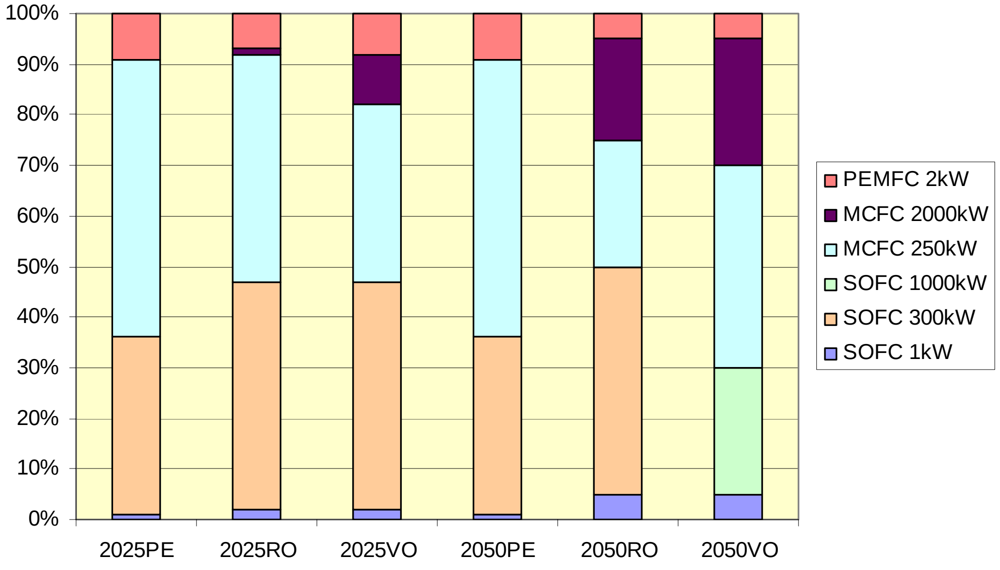


Figure 4.1 – Mix of fuel cell based technologies for electricity production according to the different scenarios

Figure 4.1 shows the assumed mix of fuel cell based technologies which are considered to produce the amount of electricity in the different scenarios. Figure 4.2, as a complement, shows the contribution of this mix to the entire electricity production mix in the next years.

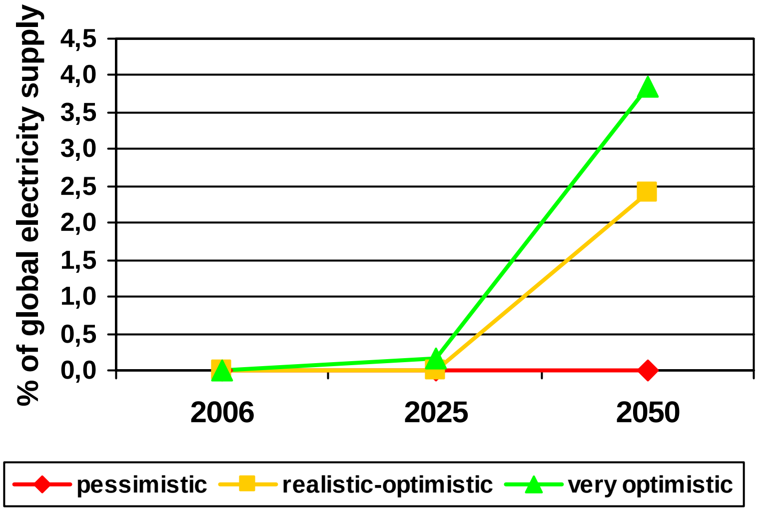


Figure 4.2 – Share of the global electricity supply produced with fuel cells in the three envisaged scenarios [32]

The following paragraphs provide a detailed description of the assumptions made.

4.2 PEMFC

Concerning the future size of the PEMFC power systems, in the last three years, the share of installed fuel cell systems among the different technologies is as shown above in Figure 2.5.

If one looks at the sizes of the installed units (Figure 4.3), it is evident that in these years the favourite size for each unit is 1 kW. This is due to the huge investment and residential research programme in Japan, where this size is suitable for most residential applications. In western regions, more powerful units are considered as appealing for the residential market (around 5 kW).

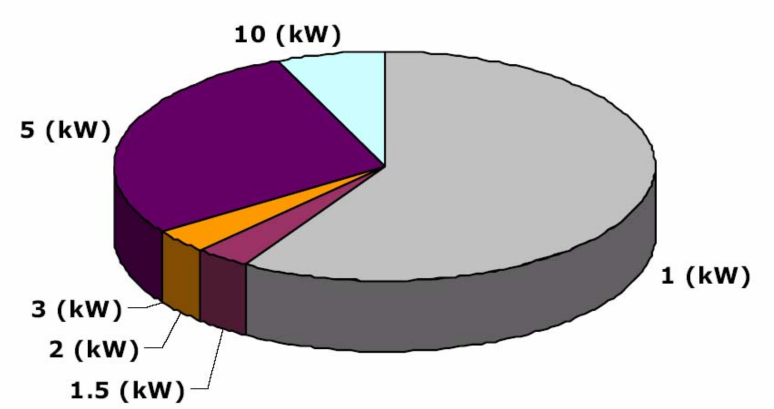


Figure 4.3 - Share of units, by size [4]

In a future (very or moderately optimistic) scenario, it is foreseeable that both sizes (1 and 5 kW) will be developed. Thus, it can be reasonable to assess a mid range fuel cell power system unit of 2 kW also for years 2025 and 2050, for which reliable data are available in the present system and which can be corrected with opportune factors for what concerns efficiency and lifetime. Table 4.2 shows the solution adopted.

Table 4.2 – PEMFC configurations

Period	Scenario	Configuration	
		Power output (kW_{el})	Supply
Today		2	NG
2025	PE	2	NG
	RO	2	NG
	VO	2	NG
2050	PE	2	NG
	RO	2	NG
	VO	2	NG

The assumed efficiencies for the future technologies are: $32\%_{el}$ and $58\%_{th}$ for the FC stage 1 development (scenarios 2025RO, 2025VO and 2050RO); $35\%_{el}$ and $60\%_{th}$ for the FC development stage 2 (scenario 2050VO). For the pessimistic scenarios all efficiencies are kept invariable.

Table 4.3 reports the technical data for all the configurations and scenarios for PEMFC.

Table 4.3 – PEMFC technical data for future technological configurations

		Scenario	Current	2025	2050
max. net el. power (busbar)	[kW]	PE	2	2	2
		RO		2	2
		VO		2	2
net el. power at el. peak load	[kW]	PE	2	2	2
		RO		2	2
		VO		2	2
net thermal power at thermal peak load	[kW]	PE	3.7	2	2
		RO		3.6	3.6
		VO		3.6	3.4
el. efficiency at el. peak load	[%]	PE	28	28	28
		RO		32	32
		VO		32	35
thermal efficiency at thermal peak load	[%]	PE	52	52	52
		RO		58	58
		VO		58	60
Technical life time stack	[a]	PE	6	6	6
		RO		8	8
		VO		8	8
Technical life time BoP	[a]	PE	15	15	15
		RO		16	16
		VO		16	16

In Table 4.4, the costs for the PEMFC technology specification in the current and future development scenarios are given. Costs were developed according to the learning rate theory detailed in paragraph 3.6.

No variable operation and maintenance costs are introduced in the description as they are assumed negligible.

Table 4.4 - PEMFC cost data for future technological configurations

	Scenario	Current	2025	2050
spec. investment costs [€/kW]	PE	4,000-10,000	4,000-10,000	4,000-10,000
	RO		5,956	800
	VO		2,271	700
fixed costs of operation [€/kW/yr]	PE	80-200	80-200	80-200
	RO		60-150	16-40
	VO		45-113	14-35

4.3 SOFC

For the future small SOFC system we maintain the 1 kW SOFC but increase the electrical efficiency to 30 %, the thermal efficiency to 55 % and therefore the overall efficiency to 85 % ("FC development stage 1"). In "FC development stage 2" (2050, very optimistic case) we further increase the efficiencies to 32 %, 58%, and 90 %, respectively.

In case of the CHP system we assume for the future the fully developed SOFC hybrid system including the SOFC coupled with a gas turbine. For "FC development stage 1" we provide a 300 kW system with an electrical efficiency of 58 %, a thermal efficiency of 22 % and therefore an overall efficiency of 80 %. In "FC development stage 2" (2050, very optimistic case) we further increase the efficiencies to 70 %, 20 %, and 90 %, respectively, and increase the power to 1,000 kW.

Table 4.5 – SOFC configurations

Period	Scenario	Configurations					
		Planar		Tubular		Tubular	
		Power output (kW_{el})	Supply	Power output (kW_{el})	Supply	Power output (kW_{el})	Supply
Today		1	NG	250	NG		
2025	PE	1	NG	300 Hybrid	NG		
	RO	1	NG	300 Hybrid	NG		
	VO	1	NG	300 Hybrid	NG	300 Hybrid	WG
2050	PE	1	NG	300 Hybrid	NG		
	RO	1	NG	300 Hybrid	NG		
	VO	1	NG	1,000 Hybrid	NG	1,000 Hybrid	WG

Table 4.6 – SOFC technical data for future technological configurations

		Scen.	Current		2025			2050		
			Planar NG	Tub. CHP NG	Planar NG	Tubular CHP NG	Tub. CHP WG	Planar NG	Tubular CHP NG	Tubular CHP WG
max. net el. power (busbar)	[kW]	PE	1	250	1	250		1	250	
		RO			1	300H		1	300	
		VO			1	300H	300H	1	1,000H	1,000H
net el. power at el. peak load	[kW]	PE	1	250	1	250		1	250	
		RO			1	300H		1	300	
		VO			1	300H	300H	1	1,000H	1,000H
net thermal power at th. peak load	[kW]	PE	1.9	268	1.9	268		1.9	268	
		RO			1.8	114		1.8	114	
		VO			1.8	114	114	1.8	286	333
electric efficiency at el. peak load	[%]	PE	27.1	47	27.1	47		27.1	47	
		RO			30	58		30	58	
		VO			30	58	58	32	70	66
thermal efficiency at th. peak load	[%]	PE	50.3	33	50.3	33		50.3	33	
		RO			55	22		55	22	
		VO			55	22	22	58	20	22
technical life time stack	[a]	PE	8	8	8	8		8	8	
		RO			8	8		8	8	
		VO			8	8	8	8	8	8
technical life time BoP	[a]	PE	20	20	20	20		20	20	
		RO			20	20		20	20	
		VO			20	20	20	20	20	20

H = Hybrid system (including a gas turbine subsequent to the fuel cell)
NG = Natural gas, WG = Wood gas, CHP = Combined heat and power plant

In the 2025VO scenario and in the 2050VO scenarios SOFCs introduce the possibility of supply of wood gas to the cell, while only in the 2050VO scenario the 300kW system is supposed to be substituted with the 2000kW (Table 4.5). In Table 4.6 the technical performances of the SOFC configurations are listed.

Table 4.7 – SOFC cost data for future technological configurations

Scenario		Current		2025			2050		
		Planar NG	Tub. CHP NG	Planar NG	Tub. CHP NG	Tub. CHP WG	Planar NG	Tub. CHP NG	Tub. CHP WG
spec. investment costs [€/kW]	PE	>10,000	10,000-25,000	>10,000	10,000-25,000		>10,000	10,000-25,000	
	RO			5,956	5,956		866	1,000	
	VO			2,271	2,271	2,498	760	1,000	1,100
fixed costs of operation [€/kW/yr]	PE	200-500	200-500	200-500	200-500		200-500	200-500	
	RO			120-300	120-300		17-43	17-43	
	VO			45-113	45-113	45-113	15-40	20-50	20-50

4.4 MCFC

As the MCFC offers only a modest temperature of the exhaust gas it is unlikely that power plant configurations with very large electrical capacities will be in the focus of fuel cell development. An exception might be coal-based MCFC systems, which, however, have been excluded in this study.

Rather, the more decentralized power region between 100 kW_{el} and several MW_{el} will be in the focus of mid- and long-term development. Therefore, for the LCA analysis of the future systems, two configurations will be investigated: a 250-300 kW_{el} device and a larger hybridised 2 MW_{el} system.

Table 4.8 – MCFC configurations

Period	Scenario	Configurations					
		Config. 1		Config. 2		Config. 3	
		Power output (kW_{el})	Supply	Power output (kW_{el})	Supply	Power output (kW_{el})	Supply
Current		250	NG				
2025	PE	250	NG				
	RO	250	NG	2000 Hybrid	NG	250	WG
	VO	250	NG	2000 Hybrid	NG	250	WG
2050	PE	250	NG				
	RO	250	NG	2000 Hybrid	NG	250	WG
	VO	250	NG	2000 Hybrid	NG	250	WG

Table 4.9 – MCFC technical data for future technological configurations

		Scenario	Current	2025			2050		
			Regular NG	Regular NG	Hybrid NG	Regular WG	Regular NG	Hybrid NG	Regular WG
max. net el. power (busbar)	[kW]	PE	250	250			250		
		RO		250	2000	250	250	2000	250
		VO		250	2000	250	250	2000	250
net el. power at el. peak load	[kW]	PE	250	250			250		
		RO		250	2000	250	250	2000	250
		VO		250	2000	250	250	2000	250
net thermal power at thermal peak load	[kW]	PE	212	212			212		
		RO		175	1272	182	175	1272	182
		VO		175	1272	182	168	1000	240
electric efficiency at el. peak load	[%]	PE	46	46			46		
		RO		50	55	48	50	55	48
		VO		50	55	48	52	60	50
thermal efficiency at th. peak load	[%]	PE	39	39			39		
		RO		35	35	35	35	35	35
		VO		35	35	35	35	30	33.6
technical life time stack	[a]	PE	8	8			8		
		RO		8	8	8	8	8	8
		VO		8	8	8	8	8	8
technical life time BoP	[a]	PE	16	16			16		
		RO		20	20	20	20	20	20
		VO		20	20	20	20	20	20

For data availability reasons, the LCA will be based on the HotModule design using primary manufacturer's data in combination with own extrapolations.

According to these configurations, Table 4.8 and Table 4.9 summarise the scenarios mix and the technological features of each solution.

In Table 4.10 costs data for all MCFC technological configurations are listed. Also in this case variable operation and maintenance costs are considered negligible. The investment costs and the fixed operation and maintenance costs are developed according the learning rate theory. Besides, an extra 10% was added to the investment cost of the MCFC supplied by wood gas.

Table 4.10 – MCFC cost data for future technological configurations

Scenario		Current	2025			2050		
		Regular NG	Regular NG	Hybrid NG	Regular WG	Regular NG	Hybrid NG	Regular WG
spec. investment costs [€/kW]	PE	9,000	9,000			9,000		
	RO		5,956	5,956	6,552	1,500	1,200	1,320
	VO		2,271	2,271	2,498	1,200	1,200	1,320
fixed costs of operation [€/kW/yr]	PE	180-450	180-450			180-450		
	RO		120-300	120-300	120-300	30-75	24-60	30-75
	VO		45-113	45-113	0	24-60	24-60	24-60

4.5 Lifetimes

Concerning lifetimes, the supposed full load hours for all technologies depend on the circumstances of operation. For the purpose of this calculation, they are consistently set at 5000/year. With this load, the lifetime per technology is specified in Table 4.11.

Table 4.11 – Lifetimes of selected technologies (in hours)

Current				
Tech. Type	PEMFC	SOFC planar	SOFC tubular	MCFC
Supply	NG	NG	NG	NG
Stack	30,000	40,000	40,000	40,000
BoP	75,000	100,000	100,000	80,000

NG = Natural gas

2025							
Tech. Type	PEMFC	SOFC planar hybrid	SOFC tubular hybrid	SOFC tubular	MCFC	MCFC hybrid	MCFC
Supply	NG	NG	NG	WG	NG	NG	WG
Stack	40,000	40,000	40,000	40,000	40,000	40,000	40,000
BoP	80,000	100,000	100,000	100,000	100,000	100,000	100,000

NG = Natural gas, WG = Wood gas

2050							
Tech. Type	PEMFC	SOFC planar hybrid	SOFC tubular hybrid	SOFC tubular hybrid	MCFC	MCFC hybrid	MCFC
Supply	NG	NG	NG	WG	NG	NG	WG
Stack	40,000	40,000	40,000	40,000	40,000	40,000	40,000
BoP	80,000	100,000	100,000	100,000	100,000	100,000	100,000

NG = Natural gas, WG = Wood gas

5 Life cycle inventory

The life cycle inventory analysis was performed per each technology and each scenario, taking into account the aggregation of scenarios as described in Table 4.1.

Several different steps of development are considered to intervene in the future configurations:

- increase in lifetime endurance of components (see Table 4.11)
- upscale of power output (for SOFC and MCFC, see Table 4.5 and Table 4.8)
- increase of efficiency (see Table 4.3, Table 4.6 and Table 4.9)
- material reduction.

5.1 Material reduction

Two different procedures were applied to evaluate the materials needed for the construction of each fuel cell in the future configurations.

PEMFC

For PEMFC it was chosen to use the "material learning curve" approach. This approach, developed for the solar thermal technologies described in NEEDS report 12.2 applies the cost reduction methodology based on leaning curves to the material reduction starting from some considerations: the reduction of cost is due to:

- technology innovation
- up-scaling
- volume production

Only a part of the cost reduction can be really ascribed to the mass reduction. We're now assuming that the mass reduction is due predominantly by technological innovation, and thus the full learning rate must be decreased accordingly and then applied to our masses. To apply proficiently this procedure the contribution (%) of each factor to the learning rate is needed, but up to now no analysis has led to the quantification of this contribution. So, for this analysis the contribution of technology innovation to the cost reduction for PEMFC is assumed to be 50%.

Now, applying the learning curve approach the following formula used:

$$M_{2025} = M_{2005} \cdot \left(\frac{CumulatedCapacity_{2025}}{CumulateCapacity_{2005}} \right)^{\frac{\log(\Pr ogressRatio)}{\log(2)}}$$

where:

M_{2025} is the mass of material in year 2025

M_{2005} is the mass of material in year 2005

CumulatedCapacity$_{2025}$ in the cumulated capacity installed in year 2025 (see Table 3.2)

CumulatedCapacity$_{2005}$ in the cumulated capacity installed in year 2005 (see Table 3.2)

Progress Ratio is then set to be equal to 90% (80% was the full progress ration according to Neji [43] to be applied to cost reduction. 10% is the learning rate due to technology innovation - 50% of 20%)

For the platinum load only, the assumption was not linked to this approach but to primary information on the reduction of material found in literature [56] and shown in Figure 5.1. The values are given for mobility applications but can be considered valid also for stationary applications as the technology is the same in both cases.

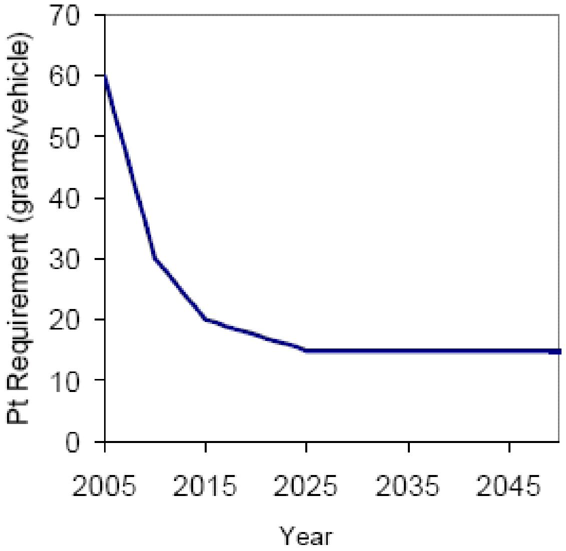


Figure 5.1 – Platinum load in Fuel cells for mobility applications [56]

5.1.1 SOFC and MCFC

For the application of the "material learning curve" approach it is necessary to know at least a rough estimation of how much the cost reduction described by the "conventional" learning curve is caused by technology innovation and therein by material reduction. Since this was not possible in case of SOFC and MCFC a different approach was chosen.

In the case of SOFC an overall reduction of materials was assumed, differentiated between BOP and stack. The same figures were used for the small and the big SOFC.

- For the reduction of BoP material consumption a decrease of 20% for development stage 1 and of 30% for development stage 2 was chosen. Only the heat exchanger, the inverter, and the gas turbine were assumed to be already matured which means no reduction rate was applied. The main impact emerges from the reduction of steel consumption since steel has the biggest share in the BOP materials.

  Additionally, the up-scaling from the 300 kW power plant in development stage 1 to 1,000 kW in development stage 2 was considered by an up scaling-factor of 0.7 for the BoP. In total this means a material reduction of 42.7%. Again, the highest (absolute) reduction emerges from the steel consumption.

- Considering the stack the material consumption was reduced by 10% for development stage 1 and by 20% for development stage 2.

For SOFC and MCFC a resizing of the Balance of Plant is foreseen as indicated in Table 5.1.

For the large 2 MW MCFC, no specific data for the Balance of plant data was available. In line with typical cost estimates for volume-determined products, it was assumed that the material need for the balance-of –plant scales with $(P/P_0)^{0,7}$, where P is the electrical capacity of the fuel cell (2000 kW) compared to the reference system. For the share of electrical capacity of the fuel cell, it was assumed that 85 % come from the fuel cell stack and 15 % from the steam turbine. For the steam turbine itself, data was available from a steam turbine manufacturer.

Table 5.1 – Reduction of components for SOFC and MCFC future configurations

				Scenarios	
	FC	Reference	Current Units	2025RO 2025VO 2050RO Units	2050VO Units
balance of plant (without heat exchanger, inverter, and gas turbine)	SOFC planar SOFC tubular	per FC system	1 1	0.8 0.8	0.7 0.7
stack	SOFC planar SOFC tubular	per FC system	1 1	0.9 0.9	0.8 0.8
electrode specific materials	MCFC NG, WG, hybrid	per stack		-10% of current	-20% of current
balance of plant	MCFC NG, hybrid*	per FC system		-20 % of current	- 30 % of current
balance of plant	MCFC WG	per FC system		-20 % of current NG plus add. material for wood gas processing	-30 % of current NG plus add. material for wood gas processing

* See text.

5.2 Allocation between electricity and heat

For the results of an LCA of cogeneration systems, the way that the co-product is considered turns out to be important. As cogeneration systems produce heat and electricity simultaneously, and the comparison to other, non-cogeneration systems often takes place based on the functional unit “1 kWh electricity” or “1 kWh heat”, both products need to be taken into account together.

Let EI_j be the environmental impact of the production of 1 $\mathrm{kWh_{el}}$ plus the equivalent amount of heat in a cogeneration device (e. g. if the system has an electrical efficiency of $\eta_{el} = 0.3$ and a thermal efficiency of $\eta_{th} = 0.5$, the functional unit would be 1 $\mathrm{kWh_{el}}$ plus 1.67 $\mathrm{kWh_{th}}$).

EI_j can be split up into a contribution which is directly caused by electricity production $EI_{j,\text{electricity direct}}$, a contribution which is directly caused by heat $EI_{j,\text{heat direct}}$ and a “base” contribution which can not be directly causally attributed to heat or electricity production $EI_{j,\text{base}}$ (see equation 2).

$$EI_j = EI_{j,\text{base}} + EI_{j,\text{electricity direct}} + EI_{j,\text{heat direct}} \qquad (2)$$

Typically, $EI_{j,\text{base}}$ dominates the total result. An example for $EI_{j,\text{electricity direct}}$ is the environmental impacts from the production of a generator, whereas the supply of a fuel or the emissions from its combustion cannot be directly attributed to the production of heat or electricity and are thus part of $EI_{j,\text{ base}}$.

The aim is to calculate the environmental impact of 1 kWh_{el} $EI_{j,\text{electricity}}$ without the co-product heat. There are several ways to deal with this problem. One is *allocation* of the environmental cost between the products with an appropriate key. The allocation factor $\gamma_{electricity}$ characterizes the share of $EI_{j,\text{base}}$ that should be accounted for in $EI_{j,\text{electricity}}$:

$$EI_{j,\text{electricity}} = \gamma_{electricity} \cdot EI_{j,\text{base}} + EI_{j,\text{ electricity direct}} \tag{3}$$

For the case of a cogeneration system, one allocation key could be the energy generated. Take the example of an electric efficiency of 40 % and a thermal efficiency of 40%. For each kWh electricity, one kWh heat is produced. The allocation key would thus be 0.5. That means that 50% of the, for instance, CO_2 emissions are related to the production of electricity and 50% to heat. However, this allocation key does not really characterize the value of the products. Instinctively, one kWh electricity seems more valuable than one kWh low-temperature heat. Therefore, often the *exergy* is used as the allocation basis [39]. Exergy describes the amount of useful energy that is contained within a product. The exergy content of electricity $\zeta_{electricity}$ is equivalent to its energy (i. e. $\zeta_{\text{electricity}}=1$), whereas the exergy of heat, in contrast, is given by the Carnot factor multiplied by the energy value (i. e. the exergy content of heat ζ_{heat} is

$$\zeta_{heat} = 1 - \frac{T_{ambient}}{\dfrac{T_{\text{supply}} - T_{\text{return}}}{\ln\left(\dfrac{T_{\text{supply}}}{T_{\text{return}}}\right)}}). \tag{4}$$

$\gamma_{electricity}$ would then be the quotient of electricity exergy and total exergy:

$$\gamma_{\text{electricity}} = \frac{\zeta_{electricity} \cdot \eta_{el}}{\zeta_{electricity} \cdot \eta_{el} + \zeta_{heat} \cdot \eta_{th}} \tag{5}$$

The second way to deal with co-products is to estimate the *avoided burden*. Thus,

$$EI_{j,\text{electricity}} = EI_{j,\text{base}} + EI_{j,\text{ electricity direct}} - EI_{j,\text{heat (substituted systems)}} \tag{6}$$

In the case of a cogeneration system example above, $\text{EI}_{j,\text{heat(substituted systems)}}$ would correspond to the environmental impacts from producing 1.6 kWh heat in a system that is likely to be substituted by micro cogeneration. This means that – if we want to compare cogeneration to other electrical power plants – we have to identify the heating systems that would actually be replaced by such systems. This depends on a number of factors, for instance the country, the type and age of the houses, the preferred fuels, and the like. It also depends on the perspective of the decision-maker: from the perspective of a politician who has to calculate CO_2 mitigation impacts of certain political measures, it is the individual, old heating system that might be superseded by a micro cogeneration system. Boiler manufacturers might think of micro cogeneration competing with other modern heating systems. A home owner who has to decide which heating system to install will have to consider, for instance, a micro cogeneration home energy system compared to a modern condensing boiler. For the results of an LCA of cogeneration systems, the way that the co-product is considered turns out to be important. As cogeneration systems produce heat and electricity simultaneously, and the comparison to other, non-cogeneration systems often takes place based on the functional unit “1 kWh electricity” or “1 kWh heat”, both products need to be taken into account together.

In the NEEDS project, it was decided to use allocation based on exergy throughout the project. As the exergy of heat is very low, this implies that small fuel cell systems with high amounts of heat generated turn out to be worse in the comparison of electricity compared to larger fuel cell systems (and better with respect to heat, which is not reported here).Table 5.2 shows the allocation factor adopted for each technology as a result of the allocation calculation in each scenario.

Table 5.2 – Allocation factors (%)

	Current		2025RO 2025VO 2050RO		2050VO	
	Electricity	Heat	Electricity	Heat	Electricity	Heat
SOFC planar	82	18	83	17	83	17
SOFC tubular NG	93	7	96	4		
SOFC tubular WG			95	5		
SOFC hybrid NG					97	3
SOFC hybrid WG					94	6
MCFC	87	13	89	11	90	10
MCFC WG			89	11	90	10
MCFC hybrid			90	10	92	8
PEMFC	82	18	83	17	84	16

5.3 Input tables

Table 5.3, Table 5.4 and Table 5.5 list the materials finally derived by the approach described above necessary for the construction phase of PEMFC and SOFC fuel cells. The values are scaled to 1 kW_{el} output. Materials for MCFC are confidential and cannot be published.

Table 5.3 – Input materials for PEMFC per kW_{el}

Component	Material	Unit/ kW_{el}	Current	2025RO 2025VO 2050RO	2050VO
stack	chromium steel 18/8, at plant	kg	0,1	0,03	0,01
	aluminium, primary, at plant	kg	0,06	0,02	0,01
	aluminium, secondary, from old scrap, at plant	kg	0,24	0,07	0,04
	platinum, at regional storage	kg	0,00075	0,00022	0,00011
	glass fibre, at plant	kg	0,1	0,03	0,01
	Carbon black, at plant	kg	0,0008	0,0002	0,0001
	graphite, at plant	kg	4,5	1,33	0,67
	polyvinylidenchloride, granulate, at plant	kg	1,1	0,33	0,16
	tetrafluoroethylene, at plant	kg	0,07	0,02	0,01
	electricity, low voltage, production UCTE, at grid	kWh	16,9	5,00	2,50
BoP	chromium steel 18/8, at plant	kg	1,1	0,33	0,16
	aluminium, primary, at plant	kg	0,15	0,04	0,02
	aluminium, secondary, from old scrap, at plant	kg	0,6	0,18	0,09
	cast iron, at plant	kg	0,8	0,24	0,12
	polypropylene, granulate, at plant	kg	0,25	0,07	0,04
	polyethylene, HDPE, granulate, at plant	kg	1,5	0,44	0,22
	steel, low-alloyed, at plant	kg	3,7	1,10	0,55
reformer	chromium steel 18/8, at plant	kg	22	6,51	3,26
	aluminium, primary, at plant	kg	0,16	0,05	0,02
	aluminium, secondary, from old scrap, at plant	kg	0,64	0,19	0,09
	platinum, at regional storage	kg	0,0006	0,0002	0,0001
	titanium dioxide, production mix, at plant	kg	0,07	0,02	0,01
	polystyrene, general purpose, GPPS, at plant	kg	0,3	0,09	0,04

	polyethylene, HDPE, granulate, at plant	kg	0,9	0,27	0,13
	steel, low-alloyed, at plant	kg	16	4,74	2,37
	Carbon black, at plant	kg	0,25	0,07	0,04

Table 5.4 – Input materials for SOFC planar per kW_{el}

Component	Material	Unit/ kW_{el}	Current	2025RO 2025VO 2050RO	2050VO
stack	nickel, 99.5%, at plant	kg	0,073	Reduction	Reduction
	diethylene glycol, at plant	kg	0,19	**10%**	**20%**
	chromium, at regional storage	kg	13,41		
	polyvinyl butyral, at plant	kg	0,21		
	ethanol, at plant	kg	0,75		
	dibutyl phthalate, at plant	kg	0,17		
	trichloroethylene, at plant	kg	1,57		
	SOFC planar specific materials, at fuel cell factory (see Table A in Annex)	kg	1		
	electricity, low voltage, at grid	kWh	9,678		
heat exchanger	reinforcing steel, at plant	kg	2	No reduction	No reduction
	chromium steel 18/8, at plant	kg	2		
	electricity, low voltage, at grid	kWh	1,306		
inverter	aluminium, production mix, at plant	kg	0,3	No reduction	No reduction
	polypropylene, granulate, at plant	kg	0,02		
	silica sand, at plant	kg	0,004		
	copper, at regional storage	kg	0,006		
	electricity, low voltage, at grid	kWh	1,203		
air and fuel supply	reinforcing steel, at plant	kg	30,5	Reduction	Reduction
	zinc for coating, at regional storage	kg	0,1	**20%**	**30%**
	electricity, low voltage, at grid	kWh	9,556		
reformer and burner	nickel, 99.5%, at plant	kg	0,5	Reduction	Reduction
	reinforcing steel, at plant	kg	55	**20%**	**30%**
	electricity, low voltage, at grid	kWh	19,139		

Table 5.5 - Input materials for SOFC tubular NG supplied per kW_{el}

Component	Material	Unit/ kW_{el}	Current	2025RO 2025VO 2050RO (NG&WG)	2050VO (NG&WG)
stack	nickel, 99.5%, at plant	kg	0,0001	Reduction	Reduction
	Water, unspecified natural origin	m3	0,00098	**10%**	**20%**
	diethylene glycol, at plant	kg	0,01		
	polyvinyl butyral, at plant	kg	0,03		
	ethanol, at plant	kg	0,19		
	dibutyl phthalate, at plant	kg	0,01		
	SOFC tubular specific materials, at fuel cell factory (see Table B in Annex)	kg	1		
	electricity, low voltage, at grid	kWh	76,275		
heat exchanger	reinforcing steel, at plant	kg	2	No reduction	No reduction
	chromium steel 18/8, at plant	kg	2		
	electricity, low voltage, at grid	kWh	1,305556		
inverter	aluminium, production mix, at plant	kg	0,3	No	No

				reduction	reduction
	polypropylene, granulate, at plant	kg	0,02		
	silica sand, at plant	kg	0,004		
	copper, at regional storage	kg	0,006		
	electricity, low voltage, at grid	kWh	1,202778		
desulphuriser	reinforcing steel, at plant	kg	0,005	Reduction **20%**	Reduction **30%**
	zinc for coating, at regional storage	kg	0,01		
	electricity, low voltage, at grid	kWh	0,002222		
pressure vessel	reinforcing steel, at plant	kg	50		
	aluminium oxide, at plant	kg	0,5		
	electricity, low voltage, at grid	kWh	15,694444		
air-fuel-supply	reinforcing steel, at plant	kg	5		
	aluminium oxide, at plant	kg	4,2		
	electricity, low voltage, at grid	kWh	2,566667		
reformer boards	nickel, 99.5%, at plant	kg	0,2		
	electricity, low voltage, at grid	kWh	0,808333		
air preheater	reinforcing steel, at plant	kg	2		
	electricity, low voltage, at grid	kWh	0,622222		
other	electricity, low voltage, at grid	kWh	44,444444	Reduction **10%**	Reduction **20%**
	gas turbine	unit		No reduction	No reduction

5.4 Energy systems scenarios description

The technological descriptions in terms of input materials have been coupled with electricity mixes which were centrally chosen do describe different energy systems scenarios pushed by the EU policy trend. The resulting matrix of cases analysed under the life cycle point of view is presented in

Table 5.6. The three energy systems scenario mixes (Table 5.7) chosen are:

- the BAU (Business As Usual) mix
- the 440 ppm (intended as maximum level of CO_2 emissions) mix
- the Ren (Renewable) mix where a strong increase is supposed for the share of electricity produced from renewable sources.

Table 5.6 Scenarios matrix: energy systems scenarios coupled with technology development scenarios

	Current	2025					2050				
Technology development scenario		PE	PE	RO	VO	VO	PE	PE	RO	VO	VO
Energy systems scenario		BAU	440 ppm	440 ppm	440 ppm	Ren	BAU	440 ppm	440 ppm	440 ppm	Ren

Table 5.7 – The selected electricity mixes

	BAU		440 ppm		Renewables	
	2025	2050	2025	2050	2025	2050
Coal	23,6%	26,6%	6.7%	5.8%	10.7%	2,9%
Lignite	9,2%	9,7%	3.2%	0.00%	1.0%	0,0%
Gas	19,5%	18,7%	40.6%	41.4%	35.2%	16,7%
Oil	0.6%	0,6%	0.7%	0.2%	0.5%	0,0%
Nuclear	24,4%	22,1%	21.6%	24.4%	0.0%	0,0%
Hydrogen	0,0%	0,0%	0.0%	0.1%	0.0%	0,0%
Hydro	15,3%	13,4%	17.0%	10.9%	16.3%	19,3%
Wind	3,7%	4,6%	4.7%	7.0%	22.5%	32,3%
Solar	0,2%	0,4%	0.2%	0.4%		
PV					3.1%	6,5%
Solar Thermal					1.0%	1,4%
Geothermal	0,2%	0,8%	1.3%	4.2%	1.1%	4,5%
Ocean Energy	0,0%	0,1%	0.1%	2.1%	0.3%	0,5%
Biomass solid / Waste	2,6%	2,9%	3.0%	2.3%	8.2%	15,8%
Biogas / DME	0,6%	0,8%	0.7%	1.0%		

5.5 Key emissions and land use

In the following tables and charts results of the life cycle analysis are presented in terms of grams of key emissions per kWh_{el} produced by the assessed technology.

The key emissions selected for the analysis are:

CO_2 CH_4 N_2O NO_x NMVOC PM10 PM2.5 SO_x

Also land use has been assessed.

The following tables show values of key emissions and land use for all the technologies in all the scenarios.

Table 5.8 - Key emissions and land use for PEMFC 2kW per kWh_{el}. Allocation of electricity and heat based on exergy

PEMFC				2025PE	2050PE	2025PE	2050PE	2025RO	2050RO	2025VO	2050VO	2025VO	2050VO
			Current	BAU	BAU	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	680	679	679	678	677	597	591	594	545	594	545
CH_4, fossil	air	mg	3101	3101	3101	3101	3100	2499	2086	2251	1778	2251	1778
N_2O	air	mg	1	1	1	1	1	1	1	1	1	1	1
NO_x	air	mg	270	265	265	264	266	222	202	210	180	210	180
NMVOC total	air	mg	371	371	371	371	371	322	311	316	285	316	284
PM10	air	mg	23	22	22	22	22	18	14	16	13	16	13
PM2.5	air	mg	11	11	11	11	11	9	7	7	6	7	6
SO_2	air	mg	330	319	319	319	319	267	226	242	207	242	207
Land use	res.	km2a	1482	1557	1557	1543	1531	1339	1244	1285	1149	1354	1275

Table 5.9 - Key emissions and land use for SOFC 1kW per kWh_{el}. Allocation of electricity and heat based on exergy

SOFC PLANAR				2025PE	2050PE	2025PE	2050PE	2025RO	2050RO	2025VO	2050VO	2025VO	2050VO
			Current	BAU	BAU	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	704	704	704	702	700	633	626	630	584	629	584
CH_4, fossil	air	mg	3311	3314	3314	3313	3310	2761	2319	2496	2008	2495	2007
N_2O	air	mg	2	2	2	2	2	1	1	1	1	1	1
NO_x	air	mg	289	283	283	282	283	245	226	234	203	234	204
NMVOC total	air	mg	383	385	385	385	385	345	335	339	310	339	309
PM10	air	mg	23	23	23	23	23	20	20	20	18	20	18
PM2.5	air	mg	11	11	11	11	11	10	9	9	8	9	8
SO_2	air	mg	289	274	274	273	273	244	237	240	218	240	218
Land use	res.	km2a	1581	1660	1660	1634	1613	1522	1471	1490	1350	1507	1627

Table 5.10 - Key emissions and land use for SOFC 250-300 kW per kWh_{el}. Allocation of electricity and heat based on exergy

SOFC TUBULAR				2025PE	2050PE	2025PE	2050PE	2025RO	2050RO	2025VO	2050VO	2025VO	2050VO
			Current	BAU	BAU	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	460	459	459	459	458	380	376	378	314	378	314
CH_4, fossil	air	mg	2102	2102	2102	2102	2102	1604	1342	1446	1034	1446	1034
N_2O	air	mg	1	1	1	1	1	1	1	1	1	1	1
NO_x	air	mg	188	185	185	185	186	154	145	147	115	147	116
NMVOC total	air	mg	253	254	254	255	254	211	205	207	169	207	169
PM10	air	mg	13	12	12	12	12	12	12	12	9	12	9
PM2.5	air	mg	6	6	6	6	6	6	6	5	4	5	4
SO_2	air	mg	181	178	178	178	177	152	150	150	122	150	122
Land use	res.	km2a	964	1000	1000	992	986	932	956	922	749	928	828

Table 5.11 - Key emissions and land use for SOFC 300kW wood gas supplied per kWh_{el}. Allocation of electricity and heat based on exergy

SOFC TUBULAR			2025VO	2050VO	2025VO	2050VO
WOOD GAS			440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	44	23	41	26
CH_4, fossil	air	mg	78	46	69	34
N_2O	air	mg	31	25	31	25
NO_x	air	mg	446	360	447	369
NMVOC total	air	mg	131	107	129	105
PM10	air	mg	40	32	40	32
PM2.5	air	mg	31	25	31	25
SO_2	air	mg	144	113	146	112
Land use	res.	km2a	253092	170476	253237	172711

Table 5.12 - Key emissions and land use for MCFC 250kW per kWh$_{el}$. Allocation of electricity and heat based on exergy

MCFC				2025PE	2050PE	2025PE	2050PE	2025RO	2050RO	2025VO	2050VO	2025VO	2050VO
			Current	BAU	BAU	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	443	417	417	416	415	413	408	411	395	410	395
CH_4, fossil	air	mg	2015	1897	1897	1897	1896	1725	1442	1555	1290	1554	1289
N_2O	air	mg	1	1	1	1	1	1	1	1	1	1	1
NO_x	air	mg	184	170	170	169	170	157	145	150	135	150	135
NMVOC total	air	mg	240	226	226	226	226	221	214	217	206	217	205
PM10	air	mg	23	22	22	22	22	19	18	18	17	18	17
PM2.5	air	mg	12	11	11	11	11	9	9	9	8	9	8
SO_2	air	mg	262	243	243	243	242	181	176	178	168	178	168
Land use	res.	km2a	1392	1434	1434	1418	1405	1299	1266	1295	1224	1305	1401

Table 5.13 - Key emissions and land use for MCFC 2000kW hybrid per kWh$_{el}$. Allocation of electricity and heat based on exergy

MCFC HYBRID			2025RO	2050RO	2025VO	2050VO	2025VO	2050VO
			440 ppm	440 ppm	440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	379	375	377	350	377	350
CH_4, fossil	air	mg	1582	1322	1426	1141	1425	1140
N_2O	air	mg	1	1	1	1	1	1
NO_x	air	mg	141	130	134	117	134	117
NMVOC total	air	mg	202	196	198	181	198	181
PM10	air	mg	13	13	13	12	13	12
PM2.5	air	mg	7	6	6	6	6	6
SO_2	air	mg	156	152	153	141	153	141
Land use	res.	km2a	1040	1016	1035	960	1042	1085

Table 5.14 - Key emissions and land use for MCFC 250kW wood gas supplied per kWh_{el}. Allocation of electricity and heat based on exergy

MCFC			2025RO	2050RO	2025VO	2050VO	2025VO	2050VO
WOOD GAS			440 ppm	440 ppm	440 ppm	440 ppm	Ren	Ren
CO_2, fossil	air	g	50	28	44	26	41	29
CH_4, fossil	air	mg	107	66	82	56	72	40
N_2O	air	mg	33	32	32	30	32	31
NO_x	air	mg	471	455	461	437	463	449
NMVOC total	air	mg	136	132	133	127	131	124
PM10	air	mg	49	48	48	45	48	46
PM2.5	air	mg	37	35	36	34	36	34
SO_2	air	mg	175	164	169	157	171	155
Land use	res.	km2a	268740	266884	267054	211257	267210	214102

5.6 Comparison of results

Figure 5.2 shows a comparison of performances of the different technologies in the current development scenario and Figure 5.3, for comparison and representing the first technology development stage, shows results of all impacts for the 2025RO 440 ppm scenario referred to a base case that is the PEMFC performance. It is clearly visible that small systems have a worse behaviour for all figures. This behaviour is maintained for all scenarios.

It has to be kept in mind, however, that the procedure of considering the co-product heat by way of exergy-based allocation, as outlined above, disadvantages small systems with respect to the functional unit electricity. In other words, if we were to compare the thermal output, which carries less burden due to the allocation factor, small fuel cells would show a better performance.

Between the two small fuel cells, the PEMFC shows a generally better behaviour compared to that of the small SOFC, except for the case of the SO_x emissions. The difference in SO_x figures is mainly due to the construction phase of PEMFC. Differences in CO_2 and generally in GHG is due to the small difference in electric efficiency.

The relative behaviour is maintained in trend also in the future configuration with absolute values for all emissions which decrease as expected and with relative differences that sharpen. The reduction of PM10 and PM2.5 in the 2025 scenario for PEMFC is consistent (>20%) while that of the small SOFC is limited to about -12%.

Regarding the large systems, in the current configuration the big SOFC (250kW) shows a worse behaviour compared to that of MCFC (250 kW) concerning CO_2, CH_4, N_2O, NO_x and NMVOC. Conversely, in the future development stage (2025VO), the big SOFC (300 kW SOFC CHP) continuously shows smaller emission values than the big MCFC (250 kW CHP). That is because of the allocation method adopted: in the current configuration, the electric efficiency of SOFC is slightly higher than that of MCFC (47% vs. 46%), and the allocation factor works against SOFC (93 vs. 87). This means that a great amount of the emissions caused by the SOFC is attributed to the electricity produced. In the future configuration, the electric efficiency of SOFC is consistently higher than that of MCFC (58% vs. 50%), while the allocation factor difference, which remains high (96 vs. 89), doesn’t compensate and this leads to the worse behaviour of MCFC.

In case of the MCFC *hybrid* version (2000kW) with the even higher electrical efficiency of 55% for some emissions the MCFC shows lower values than the big SOFC (and even lower values than the MCFC without hybrid operation).

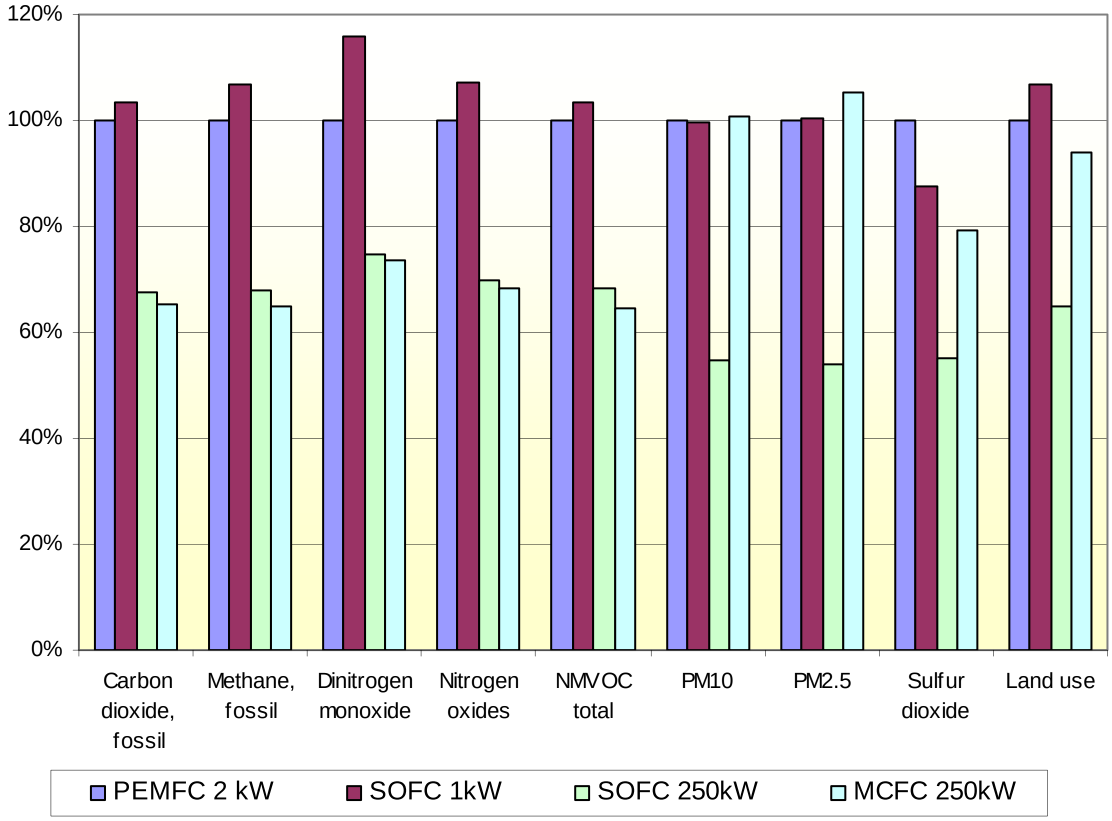


Figure 5.2 - All impacts shown for the current technology development scenario

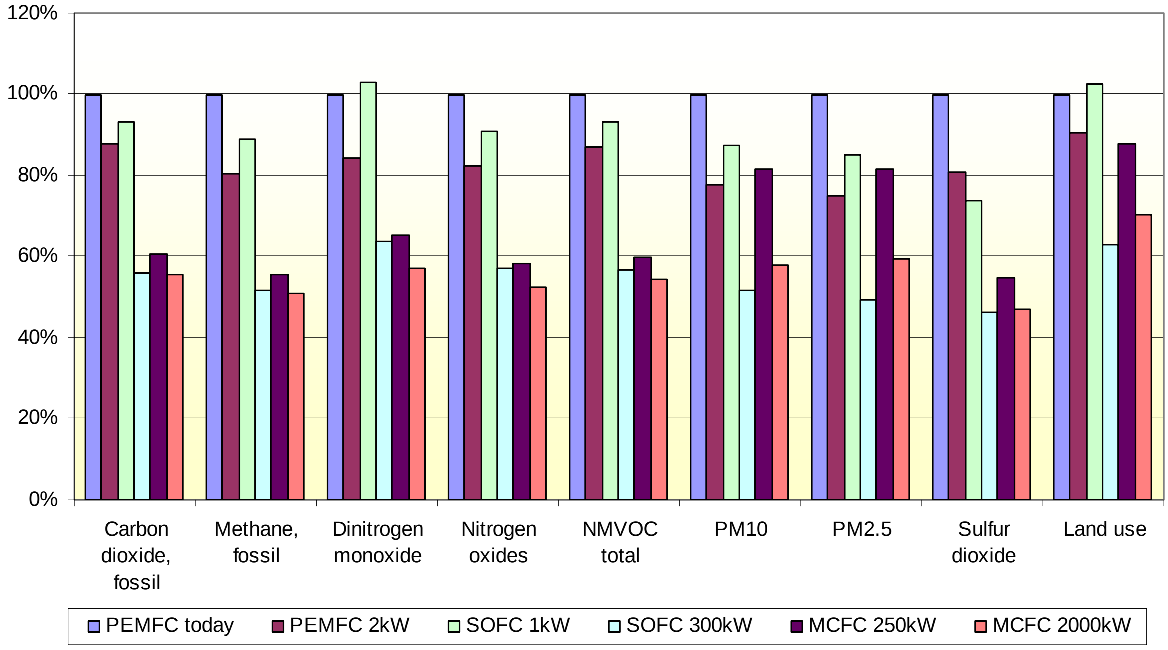


Figure 5.3 – All impacts shown for the 2025RO scenario. MCFC 250kW WG (not shown) presents a value of land use which is in the order of magnitude of 20000% with respect to the reference case (PEMFC today) due to the upstream process of wood.

The next figures show, scenario by scenario, the performances of the systems with a focus on CO_2, SO_x and GHG performances resulting in the following interpretation.

Variations of emissions within one development stage

As described above the fuel cells are considered to have only three development stages

- No development (during the scenarios TODAY, 2025PE and 2050PE)
- Development stage 1 (during the three scenarios 2025RO, 2025VO, and 2050RO)
- Development stage 2 (only scenario 2050VO)

Although the fuel cells' specification does not change within one development stage, their performances are slightly different from scenario to scenario due to the different underlying energy systems scenarios (different energy mixes) and to the different performances of the background processes according to the various scenarios.

Development from current systems to 2050 systems in total

Figures 5.9 to 5.11 give a view on the development until 2050 in total. Basically the following features are shown:

- quite the same performances between current, 2025PE, and 2050PE scenarios (as per definition)
- a decrease by 10 to 20 percentage points if applying the development stage 1. Whereas in case of emissions of CO_2 and greenhouse gases in total a maximum of 10% reduction appears, other emissions (SO_x, for example) result in a higher reduction.
- a decrease by 5 to 10 percentage points if moving to development stage 2
- considering the wood gas fired CHP plants (MCFC 250kW in RO and VO scenarios, SOFC 300kW in VO scenarios) results in quite low emissions of fossil CO_2 and GHG (mainly caused by the wood gas production process). Regarding the other emissions only a small reduction is visible for SO_x, while for PM10, PM2.5 and NO_x the contribution of the upstream process of wood gas is very evident.

Influence of the different energy systems scenarios

As explained in paragraph 5.3 different electricity systems scenarios were applied to the development scenarios. The results show only slight differences between the scenario cases (for example, between the "very optimistic 400 ppm" and the "very optimistic renewables" scenarios). This shows that the most important material up-stream processes do not depend heavily on the underlying electricity mix. In addition, the results are dominated by the operation (in the case of natural gas and CO_2/GHG) and fuel supply (see below). Here, electricity consumption is marginal.

Contribution analysis

The figures given below also show the shares between the four main life cycle phases as there are the construction, operation, fuel, and dismantling phase. The main results are:

- The fuel phase (natural gas supply) dominates all emissions (except for CO_2 and GHG in total) with contributions from 50% to more 90%. The rest is mainly caused by the construction phase.
- Only the CO_2 and the GHG emissions are dominated by the operation phase with about 80% of the total amount. The rest is mainly caused by the fuel phase whereas the construction phase is negligible.
- In the case of SO_x emissions, the construction phase is of significance. This is so because on the one hand, as the fuel cells do not emit any SO_x emissions during operation and as the natural gas supply does not cause high amounts of SO_x, the relative

share of construction is rather high. Additionally, some materials employed in a fuel cell (e. g. Nickel and other metals) lead to SO_x emissions because they are produced from sulfidic ores; here, SO_x is emitted along the production chain of these materials.

- In the case of $NO_{x,}$ also the operation phase gives a non-negligible contribution.

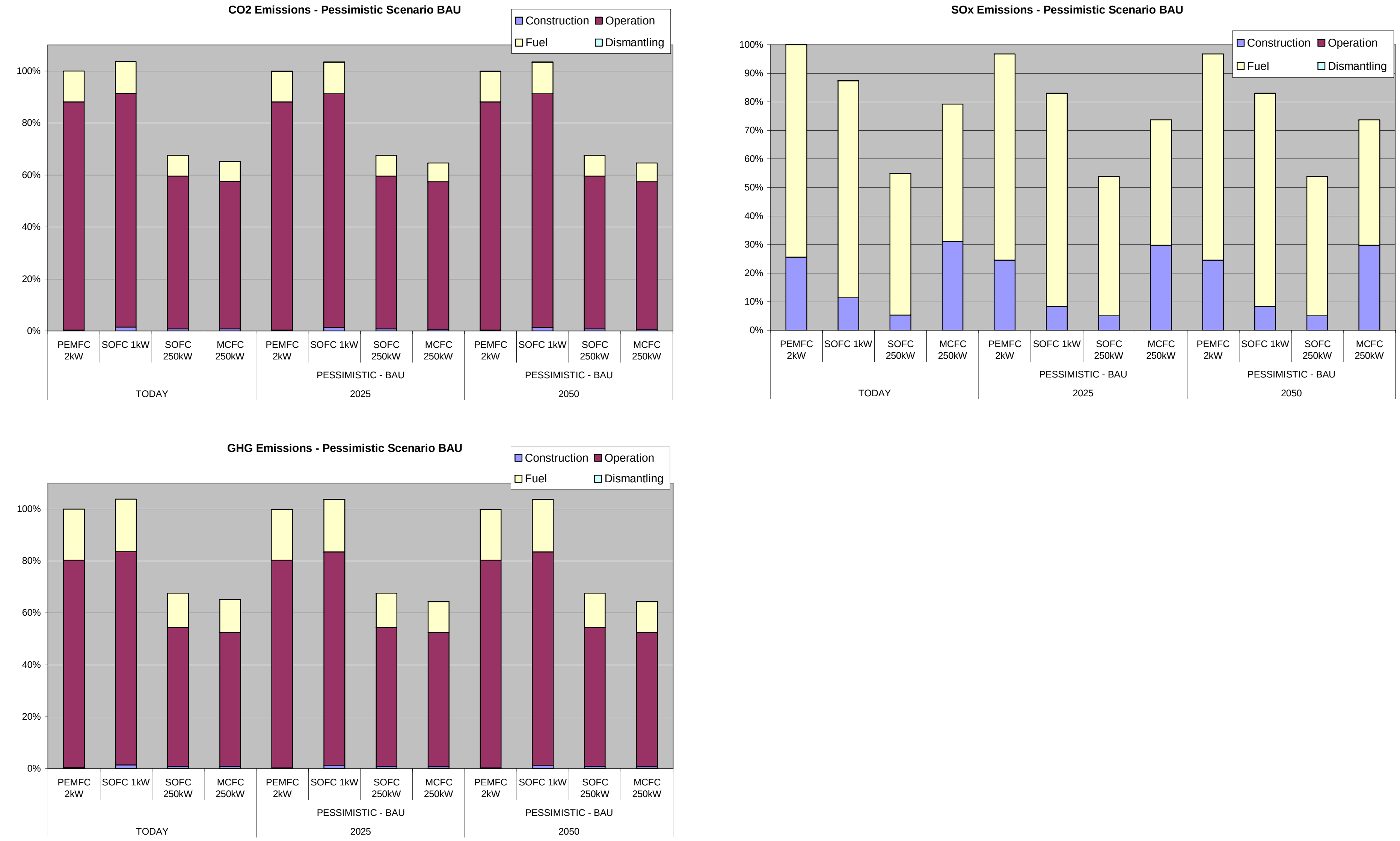


Figure 5.4 – Pessimistic scenario BAU development from present to 2050 (emissions of CO_2, GHG and SO_x)

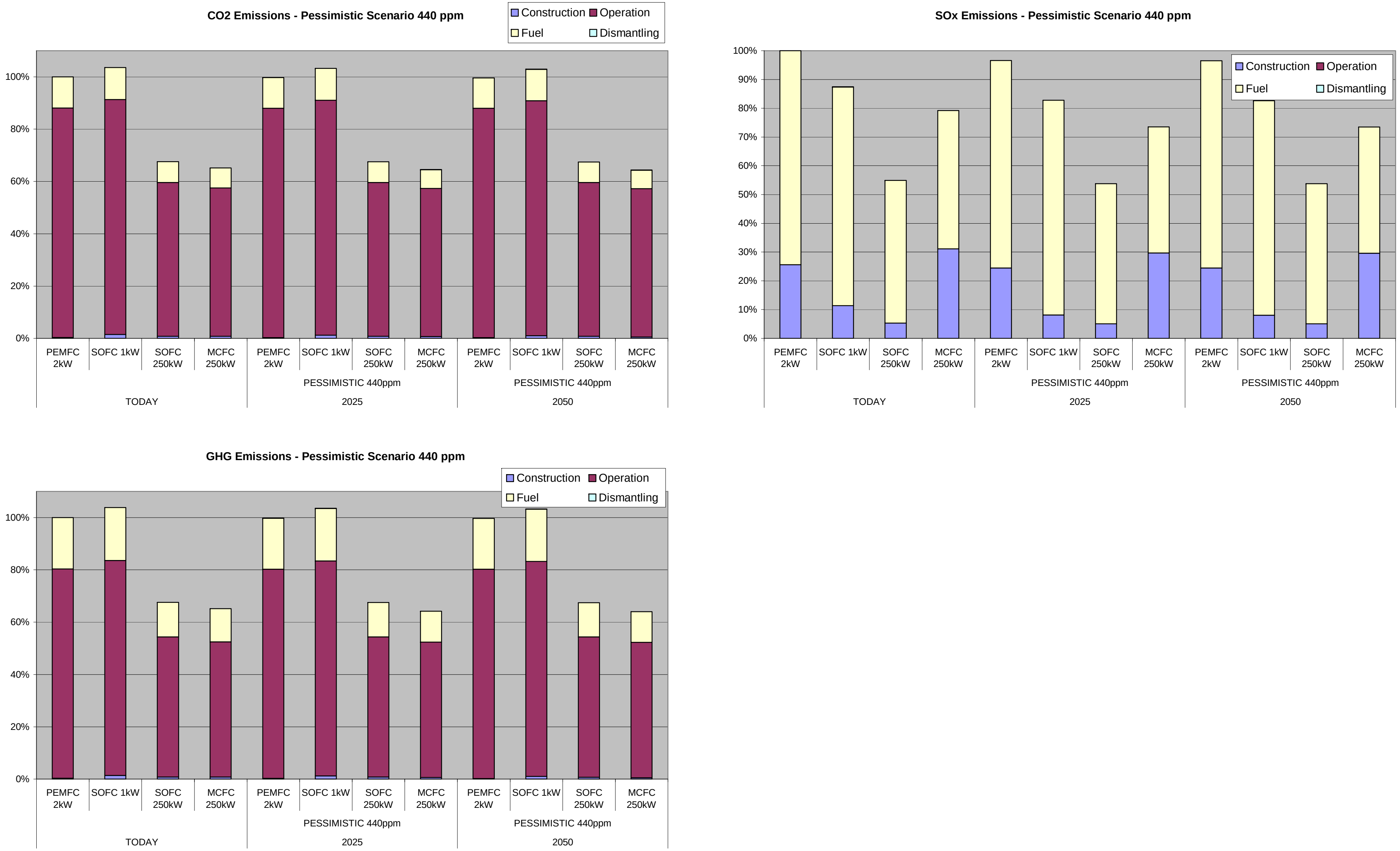


Figure 5.5 – Pessimistic scenario 440 ppm development from present to 2050 (emissions of CO_2, GHG and SO_x)

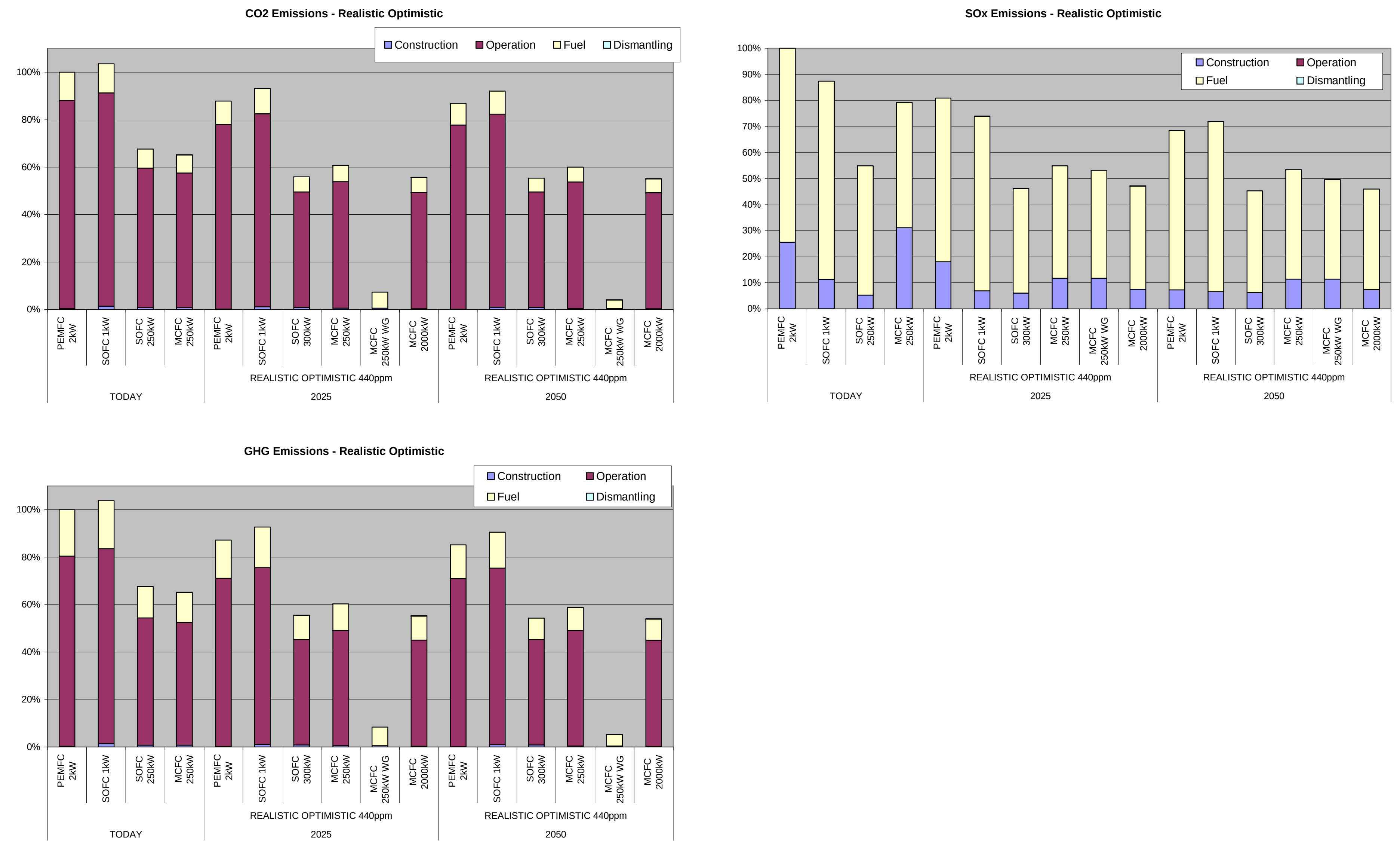
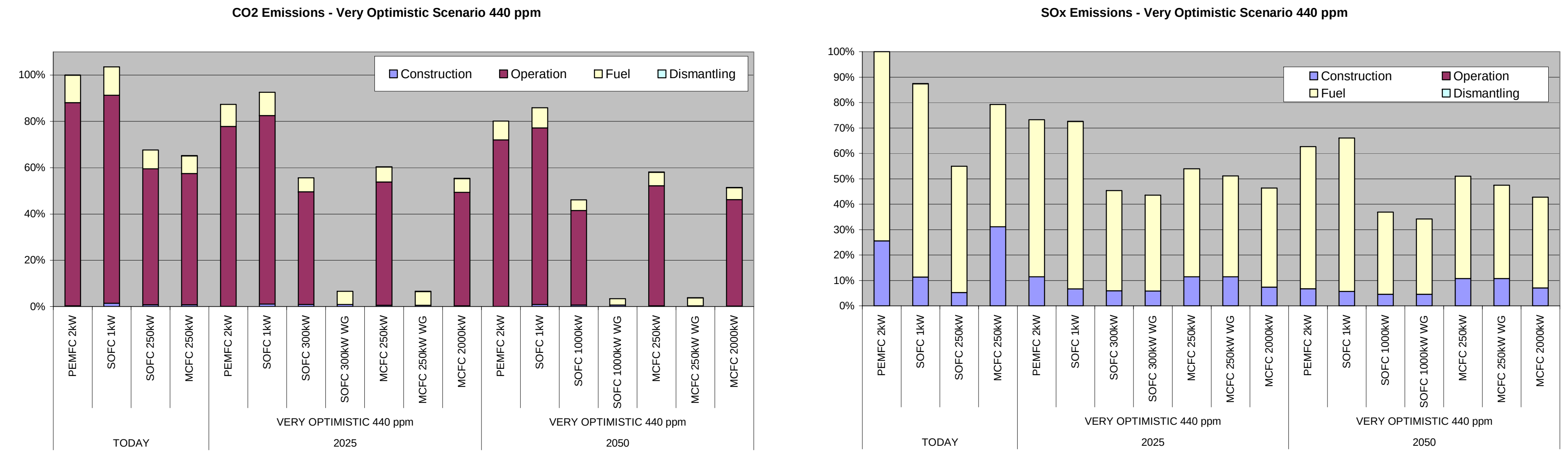


Figure 5.6 – Optimistic realistic scenario development from present to 2050 (emissions of CO_2, GHG and SO_x)



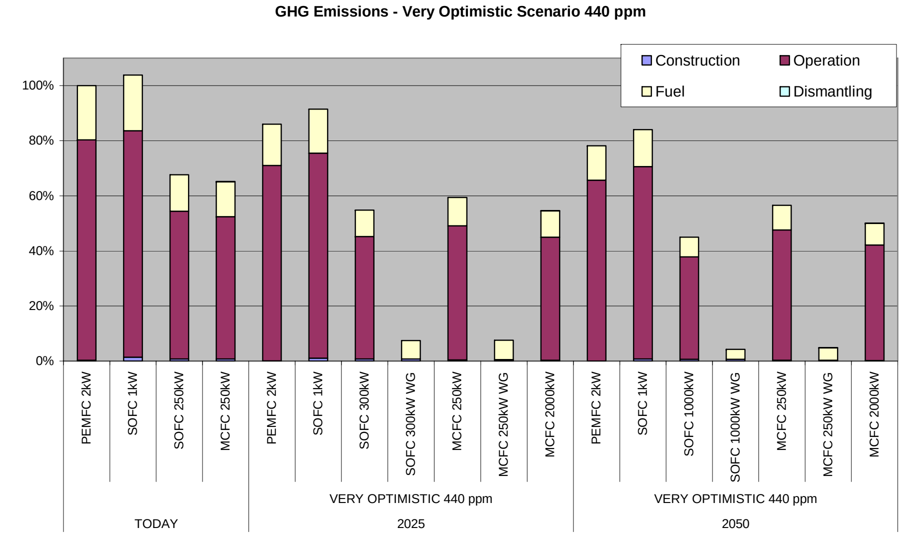


Figure 5.7 – Very optimistic scenario 440 ppm development from present to 2050 (emissions of CO_2, GHG and SO_x)

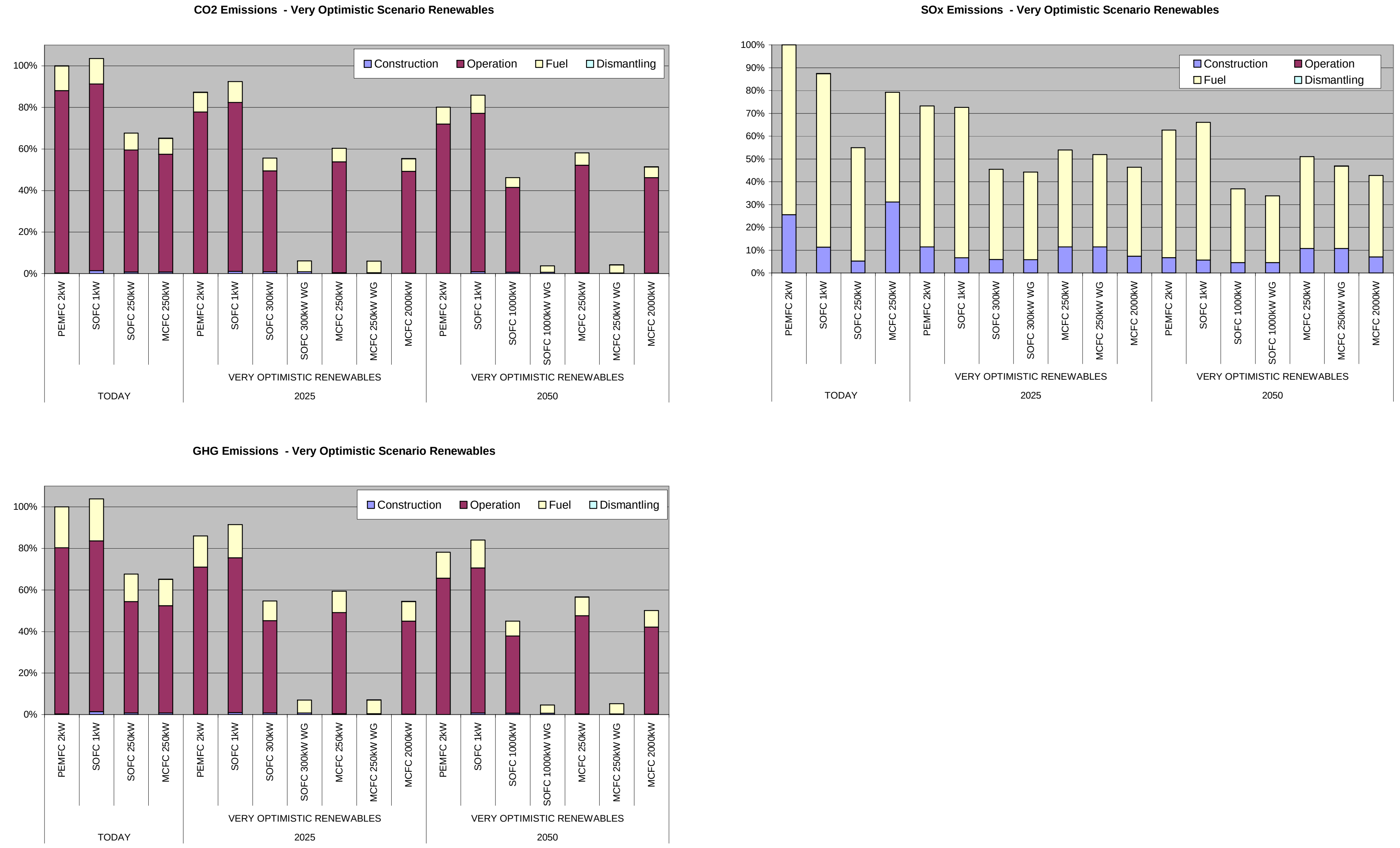


Figure 5.8 – Very optimistic scenario renewables development from present to 2050 (emissions of CO_2, GHG and SO_x)

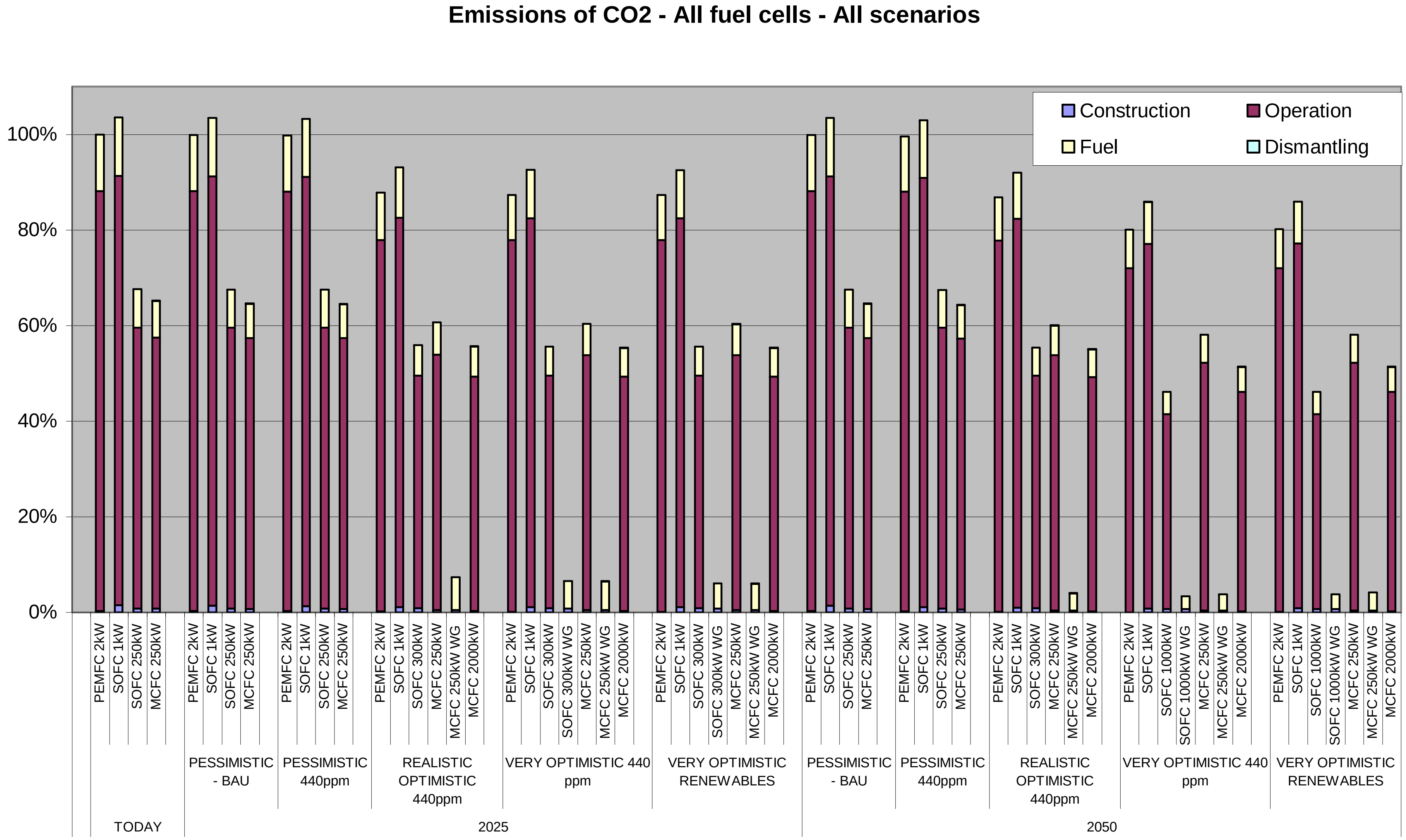


Figure 5.9 – CO_2 emissions for all scenarios and technologies

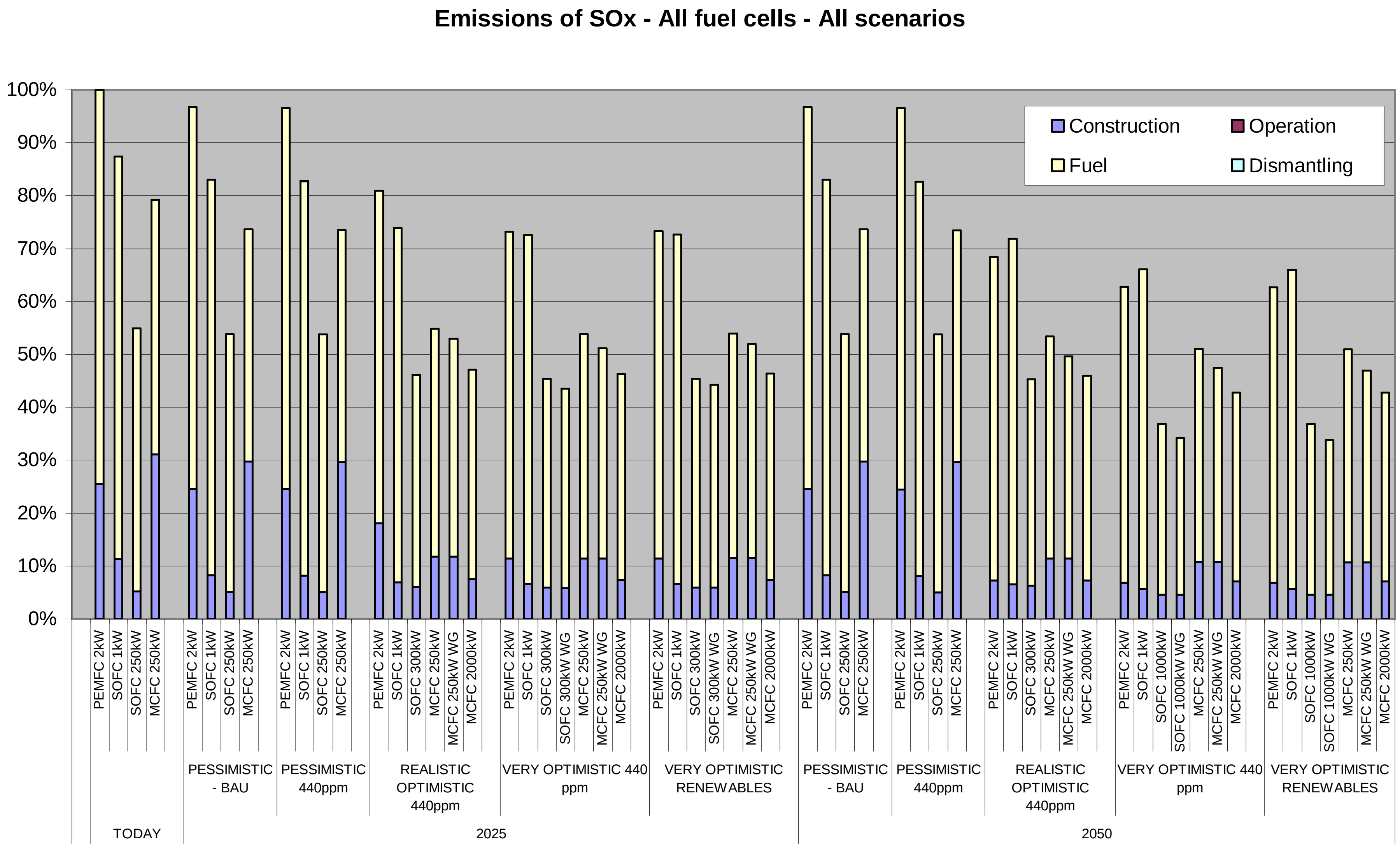


Figure 5.10 – SO_x emissions for all scenarios and technologies

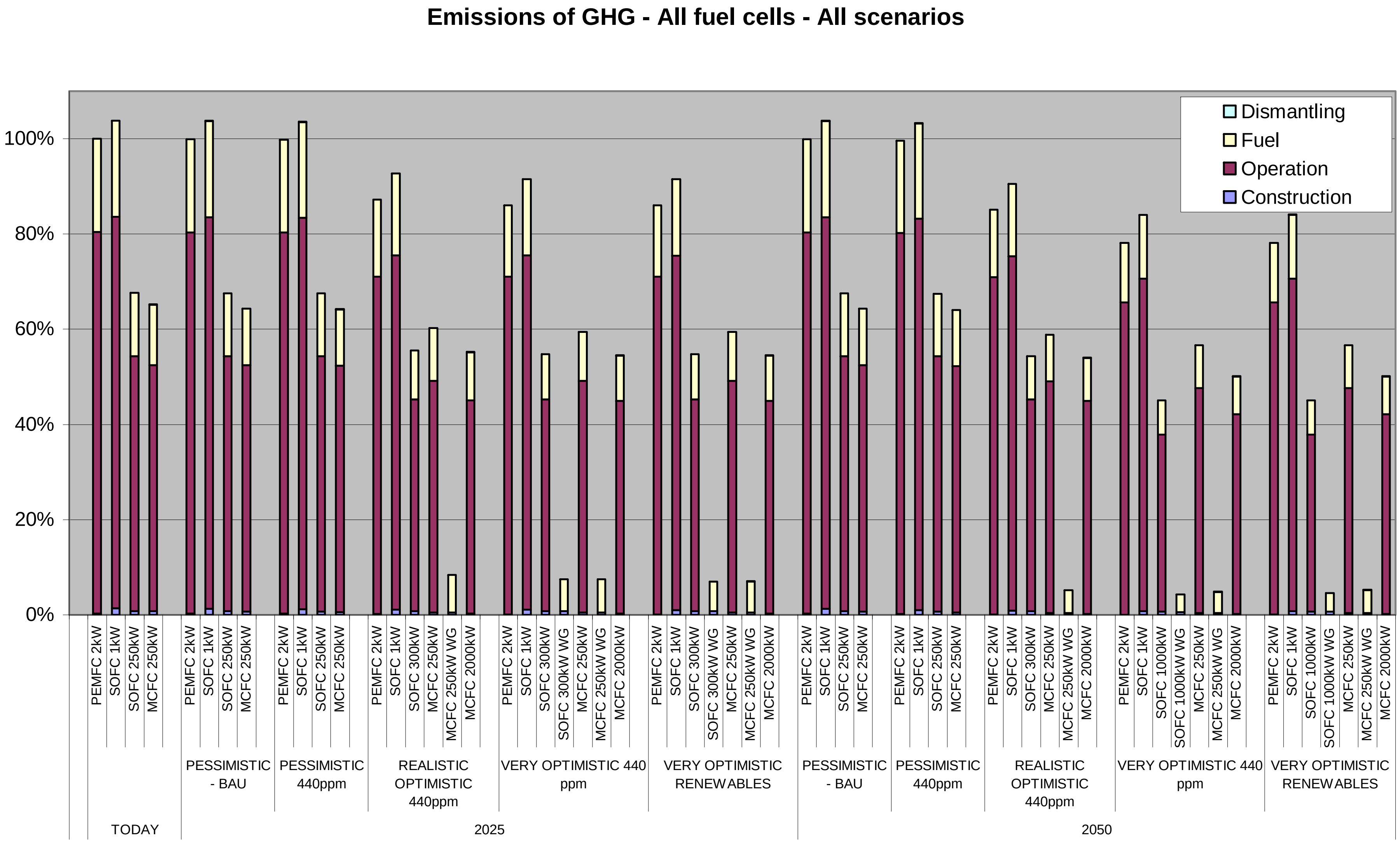


Figure 5.11 – GHG emissions for all scenarios and technologies

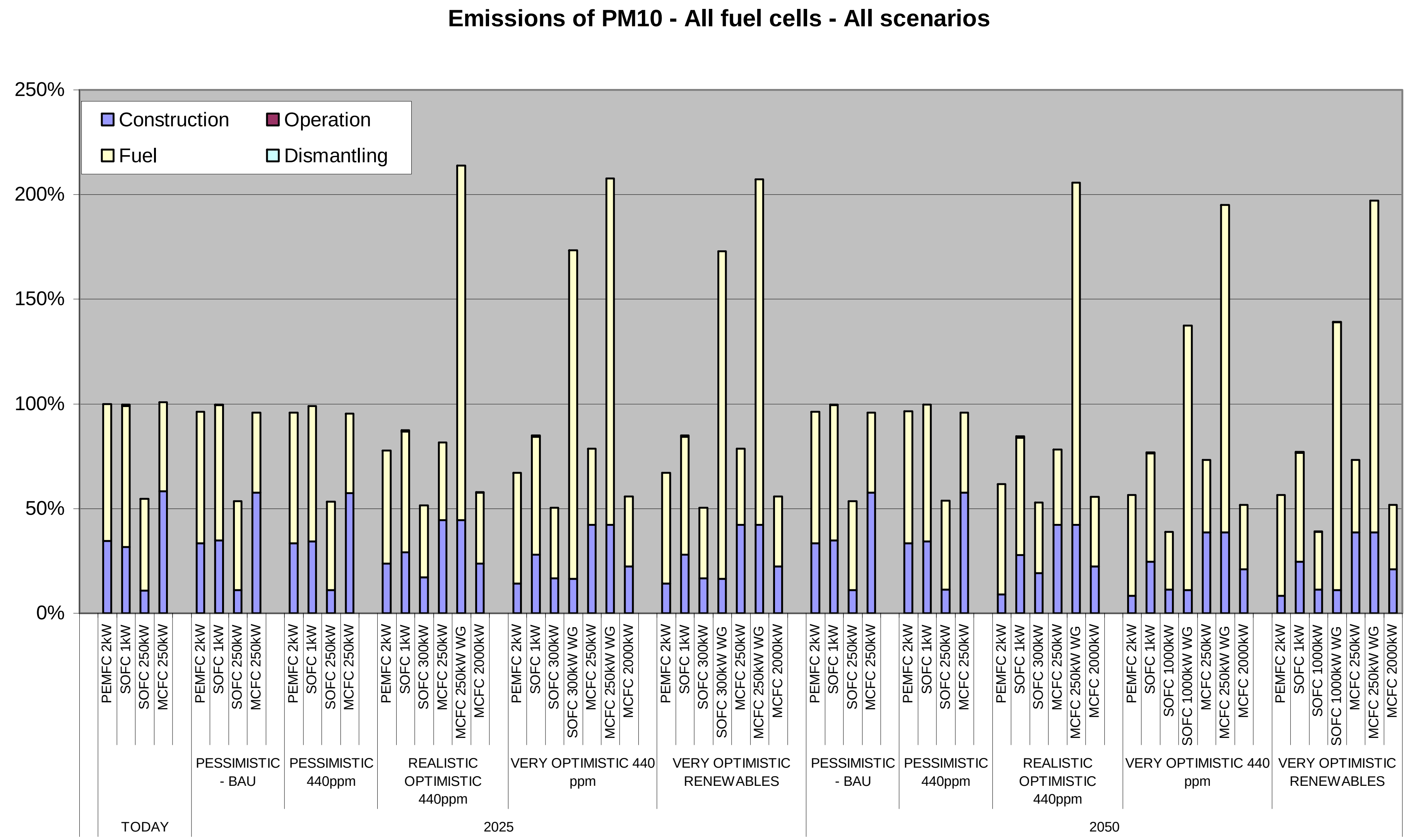


Figure 5.12 – PM10 emissions for all scenarios and technologies

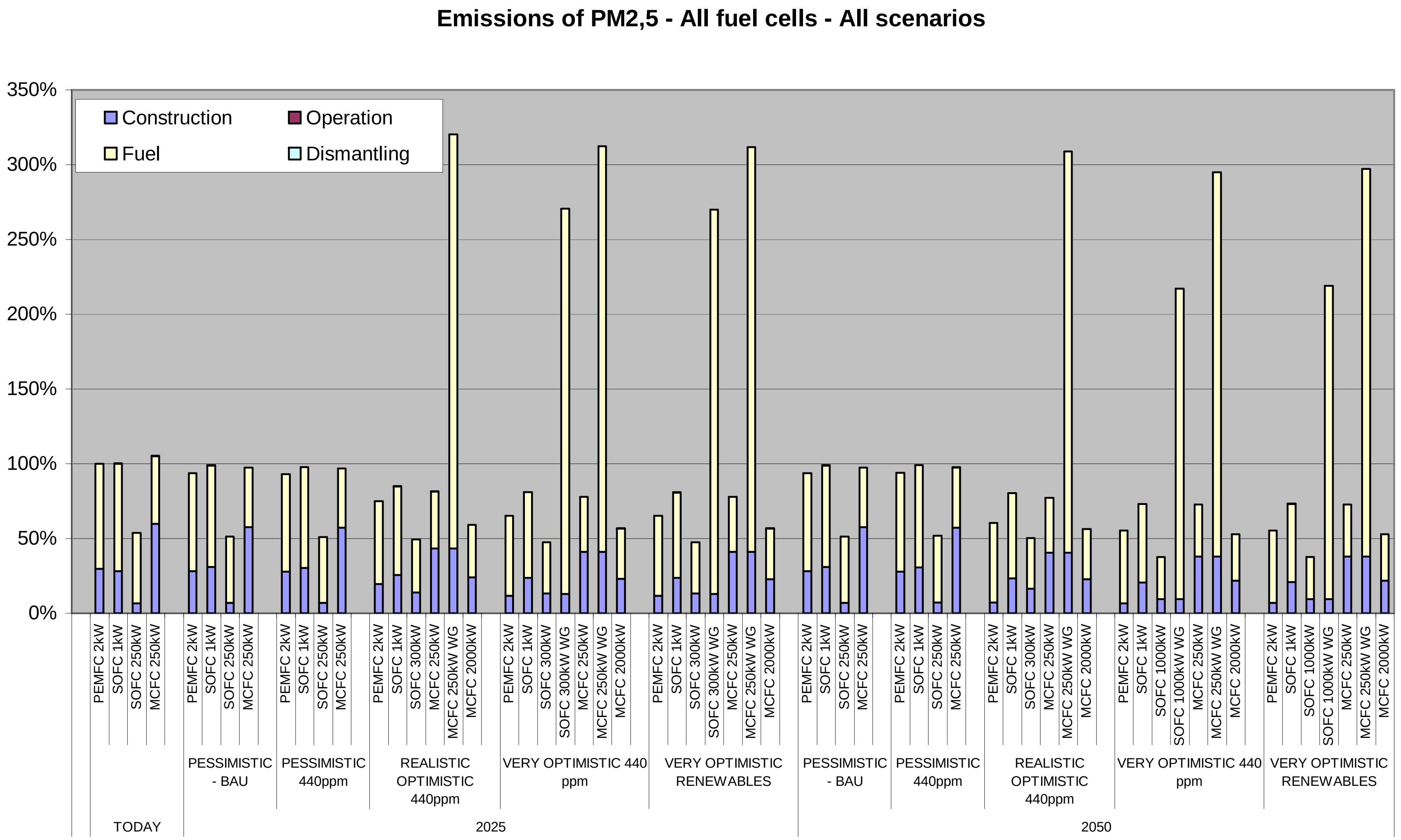


Figure 5.13 – PM2.5 emissions for all scenarios and technologies

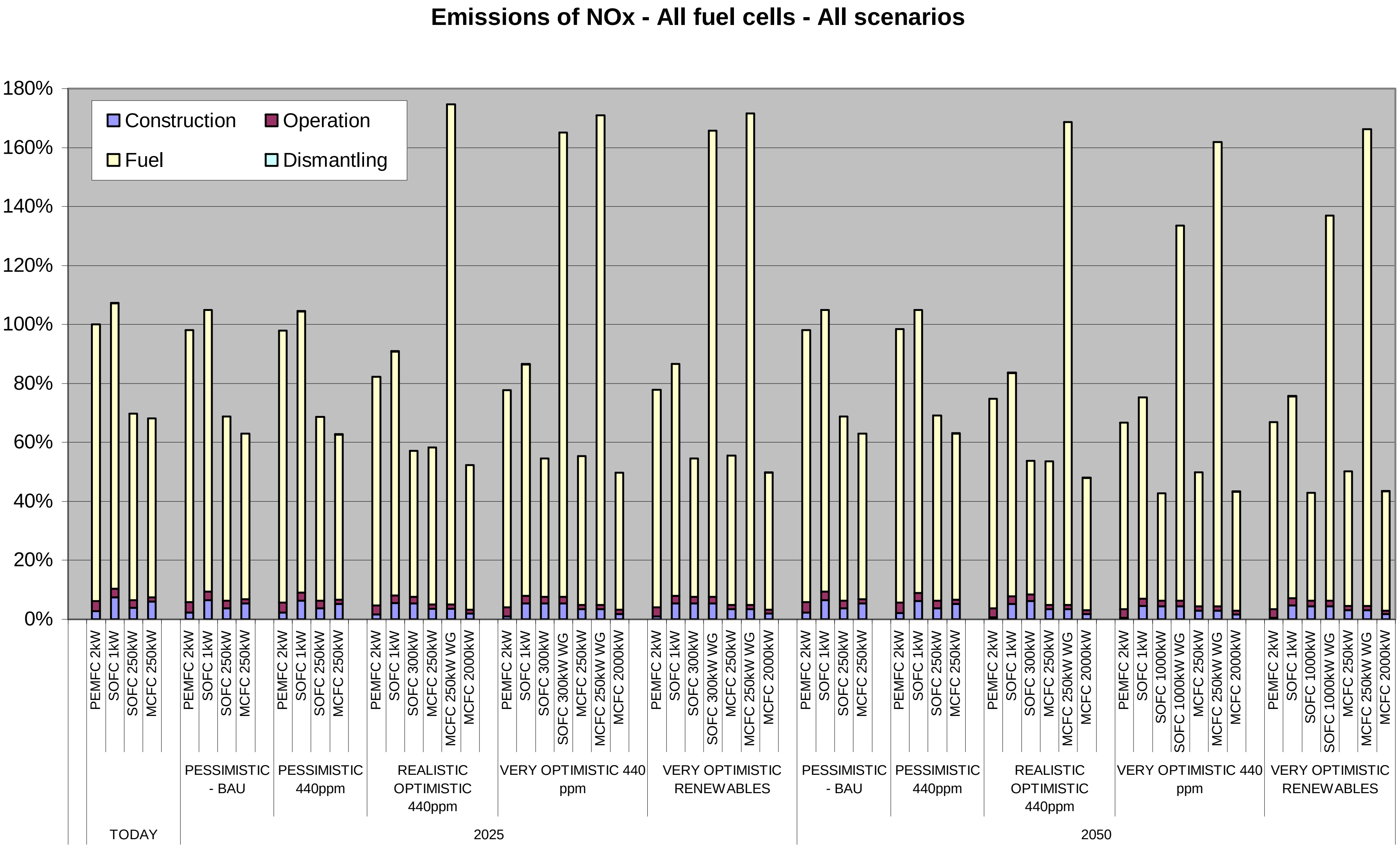


Figure 5.14 – NO_x emissions for all scenarios and technologies

5.7 Temporal and spatial disaggregation

The temporal disaggregation means the duration of and time between the phases with reference to start of commercial operation. Table 5.15 shows the values for the reference fuel cells with year number 1 as start year of commercial operation, assuming 5,000 full load hours per year.

Table 5.15 - Temporal disaggregation for fuel cells considered for the current situation

Phase	Unit	2000			
		SOFC small	SOFC big	PEMFC	MCFC big
Fuel supply	Start year	1	1	1	1
	End year	20	20	15	16
Production	Start year	- 1	- 1	-1	-1
	End year	- 1	- 1	-1	-1
Operation	Start year	1	1	1	1
	End year	20	20	15	16
Disposal	Start year	21	21	16	17
	End year	21	21	16	17

For the future situation, the operation of MCFC will last until year 20 (with disposal at year 21), while for PEMFC the operation phase will end at year 16 (with disposal at year 17). The fuel supply phase will follow the same temporal disaggregation of the operation phase.

Table 5.16 instead show the spatial disaggregation indicating the provenience of the fuel supply and of the components of the system. The natural gas mix is described according to the average European supply mix.

Table 5.16 - Spatial disaggregation for current fuel cell power plants

	SOFC big			
Region	**Construction**	**Operation**	**Fuel supply**	**Disposal**
% R1	100	100	29	100
% R2				
% R3			4	
% R4			17	
% R5			34	
Africa			16	

	SOFC small			
Region	**Construction**	**Operation**	**Fuel supply**	**Disposal**
% R1	100	100	29	100
% R2				
% R3			4	
% R4			17	
% R5			34	
Africa			16	

	PEMFC				MCFC			
Region	**Construction**	**Operation**	**Fuel supply**	**Disposal**	**Construction**	**Operation**	**Fuel supply**	**Disposal**
% R1	100	100	29	100	100	100	29	100
% R2								
% R3			4				4	
% R4			17				17	
% R5			34				34	
Africa			16				16	

The European regions R1, R2, R3, R4 and R5 are used according to the definition given by RS 1b.

6 Conclusions

The report presents a detailed analysis of the present and of the future configurations of fuel cell systems defined according to the IEC standard.

The analysis was performed both on the economical and on the technological aspects.

The overall results show that a reduction of the investment costs and of the O&M costs depend on the learning rate, but uncertainty on this figure is considerable as the technology is still at an early stage of development and the construction of the learning curve presents some margins of arbitrarity. Besides, it has been shown how small (less than 4,0% in the best case) the fuel cell contribution would be to the global energy production in year 2050. Nevertheless, fuel cells, which can be supplied also with wood gas, may represent a viable solution for the target of increasing the independence from the non-renewable fossil fuels energy source.

An LCA has been performed on the current and future technology development under certain hypotheses:

- three technological development stages
- three electricity mixes.

The environmental performances have shown a progressive improvement in the future configurations which consider an improvement of the technology (thus, not in the pessimistic scenario).

Key emissions have been quantified and represented (CO_2, SO_x, NO_x, PM2.5, PM10) together with the GHG for all technologies and scenarios.

The land use issue becomes important only for the case of wood gas supplied fuel cells, due to the upstream processes to produce the gas itself.

Wood gas fuel cells, besides, show an important contribution in terms of NO_x, PM2.5 and PM10 again caused by the fuel supply chain.

The whole assessment is, anyway, influenced by the allocation method applied which is an exergy based. This assumption leads to the result that the small fuel cells, which provide a high amount of heat are generally worse than big ones.

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Annex

Table A – Upstream process materials for the production of 1kg SOFC planar specific materials

Material	Unit/ kWel	Current	2025RO 2025VO 2050RO	2050VO
explosives, tovex, at plant	kg	0,00011	Reduction	Reduction
Gas, natural, in ground	Nm3	13,178	**10%**	**20%**
Oil, crude, in ground	kg	9,014		
Coal, brown, in ground	kg	22,717		
Coal, hard, unspecified, in ground	kg	12,852		
Uranium, in ground	kg	0,00064		
Calcite, in ground	kg	3,979		
Sodium chloride, in ground	kg	35,690		
Iron, 46% in ore, 25% in crude ore, in ground	kg	0,0071		
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	kg	0,0276		
Sulfur, in ground	kg	0,00003		
Water, cooling, unspecified natural origin	m3	1112,431		
Water, turbine use, unspecified natural origin	m3	2146,131		
Water, unspecified natural origin	m3	1371,684		

Table B – Upstream process materials for the production of 1kg SOFC tubular specific materials

Material	Unit/ kWel	Current	2025RO 2025VO 2050RO (NG&WG)	2050VO (NG&WG)
explosives, tovex, at plant	kg	0,004	Reduction	Reduction
aluminium, production mix, at plant	kg	0,011	**10%**	**20%**
Gas, natural, in ground	Nm3	13,061		
Oil, crude, in ground	kg	9,072		
Coal, brown, in ground	kg	30,039		
Coal, hard, unspecified, in ground	kg	16,480		
Uranium, in ground	kg	0,001		
Calcite, in ground	kg	6,113		
Sand, unspecified, in ground	kg	0,000		
Sodium chloride, in ground	kg	47,845		
Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	kg	0,013		
Iron, 46% in ore, 25% in crude ore, in ground	kg	0,010		
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	kg	0,980		
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	kg	0,062		
Sulfur, in ground	kg	0,000		
Water, cooling, unspecified natural origin	m3	1454,524		
Water, turbine use, unspecified natural origin	m3	2673,337		
Water, unspecified natural origin	m3	1733,330		