System development and commercialisation activities by Kinetics Technology International Group (KTI)/ Mannesmann

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Abstract

Kinetics Technology International Group (KTI), a subsidiary of the Mannesmann Plant Construction division, has been involved in fuel cell system development for almost a decade now. Starting with trouble shooting, consultancy and hydrogen production studies, KTI gradually built up know-how of system design, engineering and construction for fuel cell power plants, incorporating cell stacks from other manufacturing companies. These efforts have led to extensive system economics studies, and to a fuel cell system construction program. To date, two systems of 25 kW have been operational (one employing a stack manufactured by Engelhard Corp., the other a stack from Fuji Electric Corp.), a third is under construction, and an 80 kW unit in Bavaria has recently been started up (the latter two with stacks from Fuji Electric). Results from the program will be presented. Larger sizes are expected to be built in the near future, and economy of scale with proven hydrogen technology will allow for acceptable system cost for small series of units of 1–10 MW size. It is expected that future systems, employing fuel cells and special rotating components, will reach very high efficiencies (above 55–65%), both with high and with low temperature fuel cells.

1. Introduction

Kinetics Technology International Group (KTI) started the activities in the fuel cell area with trouble shooting, consultancy and hydrogen production studies, approximately 10 years ago [1–5]. During the eighties, KTI gradually built up special know-how in system design, engineering and construction of fuel cell power plants, incorporating stacks from fuel cell manufacturing companies. The main basis for technology input in KTI was the experience as a hydrogen plant contractor. With a high market share worldwide in turnkey delivery of customer-tailored hydrogen plants, KTI has contributed significantly to the development of a technology which is now considered as a very reliable, fairly low cost necessity for any refinery industry, many food and electronics industries, and other applications. When entering the fuel cell area, our philosophy was to 'transfer' this existing and proven reliability of hydrogen technology to fuel cell plants. In doing so, we also chose not to become a fuel cell developer ourselves. Our know-how should be in introducing the fuel cell into the system, developing system synergetic potential and fine-tune the system design. Our decision was strengthened by the observation that most fuel cell demonstration plants

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TABLE 1

KTI/Mannesmann fuel cell activities

Fuel processing studies
System studies
Pressurised combustion
Trouble shooting 4.5 MW
40 kW consulting
First fuel cell tests on landfill gas
Process optimisation (pinch technology)
Cost estimating studies
25 kW program
MCFC, SPEFC, AFC system designs
Dynamic simulation
Reformer development and testing
Hydrogen purification
Mini H_2-program (FG-1 design, etc.)
Ultra low NO_x burner testing

built to date did not yet conclusively demonstrate that reliability could be achieved: too many problems were faced, largely in so-called peripheral system components, such as the reformer, the rotating equipment, and especially the control and instrumentation area. This approach led KTI/Mannesmann stepwise into system development, market introduction and early commercialisation efforts (see Table 1). In our previous contribution to the first Grove Symposium, the background and history of this process has been described [6]. In this paper, some results of the system development, demonstration and testing achieved to date will be shown. Attention will also be paid to the system capacity increase and cost reduction efforts being undertaken at the moment, and some technical as well as market concepts concerning new designs will be presented, in which combinations of rotating equipment and fuel cells play a major role.

2. System development

System development has concentrated on the design, construction and testing of special compact reformers, special burners, flowsheet developments employing modern design concepts such as pinch technology, dynamic simulation etc., as well as techno-economic studies and cost evaluations. Traditional, proven methods of plant construction industry have been used throughout, as we have considered it to be necessary to achieve conservative and reliable plants, as well as reliable cost estimates. The cost data achieved have been compared to data of other technologies, either on the market or under development during this decade, and extensive sensitivity analyses have been made on the basis of life cycle cost as well as total cost of electricity. Even though the absolute values of the calculated cost of electricity are strongly dependent upon individual economic assumptions, a relative comparison of technologies of a certain capacity is usually quite accurate. Results of these studies have been summarised for

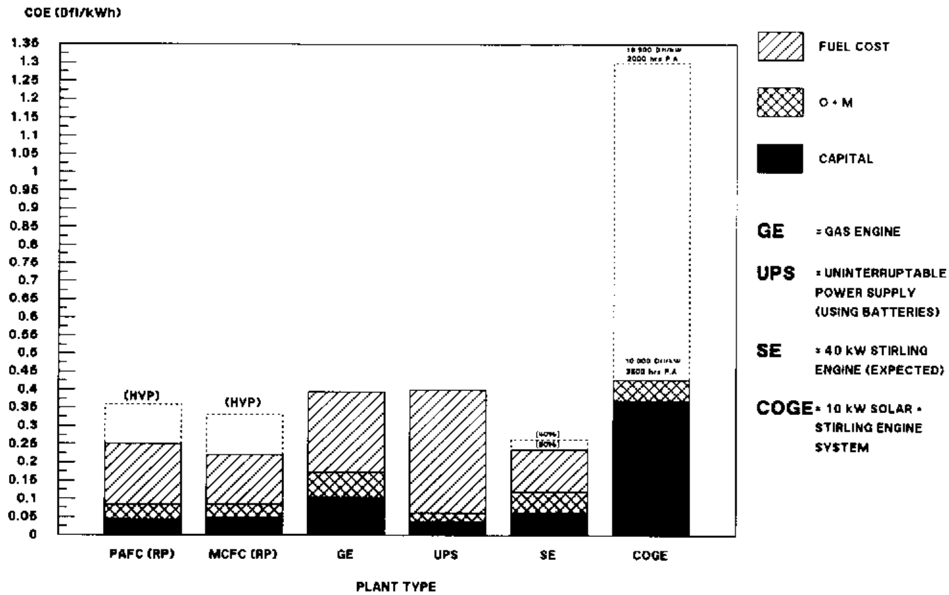

Fig. 1. Comparing fuel cells with other technologies for a 25 kW power plant.

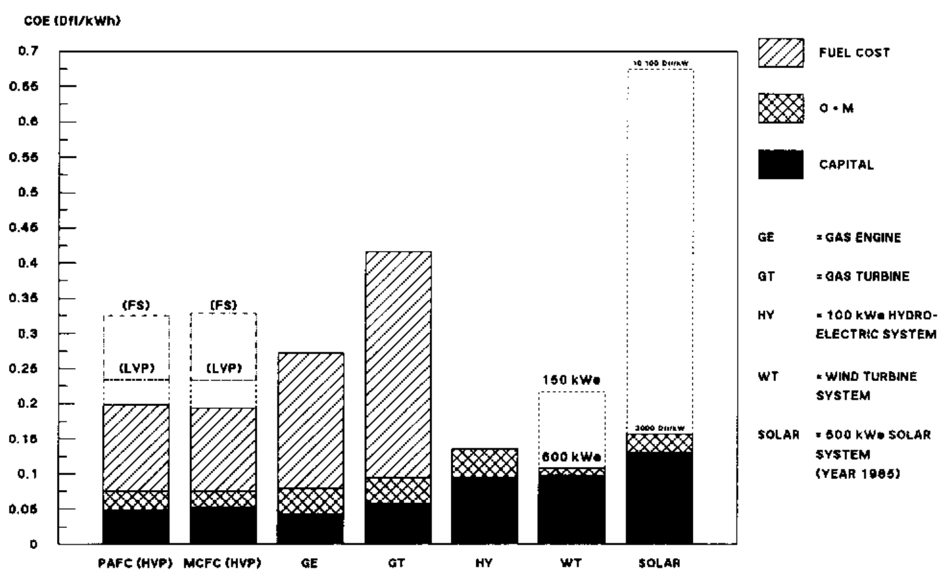

Fig. 2. Comparing fuel cells with other technologies for a 250 kW power plant.

four typical capacities in Figs. 1–4. An explanation of the abbreviations used and some of the assumptions behind the calculations is given in Table 2. As conclusions from Table 2, the following can be stated.

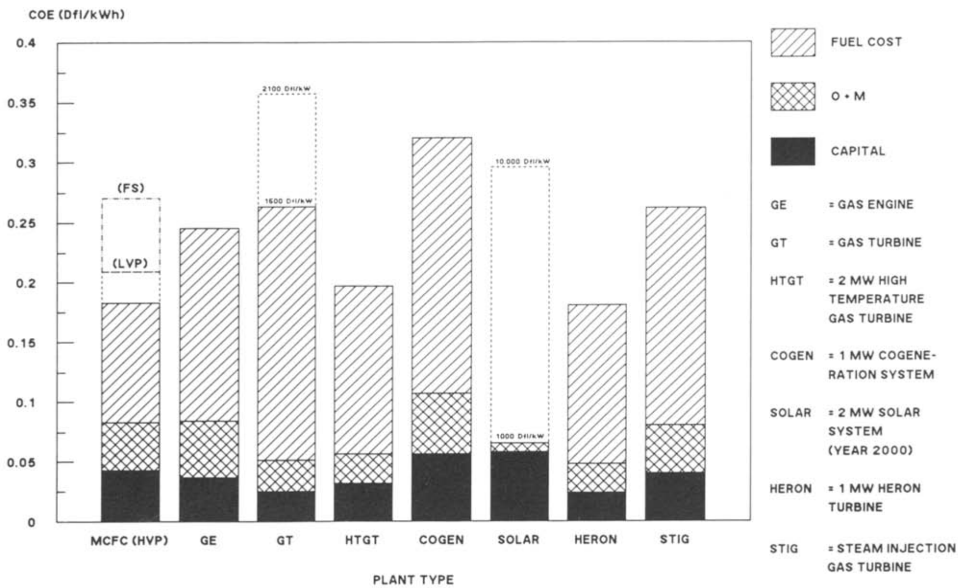

Fig. 3. Comparing fuel cells with other technologies for a 3.25 MW power plant.

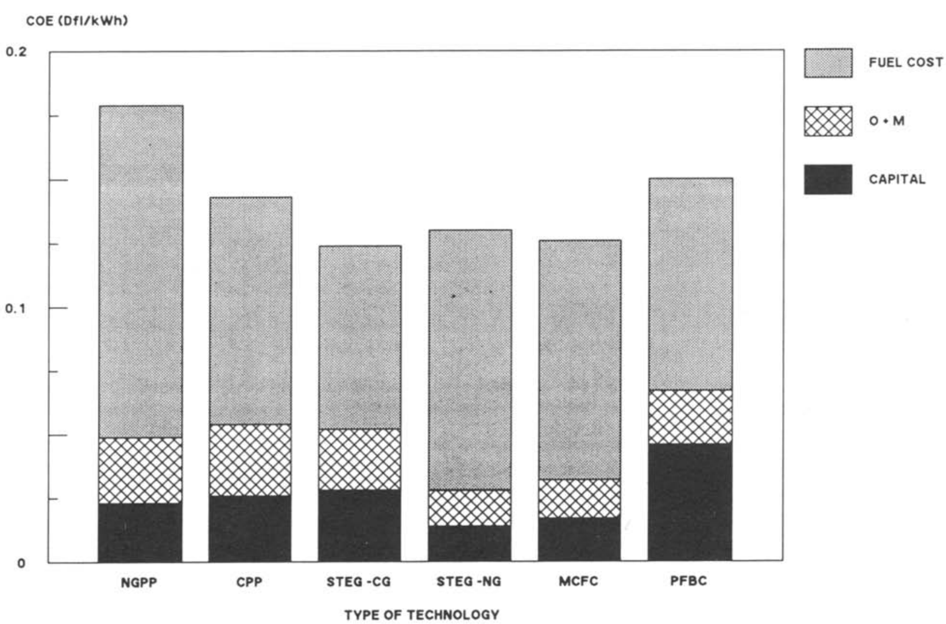

Fig. 4. Cost of electricity for 600 MW power plants.

TABLE 2

Abbreviations and assumptions of Figs. 1–4

Abbreviations	
O+M	operating and maintenance cost
RP	robotised production (200th unit in a series of 1000)
HVP	high volume production (20th unit in a series of 100)
LVP	low volume production (5th unit in a series of 20)
FS	first series (2nd unit in a series of 5)
COGEN	*averaged* US installed co-generation system (1 MW)
NGPP	natural gas fired power plant
CPP	(powder) coal fired power plant
STEG-CG	coal gas fired combined cycle power plant
STEG-NG	natural gas fired combined cycle power plant
PFBC	pressurised fluidised bed combustion power plant
PAFC	phosphoric acid fuel cell
MCFC	molten carbonate fuel cell
Assumptions	
Method	EPRI TAG method [7]
Fuel price	average EEC country fuel prices 1987
Write-off period	15 years (small capacity) → 30 years (large capacity)
Economic assumptions	detailed in refs. 8 and 9

(1) For small capacities (25 kW typically) fuel cell systems become competitive in production volumes of a few hundred systems. Main competition for these systems is the electric grid, or perhaps during next decade the Stirling engine.

(2) For 250 kW power plants, fuel cell units will have a reasonably competitive position compared to gas engines and especially gas turbines in relatively small production series. Hydroelectric and wind turbine systems, and in the future also perhaps solar systems will be strong competitors, but only if cheap energy storage systems can be combined, or if demand and supply follow closely matching patterns. Obviously hydroelectric power has the best relative availability of these three technologies.

(3) It can be noted that the cost of electricity of MCFC and PAFC systems is similar. The higher efficiency of the MCFC system is usually offset by a higher price to achieve such high efficiency (higher pressure system). System developers are only recently becoming aware of this issue which will raise the performance and cost targets of second and third generation fuel cells in order to be competitive against first generation systems (note that internally reformed systems may have a better position due to lower system costs).

(4) For systems with a capacity of approximately 3 MW high temperature gas turbines and some new cycle turbines, such as the so-called Heron turbine, will reach similar performance to PAFC, and fuel cells will have to be produced in reasonably large serial production in order to compete. As pointed out in the Arthur D. Little paper at this conference, the situation for fuel cells improves once environmental benefits are given a specific value. In particular high temperature gas turbines will then increase in relative cost, in order to achieve similar environmental characteristics as the fuel cell systems. Solar energy may for this size range also fill a gap, if the availability/storage/cost reduction scenario is favorable.

(5) Finally, it seems that even for the 'central' power plant size range (approximately 100–1000 MW or so) fuel cells may have some impact, even though the fuel cell

system maximum size would probably be about 100 MW, and a 600 MW system would therefore cost exactly the same per kW as a 100 MW system (since it would be 6 systems of 100 MW each). Major competition for fuel cells will be natural gas fired combined cycles for sizes above ~50 MW, and coal gasified combined cycles for sizes above 200 MW. With the increasing trend towards decentral power generation (see also Section 6) the relative position of fuel cells will even be better, and perhaps fuel cell power stations of sizes larger than 100 MW will then be built, given additional cost benefits in the transmission and distribution costs, as well as diminished transmission losses of energy.

3. System demonstration and testing

To date, KTI has contracted to construct four full PAFC systems. Three of these have 25 kW electric capacity, the fourth is 80 kW. The first unit was designed and engineered by KTI, built by Engelhard Corporation together with KTI, and tested by Engelhard Corporation with an Engelhard 25 kW fuel cell stack. The plant was operated successfully for almost a year, without unexpected shutdowns after the initial trial period, and dismantled for post-mortem analysis after testing.

The second plant of 25 kW capacity was designed, engineered and built by KTI in The Netherlands, and was started up at the Delft University of Technology for testing and demonstration purposes in Oct. 1989. A subcontractor's mistake caused water inflow into the fuel cell, and part of the phosphoric acid was dissolved, which necessitated replacement of the fuel cell stack. This took considerable time and caused quite some delay. Table 3 contains the target specification values of the demonstration unit, which have now been proven in operation. Figure 5 shows the overall system efficiency as a function of d.c. load. It should be pointed out that this represents a demonstration unit which has not yet been optimised for maximum efficiency.

TABLE 3

Target specification 25 kW PAFC demo unit

Item	
Rated power (kW)	29.5 d.c./25 a.c.
Fuel and feed	natural gas
	8.2 Nm^3/h @ 100% load
Pressure (bar)	max. 1.8
Efficiency (LHV) %	36
Start-up time (h)	5–6
Weight (kg)	*c.* 10 000
Dimensions (m)	6×2.5×3 (l×w×h)
Control system	PC/PLC
Emissions (ppm)	
NO_x	<5
SO_x	<0.1
Installation	indoor
Cooling method of fuel cell stack	boiling water
Waste heat	recovered

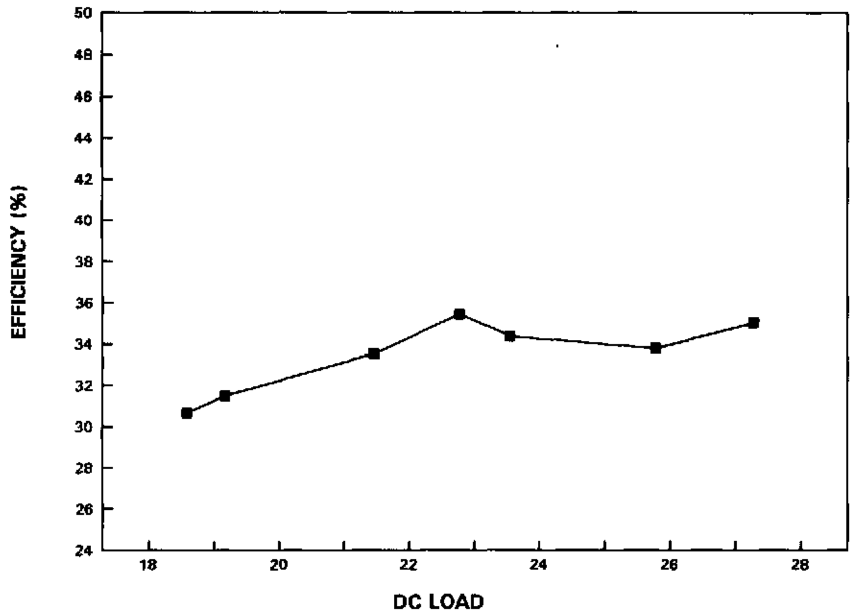

Fig. 5. Overall d.c. efficiency, LHV basis.

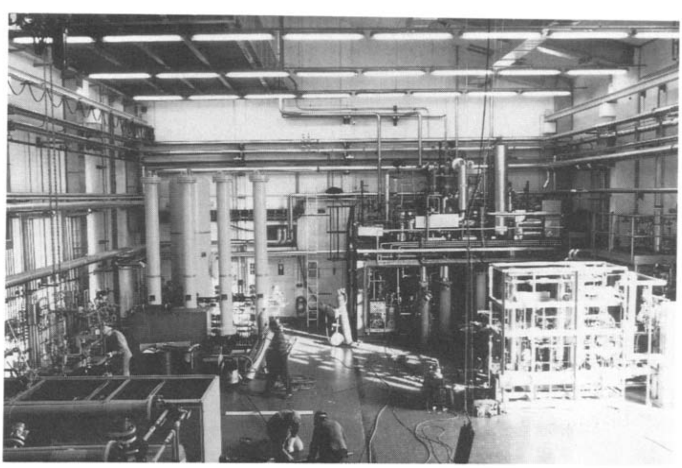

Fig. 6. 80 kW fuel cell plant built by KTI for the SWB (Solar-Wasserstoff-Bayern) demonstration facility.

A similar unit, but with simplified design, was contracted with ENEA, for ENEA's Casaccia R&D facility. Because of the financial situation of Italian energy R&D, this project has also suffered considerable delays. However, the plant is handled as a standard project from KTI's side (similar to a standard hydrogen plant).

The 80 kW plant referred to above (see Fig. 6) was built as a commercial plant (with guarantees, guaranteed delivery time etc.) to SWB (Solar Wasserstof Bayern), the Bavarian demonstrator of a total hydrogen economy model. The plant can operate on natural gas or on solar electrolyser-produced hydrogen, and can also operate on air or enriched oxygen. The plant can produce either a.c. or d.c. electric power or pure hydrogen to be fed back into storage, and therefore is suitable for future application into transition stages from natural gas to hydrogen driven energy applications. Table 4 shows the specification of the system and the fuel cell. In the meantime, all efficiencies have been confirmed in operation. Table 5 contains some more specific data on the fuel cell system, as well as the d.c./a.c. convertor which has been employed. The plant is currently under a further 'fine-tuning' program, in which several parts are being

TABLE 4

Technical data for 80 kW SWB PAFC plant

Design, turnkey supply	KTI BV, The Netherlands			
Assembly	KTI Mol, Belgium			
Fuel cell stack	Fuji Electric Co., Ltd.			
	130 V d.c./610 A d.c. (max. voltage 154 V d.c.)			
	190 °C; 40 mbar (g)			
Modes of operation	1	2	3	4
Fuel	17.5 Nm^3 natural gas/h		51.6 Nm^3 H_2/h	
Oxidant	air	air/50% O_2	air	air/50% O_2
Rated power kW_e d.c.	76.1	79.3	76.1	79.3
kW_{th} (180 °C)[a]	30	30	60	60
Electric efficiency (a.c.) (%)	41	43	46	48
Overall efficiency (a.c. + heat) (%)	58	60	85	87
Start-up from cold (h)	4		3	
Start-up from hot stand-by (h)	1.5		0.75	
Max. load change velocity (%/s)	1.25		2.5	
Parasitic power losses (kW)	25		8.6	

[a]Heat decoupling via intermediate circuit into existing building heating circuit.

TABLE 5

More technical data for 80 kW SWB PAFC plant

Exhaust gas emissions	(operating modes 1 and 2)
CO_2	18 Nm^3/h (20 vol.%)
CO_x	non-detectable
NO_x	< 19 vol. ppm
CO	< 1 vol. ppm
H_3PO_4	ppm range
H_2-purity	≥ 99.9 vol.%
H_2-delivery pressure	15 bar(g)
d.c./a.c. converter	Siemens AG, mains controls SCR-type a.c. busbar connection 80 (max. 85) kW
Voltage/current	130–160 V d.c. 150–650 A d.c. } → 3 phase 220/380 V a.c., 50 Hz
Efficiency	100% capac. > 94% 25% capac. > 91.5%

improved for longer period operation in heavy cycle duty. Soon after that (perhaps at the time of the conference) guarantee test runs for full performance, both on natural gas, pure hydrogen, and with either air or enriched oxygen, will be in the process of being performed.

All systems have been designed such that customers can continue long term testing. Just as Engelhard has done with the first 25 kW unit, the units can be operated fully on the basis of Design and Operating Manuals. Historically, during the course of the projects, the state of automation of the projects has proceeded to almost push button control. Future stages in the development of these systems will provide fully automatic control, independent of operating personnel.

4. System capacity increase and cost reduction: commercialisation activities

Although some of the systems referred to in the last paragraph are still under testing, the following conclusions can already be made:

- the key design items (compact steam reformer, steam drum including coils etc.) have been proven
- designs like the ones having been selected can be applied in a wide range of capacities (25 kW to several MWs)
- most design targets have been met
- tasks for improvement include simplified control, improvement of flow instruments (especially for smaller capacities), and insulation as well as compactness

However, so far system demonstration efforts have only been made to test designs and technology development, and to demonstrate reliability of the plants. On the basis of the gathered experience, KTI/Mannesmann decided a few years ago to only continue PAFC activities on a larger scale, since the economy of scale can be fully utilised. Many items of plant technology cannot be decreased by very large scale mass production in the same efficient manner as by economy of scale increase. It was therefore decided to focus commercialisation activities on higher capacities.

Figure 7 shows the cost reduction effort and the results reached to date, with even more units than the ones we have built so far. Two additional 25 kW units have been planned, but have not been built due to the internal political decision to focus on larger capacity units as soon as possible. Although the first plant was 'relatively cheap', it was not a full size industrial design, did not contain automated instrumentation, and was highly simplified. Therefore the second plant in the series (which was the first European fuel cell plant) was the most important point on the learning curve, and its cost was over 65 thousand dollars per kW. The 80 kW plant has been more than three times cheaper per kW, mainly because of the learning curve (the economy of scale is not very strong at that capacity as yet). Lump sum turnkey offers have thereafter been made for 300 kW and 2 MW power plants at much lower cost levels, and both of these projects benefit strongly from the economy of scale. Table 6 contains the effect of production of small series combined with the economy of scale, resulting in overall system prices which we intend to offer on the market for 2, 5 and 10 MW units as specified in the Table. For reference, 250 kW cost are also included. From these data it is evident that PAFC can be commercially introduced in the market (for economic prices) at sizes above 2 MW, as soon as a total number of approximately 20 units can be realised. For 5 MW units this number decreases to 5–10, for a 10 MW size even to 1–3 units. Reference is made to the Arthur D. Little contribution at this conference, which implies that 1500 $US per kW is an acceptable price to

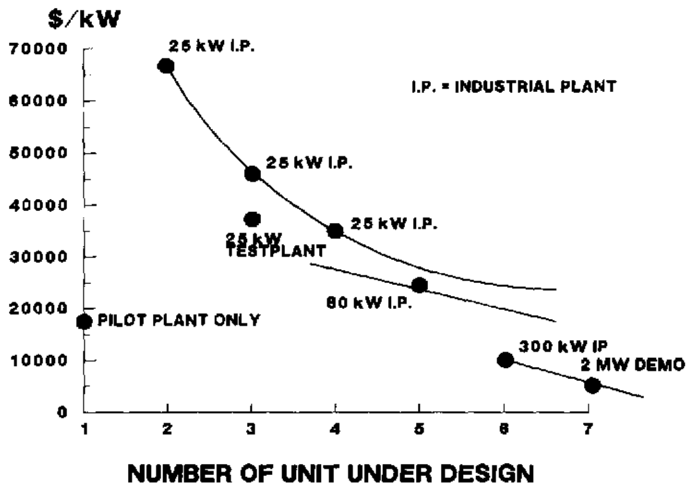

Fig. 7. Actually committed or proposed KTI projects (total investment).

TABLE 6

Economy of scale 2, 5 and 10 MW (total system turnkey prices for typical 'average' site conditions). Data for 250 kW_e included for comparison. All numbers are approximate only

	$/$kW_e$			Necessary no of units to achieve 1500 $/$kW_e$
	First unit (demo)	Series of 5 units	Series of 20 units	
250 kW_e	13500	8000	2500	50
2 MW_e	7500	3700[a]	1500	20
5 MW_e	n.a.	2600[a]	1300	5–10
10 MW_e	n.a.	<1500[a]	≪1000[a]	1–3

[a]Following 1×2 MW demo.

reach a high market share in the forthcoming years, certainly if one is taking into account 'monetarisation of externalities' like environmental advantages, transmission and distribution credits, etc. Table 7 contains the expected system improvements which will add to the competitive position of PAFC systems in this decade. It is expected that during this period the total net system efficiencies will probably increase from the current level of about 42% LHV, to above 50% LHV. This still excludes the development of hybrid systems with high performance rotating equipment, which will briefly be referred to in the next few sections.

5. Hybrid system development

A few companies in the world have concentrated more recently upon development of hybrid systems, combining power sources of different types by utilising the unemployed heat of one system as a heat source for the other, and perhaps even to apply this principle both ways. Similarly, waste products (mass streams) of one plant can be

TABLE 7

PAFC expected improvements (%)

	1989		2000	
Stack performance	40	⟶	45	(LHV)
Fuel processor (net)	110	⟶	125	(LHV)
Inverter	95	⟶	98	
System (net)	42	⟶	55	(LHV)
CF: ER-MCFC	(50) (1995!)	⟶	57–62	
IR-MCFC	(55) (1995!)	⟶	60–65	

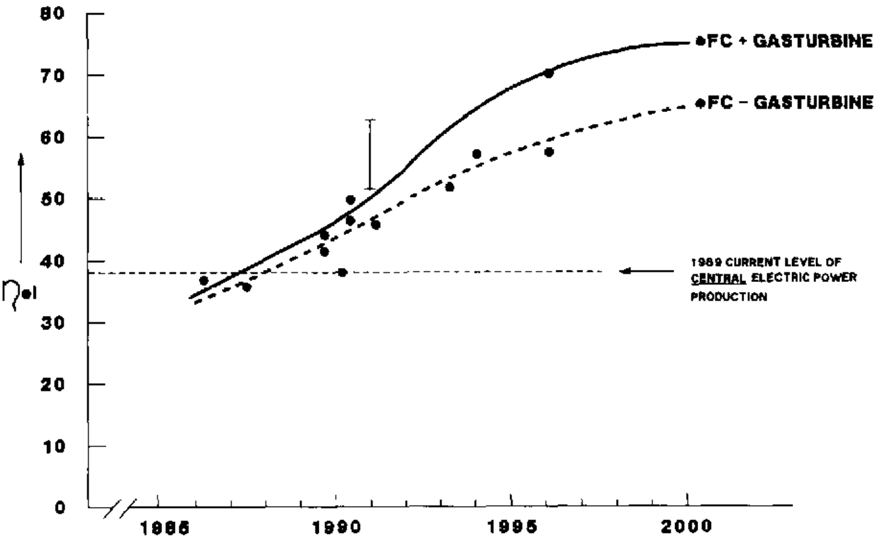

Fig. 8. Expected efficiency development for fuel cell systems with (——) and without (– – –) integrated gas turbines.

used as feedstock in the other (e.g. water formed in combustion can be used as reactant in steam reforming, non-utilised oxygen be used in combustion, etc.). This combination enables a close interaction of mass and energy between the systems. To this end, KTI/Mannesmann has cooperated intensively during the last few years with a small company called Heron Turbines BV, which has developed the so-called Heron turbine referred to in Fig. 3.

On the basis of undisclosed studies of the gas turbine and fuel cell systems, hybrid combination systems have been developed, which can employ both low temperature fuel cells and high temperature fuel cells. These systems have efficiencies approaching 55% or even much higher (65%). Some of these systems will utilise early generation fuel cells, and can be demonstrated in a couple of years from now. Figure 8 contains the starting dates of potential realisation of the different increased efficiency systems, and it can be seen that systems combined with gas turbines are targeted to yield much higher efficiencies, especially starting from 1993 onwards. In comparison, the systems without gas turbines are also developing to high efficiencies (but have to rely on the availability of high temperature fuel cells in order to reach the efficiencies above 55%). The combination with gas turbines may therefore increase the life cycle of low temperature fuel cells, and offer sufficient efficiency and performance benefits to compensate for the relatively low development efforts involved. Because of the expectation that such systems will be possible in the next few years, it is a legitimate question to investigate the size and the development of the market potential for such systems.

6. Market expectations for hybrid systems

The most important factor in assessing market potential and penetration of integrated systems (or other systems with similar efficiencies) is the absolute size of the decentral power generation market that is currently developing and will further develop during this decade. Table 8 contains the main advantages of decentral power generation. Of these, investment cost is undoubtedly the main factor, especially in countries where long term planning is not easy and where money for large power plants is not easily available. The cost of transmission of a.c. power in large capacity lines is approximately $20 per MW transmitted per km per year. As shown in the Arthur D. Little paper in this book, average investment of power transmission and distribution (T&D) in industrialised countries contributes to about $500 per kW of installed generating capacity. Added to this should be the reduced losses and other political factors, and it becomes evident that there will be a further decentralisation trend. We should perhaps not forget that originally central power plants were only chosen because in the past it was the only way to economically produce power at a reasonable efficiency and cost. It even brought into existence a full new branch of industry: high voltage electronics. Only now are new technologies coming on the market which have acceptable efficiency and economy at a small capacity scale.

Table 9 summarises the main factors affecting market penetration of decentralised power in the electricity generating industries. Most important in this respect is of course co-generation, which, apart from all the efforts to raise the electrical efficiency of the system, almost doubles each system's efficiency automatically. However, electricity is the most valuable form of energy for most applications, and therefore the trend for continued emphasis on increased *electrical* efficiency will continue, even if co-generation would become omni-present. Table 10 contains the factors which can have an increasing effect on the number of decentral producers. Dependent on local legislation,

TABLE 8

Main advantages of decentral generation

Smaller investment cost (T&D; serial production)
Shorter planning and construction time (factor 4)
Waste heat utilization
Grid flexibility, less peak power
Reduced losses (central: 8% of power)
Possible in developing countries (infra-structure, low investment, biogas)
Requires less long term stability
Lowers risk of poor investment

TABLE 9

Main factors affecting market penetration of decentralised power

Environmental awareness
Global warming issues
Longer use of exhaustible fossil fuels
Co-generation (⟶ urban sites ⟶ stringent legislation)
T&D cost

TABLE 10

Factors to increase the number of decentral producers

Delivery of excess power to grid
Low gas price for efficient producer
Subsidies (dependent upon electrical capacity)
Standardisation contracts
Excess demand rates reasonable
Enable direct sales to end users
Pollution penalties
Evaluation of 'total environmental effects'
Long-term legislation planning (emissions, tariffs)
Tax effects
Control of unfair competition

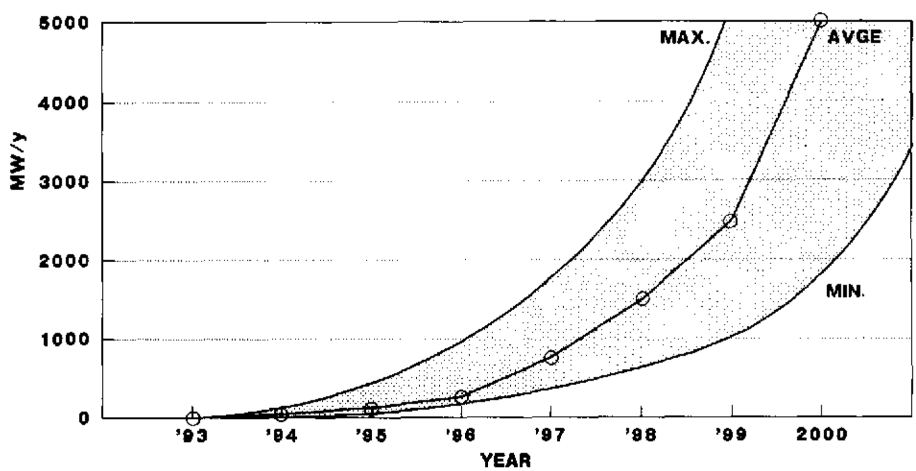

Fig. 9. A potential market estimate for integrated systems (η_{el}>55%).

one or more of these factors may play the most decisive role in stimulating the trend for high efficiency, clean, decentral power production [10].

On the basis of market studies, as well as, independently, on the basis of some current and future scenarios for the development of the relative role of natural gas in power generation during the next decades, a study has been made [11]. A potential market penetration of high efficiency systems can be projected as indicated in Fig. 9. It should be emphasised that the accuracy of this prediction is low, and data should be seen as an indication only. However, the conclusion is evident, that even if only the minimum estimate is realised, there is a substantial drive behind the industrial development during the last decade of this century. This market drive is the ultimate force steering all present activity.

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