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BARAKA
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PUBLISHABLE FINAL REPORT

TECHNICO-ECONOMIC ANALYSIS OF THE URBAN FUEL CELL NETWORK WITH COAL GASIFIER

Checked by	ALBERT Alain	*Engineer*		
Written by	JACQUINOT Bernard	*Project Coordinator*		
RESPONSABILITIES	Name First Name	Function	Date	Visa

DIFFUSION : EC DGXII — Mr PONTHIEU, Mr LEQUEUX

Partenaires

JACQUINOT
A. ALBERT

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BARAKA

Feasibility study of an urban fuel cell network with coal gasifier

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Bertin Technologies
Centre de Tarnos
Zone Industrielle
40220 TARNOS - FRANCE
B. JACQUINOT - Coordinator
A. ALBERT

✹◆◆✹

Energionderzoek Centrum Nederland - ECN
Fuels, Conversion and Environment
Westerduinweg, 3 - P.O. BOX 1
NL 1755 ZG PETTEN - PAYS-BAS
MM. JANSEN & De GROOT

✹◆◆✹

KUNGL TEKNISKA HÖGSKOLAN - KTH
Royal Institute of Technology
Department of Chemical Engineering and Technology
Chemical Technology
S - 10044 STOCKHOLM - SUEDE
MM. BJÖRNBOM & KIVISAARI

✹◆◆✹

Usine d'Electricité de METZ
2, Place du Pontiffroy
B.P. 20129
57014 METZ
M. WANNENMACHER

✹◆◆✹

CdF INGENIERIE
2, rue de Metz
B.P. 40142
57804 FREYMING-MERLEBACH
M. KELLER

M. REKIK & Mrs DELECOUR
CERCHAR

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1. OBJECTIVES OF THE PROJECT / PERFORMANCE CRITERIA

The BARAKA project is aimed at evaluating the technical feasibility and the commercial advantages of connecting a cogeneration power plant using an High Temperature Fuel Cell (SOFC or MCFC) fed with gas issued from coal gasification to urban networks.

In order to fulfil the objective, the BARAKA process was established - in accordance to the requirements of the electricity and heat networks - exploited in Metz by UEM. The system study and preliminary design were followed by the economic analysis and the technico-economic evaluation.

The process had also to comply with specific performance criteria :

- Overall energy efficiency : 80 % minimum
- Emissions limits for the off-gas : SO_2 < 35 mg/Nm^3
  NOx < 100 mg/Nm^3
  dust < 5 mg/Nm^3
- Equipment criteria :

1 maximum of basic research and	2 maximum of development
1 max of high complexity	2 max of important complexity
1 max of high cost	2 max of important cost

The BARAKA process was designed in order to fulfil the above-criteria.

2. COGENERATION SPECIFICATIONS

The BARAKA process has been studied in order to be operated by UEM thus connected to both existing electricity and Heat Networks. The networks of Metz distribute heat to 80 000 people and electricity to 270 000. The heat is transported through hot water (140 to 180 °C and 80 °C for return).

The maximum heat capacity of the network is 280 MW which are distributed through a 44 km length piping. The heat demand mostly drives the operation of the different power systems exploited in Metz (gas turbine MW, steam turbines and associated boilers as well as the Municipal Waste incinerator which is also connected to the Network and produces thermal 10 MW all along the year).

The electricity and heat demand profiles are represented in Annex 1. To comply with the resulting effective heat demand, the two scenarios B and C were considered and compared with the full capacity scenario A. Such a necessity to operate the power plant at low capacity during a part of the year is encountered by all cogeneration plants delivering heat to tertiary customers. The heat supply to industrial application corresponds to the most favourable situation for cogeneration plants as the heat demand does not vary so much along the year.

3. THE BARAKA PROCESS

The BARKA process designed on purpose correspond to the flow sheet shown in Annex 2. It comprises 4 sections devoted to :

- the coal gasification
- the gas treatment
- the electricity production
- the heat production

The process has been established and the equipment selected with keeping in mind the acceptance criteria that have to be fulfilled (refer to1) : for instance the status of the stack itself correspond to R and D. As a consequence no more equipment of the balance of plant (BOP) can be of R and D development status.

3.1 Solutions selected for the gasification section

3 existing process categories are possible and have been compared : fluidised, fixed and entrained bed.

The fluidised bed leads to low energy yields and has been rejected.

The fixed bed generates a large quantity of tars which removal for the stack protection is difficult and creates residues to be managed complimentarily.

The dry- process entrained bed by Shell or Koppers was selected as it produces almost no tars when fed with oxygen instead of air.

3.2 Solutions selected for the gas treatment

As shown in the table below the coal raw-gas is largely far from the cell specification and needs to be treated efficiently for sulphur compounds (H_2S,COS) Halides (HF, HCl) particles and Heavy Metals removal.

In order to not use technologies which are now industrial (acceptance criteria already mentioned) the mid-temperature route was disqualified as the Tin-oxide absorber is not mature enough.

The dust removal has also been designed at low temperature (200 °C) in order to use commercial equipment for filtration such as Gore-Tex bags that are also efficient for Heavy Metals removal at such a temperature.

For sulphur removal a first hydrolysis of COS (and CS_2 if present) into H_2S is achieved on a platinum based catalyst (supplied by HENSON) at 200 °C. H_2S is then removed in two successive steps : a first Red-Ox process is operated at low temperature (50 °C max) to convert H_2S into solid sulphur which is then filtrated. The reaction occurs in a Gas/Liquid packed absorption column with a liquid catalyst (Fe_{II}-chelate) which has to be regenerated in presence of air. This allows for a 5 to 10 ppm H_2S content in the gas which remains above the FC specifications.

In a second step the gas flows through a Zinc-oxide fixed absorption bed that captures the remaining H2S or COs to form Zinc sulphide. The absorption media is therefore consumed progressively and has to replaced once a year. The zinc sulphide is destined to its recycling in Zinc industry.

3.3 Solutions selected for the electricity production

The major part of this section corresponds to the HTFC. Two possible technologies have been compared in accordance to specific selection criteria : energy efficiency, electricity yield, reliability, complexity, status of the product :

- MCFC (Molten Carbonate Fuel Cell) developed by Ansaldo and MTU
- SOFC (Solid Oxygen Fuel Cell) developed by Siemens

- Both SOFC and MCFC are at present in the development step as only prototypes are now operated (same capacity, 100 to 200 kWe for both technologies).
- The cost of the stacks is consequently difficult to appraise as no commercial product is available.
- Both SOFC and MCFC are to be considered as complex systems even if SOFC is more simple.
- SOFC is nevertheless easier to be operated : no need for CO2 recycle, no strict specification for pressure difference between cathode and anode, no limitations for reactant concentration at he cathode.
- SOFC allow for an higher fuel utilisation and for lower degradation of performances
- MCFC requires on the other hand lower operating temperature than SOFC.

The SOFC has been selected for the BARAKA process although the differences described above are relatively small in comparison with the uncertainties in HTFC development.

The stack has been designed on the following basis :

- It is operated at 1 000 °C under a pressure of 8 bar
- The technology corresponds to planar SOFC
- The required electrical power is ensured by the association of modules of 1 MWe each.
- Each module comprises 660 cells and its size is 1.1 x 1.1 x 2 m
- The maximum size of 300 x 300 mm has been chosen for the PEN
- The modules are installed in four pressure vessels

For the equipment associated to the stack the solutions have been selected in order to minimise the electricity consumption :

The air recycle to the anode is achieved in a gas ejector propelled by the fresh air supplied by the compressor. The anode gas is recycled by an ejector as well.

In order to enhance the electrical yield of the overall BARAKA process a steam turbine and a gas turbine have been designed for energy recovery and transformation on to electricity.

3.4 Solutions selected for Heat production

A set of exchangers is necessary to control the required temperature levels of the BARAKA process, to ensure the heat recovery and to transfer it to the network. Two HP and MP steam loops have been designed on purpose and standard equipment selected.

4. OVERALL APPRAISAL OF THE TECHNICAL FEASIBILITY OF THE BARAKA PROCESS

The overall BARAKA process was designed after different simulations aimed at identifying the most efficient figure in terms of energy recovery. The compliance of the BARAKA process with the acceptance criteria was then checked as follows :

- **Overall energy yield** : the overall energy balance was determined on purpose :

Overall energy balance

	kW thermal	kW electric
Coal	50 000	
Energy supply	50 000	0
Gas turbine (C2)		10 017*
Fuel Cell stacks		17 616**
Steam turbine (C3)		3 629*
Heat network (E13)	19 034	
Fuel cell air compressor, C4		- 6 815*
Syn. Gas blower, C5		- 119*
Compressor for red-ox regenerator, C6		- 886*
Pumps (P1, P2, P3, P4,P5)		- 70
Energy output	19 034	23 372
Efficiency	38.0 %	46.7 %
Overall energy efficiency		**84.7 %**

* The power production and consumption taking the electrical efficiency into account.
** Taking inverter efficiency of 98 % into account.

The overall energy yield of 84.7 % meets therefore the corresponding criteria

- **Status** : In order to be sure to meet this criteria, all equipment except the stack itself - which is currently being developed - have been selected as commercial products.

- **Complexity** : The equipment design took care of this criteria and except the stack no equipment of high complexity is comprised in the BARAKA process.

  The association of a significant numbers of equipment makes nevertheless the BARAKA process rather complex.

- **Capacity** : The capacity of the BARAKA process has been determined to fit with a possible application at UEM. This capacity is small for a part of the process and especially for the gasifier : the prototype of the PRENFLO gasifier in Puertollano has a capacity of 330 MWe, therefore more than 10 times this of BARAKA.
  In a lower extend, the capacity of the gas and steam turbines is rather small.
  On the other hand, the capacity for the stack is high in comparison with these targeted by the HTFC future suppliers.

In conclusion, the BARAKA process is technically feasible provided the HTFC stack will attain a commercial status.

5. ECONOMIC ANALYSIS

5.1 Investment cost

According to the equipment design, the cost for the principal equipment (battery limit) has been evaluated as follows :

- For the stack itself, evaluation was necessary as no commercial product nor price exist at present.

  The investment cost was determined by the evaluation of the costs of material and of the manufacturing for an expected situation in 2005 allowing a production capacity of 200 MW/year. The BARAKA stack itself corresponds to 8 % of this annual production.

  This leads to an investment cost of 11.7 millions Euros for the complete stack and to a final cost of 13.3 millions Euros for the stack installed in the plant.

  The stack is expected to be operated during 5 years. The depreciation period commonly used at UEM for power plant being 25 years, the stack has therefore to be replaced 4 times during this period. 5 stacks have to be purchased.

- The BOP investment cost has been determined from regular tenders collected from suppliers as commercial products were selected.
  The corresponding investment cost is 37.3 millions Euros.

With adding the replacement costs for a 25 years operation to the BOP cost a total investment cost of 79 millions is attained. The figure in annex shows the investment cost distribution between the main parts of the plant.

5.2 Operating cost

5.2.1 Capacity of the plant along the year

As the operating cost depends on the operation of the plant, different scenarios were considered for the capacity profile of the plant in order to fit with the heat and electricity demands at Metz.

Scenario A : 8 000 hours at full capacity (only considered to evaluate the effect of the cogeneration figure on the operating cost)

Scenario B : 4 500 hours at full capacity
3500 hours at variable capacity
(annual capacity = 76 % of full capacity)

Scenario C : 500 hours at full capacity
Shut-down of the plant during 3 000 hours
(annual capacity = 62 % of full capacity)

5.2.2 Operating cost breakdown

	SCENARIO A	SCENARIO B	SCENARIO C
Variable charges : coal, oxygen, nitrogen	30 %	27 %	24 %
Labour cost	8 %	9 %	6 %
Replacement cost	13 %	11 %	11 %
Maintenance, taxes, insurance, overheads	15 %	17 %	19 %
Financial charges (capital depreciation over 25 years, and interest)	33 %	36 %	40 %

5.3 Evaluation of the electricity production cost

It is obtained by deducting the selling price of the heat add from the total operating cost.

The heat selling price at UEM is of 15.2 ∈/MW.

This method is commonly applied for cogeneration plants. For BARAKA process it leads to the following electricity costs :

- Scenario A : 0,070 ∈/KWe
- Scenario B : 0,085 ∈/KWe
- Scenario C : 0,092 ∈/KWe

5.4 Analysis of the BARAKA cost for electricity production

5.4.1 Market price for electricity

The incoming electricity market deregulation is expected to be responsible for large fluctuations associated to a possible average decrease of the electricity market price within the next years.

UEM indicated an expected market price of 0,038 ∈ /KWe that should be valid for the next years.

5.4.2 Corresponding situation of the BARAKA process

As shown on the table below it is clear that the electricity production cost of the BARAKA process is higher than the market price whatever the operation profile could be :

		Electricity cost ∈ /KWe	Comparison with market price
Scenario A	(full capacity during 8 000 h)	0.068	+ 79 %
Scenario B	(4 500 h full capacity 3 500 h variable capacity)	0.082	+ 115 %
Scenario C	(5 000 h full capacity)	0.089	+ 134 %

The operating cost breakdown makes clear that the investment cost is responsible for the high electricity cost : financial charges, other fixed charges, replacement costs are directly related to the investment cost which consequently accounts for respectively 61 %, 64 % and 70 % of the electricity production cost.

6. TECHNICO ECONOMIC ANALYSIS

6.1 Technical feasibility

This has been demonstrated in chapter 3.

For all equipment except the stack, mature technologies have been selected and this leads to a reliable consistent system even if the number of equipment makes it not simple.

Provided that the performances of the stack in 2005 will be proven in terms of reliability, life-time at nominal capacity and that manufacturing of the stack will be possible for large series, the BARAKA process has been shown to be technically feasible.

6.2 Economic competitiveness

As indicated in chapter 5, even on the basis production capacity of 200 MWe excepted to be attained in 2005, it appears that the BARAKA process is not competitive in comparison with the electricity expected market price.

- The electricity market prices as well as the capacity profile of cogeneration plants have and effect on the economic interest of the BARAKA process. Nevertheless for the targeted application it is unavoidable to deal with.

- The most critical question is to appraise the interest of the coal gasification for supplying the HTFC with fuel gas : This possible route is considered by the HTFC actors but it is clear that the association of the coal gasification system to the stack makes the process more complex as it comprises necessary equipment aimed at :
  - gasifying the coal
  - treating the coal gas
  - recovering energy
  - enhancing the electrical yield

The two last points are worth to be developed :

The gasification itself converts a part of the feeded coal into heat for reaching the required reaction temperature and this is responsible for a greater heat efficiency and therefore a lower electricity yield.

In order to maintain a high overall energy yield a maximum heat has to be recovered and for an enhanced electricity yield it has to be converted into electricity. Complementary equipment for electricity production were therefore associated to the stack in the BARAKA process : gas and steam turbines were designed on purpose.

This leads to the electricity yield of 47 % for the BARAKA process.

		Electricity capacity MW	Contribution to the electricity production (%)
Electricity Production :	Stack	17.6	56
	Gas turbine	10.	32
	Steam turbine	3.6	12
Gross Electricity production		31.2	100
Electricity consumption (compressors, pumps,...)		7.9	
Electrical net capacity		23.4	
Electrical efficiency		47 %	

In order to know if the cheaper feedstock of BARAKA could compensate for the higher investment, the comparison with an HTFC process of same electrical capacity and fed with Natural Gas (the "NG route") has been achieved : the process for this NG route was designed and the investment and production costs evaluated as shown in the table below.

			NG Route	BARAKA process
Capacity and yields :				
Electricity capacity		MW	23.4	23.4
Heat capacity		MW	7.2	19.
Electrical yield		%	60.4	46.7
Thermal yield		%	18.4	38.
Overall energy yield %			78.8	84.7
Electricity production				
Gross electricity production	Stack	(MW/%)	23.1 (81 %)	17.6 (56 %)
	Gas turbine	(MW/%)	5.5 (19%)	10. (32 %)
	Steam turbine	(MW/%)	-	3.6 (12 %)
	TOTAL	MW	28.5	31.2
Total electricity consumption	MW		5.1	7.9
Electricity net production		MW	23.4	23.4
Investment costs :				
Stack cost (equipment cost)		M∈	15.0	11.7
		k∈ /kWe from stack	0.650	0.660
		(k∈ /kWe from plant)	(0.641)	(0.500)
BOP investment cost		M∈	24.77	37.7
		k∈ /kWe from plant	1.060	1.611
Total investment cost		M∈	39.77	49.4
		k∈ /kWe from plant	1.70	2.11
Electricity production cost according to the scenario B		∈ /MWe	67.3	85.2

It makes clear that the NG route enables :

- large simplification of the process and therefore a lower investment cost
- an higher electricity yield (60 % versus 47 %)
- a lower energy consumption from the process itself (compressors, pumps, ...)
- a lower electricity production cost (67 ∈ /MWe versus 85 ∈ /MWe)

The BARAKA process based on coal gasification for supplying the stack in with fuel gas is therefore not so attractive than the NG route for an economic point of view.

Nevertheless the NG route is neither competitive and further investigations were achieved to explain this situation.

6.3 Comparison of the economic results with the target prices indicated by HTFC actors

In the framework of the FUNTY project (JOE3-CT98-0097) the HTFC actors indicated that the acceptance price for HTFC is to be 1 000 ∈/KWe in 2008 for the system (500 ∈/KWe for the stack and 500 ∈/KWe for BOP).

They all agree that large efforts are necessary for reducing material and manufacturing costs related to the stack and to the BOP for meeting the target in 2008.

Applying acceptance price for stack and BOP (500 ∈/KWe per each) to the cost evaluation method used for BARAKA and NG route, the electricity production cost becomes 36 ∈/MWhe therefore just below the market price.

It shows that the acceptance price and calculation method are consistent. For the BARAKA process and for the NG route, the stack and systems costs are reminded in the table below

			BARAKA	NG route
Stack capacity (electricity)	MW	(1)	17.6	23.1
Plant capacity (electricity)	MW	(2)	23.4	23.4
Stack cost related to the stack capacity	∈/KWe	(1)	650	660
System cost related to the plant capacity	∈/KWe	(2)	2 110	1 700

The stack investment cost in ∈/KWe is the same for BARAKA and NG route as the stack capacity is obtained by the association of 1 MW modules.

The cost of the stack is not much far from the target price for stack : 650 ∈/KWe versus 500 ∈/KWe (30 % higher). The cause for excessive investment cost comes mostly from the Balance of Plant (BOP) as it is much higher than the target price :

- 1 611 ∈/KWe for BARAKA (3 times higher than target price)
- 1 060 ∈/KWe for NG route (2 times higher than target price)

6.4 Possible improvements to the economic situation

It is to be reminded that the price of the stack has been evaluated in accordance to an expected situation in 2005 (stack production capacity : 200 MW/year).

On the other hand the investment cost for the BOP of BARAKA has been determined on the basis of commercial current prices collected in 1999 from suppliers for all the equipment. The BOP cost for the NG route has been estimated by extrapolation of prices based on equivalent equipment existing in the BARAK process or else by evaluation or budget prices when the equipment has no equivalent in BARAKA (the prereformer belongs to this category).

As the stack designed for the BARAKA process (as well a for the NG route) is composed of the association of 1 MWe modules, it will take profit of any improvement of stack manufacturing with no restriction due to the large capacity of the BARAKA process.

For BOP the situation is different : the HTFC expected market is more likely to correspond to power generation system of smaller capacity (500 KW to 1 MW). The equipment comprised in the BOP will take benefit of series production as well as improvements in terms of compacity, manufacturing, standardisation provided that this will be applied to units of small capacity (0,5 to 1 MW) and not to larger ones.

For the UEM application the necessary capacity of the plant represents a drawback as no large series of such plants can be expected with realism within the next 10 years for allowing large reductions of material and manufacturing costs.

It is therefore likely unrealistic to reach in 2005 or even in 2008 the target price of 500 ∈/KWe for the BOP cost related to the capacity considered for the BARAKA process design.

7. CONCLUSIONS

The BARAKA process based on the combination of coal gasification and of an HTFC to produce heat and Electricity in accordance the UEM situation has been designed and evaluated.

- The technical feasibility has been demonstrated provided that the HTFC performances will be demonstrated for a sufficient operating time. The equipment comprised in the balance of plant (BOP) are all commercial product based on mature technologies.
- The economic evaluation of the BARAKA process revealed its low competitiveness due the high investment cost : based on the UEM scenario for the operation of the plant along the year, the cost of the electricity produced by the BARAKA process is far higher than the market price.
- In order to appraise the interest of the coal gasification for supplying the stack with fuel gas, the alternative HTFC process using Natural Gas as fuel was studied. Although this NG route was evaluated with less accuracy than for BARAKA, it allows the reduction of the investment and electricity production of about 20 %.
- The evaluation of the stack cost based on an expected production of 200 MWe in 2005 led to 650 ∈/KWe. This is rather consistent with the acceptance price indicated by HTFC industrial actors : 500 ∈/KWe in 2008.
- The BOP investment cost is the major cause for the low competitiveness of the BARAKA process - and in a lower extend of the NG route. To meet the acceptance price of 500 ∈/KWe for 2008, the BOP cost has to be divided by 2 for the NG route and by 3 for the BARAKA process.
- the stack - even for the BARAKA capacity - can take profit of any future improvements for material and manufacturing as it is composed of elementary modules of 1 MWe which correspond to the capacity

range of the expected future market (0,5 to 1 MWe). The series effect will therefore allow further reduction of the stack cost.

- The reduction of the BOP cost for the BARAKA process is likely to be more difficult as there is low chance to take benefit of series production for equipment of such capacity.
- For NG route the need for BOP cost reduction is less critical but remains important (BOP cost to be divided by 2). The benefit of series production will be profitable to NG route units of smaller capacities.