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Technical note

Economics of combined nuclear–gas power generation

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1. Introduction

Nowadays nuclear energy is facing increasingly stiff competition with other energy sources in many countries. Particularly, in places where gas is available at low prices, combined cycle gas turbines (CCGT) appear as serious competitors against nuclear power plants (OECD, 1993).

Considering the most favorable scenario, assuming 90% load factor and 10% discount (interest) rate, the current cost of the nuclear power results at least 36 mills/KWh. On the other hand, under the same conditions, the cost of gas power generation ranges between 29 and 45 mills/KWh in Europe, and between 20 to 29 mills/KWh in Argentina, where gas is abundant and inexpensive. Clearly, in regions where gas is available at low prices, the electricity generation by means of CCGT represents a formidable competitor against nuclear energy.

One of the major obstacles to the profitability of water-cooled nuclear power plants is the relatively low efficiencies of their thermal conversion cycles. In effect, water-cooled reactors performance is limited by the primary coolant temperature, which cannot exceed 300°C due to materials constraints. Even if the technical limitations could be solved, higher temperatures would require higher pressures, which in turn would increase the capital cost to the point of cancelling any advantage obtained through the efficiency gain. High temperature gas reactors, on the other hand, constitute a good alternative, but currently they are not commercially available.

During the 1960's, when the thermal efficiency and reliability of LWR were still poor, a few nuclear power plants with secondary reheating by means of fuel oil were constructed (i.e. Indian Point 1 in USA, Garigliano in Italy and Lingen in Germany). However, the performance of the combined cycle was questionable, due to low load factors and material failures. Currently the technology of thermal power plants, nuclear and conventional, is more reliable (90% load factors). Consequently, it is reasonable to reconsider the feasibility of combined advanced cycles that produce vapor by means of nuclear power — taking advantage of the lower heating costs — and superheat the secondary flow by means of the exhaust gases coming from gas turbines. Recently, Tsikauri (1996) presented a technical analysis of an alternative proposal for electric power genera-

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tion, which consists of a combined cycle with nuclear and gas thermal power. The concept combines the lower costs of nuclear fuel cycle with the higher thermal efficiency of CCGT. In the present article, the economic assessment of this new generation concept, that ensures higher thermodynamic efficiencies without resigning the reliability of water reactors, is presented.

2. Energy cost analysis

The base case for the assessment of the nuclear power costs was taken from a comprehensive OECD compilation on power generation alternatives (OECD, 1993, 1998). The total cost of a nuclear power plant is partitioned in three components: capital, fuel and operation and maintenance costs. Operation and fuel costs are naturally calculated in terms of mills/KWh. Operation and maintenance costs were taken as 7 mills/KWh (lowest values in OECD, 1998), close to those expected in advanced models (Bruschi and Henderson, 1990). Nuclear fuel costs (6.36 mills/KWh) were calculated based in the AP-600 values (Bruschi and Henderson, 1990; Candlish, 1988). The back-end and decommissioning costs were calculated as the average of the values included in (IAEA, 1994).

The capital cost of a nuclear power plant is usually given in terms of mills/KWe. This value should be distributed in time along the project in order to be compared with the other cost components. Assuming a total operation period of 30 years, the capital cost per KWh is given by:

$$C_{\mathrm{N}}^{\mathrm{c}} = 1510\,\frac{US\$}{KWe}\left(\frac{F_{\mathrm{N}}^{\mathrm{c}}}{8760\,c_{\mathrm{LF}}}\right)\left[\frac{1-\dfrac{1}{1+i}}{1-\left(\dfrac{1}{1+i}\right)^{30}}\right] \tag{1}$$

The factor 8760 in the denominator of Eq. (1) is the number of hours in a year. The value 1510 US$/KWe is in agreement with the expectations for new generation reactors such as AP600 (Farin and Cummins, 1992), and is the minimum value calculated in (OECD, 1998) over a wide range of reactor powers. Taking into account that the construction times can be significantly reduced using advanced engineering (Suzuki et al., 1992), the following cash flow was assumed during five years (Sesonske, 1973): 0.07, 0.04, 0.18, 0.67, 0.04 (i.e. 7% of the capital is spent in the first year, 4% in the second, and so on). The resultant financial cost factor is $F_N^{(c)} = 1.15$. The amortization cost for the capital results 21.35 mills/KWh.

Partitioning the gas energy cost in three components (capital, fuel and operation), the cost of power generation by means of CCGT can be calculated similarly to the nuclear case. Operation and maintenance of CCGT costs were taken as 4 mills/KWh (OECD, 1993), and the value of gas price 2.2 US$/GJ, which is the average value in Argentina (Florido and Bergallo, 1994). The construction costs of the CCGT were taken from (OECD, 1993), about 800 US$/KWe for thermal efficiencies around 46%. The construction was distributed in two years with constant investment, corresponding to a financial cost factor of 1.05. The resulting capital amortization value is 8.22 mills/KWh.

Table 1 shows a comparison of nuclear and gas economic values. It can be seen that the relative cost composition of electric power is different in gas and nuclear generation. In the nuclear industry, operation and fuel costs are relatively low, while construction costs represent the major component of investment. On the contrary, for the CCGT, fuel costs are significantly higher than capital costs. Therefore, the economic competition between both technologies is mostly determined by the current relation between the gas price and the capital cost of nuclear plants, which varies from region to region.

Table 1
Costs comparison of different generation alternatives

Cost component	Nuclear	CCGT	N+G
ε_G	0	1	0.4
Capital [mills/KWh(e)]	21.35	8.2	12.17
O&M [mills/KWh(e)]	7	4	2.79
Fuel + back end [mills/KWh(e)]	8.13	16.8	9.62
Thermal efficiency (%)	32	47	47
Vapor temperature (°C)	271	450	450
Total [mills/KWh(th)]	11.63	13.65	11.55
Total [mills/KWh(e)]	36.35	29.05	24.58

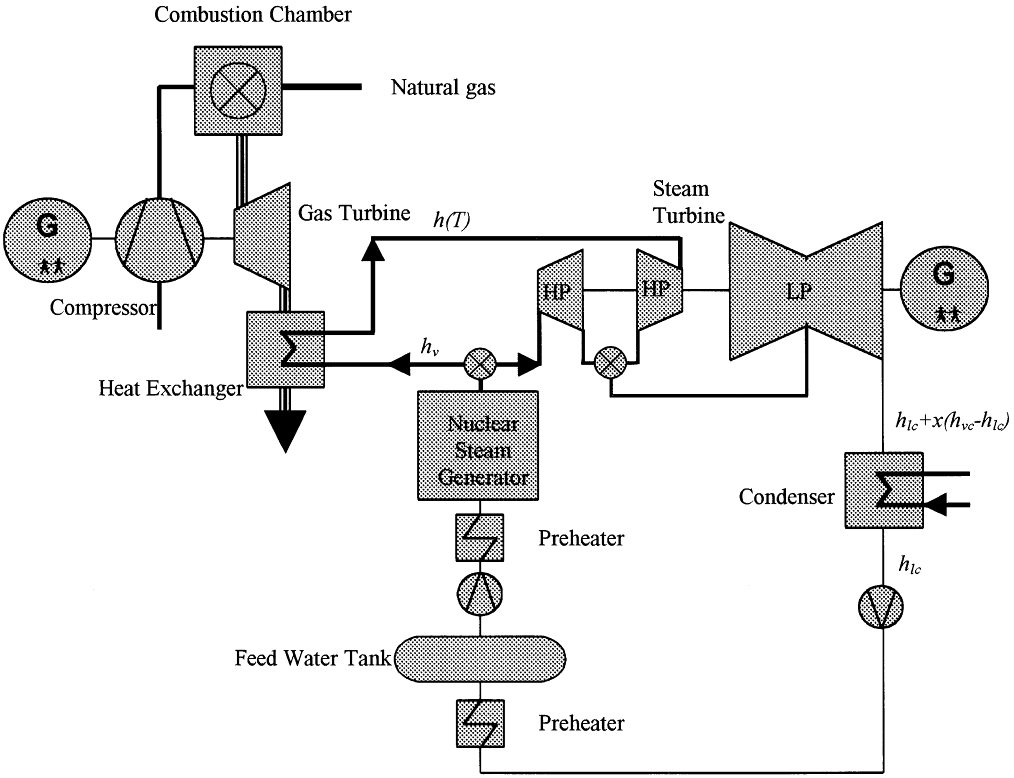

Fig. 1. Diagram of the combined nuclear–gas thermal cycle.

A significant observation is that the nuclear cost per thermal KWh is lower than the corresponding to the gas, indicating that the nuclear generation is still the cheapest heating technology. Nuclear energy looses the game when the heat is converted in electricity.

3. The combined nuclear–gas cycle

Let us consider a thermodynamic cycle, which generates vapor by means of nuclear power — taking advantage of the lower thermal costs — and superheats the secondary flow by means of the exhaust gases coming from gas turbines — seeking for higher energy conversion efficiency. From the economic point of view, two effects are produced by the combination. On the positive side, due to the higher efficiency of the overall cycle, the effective power output of the combination is larger than the summation of the outputs of both sources operating separately. However, the total cost is also larger than the individual costs of the sources, for the combination generates extra costs. The objective of this section is the analysis of the balance of this economic scenario.

3.1. Thermodynamics of the nuclear-gas power cycle

Consider a pressurised water reactor connected to a steam turbine that generates electric energy by means of a Rankine thermal cycle. The electrical power output of the turbine is given by:

$$P_{\mathrm{N}}(h_v) = \dot{m}[h_v - x(h_{vc} - h_{lc}) - h_{lc}] \tag{2}$$

The main idea of the nuclear–gas combination is to take advantage of the exhaust gases coming out from a gas turbine, to superheat the secondary steam (Fig. 1). In such a situation, the electrical power output of the nuclear steam turbine is increased to:

$$P_N = \dot{m}[h(T) - x(h_{vc} - h_{lc}) - h_{lc}] \tag{3}$$

The superheated temperature, T, that can be reached depends on the amount of heat that is possible to transfer from the exhaust gases from Brayton cycle turbine outlet to the steam. This operation should be performed by means of a heat exchanger. The stored heat carried by the exhaust gases is proportional to the temperature difference between the gases and the environment. The fraction of this energy that can be used to superheat the vapor is given by Cigarini and Dalle Donne (1988) and Dalle Donne and Hame (1982):

$$f(T) = \frac{(T + \Delta T_{in}) - (T_{sat} + \Delta T_{out})}{T + \Delta T_{in} - T_{env}} \qquad \text{(T in K)} \tag{4}$$

For typical gas turbines (Hines et al., 1994), $f(T)$ is about 0.42. This should be taken as a conservative value, since the remaining gases can still be used to preheat the feedwater to the steam generators. The corresponding electrical output of the gas turbine required to provide the energy fraction $f(T)$ can be calculated by energy conservation, that is:

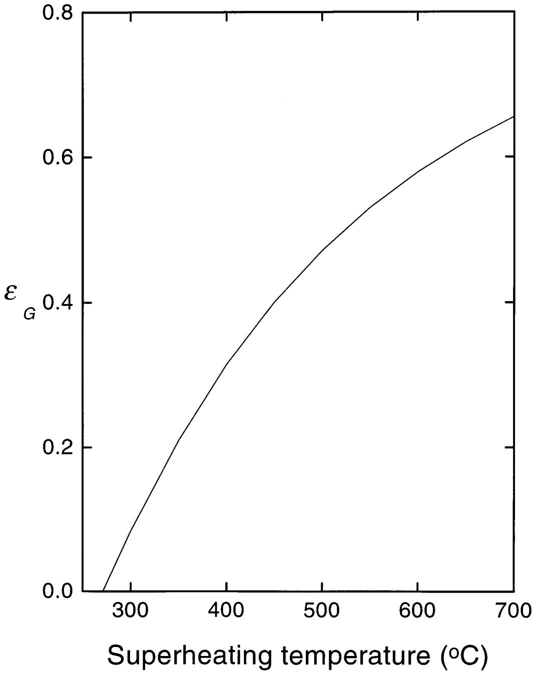

Fig. 2. Gas energy shear required for superheating the nuclear secondary system.

$$P_G(T) = \frac{P_N(T)}{\eta_v}\left(\frac{\eta_G}{1 - \eta_G}\right)\frac{\left(\dfrac{h(T) - h_v}{h_v - h_{lc}}\right)}{f(T)} \tag{5}$$

In Eq. (5), the efficiency of the vapor cycle, η_v, is given by:

$$\eta_v = \frac{h_v - x(h_v - h_{lc}) - h_{lc}}{h_v - h_{lc}} \tag{6}$$

and η_G is the gas turbine efficiency. Fig. 2 shows the relative contribution of the gas source to the total power of the combination, defined as:

$$\varepsilon_G = \frac{P_G(T)}{P_G(T) + P_N(h_v)} \tag{7}$$

3.2. Cost analysis of the nuclear–gas combination

The total cost of a combined nuclear-gas plant is the summation of each individual cost taken separately, plus an extra cost accounting for the additional equipment required by the effective combination. Therefore, the cost of the combined nuclear-gas plant can be written as:

$$C_{N+G} = \frac{C_N P_N(h_v) + C_G P_G(T) + C_C[P_N(T) - P_N(h_v)]}{P_N(T) + P_G(T)} \tag{8}$$

The extra costs generated by the combination are mainly the capital costs of the additional equipment — the extra maintenance cost being negligible compared with the nuclear operation costs. The corresponding extra costs are given by:

$$C_C = 510\,\frac{US\$}{kWe}\left(\frac{F_G^c}{8760 c_{LF}}\right)\left[\frac{1 - \left(\dfrac{1}{1+i}\right)}{1 - \left(\dfrac{1}{1+i}\right)^{30}}\right] \tag{9}$$

In Eq. (9) the time distribution of the investment and the financial cost factor are the same as the CCGT. The value 510 US$/KWe of the additional equipment is recommended in OECD (1993).

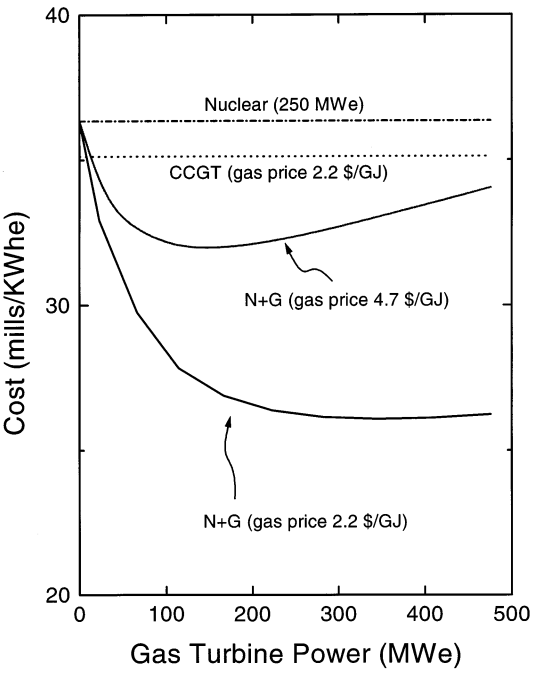

Fig. 3. Energy cost of a combined nuclear–gas plant.

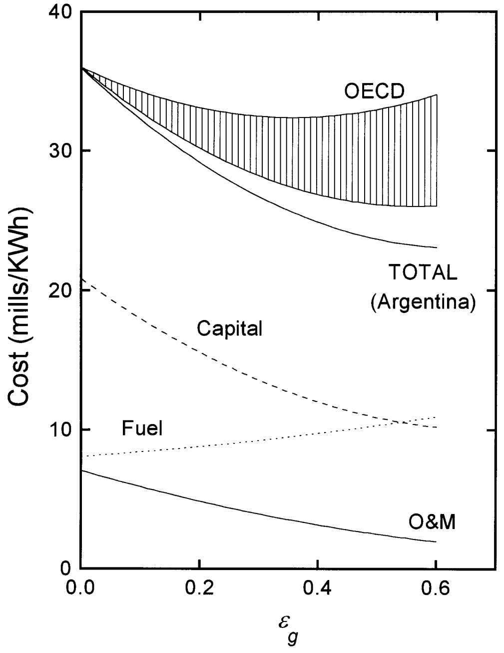

Fig. 4. Effect of the gas contribution in the energy generation cost.

The cost composition of the combined cycle (60% nuclear, 40% gas) is shown in Table 1 and compared with separate nuclear and gas plants of the same power. It is observed that the capital and fuel costs are balanced in the combined plant, resulting in a better economic alternative. Fig. 3 shows the energy cost of a 250 MWe nuclear source, combined with different gas turbine contributions. It can be seen that it is possible to reach energy costs lower than the individual sources. There is a minimum in the cost, which reflects the point of optimum balance between the efficiency gain and the combination cost.

One may question the sensibility of the results shown in Table 1 to the changes that the gas price may experience during the nuclear plant lifetime. The question is valid, but one has to remember that with 10% annual discount rate (OECD, 1998), any change beyond 5 years is damped, and consequently only the near future variations affect the net present value.

It is interesting to analyze the cost composition of the combined generation in terms of the relative contributions of each power source. The economic impact of the gas energy share ε_G is shown in Fig. 4. The calculation was performed for low gas prices — 2.2 US$/GJ in Argentina (Florido and Bergallo, 1994) — and OECD values — 2.9 to 4.7 US$/GJ. Note that if the gas price is high, the optimum ε_G does not correspond to the highest superheating, but to the situation where the impact of the lower nuclear costs and the gas thermal efficiency is maximum. A similar feature is observed if the calculation is performed varying the construction cost of the nuclear plant while keeping constant the gas prices.

Comparing the combined nuclear-gas cost with the individual gas and nuclear costs, it is possible to determine the best generation alternative. Fig. 5 shows the position of different countries in a map of competitivity regions. The gas prices and construction costs of nuclear plants corresponding to each country are plotted in a two dimensional graphic, where the best alternative for power generation can be visualized by zones (i.e. indicating the lowest energy cost). Interestingly, most of the countries fall in the region where the combined nuclear-gas cycle is more competitive. The dashed line indicates the competitivity boundary without taking into account the combined option, that is comparing nuclear against gas separately. The conclusion of this figure is that the competitivity between both energy sources is determined by the gas price. Wherever the gas is expensive, nuclear power plants would be recommended; whereas in regions where gas is available at low prices, CCGT are preferable. The combined nuclear-gas cycle appears as the most convenient alternative in the range of moderate gas prices. Presently, countries like the UK and Argentina are constructing CCGT since it is the best available option comparing with nuclear. It is worth noting that this scenario may change completely if the combined nuclear–gas cycle is seriously considered as a feasible power generator.

4. Conclusions

An assessment of the economy of combined nuclear–gas power plants was presented. The combined thermal cycle is viewed as a convenient 'strategic alliance' between both types of fuels (nuclear and natural gas), which offers an alternative of electric power generation at lower costs. It was shown that the dominant economic parameters are the gas price and the capital costs of nuclear power plants.

Contrary to the trends followed from classical assessments of nuclear and gas power generation taken separately, the maximization of the superheated temperature was not found to be a good design criterion. In dealing with situations where gas prices are high, the optimum superheating can result lower than the technically achievable.

Moreover, within rather wide cost ranges, the combination of nuclear and gas presents interesting possibilities to successfully compete in the near future electric market.

Appendix A. Nomenclature

C_C	costs generated by the combination
C_G	gas energy cost taken separately
C_N	nuclear energy cost taken separately
C_N^c	capital cost of a nuclear power plant, Eq. (1)
c_{LF}	load factor, 0.9
$f(T)$	fraction of energy available for superheating, Eq. (4)
F_G^c	financial factor of the capital cost of CCGT, 1.05
F_N^c	financial factor of the capital cost of a nuclear power plant, 1.15

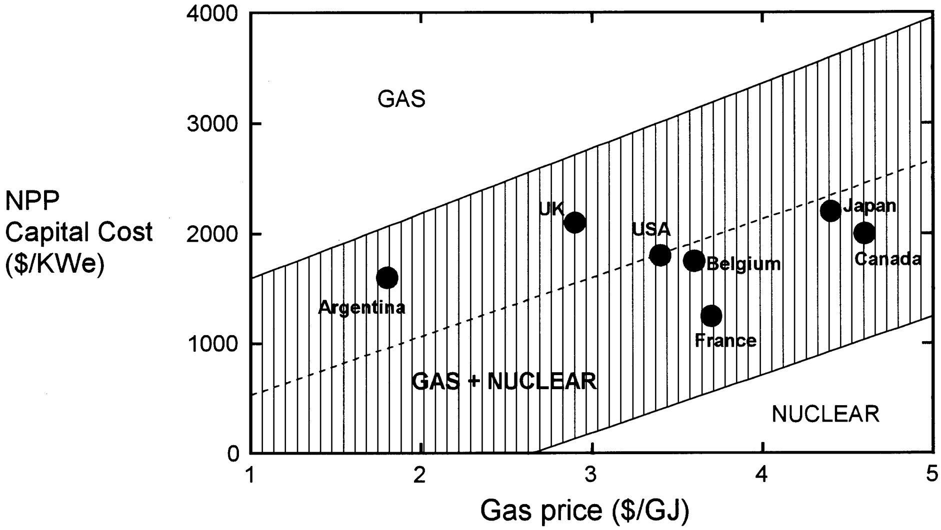

Fig. 5. Competitivity map showing the most convenient energy generation alternative.

$h(T)$	superheated vapor enthalpy, 3312 KJ/kg at 450°C
h_v	saturated vapor enthalpy exiting the steam generator, 2803 KJ/kg
h_{lc}	saturated liquid enthalpy in the condenser, 132.8 KJ/kg
h_{vc}	saturated vapor enthalpy in the condenser, 2560 KJ/kg
i	annual discount rate, 0.1
$\dot{m}$	secondary flow rate
$P_{\mathrm{G}}(T)$	electric power generated by gas means, Eq. (5)
$P_{\mathrm{N}}(h_v)$	electric power generated by nuclear means without superheating
$P_{\mathrm{N}}(T)$	electric power generated by nuclear means with superheating
T	superheated vapor temperature
T_{env}	temperature of the environment, 27°C
T_{sat}	saturation temperature, 271°C
x	turbine exit quality, 0.85
ΔT_{out}	exit temperature jump in the heat exchanger, 88°C
ΔT_{in}	inlet temperature jump in the heat exchanger, 150°C
ε_{G}	gas energy share, Eq. (7)
η_{G}	gas turbine efficiency, 0.32
η_v	vapor turbine efficiency, Eq. (6)

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