NATURAL GAS TURBINE TOPPING FOR THE IRIS REACTOR

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ABSTRACT

Nuclear power plant designs are typically characterized by high capital and low fuel costs, while the opposite is true for fossil power generation including the natural gas-fired gas turbine combined cycle currently favored by many utilities worldwide. This paper examines potential advantages of combining nuclear and fossil (natural gas) generation options in a single plant. Technical and economic feasibility and attractiveness of a gas turbine – nuclear reactor combined cycle where gas turbine exhaust is used to superheat saturated steam produced by a low power light water reactor are examined.

It is shown that in a certain range of fuel and capital costs of nuclear and fossil options, the proposed cycle offers an immediate economic advantage over stand-alone plants resulting from higher efficiency of the nuclear plant. Additionally, the gas turbine topping will result in higher fuel flexibility without the economic penalty typically associated with nuclear power.

INTRODUCTION

The idea of combining nuclear and fossil heating in one thermodynamic cycle is by no means new. Additionally, mixing of "nuclear" and "fossil" (produced in a heat recovery steam generator of a Gas-Turbine Combined Cycle, CCGT) steam streams was proposed recently as a way to gradually phase-out nuclear power and/or de-rate nuclear steam supply systems.

Fossil superheating of initially saturated nuclear steam was demonstrated in two nuclear plants. Indian Point 1, a B&W built PWR with 275 MWe gross capacity was operated from 1962 to 1974. The maximum secondary steam temperature was 271 °C. It was raised to 540 °C at the turbine inlet at 2.6 MPa. 163 MWe of the gross output were attributed to the nuclear reactor, with the oil fired super-heater adding 112 MWe. An efficiency improvement of about 21% was predicted and demonstrated, and a Cost of Electricity (COE) reduction of ~25% was predicted [1]. The plant has suffered several technical failures, but the only failure associated with

the fossil fuel super-heating was due to the poor integration of the super-heater and turbine [1].
Another plant with fossil super-heating (a 240 MWe BWR) was built in Lingen, Germany, achieving an efficiency improvement of nearly 33% [2].

While oil or coal burning topping cycles are hardly acceptable option at this time as the obtained efficiency gain is below that achievable in stand-alone plants, gas turbine exhaust appears to be very suitable for super-heating nuclear steam. In this scheme the nuclear steam generator effectively replaces the Heat Recovery Steam Generator (HRSG) boilers of a combined cycle. This would lead not only to a higher efficiency of converting "nuclear" heat, but also allow for a better use of GT exhaust gases because of (a) the HRSG approaching an ideal heat exchanger and (b) stack temperature reduction.

On the other hand, a slight reduction in the efficiency of converting GT exhaust is expected due to the use of single pressure steam cycle in contrast with a modern three pressure cycle with re-heating.

The objectives of this work were to quantify the resulting overall system conversion efficiency, and assess the range of thermodynamic, market and plant performance parameters that would make the described nuclear-fossil combined cycle economically attractive.

LOW POWER LIGHT WATER REACTORS (LWRs)

In recent years a growing interest has been directed to small power reactors as opposed to 1000 MWe and above class plants. The major drivers for this phenomenon are deregulation, financing considerations and grid requirements in developing countries. Most of such LWR designs employ integral primary circuit that allows for higher safety, lower capital investments and better performance, but limited to reactor thermal power of about 1000-1200 MWt. Examples of such designs include SIR [4], CAREM [5], NILUS [3,6], SMART [7] and IRIS [8,22]. In this paper, IRIS is used as an example of low power integral PWR.

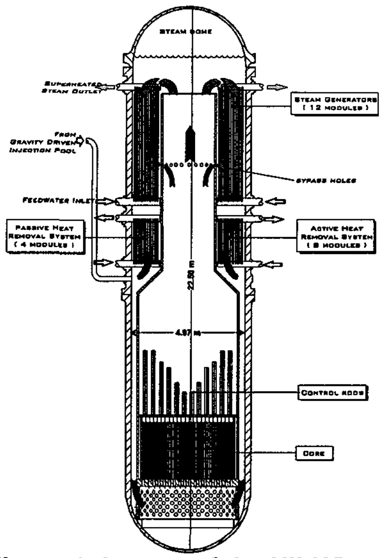

Figure 1: Layout of the NILUS reactor

In addition to increasing plant efficiency, a Gas fired super-heating would also have a positive effect on the plant capital cost. In a typical integral reactor, Steam Generators (SGs) are once-trough, and located inside the Reactor Pressure Vessel (RPV). Because of the need for a high heat transfer surface area, and the limited space available in the RPV annular region, SGs account for ~1/3 of the RPV height. If no steam drums are employed in conjunction with once-trough SGs, a significant superheating of the steam will be required to achieve the necessary dry steam at the turbine inlet. The use of a fossil fueled superheating would lead to a 1/3 reduction of in the SGs heat transfer surface area, an overall RPV height reduction of around 10% and a corresponding overall plant capital cost reduction. Beside this potential reduction in the SGs heat transfer area, another advantage from the point of view of capital costs for the Nuclear plant would be given by less demanding conditions for the turbine than those achieved is the typical nuclear saturated steam cycle.
Since the evaluation of this capital cost reduction is beyond the scope of this work, it has instead been considered that keeping the same heat transfer surface the secondary side pressure can be risen (maintaining the same primary fluid thermodynamic conditions), so to improve efficiency. From a rough preliminary calculation, it has been evaluated that in this case the secondary side pressure could be risen from 70 bar to 80 bar without having to increase the SGs surface.
Additionally, a low power nuclear reactor is perfectly compatible with the size of modern Combined Cycle Gas Turbine (CCGT) plants. For example, in a 400 MWe CCGT, ~1/3 of the power is produced by the steam cycle.

REFERENCE CCGT AND IRIS PLANTS

For the purpose of this analysis of a Combined Cycle (CCGT) plant a GE- Frame 9F Gas Turbine has been considered [9]. The Lower Heating Value (LHV) for the plant is 687 MWt, of which 50.6 MWt is discharged with the stack gases and 380 MWt are introduced in the steam cycle. The gross GT output is 256.4 MWe. GT exhaust and stack temperatures are 611 °C and 90 °C, respectively. The bottoming steam cycle produces 113.5 MWe at a gross efficiency of 35.1%. A three-pressure cycle with reheat is used: 77kg/s of steam are produced at 130.8 bar and 541 °C, then expanded in the high-pressure turbine to 28 bar and 323 °C. This steam is mixed with the steam from the intermediate pressure boiler and thus 91 kg/s of steam are produced at 26 bar and 540 °C and introduced in the medium and low-pressure turbine. 8.9 kg/s of steam are produced at low pressure (4.7 bar and 266 °C). The steam is then condensed at a back-pressure of 0.05 bar (32.8 °C).

Typically, triple-pressure cycles are used in CCGT to minimize stack losses. For the same reason, a significant difference between CCGT and typical steam cycle is that in a steam cycle the feed-water temperature is kept as high as possible through multiple stages preheating, while for CCGT the feed-water temperature is instead kept as low as possible to maximize stack utilization [14].

Usually feed-water temperatures of about 60 °C are used in CCGT, in order to keep the temperature as low as possible. The net power output of the plant being considered is 375 MWe and net efficiency is 54.6%.

For the IRIS-type integral LWR, a thermal power of 454 MWt, steam pressure of 7.0 MPa and 25 °C of superheating are assumed. A typical regenerative scheme with 5 turbine extractions is considered. The regenerators bring the feedwater from a condensation temperature of 32.8 °C to that corresponding to 80% of the difference between the condensation and saturation enthalpies.

To evaluate the efficiency of steam cycles the data from figure 2a and 2b obtained in POLIMI and based on Ref.10 have been used. Figure 2a is used for simple steam cycles with no regeneration and no re-heating. These curves have been tested with data from several other sources [14, p. 37] and with the TURBOGAS code, developed in the Polytechnic of Milan for CCGT plant analyses. Figure 2b instead is used for regenerative cycles, and the data have been tested with several data from nuclear plants and coal plants. According to Figure 2b, an estimated efficiency of a stand-alone IRIS-type plant is 34.2%. The corresponding total net power is 155.48 MWe.

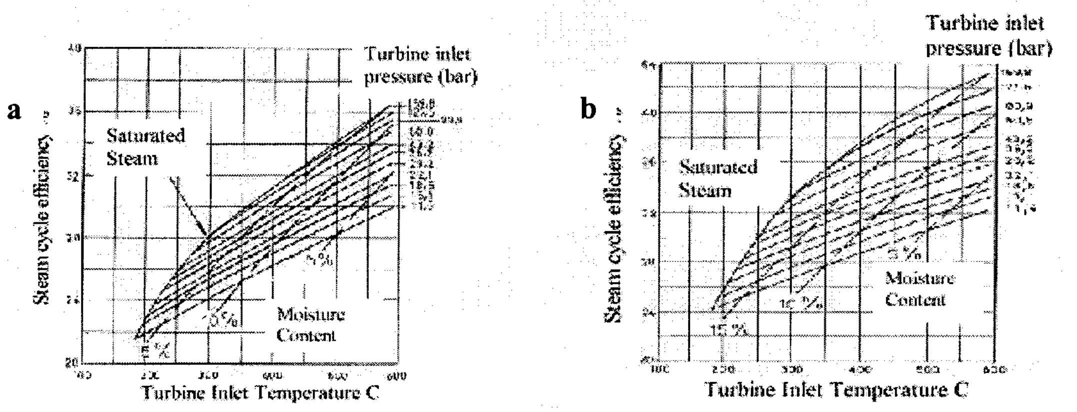

Figure 2: Efficiency for a simple steam cycle and for a typical regenerative cycle.

THERMODINAMIC ANALYSIS OF THE COMBINED NUCLEAR AND GAS PLANT (CNGT)

First, CNGT Balance of Plant (BOP) is assessed. A condensation pressure of 0.05 bar (32.8 °C) is assumed. In a typical regenerative cycle the feed-water is heated up to 80% of the enthalpic jump between condensation and saturation temperatures through regenerative heaters. The typical bottoming cycle of a CCGT instead is a simple, not regenerative cycle. In the CNGT plant it will be considered that part of the water will be heated by the exhaust gases (in a Low Temperature Economizer (LTE)) and part through a regenerative cycle.

Figure 3 illustrates a possible scheme of the CNGT plant: the condensate is preheated in a series of low-pressure regenerative pre-heaters and in a condensate pre-heater that recovers low temperature heats from the exhausts. The condensate is then sent to a deaerator and then the feed water is sent to another preheating stage, partially completed in the LTE and partially through multiple stage pre-heating with steam extracted from the turbine. The feedwater then enters the HTE (High Temperature Economizer) and the Nuclear SG, and the steam is then superheated to 550 °C in the HRSG.

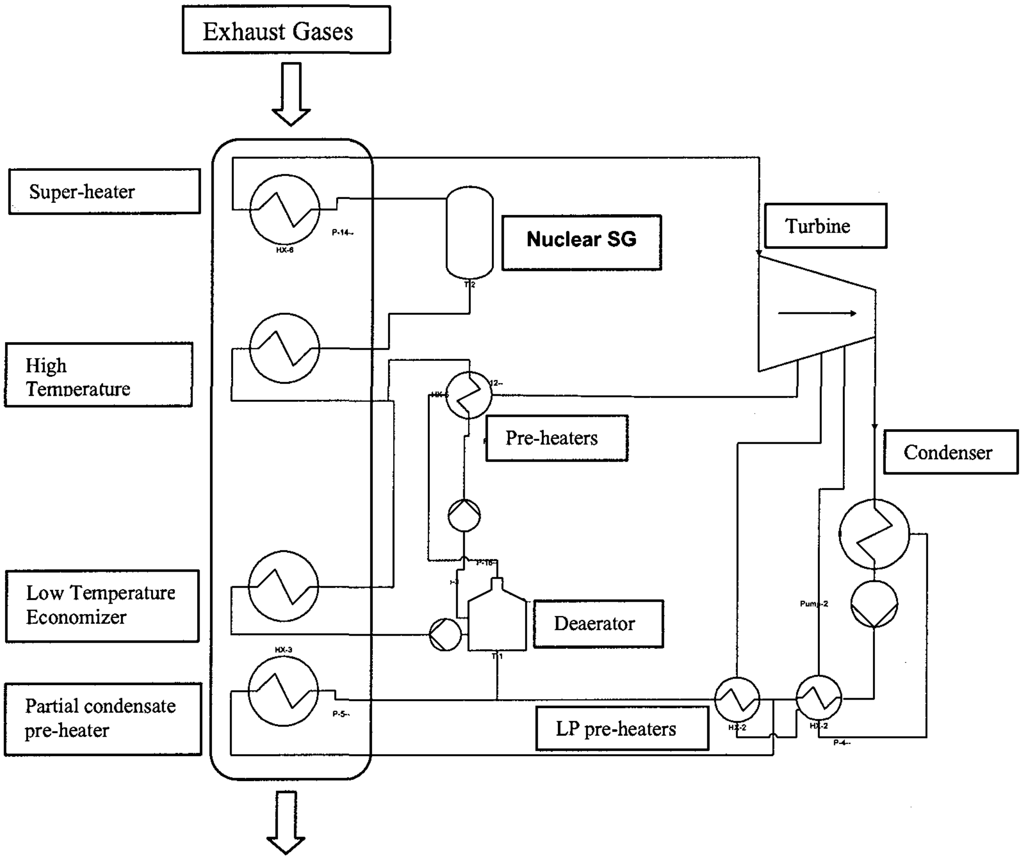

Figure 3: Conceptual scheme of the CNGT

For the purpose of the analysis simplification, two separate cycles are considered in the thermodynamic analysis. One cycle is a typical regenerative cycle, with five turbine extractions, while the second one is a non-regenerative cycle, typical of Gas stations. A HTE, the nuclear boiler and the super-heater are in common for both "cycles".

CNGT will allow to recover more heat from the stack: in a typical CCGT plant the heat recovery from the exhaust gases is limited by the amount of steam produced in the boiler and super-heater, which in turn is limited by the total power that is extractable from the combustion products at temperatures higher than the saturation steam temperature.

In the CNGT plant the high temperatures gases are used only to super-heat the steam so that a greater amount of steam can be produced, and thus should allow for a complete recovery of the exhaust gases heat. We will assume that the stack will be discharged at the chimney at 60 °C, and this assumption will be verified in the remaining part of this analysis (i.e. it will be verified that the heat recovered in the economizer is lower than the heat needed to heat the water up to 250 °C).

A feed-water temperature for the LTE of 50 °C is considered, and assumed to be well higher than the water dew point (a sulfur-free fuel is considered). This leads to a better exploitation of the heat of the exhaust gases, and an introduction in the cycle of another 25.0 MWt.

The fumes from 611 °C to 310 °C are used to superheat the steam, from 310 to 260 °C in the HTE and from 260 to 60 °C in the preheating of water. The power introduced in the super-heater, in the HTE, in the LTE and discharged at the chimney is easily calculated (considering a typical exhaust gases composition) as:

	Exhaust gases temperature	**Total Power exchanged**
Super-heater	611-310 °C	224 MWt
HTE	310-260 °C	36.1 MWt
LTE	260-60 °C	144.9 MWt
Chimney discharge	60 °C	25.6 MW
Total		430.6 MWt

224 MWt are sufficient to superheat (at the given conditions) 293.6 kg/s of water, which is the overall mass flow rate in the cycle. In the HTE the 36.1 MWt allow to rise the enthalpy of the water from 1088 kJ/kg (80bar, 250 °C) to 1211 kJ/kg (80bar, 276 °C), and thus the HTE outlet water temperature is 276 °C.
The needed power input from the IRIS reactor would thus be the power needed to bring water from an enthalpy of 1211 kJ/kg (80 bar, 276 °C) to 2759 kJ/kg (saturated steam at 80 bar) 293.6 kg/s of water.
Therefore the thermal power output of the IRIS reactor coupled with this GT should be (at least for this configuration) 454 MWt.

In the simplified scheme, it can be easily evaluated that 166.2 kg/s of water are produced in the LTE, while the remaining 127.4 are produced in the regenerative heat exchangers. The efficiency connected to each of the two virtual cycles is therefore (from figure 2a and 2b) respectively 34.5% and 41.1%. The efficiency of the overall cycle can be evaluated as:

$$34.5 * (166.2/293.6) + 41.1*(127.4/293.6)=19.54+17.83= 37.37\%$$

Thus the total produce power from the steam cycle will be 321MWe, and the total net power produced by the combined nuclear-gas plant is 562.5 MWe, against 530.48 MWe of the separate option, with an improvement in overall energy production of 32.02 MWe or 6.03%.

If we assume no modification in the Gas part, this is equivalent to having increased the nuclear energy production by 20.5%.

A detailed analysis of the steam cycles and above all a detailed model of the BOP will be needed to confirm these results, but the results is very interesting and worth of further investigation.

ECONOMICAL ASSESSMENT

The DOE Power Generation Cost Methodology as defined in the DOE report "Nuclear Energy Cost Data Base (NECDB)" [11] and in the ORNL report "Cost Estimate Guidelines for Advanced Nuclear Power Technologies (CEG)" [12] has been used to evaluate CNGT Cost Of Electricity (COE). The NECDB methodology was developed for fission reactor studies, but it also provides a consistent basis for the evaluations of other power generation options.

All costs are expressed in constant 2000 dollars. The main financial assumptions are based on ORNL TM/109 report [13] and summarized in Table 1.

For the availability of CCGT plants, a range between 86-93% is assumed [14]. For ALWR (such as, for example, AP600), the projected availability is ~90%. Even higher availability rates are foreseen for integral reactors due to the simplification of the plant. For the purpose of the present analysis, an availability rate of 90% and capacity factor of 85% has been considered for both plants.

This study will compare different power generation alternatives for plants going in operation in 2010. Due to the small size of the plant and the high level of modularization and standardization of integral reactor plants, construction time of 33 months years is assumed.

Capacity Factor		85%
Design and construction times		
CCCT	**(months)**	33
Nuclear plant	**(months)**	33
NCGT	**(months)**	36
Plant Life	**(years)**	30
Levelization period	**(years)**	30
Reference cost year		2000
Year of plant startup		2010
Average inflation ratio		3%
Escalation factor		3%
Weighted Average Cost of Capital		
Capitalization		
	Debt	47%
	Preferred stock	6%
	Equity	47%
	Debt interest rate	7.40%
	Preferred stock dividend	6.90%
	Return on equity	12.00%
Income tax rates		
	Federal	35%
	State	6%
	Combined tax rate	38.90%
Cost of money during construction		9.53% Real(*): 6.34%
Effective cost of money (including taxes)		8.18% Real(*): 5.03%
Property tax rate		2.0%
Yearly Interim Replacement Rate		0.5%

(*) Inflation adjusted parameters

Table 1: Main Financial Assumptions

Capital cost

CCGT capital cost has been derived from [14] and [15], and has been verified with other industrial data for plants both in Europe and in the US to be ~550$/kWe. A range of capital cost from 1000 to 2000 $/kWe has been considered for the nuclear installation to reflect the corresponding uncertainty. 1000 $/kWe is the capital cost objective of both conventionally sized and small power advanced reactors (IRIS, AP-

1000), 1500-1700 $/kWe is representative of ALWR plants like EPR, AP600 [15] and SIR [4] cost estimates. 2000$/kWe is assumed to represent the most conservative estimate [15,13]. CNGT capital cost has been assumed to be the sum of the capital costs of the two installations. This is a conservative assumption since a possibility of common facilities and structures should allow for a reduction in the capital cost of the combined plant. It must be stressed, however, that for safety reasons the two installations must be kept separate, so to prevent accidents in the gas part of the plant leading to a nuclear accident. Preliminary estimates [16] indicate that a distance of 1km is sufficient. The conservative assumption made in this study is that the cost of connecting the two parts and the associated losses will balance the savings from the shared structures and facilities.

Fuel cost

Although some low power integral reactors such as IRIS are being designed to achieve a long life core and therefore will require a different enrichment and core design than current PWR, only a standard refueling cycle [13] typical of other designs has been considered.

In 1998 DOE/EIA projected [17] natural gas price between 2.9 and 3.5 $/MBtu for 2010 Figure 4. However, as shown in Figure 5 [18], the price of natural gas in the US has dramatically increased during the last year.

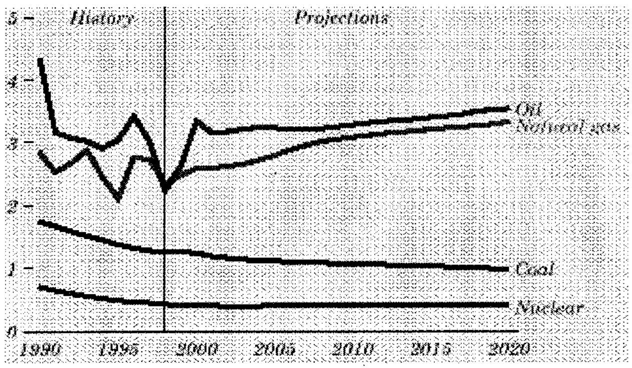

Figure 4: Fuel prices forecasts for 2000-2020 (1998 dollars per million Btu) [7]

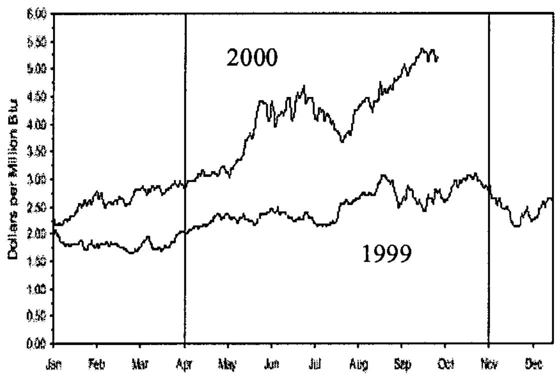

Figure 5: Historical Gas price for 1999-2000 [18]

In the following analyses a range of natural gas average yearly price between 2 and 5 $/MBtu has been considered to reflect the high degree of uncertainty connected to these forecasts.

Operation and maintenance

A fixed O&M cost of 28.1 $/kWe per year and a variable cost of 0.5 mill/kWh are assumed [13,14] for the CCGT plant. For a typical ALWR, Reference 13 suggests a fixed cost of 57.6 $/kWe and a variable cost of 0.4 mill/kWh. The overall O&M cost is also in good agreement with [14] and represents Best Experience nuclear plants currently in operation [19].
It is assumed that lower complexity and higher relative staffing requirements of integral plants will balance each other, and operating costs typical of ALWR are used. This should be a conservative assumption, especially in the "multiple units on the same site"scenario.

For the CNGT plant, the same overall O&M cost has been considered. This leads to a lower cost per kWh due to the higher efficiency of the system.

Decomissioning

Decommissioning costs have been considered only for the nuclear installation. Integral type reactors are smaller than state-of-the-art PWR plants now available on the market and this should lead to higher decommissioning costs on the basis of per kWe of installed capacity. However, the compact primary circuit and the reduced activation of the vessel are expected to significantly reduce decomissioning costs. For this study a decomissioning cost of 0.8 mill/kWh has been adopted [13].

ECONOMICAL ANALYSIS AND CONCLUSIONS

The described above technical and economic assumptions regarding plant performance and market conditions were used to estimate CNGT COE. For consistency, COE for stand-alone CCGT and Nuclear Plants (NP) were also estimated on the same basis (Figure 6).

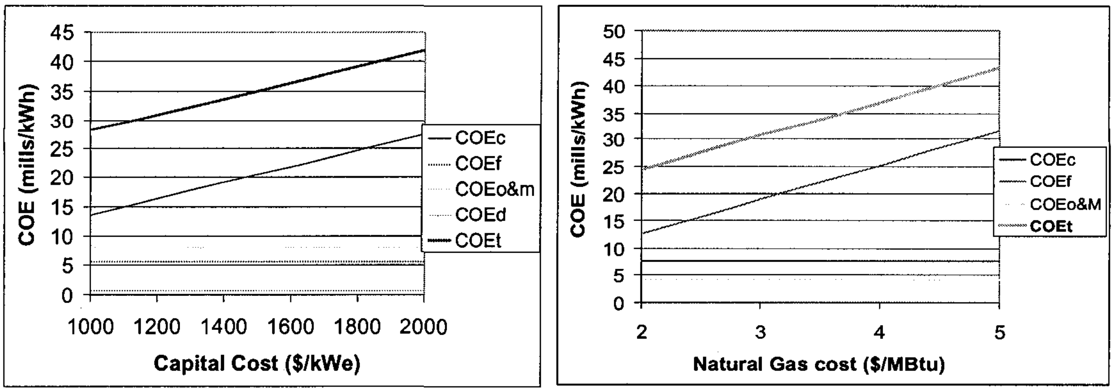

Figure 6: Total, COE_t, and capital, COE_c, fuel, COE_f, and O&M, $COE_{O\&M}$, contributions for NP as a function of capital cost and for CCGT as a function of Natural Gas price.

In line with conventional wisdom of the last years and historical data [20,21], nuclear plants at any capital cost in the range from 1200 $/kWe to 2000 $/kWe are not competitive with CCGT and the price of natural gas that prevailed in the last years

(~2-2.5 $/MBtu). If the gas price remains at the level of 1998-1999, nuclear power becomes competitive with CCGT only at capital cost below 1100 $/kWe.
To evaluate COE of the CNGT, three different nuclear plant capital cost scenarios were considered: a low capital cost (1000 $/kWe) expected for AP1000 and IRIS-type plants, an intermediate case (1600 $/kWe) typical of ALWR and a high capital cost (2000 $/KWe or more), typical of present day nuclear plants. The results are summarized in Figures 7 - 9.

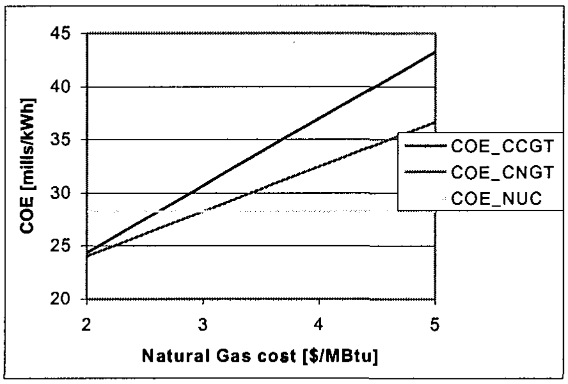

Figure 7: COE for NP, CCGT and CNGT in the low nuclear power capital cost scenario {NP Capital cost of 1000$/kWe}

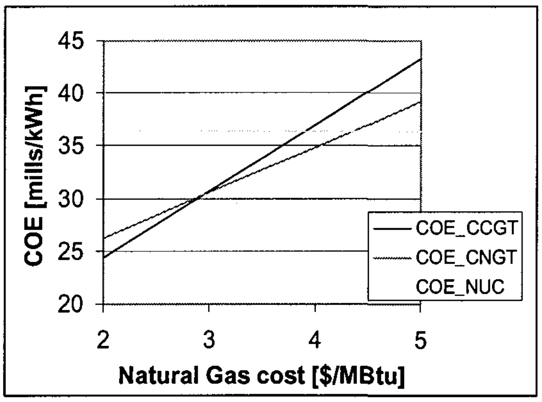

Figure 8: COE for NP, CCGT and CNGT in the intermediate nuclear power capital cost scenario {NP Capital cost of 1600$/kWe}

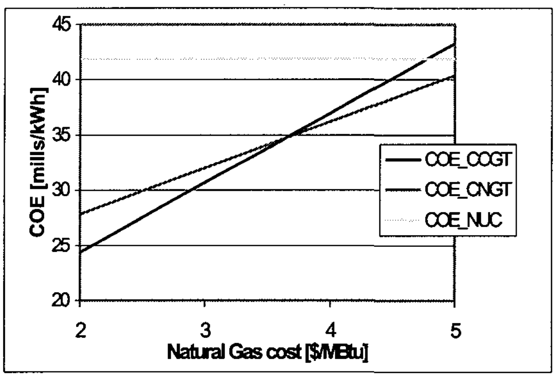

Figure 9: COE for NP, CCGT and CNGT in the high nuclear power capital cost scenario {NP Capital cost of 2000$/kWe}

For the low NP capital cost (Figure 7), the lowest COE is achieved with the CNGT plant for a cost of gas below 3 $/MBtu, while for higher cost of gas, the self-standing NP is the best option. In this scenario, the self-standing CCGT does not appear to present any convenience over the CNGT. However, for very low natural gas price (around 2 $/MBtu) the difference in the COE between the CNGT and the CCGT is minimal and well within uncertainties of the analysis.

At a high NP capital cost (>1600 $/kWe), the CCGT remains the best option for low gas prices (between 2-3 $/MBtu), while the CNGT plant becomes competitive for gas price in the range 3-4 $/MBtu. For even higher gas price, a self-standing NP becomes competitive.

Finally, for the high NP cost scenario (Figure 9) the self standing CCGT remains the most economical way of producing electricity for Gas prices up to around 4 $/MBtu, while the CNGT plant becomes competitive for higher gas prices.

As one would expect, the CNGT COE is less sensible to the natural gas price as compared to the self-standing CCGT. This will lead to reduced risk associated with the natural gas price. At the same time, CNGT reduces the initial investment requirement and associated financial risk as compared to a self-standing NP.
Another advantage of the Nuclear–Gas coupling whose effect on the COE is not easily quantifiable is the reduction of CO2 production per kWh compared to a stand-alone CCGT. On the negative side, it must be stressed that the previous comparison does not take into consideration the complications of the technical management for a system consisting of two completely different technologies and with two different fuels.

The Fundamental requirement for this solution to become interesting is of course that NPs are effectively able to achieve the Capital Cost reduction promised by several advanced concepts.

SUMMARY

The possible economical advantage of a Gas Turbine coupling with a small sized nuclear plant has been investigated. A simple BOP model has been proposed for preliminary thermodynamical evaluations, and an economical comparison of CCGT, NP and CNGT plants have been developed for different gas price and nuclear capital cost scenario.

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