Efficiency Increase and Environmental Benefits of Using A Gas Turbine Hybrid Cycle in Mount Amiata Geothermal Area

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ABSTRACT

A hybrid cycle scheme is described, integrating a gas turbine unit firing natural gas and a geothermal power plant. Gas turbine exhaust is used to superheat geothermal steam and, possibly, to feed a bottoming binary unit. The proposed cycle can retrofit existing geothermal plants and displays efficiencies (referred to fossil fuel use) comparable to those typical of large-size combined cycle plants.

In the situation of Mount Amiata deep geothermal fields, other favorable features of this scheme include the possibility to take advantage of the water separated at wellhead. Of foremost importance, however, is the option of using the noncondensable gas discharged by the geothermal plant, mixed with the inlet air, to feed the gas turbine. Oxidation of hydrogen sulfide to sulfur dioxide can thus be cheaply accomplished, with an added efficiency increase.

Technical aspects arising from the proposed scheme are discussed, and preliminary economic evaluations are presented.

Introduction

Integrating a geothermal power source in a fossil fuel plant is not a technical novelty since many such proposals are found in the literature (Khalifa, 1980; Tiangco et al., 1996). However, despite its theoretical advantages (at least thermodynamic), no hybrid plant has ever been built anywhere in the world.

This can be at least partly explained by the fact that in many proposed schemes, the contribution of the geothermal source to total generation is modest. As a result, the increased efficiency that can be achieved is insufficient to offset the disadvantages of locating large, complex plants in geothermal areas, which are generally unfavorable for such plants both from the logistical standpoint and due to the lack of cooling water.

In addition, the degree of plant integration required by many hybrid cycles means they represent an alternative to building geothermal power plants. This involves insurmountable economic problems where the geothermal resource is already being exploited, due to the impossibility of retrofitting the existing generating plants, and also where an identified resource is awaiting utilization, due to the longer construction time of a hybrid plant. Furthermore, complex hybrid cycle schemes make it difficult to use a modular approach, that is, installing several small units in stages to reduce the risks related to the decline of the geothermal reservoir.

The hybrid cycle proposed here is appealing both technically and economically thanks to the particular characteristics of the geothermal fluid of the Mount Amiata deep geothermal fields and ENEL's standardized 20 MW geothermal units.

Characteristics of the Mount Amiata Geothermal Fields

Piancastagnaio geothermal field, located in the Mount Amiata area (Figure 1), has long been used to produce geothermal power.

It is made up of two distinct geothermal systems:

- A shallow field (reservoir depth approximately 1,000 m), extensively exploited in the past and now feeding only the Piancastagnaio 2 power plant (PC/2), which produces 8 MW_e and supplies heat to a greenhouse complex.
- A deep field (reservoir depth approximately 3,000 m), now being developed, where four power plants based on standardized 20 MW_e units have been installed (Bellavista, PC/3, PC/4 and PC/5) and where additional generating plants will soon be installed to produce another 60 MW_e from the geothermal source.

When it reaches the surface, the fluid from the deep reservoir is composed of a two-phase mixture of steam and water at

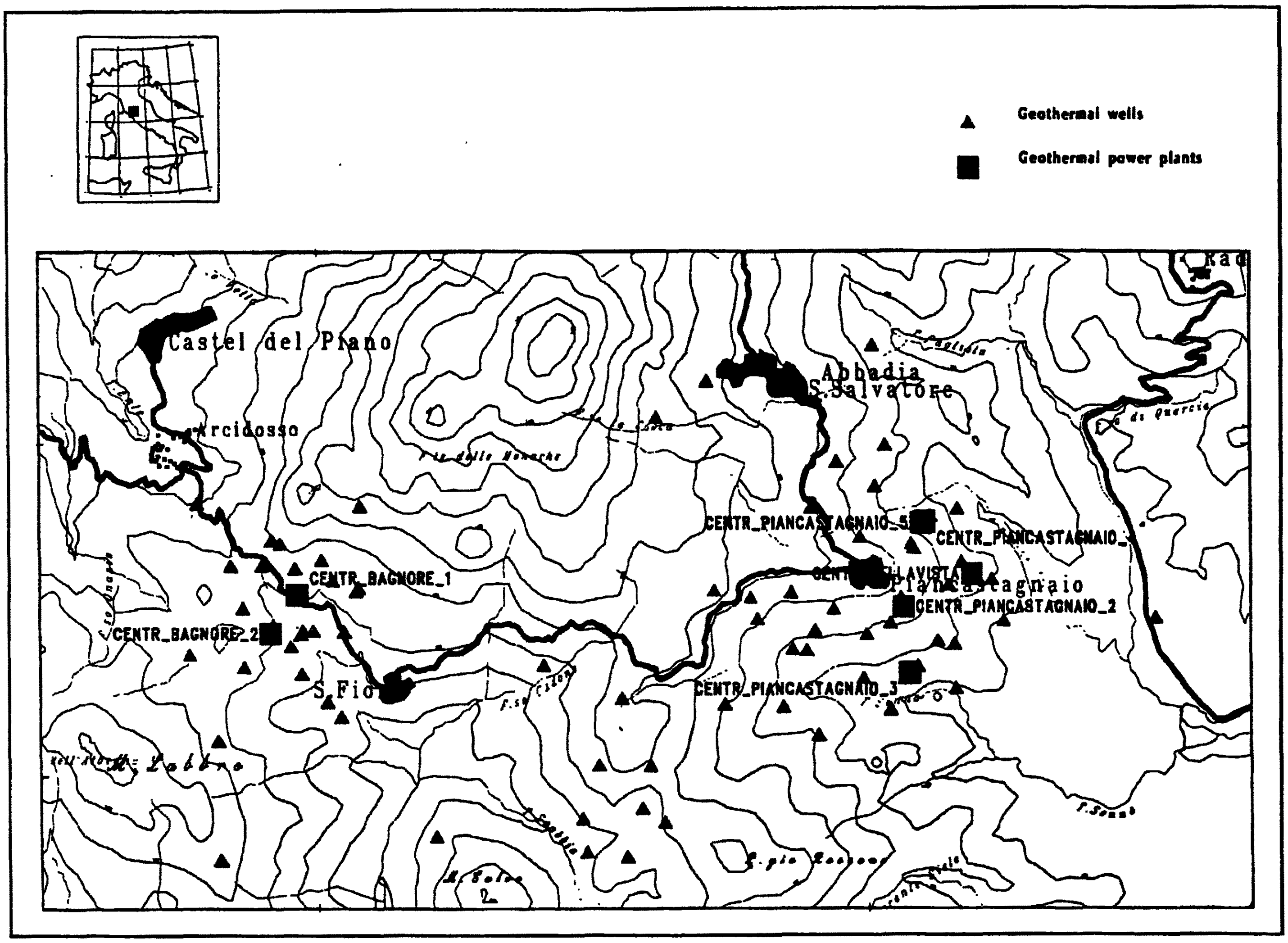

Figure 1. Mt. Amiata geothermal area.

considerably high pressure. The 20 MW units are fed with the steam (also containing noncondensable gases) separated at wellhead, while the liquid phase is reinjected.

The separation occurs at an absolute pressure of just under 20 bars. Each 20 MW plant is fed with approximately 110 t/h of steam with an average gas content of about 8% by weight. The typical inlet conditions of the turbine (corresponding to the state of saturation) are 18 bars and 205°C.

The nearby geothermal field of Bagnore (west of Piancastagnaio) has a deeper reservoir which is now being developed (the first power plant, Bagnore 3, is slated to go into operation in 1998). In the Abbadia San Salvatore field (northeast of Piancastagnaio), deep exploration has yielded positive results, and a drilling program is envisaged.

These two fields produce fluids with physical and thermodynamic characteristics similar to those of Piancastagnaio, so the solutions described below can be applied without significant variations also to these other fields, currently in the initial development phase.

Proposed Hybrid Cycle

The proposed scheme (Figure 2) envisages adding a gas turbine unit firing natural gas to a geothermal power plant. The exhaust from the gas turbine (which has a temperature around 500°C) is first used to superheat the geothermal steam in a surface exchanger and then to feed a bottoming binary unit (Organic Rankine Cycle, ORC) before being discharged to the atmosphere (Bidini et al., 1997).

After heat exchange with the gas turbine exhaust, the geothermal steam is made available for utilization in highly superheated conditions: the pressure is around 18 bars, the temperature over 400°C. The standardized 20 MW geothermal units are able to accept inlet steam at pressures in the 5-20 bar range and temperatures up to 280°C (Allegrini *et al.*, 1985). Therefore, steam superheated to temperatures over 400°C cannot be used directly in the geothermal turbine. However, it is possible to bring the steam temperature within the admissible limit of 280°C with an expansion to be carried out in a separate machine, called a "pre-expander" in the following.

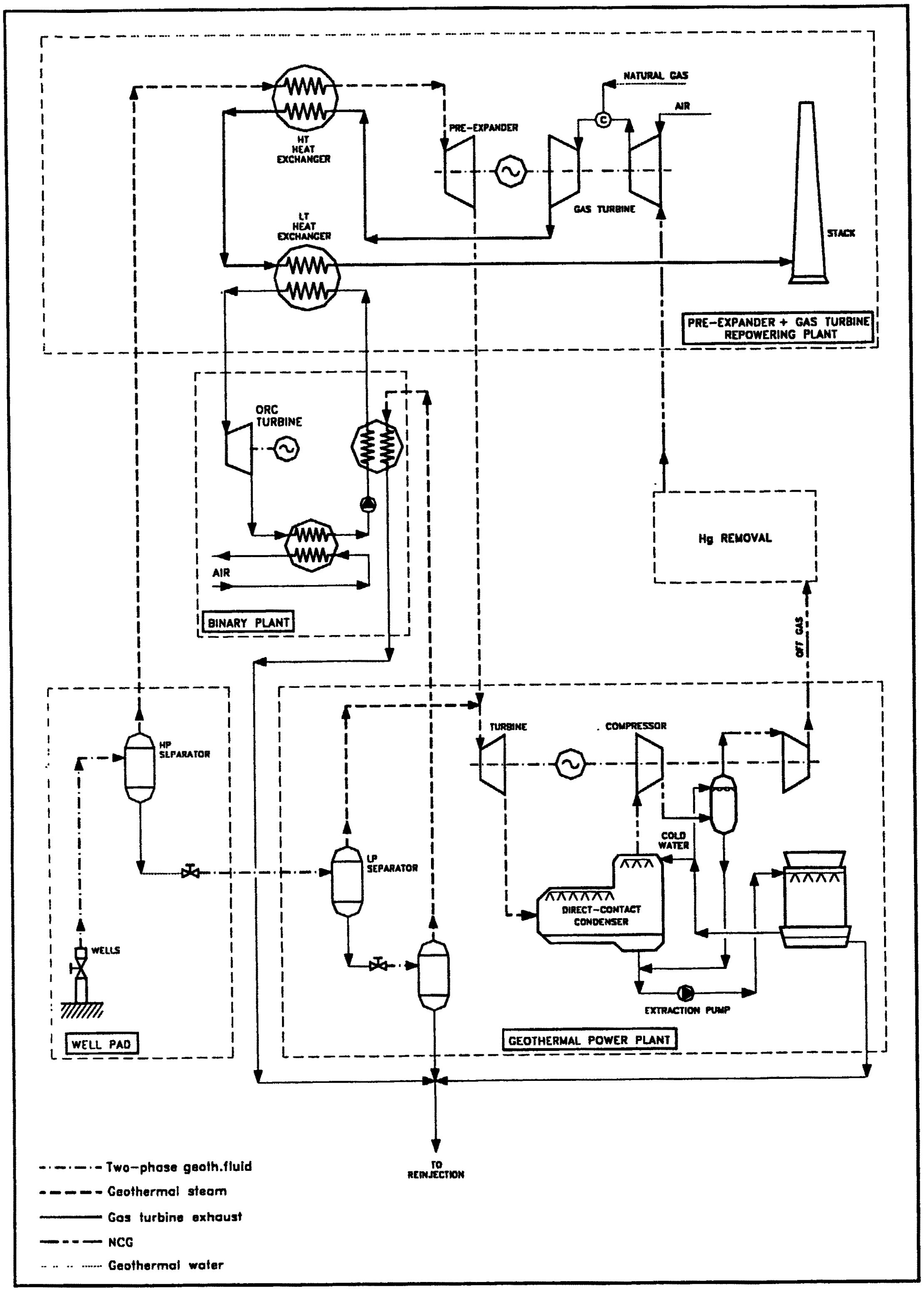

Figure 2. Schematic diagram of the hybrid cycle.

By setting the discharge pressure of the pre-expander at (or slightly above) 5 bars, it is in fact possible to obtain a steam outlet temperature not higher than 280°C, at the same time keeping the volumetric flowrate at the geothermal turbine admission within the design value (13.9 m^3/s, corresponding to 104.2 t/h of steam at 5 bars and 280°C with 8% NCG, or 110 t/h at 5.3 bars and 280°C, again with 8% NCG).

The superheated steam leaving the pre-expander (at about 5 bars and 280°C) can then be used in the existing geothermal generating units just by modifying the turbine configuration (reducing the number of stages by removing a few rows of blades and opening the admission diaphragms). In the case of units still to be built, the turbines would of course be installed with the configuration required for integration in the hybrid cycle.

The air-cooled bottoming binary unit (optional) allows recovering additional heat from the gas turbine exhaust after the heat exchange with the geothermal steam. Again by means of surface exchangers, the waste heat (until the minimum allowed discharge temperature to the stack) is used to heat and vaporize an organic working fluid which then expands in a dedicated turbine, producing electricity. At the turbine outlet, the organic fluid is condensed (by cooling with ambient air) and recirculated by a feed pump.

By choosing a gas turbine of suitable size, the hybrid cycle scheme described above can be implemented to superheat the steam needed to feed a 20 MW geothermal power plant such as Bellavista or PC/3 (110 t/h), or two 20 MW power plants located on the same site, such as PC/4 and PC/5 (220 t/h), or a 60 MW unit that could be installed in the future (400 t/h).

The other components of the cycle (heat exchanger for steam superheating, pre-expander and binary cycle) should be sized according to the rating of the gas turbine.

In the hybrid cycle scheme previously described the following generating units are present:

1. The (existing) geothermal power plant(s) (one 20 or 60 MW unit, or two 20 MW units)
2. The gas turbine
3. The pre-expander
4. The air-cooled binary cycle (optional)

Characteristics of the Proposed Cycle

The main features of the proposed hybrid cycle are the following:

- It is possible to implement the proposed hybrid cycle as a retrofit of existing geothermal power plants with modifications to them that can be performed cheaply and quickly (during scheduled maintenance).
- The additional plant components needed to integrate the geothermal power plants in the hybrid cycle can be supplied as skid-mounted, preassembled units with modest dimensions.
- The contribution of the two sources, geothermal and fossil, to the total installed capacity is balanced, not far from a 1:1 ratio.
- With reference to fossil fuel use, the proposed hybrid cycle displays efficiencies comparable to those typical of large-size combined cycle plants.

The hybrid cycle also offers other advantages, both thermodynamic and regarding the environmental aspect, which will be described below.

Additional Benefits of the Proposed Hybrid Cycle

Resource Use

The basic hybrid cycle scheme described above can be further improved by taking into account the specific situation of the deep reservoirs of Mount Amiata.

As stated earlier, the steam that feeds the geothermal power plants is obtained by separation at wellhead of the entrained water, present in amounts averaging between 50 and 100% by weight of the steam. In the current configuration, the power plants cannot use this water, since the turbines do not allow the admission of flashed steam at lower pressure than that of wellhead separation.

Electricity could be generated only by installing small binary units fed with flashed steam (at pressure slightly higher than atmospheric) obtained by the water separated at wellhead (approximately 9 kWh net for each metric ton of separated water)[1].

In the proposed hybrid cycle scheme, this water could be flashed at the outlet pressure of the pre-expander (the same of turbine admission), about 5 bars, and the flashed steam thus obtained - mixed with the outlet steam of the pre-expander - fed in the turbine of the geothermal plant.

This last scheme allows greater energy recovery at a smaller investment: around 12 kWh per metric ton of separated water could be obtained from the increased steam flow feeding the power plant and another 4 kWh/t from the binary units (by additional flashing of the water from 5 bars to slightly higher than atmospheric pressure). It would also be possible to use the same binary units for the atmospheric flash steam and the exhaust of the gas turbine (Figure 2).

Environmental

The geothermal power plants of Mount Amiata will be equipped in the near future with removal systems for hydrogen sulfide (H_2S) and mercury (Hg) associated with the NCG in the geothermal steam, presently discharged to the atmosphere from the compressor.

The technology that allows achieving the desired results at the lowest cost appears to be the oxidation (catalytic or thermal) of H_2S to sulfur dioxide (SO_2) downstream from mercury adsorption on sulfur-impregnated activated carbon. A demonstration plant will be installed at the Bagnore 3 power plant mentioned earlier.

In a geothermal power plant forming part of a hybrid cycle, it is possible and advantageous, in alternative to the above solution, to feed the compressor exhaust, after mercury removal, to the gas turbine for mixing with the combustion air.

Owing to the temperatures, almost total conversion of the H_2S entering in the combustion chamber can be achieved while simultaneously recovering the heat, even if modest, derived

[1] Using the separated water directly is not advisable because of its high silica content, which could produce scaling in the heat exchangers of the binary cycle units.

from the combustible compounds of the NCG (methane and hydrogen, besides the H_2S itself), thereby reducing natural gas consumption by the gas turbine.

This makes it possible to eliminate the H_2S oxidation stage, with considerable economic advantages, in addition to simplicity of operation.

It must be considered that a small part (less than 10%) of the stream entering the compressor of the gas turbine is used to cool the blades of the turbine and does not pass through the combustion chamber. As a consequence, the H_2S present in this stream is not oxidized and a small share of unconverted H_2S is present in the gas turbine exhaust, but in low concentrations (on the order of 100 mg/Nm^3).

The SO_2 outlet concentrations for the typical Piancastagnaio NCG content (8% by weight in the steam) and composition (H_2S represents 1.6% by weight of NCG) are around 2,000 mg/Nm^3. Of course, much lower values would be obtained in other fields (e.g. Larderello).

Thermodynamic Evaluations

Assumptions

The proposed hybrid cycle scheme has been evaluated from the thermodynamic viewpoint by considering the following possibilities with regard to the geothermal power plants (existing or future) to be integrated:

1. One 20 MW unit
2. Two adjacent 20 MW units
3. One 60 MW unit

On the basis of a preliminary market survey, a few commercial gas turbines were identified for each case with suitable characteristics in terms of exhaust gas flowrate and temperature (and therefore power). The nameplate characteristics of the best fitting gas turbine for each coupling (although the survey is by no means complete) are reported in Table 1.

The assumptions made for the evaluations were as follows:

- Constant 80% isoentropic efficiency of the pre-expander (conservative value) and 97% efficiency of the generator paired with it, also constant
- A geothermal steam flow of 110 t/h for the 20 MW units (400 t/h for the 60 MW unit), available at the absolute pressure of 18 bars in the state of saturation (205°C), with a NCG content (assumed as CO_2) of 8% by weight
- Negligible pressure drops in the exchanger for steam superheating (the pressure drop of geothermal steam can be offset by an increase of the wellhead separation pressure without significantly affecting the flowrate from the wells)
- A minimum pressure of the steam admitted to the geothermal turbine adjusted so as to keep the volumetric flowrate within the design limit, with a lower limit of 5 bars
- A maximum temperature of the steam admitted to the geothermal turbine of 280°C
- Temperature of the gas turbine exhaust to the stack set at 150°C when the binary unit is installed to avoid acid condensation as a consequence of trace SO_3 being present in this stream
- A minimum LMTD in the steam superheater of 40°C

Conservatively, the steam temperature at the pre-expander outlet has been kept at 280°C even in the case where the temperature of the steam entering the geothermal turbine could be brought within this limit by mixing with the flash steam at 5 bars produced by water separated at wellhead. This was done to avoid any negative conditioning resulting from unavailability or reduced availability of flash steam (due to problems with the flash tank or a gradual decline in the amount of water entrained from the reservoir).

The effect of the possible utilization of the flashed steam (at 5 bars) from the water separated at wellhead (at a pressure of 18 bars) on the efficiency of the hybrid cycle was evaluated by assuming the availability of a water flow of:

- 50 t/h, in the case of a 20 MW unit
- 100 t/h, in the case of two 20 MW units
- 200 t/h, in the case of a 60 MW unit

The performances of the hybrid cycle were evaluated both with and without the use of a bottoming binary cycle to recover the waste heat of the gas turbine exhaust downstream from the steam superheating.

In the case where the binary cycle is present, it is also fed with the flash steam at 1.1 bars, obtainable from the water previously flashed at 5 bars.

Likewise, the calculations were carried out both taking into account the heat contribution of the combustible compounds present in the NCG contained in the geothermal steam (assuming that the compressor exhaust will be admitted into the gas turbine and 90% burned) and also without this contribution. The composition of the NCG typical of the Piancastagnaio field, in the conditions existing downstream from the mercury removal stage, was taken as a reference.

Table 1. Characteristics of the selected gas turbines

		GAS TURBINE 1 (GT1)	GAS TURBINE 2 (GT2)	GAS TURBINE 3 (GT3)
Output	[MW]	13.4	24.6	52.8
Exhaust flowrate	[kg/s]	45.5	79.0	179.0
Exhaust temperature	[°C]	493	534	517
Efficiency	[%]	34.9	34.2	34.4

Regarding the geothermal power plant, in passing from a stand-alone unit to the integration in the hybrid cycle the working conditions of the compressor remain unvaried, and the differences are modest for all the other major components (cooling tower and water circulating pump), but the turbine.

In fact, as a result of the new inlet conditions (lower pressure and high superheating), the moisture content at the outlet is much lower. On the basis of the manufacturer's data, this allows an efficiency increase estimated at 0.5 percent points for each 1 point percent increase in steam quality at the outlet, which was taken into account in evaluating the performances of the hybrid cycle.

Results

In addition to a sizable increase in the net power obtainable, integrating a geothermal power plant and a gas turbine makes it possible to achieve clear thermodynamic advantages. The overall efficiency of the hybrid cycle is in fact greater than the weighted average of the efficiencies of the two components (geothermal plant and gas turbine) considered separately.

Even more than the overall efficiency, however, the most indicative parameter in evaluating the performance of the hybrid cycle is the natural gas utilization factor (NGUF), defined as the ratio between the increase in net power (net power of the hybrid cycle minus the net power of the geothermal power plant as a stand-alone unit) and the thermal power of the natural gas used[2].

In practice, the NGUF is an index of the efficiency of the gas generation stage, which can therefore be compared with that of other gas cycles, such as large combined cycle plants.

The NGUF is influenced both by the efficiency of the gas turbine and the relation between gas turbine size and the flowrate of geothermal steam to be superheated. Excessive turbine size is disadvantageous, particularly without the binary cycle, since the a large amount of waste heat in the gas turbine exhaust remains unused.

The results of the evaluations are summarized in Table 2, which shows the net power output of the hybrid cycle components and the NGUF for each combination between the selected gas turbines (Table 1) and the 20 and 60 MW geothermal units. The net power output of the geothermal plant as a stand-alone unit is also shown as a reference.

The data were calculated for a cycle configuration with and without the addition of a bottoming binary cycle; in both cases, reference is made to a conservative evaluation and to a more optimistic one. In the conservative evaluation, NCG exhaust from the compressor is not fed to the gas turbine and the water separated at wellhead is not used. In the optimistic evaluation, the opposite is true.

The calculated NGUF values of all the hybrid plants considered fall between 51 and 57%. These are extremely good values, comparable with the typical efficiencies of combined cycles, even though the typical power of the latter is considerably larger.

Problems With the Hybrid Cycle

Integrating geothermal power plants in the proposed hybrid cycle poses a few potential technical problems that must be carefully assessed before passing to the demonstration phase.

The biggest problem seems to be the chemistry of the numerous compounds present in the geothermal steam, which might react with each other and/or decompose at high temperature (the superheating can exceed 400°C), and any corrosion problem of the materials in contact with the steam that might derive from these phenomena.

In this regard, in addition to preliminary literature survey and theoretical evaluations, field tests could be carried out on a pilot scale.

It is felt, however, that corrosion in the pre-expander should not constitute a major item, as the geothermal steam remains in the superheated state throughout the whole expansion path, and it is well known that the onset of corrosion is generally tied to the crossing of the Wilson line.

Another problem seems to be possible fouling of the heat exchange surfaces of the superheater in contact with the steam, given also the presence of unavoidable trace quantities of entrained liquid with high TDS.

Possible solutions might be improved efficiency of the entrained liquid separating equipment upstream from the power plants, and/or a small throttling to bring the steam into slightly superheated conditions immediately upstream from the superheater, or adopting two exchangers in parallel, one as backup to the other.

Also in this case, pilot-scale tests would be useful to get a realistic indication on the extent of the fouling phenomena that could occur.

Finally, the possible onset of any corrosion problem arising from the presence of sulfur compounds in the gas turbine (hydrogen sulfide in the compressor and sulfur dioxide in the turbine) should be investigated and checked with the manufacturers.

However, as gas turbines already use liquid fuels containing sulfur, it should be possible for these components to manage also the geothermal gas with its H_2S content.

Economic Assessments

Some preliminary economic evaluations were carried out in order to evaluate the economical feasibility of the gas turbine-geothermal hybrid cycle.

The main results can be briefly summarized as follows:

- The unit investment (on the basis of the installed kW) needed to retrofit a geothermal plant into a hybrid cycle is comparable or slightly lower than that for a large combined cycle plant
- The incidence of the fuel cost on the additional power generated by the hybrid plant is practically equivalent to

[2]The thermal power of the natural gas used is the product of th natural gas flowrate multiplied by its lower heating value.

Table 2. Geothermal plant and hybrid cycle thermodynamic data.

		1 x 20 MW STAND-ALONE UNIT		HYBRID PLANT 1 x 20 MW + GT1			
		without separated water utilization in binary unit	with separated water utilization in binary unit	without separated water and NCG utilization		with separated water and NCG utilization	
				without binary unit	with binary unit	without binary unit	with binary unit
Geothermal plant output	[MW]	15,67	15,67	14,83	14,83	15,50	15,50
Pre-Expander output	[MW]	-	-	7,26	7,26	7,26	7,26
Gas turbine output	[MW]	-	-	13,40	13,40	13,40	13,40
Binary cycle output	[MW]	-	0,43	-	0,54	-	0,64
Total output	[MW]	15,67	16,10	35,49	36,03	36.16	36,80
Natural gas utilization factor	[%]	-	-	51,6	53,0	55,5	56,1

		2 x 20 MW STAND-ALONE UNIT		HYBRID PLANT 2 x 20 MW + GT2			
		without separated water utilization in binary unit	with separated water utilization in binary unit	without separated water and NCG utilization		with separated water and NCG utilization	
				without binary unit	with binary unit	without binary unit	with binary unit
Geothermal plant output	[MW]	31,34	31,34	29,45	29,45	31,62	31,62
Pre-Expander output	[MW]	-	-	15,01	15,01	14,55	14,55
Gas turbine output	[MW]	-	-	24,60	24,60	24,60	24,60
Binary cycle output	[MW]	-	0,86	-	0,90	-	1,01
Total output	[MW]	31,34	32,20	69,06	69,96	70,77	71,78
Natural gas utilization factor	[%]	-	-	52,4	53,7	57,2	57,4

		1 x 60 MW STAND-ALONE UNIT		HYBRID PLANT 1 x 60 MW + GT3			
		without separated water utilization in binary unit	with separated water utilization in binary unit	without separated water and NCG utilization		with separated water and NCG utilization	
				without binary unit	with binary unit	without binary unit	with binary unit
Geothermal plant output	[MW]	56,98	56,98	54,12	54,12	56,89	56,89
Pre-Expander output	[MW]	-	-	28,78	28,78	28,78	28,78
Gas turbine output	[MW]	-	-	52,80	52,80	52,80	52,80
Binary cycle output	[MW]	-	1,72	-	2,74	-	3,10
Total output	[MW]	56,98	58,70	135,70	138,44	138,47	141,57
Natural gas utilization factor	[%]	-	-	51,3	53,1	55,0	56,0

that of a state-of-the-art combined cycle (the NGUF values being comparable to combined cycle efficiencies)

- The incidence of operation and maintenance costs on the additional power generated by the hybrid plant is lower than that of a combined cycle, due to the hybrid plant simplicity and to the fact that it does not need any additional operating personnel with respect to the geothermal

This means that the cost of the additional power generated by the hybrid plant with respect to a stand-alone geothermal plant is somewhat lower than the generation cost from a combined cycle plant, notwithstanding the larger size of the latter.

The environmental benefit deriving from the integration of the geothermal plant into a hybrid cycle thus constitutes a major advantage of the proposed scheme.

Even if more detailed analyses, taking into account the rapidly changing conditions of the Italian electricity market, will be necessary to establish the viability of the proposed hybrid cycle, these encouraging preliminary data could lead to the decision of starting pilot field tests to investigate the previously mentioned possible technical problems.

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