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Feedwater repowering of 800 MW supercritical steam power plant

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Abstract

The paper presents the concept of using hot exhaust gases from the gas turbine to heat up feedwater in a supercritical power plant unit. The gas turbine is connected to the system, bypassing a high pressure regenerative heat exchanger. The benefits of this solution are discussed and the factors to be taken into account are listed. The criteria to be met by gas turbine, in order to be safely and optimally connected to the steam system, are discussed. A reference unit model with 800 MW electric power (one of the existing supercritical power units in Poland—Belchatow II) was created, which was later supplemented with a gas turbine (A PG7161-EC by General Electric). The system with a gas turbine, compared to a "clean" steam system, enjoys greater power and efficiency. The power increase is due to the extra power generated by the gas turbine and the higher output of the steam system caused by increasing the steam flow through the turbine (closed extraction to the "bypassed" high-pressure heat exchanger). System power is changed linearly with the steam flow and reaches the nominal point 20% higher than without an added gas turbine. The characteristics of the efficiency of the whole system are flatter, having higher values. At the nominal point the difference is about 1% and rises from 43.5% to approximately 44.5%.

Keywords: gas turbine, steam turbine power plant, feedwater repowering

1. Introduction

The concept of co-operation of the steam and gas turbine in the common system essentially follows directly from a review of the main advantages and disadvantages of steam and gas systems treated separately.

The advantage of the steam turbine is the very low ratio of compression work to expansion work (due to water condensation which runs at a constant temperature, only slightly higher, 5–7°C, than ambient temperature). The disadvantage of this system is the process of heat supply, implemented through a metal wall, mechanically and thermal loaded. Substantial heat transfer surfaces are needed, forcing a reduction in the temperature used in the live steam to below about 570°C.

The most efficient solution from the viewpoint of the efficiency of the system is the classical Gas Turbine Combined Cycle (GTCC), in which several gas turbines supply waste heat to the Heat Regeneration Steam Generator (HRSG) which works with one steam turbine. The efficiency obtained this way is about 30–40% higher than the steam-only unit, and the power achievable can be as much as 200% compared to Coal-Fired Power Plants (CFPP).

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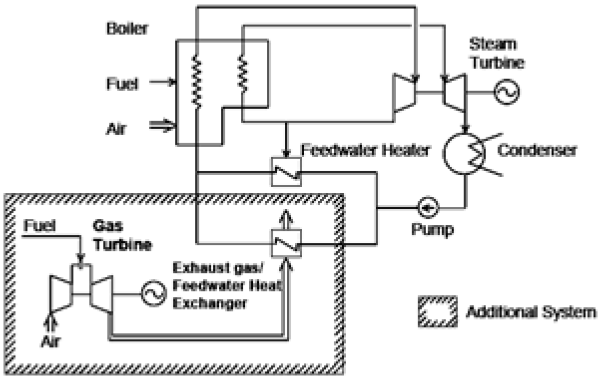

Figure 1: Schematic diagram of using a gas turbine to repower a coal fired power plant to cover peak loads [1–3]

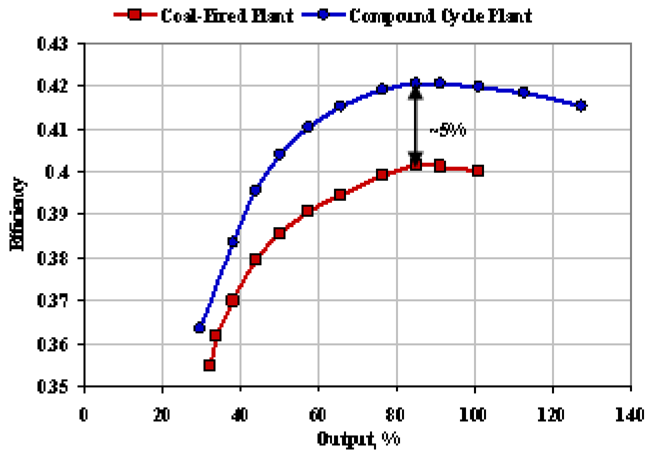

Figure 2: Use of feedwater repowering to increase the efficiency of the steam turbine cycle

Another possible solution is to discharge gas turbine exhaust to the coal-fired boiler as an oxidant (as the gas turbine exhaust gases have a considerable amount of oxygen) [4]. This solution can increase efficiency by 5–15%, and power by 30-40% [2].

Another possibility for steam cycle repowering is to use the hot exhaust of the gas turbine, not of the steam turbine, to raise the temperature of the feedwater. This is called feedwater repowering. The benefits of this solution depend on the amount of "energy saved"; the achievable increase in power here is 30–40% and in efficiency of 5–10%, limited by the nominal capacity of the steam turbine. The actual values are 2% for improving efficiency and 20% for power, respectively. The layout of this type is used to cover peak loads, as shown in Fig. 1.

The steam cycle has the typical layout of an existing primary system and the gas turbine sub-system is the typical peak system. Both cycles work only at times of the peak load and are connected by the feedwater heater, which is fed by gas turbine outlet. Peak power grows by forcing steam turbine power through the regenerative heater is disconnected. This is done without compromising performance by include heat recovery of gas turbine in place of the steam turbine regeneration.

Feedwater is heated up by bypassing the original regenerative heat exchanger and directing it to the gas/water heat exchanger. In this case, bypassed regenerative heat exchanger does not take steam from a steam turbine, which increases power. Additional power is generated by the added gas turbine. This system has considerable flexibility: the gas turbine can operate even if the steam cycle is out of operation, and vice versa.

Increasing the capacity of existing installations is a serious alternative to the construction of new facilities to achieve several objectives:

1. reduction of specific fuel consumption (efficiency gains of around 2%),
2. reduction in unit operating costs,
3. reduced emissions (including CO_2 [5]),
4. lower cost of growing existing installed capacity,
5. minimization of investment costs.

Leaving the regenerative heat exchangers enables the steam turbine system to function independently if the gas turbine is not in operation (e.g. due to maintenance).

The efficiency of the gas turbine system itself is 35.1% at rated power (60 MW). The efficiency of the steam turbine cycle at its maximum power is 39.9%. With simultaneous operation of both uncoupled systems, their average efficiency is 39.1%, while combining the system into one gives efficiency of 41.5% (5.5% increase compared to the nominal value—see Fig. 1).

The power needed to cover the peak load is generated at a very low natural gas consumption rate because: (i) part of this power comes from the steam turbine and (ii) the entire system enjoys relatively high efficiency—up to 50%.

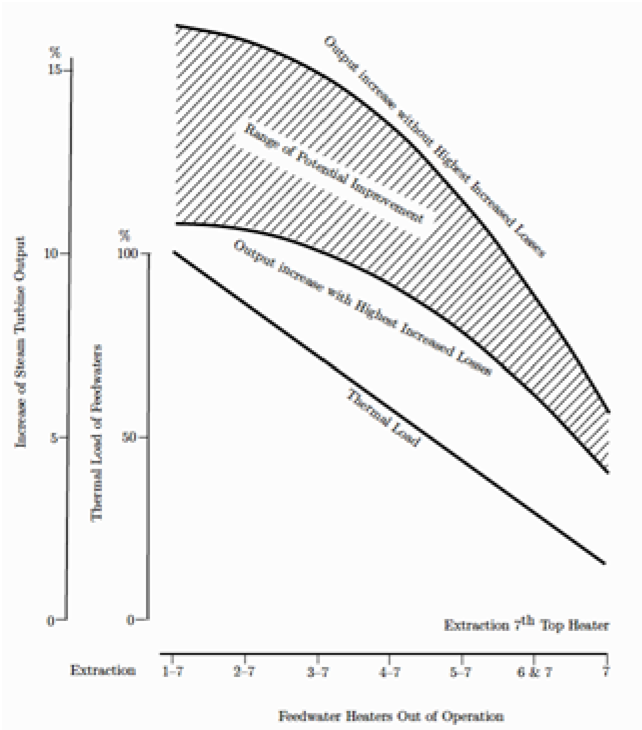

Figure 3: Effect of replacing selected regenerative heat exchangers to increase the power of a steam turbine [4]

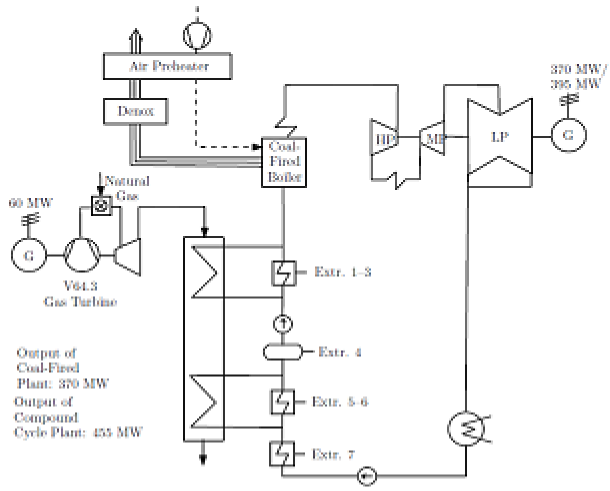

Figure 4: Example of use of a gas turbine to regenerate the coal boiler feedwater [4]

Nevertheless, it should be remembered that this solution will always have lower efficiency than the classic GTCC, as it is associated with non-optimal parameters such as:

1. steam pressure,
2. quantity and pressure level of steam in Heat Recovery Steam Generator,
3. LP turbine capacity,
4. steam turbine outlet pressure.

On the other hand, upgrading the existing structure of the steam turbine, for example by replacement of the LP part of the steam turbine, can offset the abovementioned shortcomings.

The most important feature of incorporating a gas turbine in a steam turbine system is the selection of the gas turbine unit, so that heat can be supplied at as high a temperature as possible. An example of such a selection is shown in Fig. 3. For the same temperature increase in each of the heat exchangers, the heat load is reduced by 15% between the first and last regenerative heat exchanger. The largest increase in steam turbine power is gained by replacing the regenerative heat exchanger employed in the first extraction of the steam turbine. Bypassing the low pressure exchanger regeneration gives very little effect in terms of the increase in power of the steam turbine (e.g. bypassing the last three regenerative heat exchangers gives only a 1% increase in power).

The development of the intercooled aeroderivative gas turbine (ICAD) allows them to be applied to the boiler feedwater heating. Due to its relatively high efficiency of 42–44% in simple cycle, and relatively low exhaust temperature (430–470°C), turbines of this type seem predisposed for use in feedwater repowering.

Systems designed as GTCC achieve efficiency levels of up to about 60%; feedwater repowering allows for enhanced efficiency to a lesser extent, for example, the supercritical steam cycle has efficiency levels of 42–46% and after repowering efficiency can be 45–49%.

On average, it can be assumed that the power of a gas turbine should be approximately one quarter of the power of the steam turbine to which the gas turbine is connected. The use of a larger gas turbine for feedwater repowering can be considered for a plant which has more than one steam turbine unit.

Such solutions have been used before, a typical example is the unit shown in Fig. 4, in which 370 MW is generated through a base steam turbine cycle. An additional 85 MW is delivered though the installation of a 60 MW gas turbine system for feedwater repowering. The use of regenerative heat exchangers leads to lower steam consumption, causing an increase in the power of the steam turbine from 370 to 395 MW. Other examples where this solution was implemented are GE plants (e.g. Oklahoma Gas & Electric—Belle Isle, and Western Power—Liberal, KS), see Table. 1.

The capital costs of adding a gas turbine to heat up feedwater are estimated at $90–110/kW for smaller units and $75–80/kW for larger units. New gas turbine units can be installed in less than eight weeks.

The installation costs comprise the following main elements:

1. installation of a gas turbine,
2. exhaust duct assembly,
3. installation of a hot stack for a gas turbine,
4. construction of a heat exchanger gas/water supply.

2. Specification of the reference power plant unit

Most of the parameters necessary for reference unit calculations have been adopted from the supercritical power plant unit Belchatow II and literature data. Parameters that are not clearly identified in the source material were established on the basis of data taken from the world's most advanced facilities of that class (in particular low-emission coal-fired power plants in Germany) and based on the experience of the authors of this paper.

The reference system correlates to the scheme at Belchatow II. It consists of an extraction condensing turbine, boiler, condenser, four low-pressure regenerative heaters, two high-pressure regenerative heaters, deaerator, condensate and feedwater pumps. The extraction condensing turbine consists of a high-pressure part—HP (1 single output casing), the medium-pressure part—MP (1 single output casing), low-pressure part—LP (3 double output casings). Since all three casings of NP turbines have identical parameters, the LP part of the turbine is taken as one casing. The HP part of steam turbine is supplied with fresh steam directly from the boiler. The steam outlet of the HP is directed back to the boiler (superheating) and one of the high-pressure regeneration heat exchangers. The MP part of the turbine is supplied with superheated steam. The steam outlet of the MP is directed to the LP and feeds low-pressure regeneration heat exchangers. The MP part has two extractions. The first feeds the deaerator and a turbine for the feedwater pump, the second feeds the steam cooler of one of the high-pressure heat exchangers. The LP part of the turbine (exhaust steam supplied from the MP) has 3 extractions, supplying steam to low-pressure heat exchangers. The steam outlet of the LP is directed to the condenser. The boiler is designed for supercritical parameters. The maximum sustainable steam yield is 2,400 t/h. The parameters of the fresh steam are about 250 bar and 554°C, and the superheated steam parameters are about 54 bar and 582°C. There are 3 basic pumps: one feedwater pump and two condensate pumps. The feedwater pump is driven by a steam turbine powered with steam from the MP extraction. The turbine driving the pump has its own condenser, from which the condensate is pumped to the main condenser. This pump raises the feedwater pressure from about 11 bar to 329 bar. The condensate pumps are powered by electric motors. These increase the pressure from 0.06 bar (pressure in the condenser) to 22 bar. The power of these pumps is about 1.1 MW. There are two other pumps pumping the condensate between the low pressure regenerative heat exchangers. Their power is 0.06 MW and 0.1 MW. The system has four low pressure regeneration heat exchangers and two high pressure regeneration heat exchangers. Three low-pressure regeneration exchangers are supplied from the extraction of the LP part of the turbine and one from the extraction of the MP part of the turbine. High pressure regeneration heat exchangers are supplied with steam from the HP and MP parts of the turbine. They are equipped with steam and condensate coolers. The nominal parameters of this unit are shown in table 2.

3. Mathematical model of the system

All calculations were performed using commercial software [7]. The steam turbine is the most important element of a mathematical model of the steam cycle. The model of the device must therefore be accurate as possible and take into account the relevant physical phenomena. An independent approach to the internal and external characteristics of the tur-

Table 1: GE plants that use feedwater repowering [6]

In operation	Owner	Place	Gas turbine	Total power, MW
1949	Oklahoma Gas & Electric	Belle Isle	MS3001	40
1952	Oklahoma Gas & Electric	Belle Isle	MS3001	40
1961	Wester Power	Liberal, KS	MS5001	65
1998	Electrabel	Langerlo, Belgium	LM6000	271
2002	SK Power	Avedore, Denmark	LM6000	390

bine is required in order to obtain the characteristics of steam turbine operation in the off-design operation mode, i.e. working at partial load and/or changed steam thermodynamic parameters. External characteristics of the turbine refers to the relationship between steam flows and its thermodynamic parameters. Internal characteristics refers to changes in efficiency associated with the off-design operation of the steam turbine.

To determine the external characteristics of the steam turbine, the modified Stodola equation was used (otherwise known as Stodola's ellipse - see equation1)

$$W = C\sqrt{\frac{p}{v}}\sqrt{1-\left(\frac{r-r^{*}}{1-r^{*}}\right)^{2}} \quad (1)$$

where: W—steam flow, C—flow coefficient, p—inlet pressure, v—specific volume at stage group inlet, r—pressure ratio, r^{*}—critical pressure ratio.

The method used to determine the efficiency of modeled steam turbines is based on experimental data and the SCC theoretical approach (creators: Spencer, Cotton, Cannon [8]). This method is recommended by the American Society of Mechanical Engineering to calculate the working efficiency of turbines in conventional power plants.

The gas turbine model is based on the characteristics of real devices provided in the form of a database. They are not available to the user. Two graphs (Fig. 5 and 6) were generated using the model in order to verify the correctness of the model (qualitative). The results generated by the model seem to be correct.

An 800 MW-class steam turbine power plant was chosen as the reference for the model. Most of the parameters required for calculation were taken from the supercritical power plant Belchatow II. Parame-

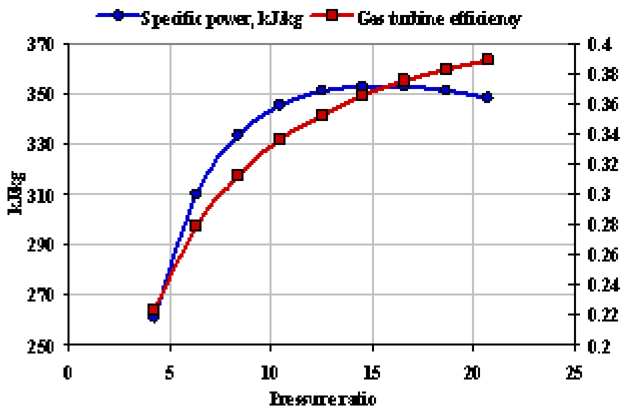

Figure 5: Pressure ratio dependence of specific power and thermal efficiency of the gas turbine

ters that are not clearly identified in the source materials have been established using data drawn from the world's most advanced facilities of that class. The thermal block diagram of the reference is shown in Fig 7.

This system has been supplemented by a gas turbine which is connected to the system as a "bypass" for one of the high pressure regenerative heat exchangers fed by steam at the highest temperatures.

Fig. 8 presents the operating characteristics of the steam turbine in relation to data given in Table 3. The power system varies in the range 83–834 MW, and depends linearly on live steam flow. The efficiency at nominal power is 37%. There were also changes in feedwater temperature in the first (from the steam flow through the turbine) regenerative heat exchanger, and the extraction steam consumed by this exchanger (reduced to 10% of its nominal value).

A General Electric PG7161 (EC) gas turbine was used to simulate the impact of feedwater repower-

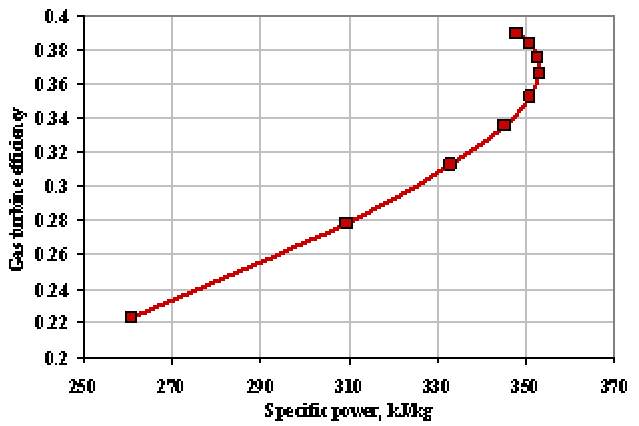

Figure 6: The characteristics of the gas turbine in simple cycle - thermal efficiency and specific power

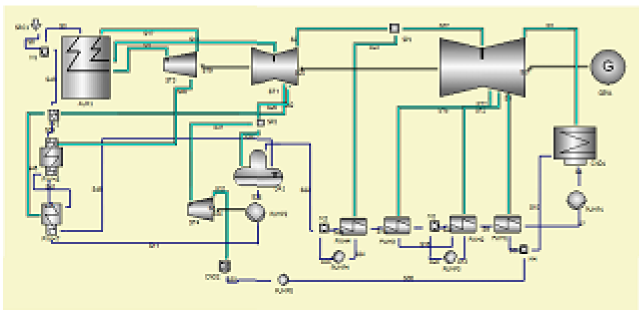

Figure 7: The chosen reference steam cycle diagram

ing. The nominal parameters of the turbine are given in Table 3.

4. Effect of feedwater repowering on steam power plant characteristics

Fig. 9 shows how to connect the gas turbine and bypass regenerative heat exchanger. Theoretically, a gas turbine can operate independently of the steam system (even when the steam unit is completely off). Placed between the regenerative heat exchanger and the boiler is the steam cooler which, at the nominal point, is supplied with water at a temperature of 270°C. During the simulation appropriate gas turbine operation parameters were chosen, so that the water temperature before the steam cooler is still at the nominal point.

Fig. 10 shows the operating characteristics of the steam turbine during off-design operation with the addition of a gas turbine. System power is changed

Table 2: Nominal parameters of the steam cycle

Parameter	Value	Unit
Life steam flow	644	kg/s
Power of steam turbine	833	MW
Steam cycle efficiency	43.5	%
Feedwater temperature at heat exchanger inlet	232	°C
Feedwater temperature at heat exchanger outlet	272	°C
Steam flow at turbine extraction	61	kg/s

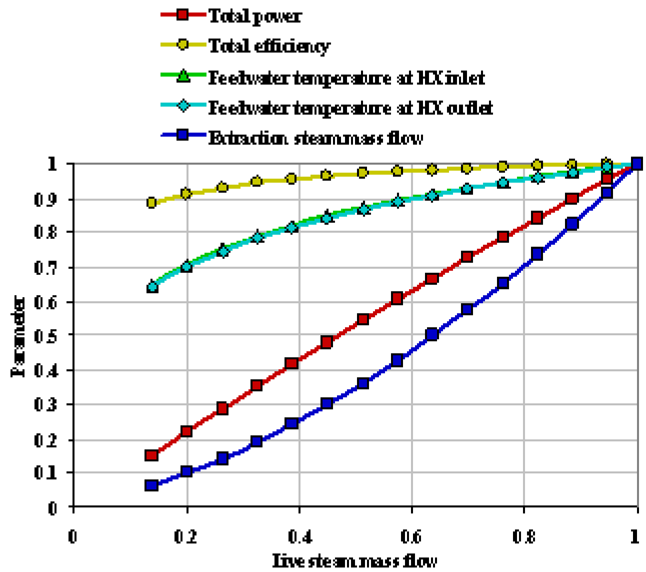

Figure 8: Steam turbine characteristics during off-design operation

linearly with the steam flow and reaches the nominal point 20% higher than it does without the addition of the gas turbine. The efficiency profile of the whole system is flatter and has higher values. The water temperature after the bypassed heat exchanger is constant, whereas the water temperature before the heat exchanger varies according to the characteristics of the block. This is due to the gas turbine power being adjusted to keep the temperature constant and equal to the temperature after the bypassed heat exchanger as for operation without the gas turbine at the nominal point (272°C). This restriction was introduced to avoid overheating after the regenerative heat exchanger (steam cooler).

Fig. 11 shows the power achieved by the gas tur-

Table 3: Nominal parameters of PG 7161 gas turbine (EC)

Parameter	Value	Unit
Mass flow	348.8	kg/s
Power	116	MW
Efficiency	34.5	%
Turbine Inlet Temperature (TIT)	1204	$^{\circ}$C
Turbine exhaust temperature	558	$^{\circ}$C
Pressure ratio	14.2	-

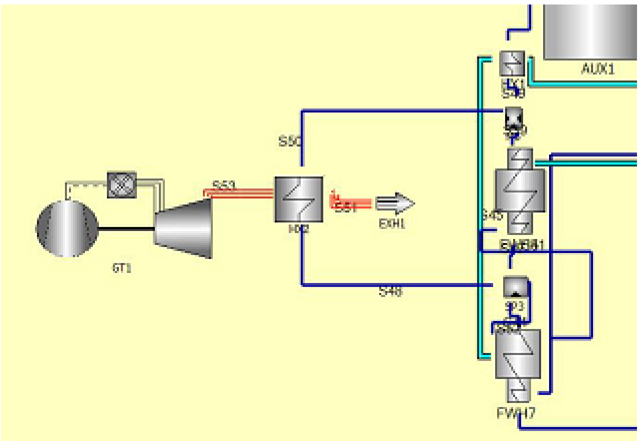

Figure 9: Connection of the gas turbine with the steam system

bine, depending on the power generated by the steam turbine. During reduction of the power of the system, gas turbine power is constant for the range 780-900 MW of steam turbine power. Then, gas turbine power is reduced and reaches approximately 35 MW for the 280 MW produced by the steam turbine.

5. Discussion and conclusions

The paper sets out the concept of using hot exhaust gases from the gas turbine instead of steam turbine extraction to raise the temperature of feedwater. The benefits of using this solution in relation to the construction of new generating capacity are discussed, and the factors affecting the lower efficiency of this solution compared to traditional IGCC are pointed out. The paper discusses the detailed criteria to be met by the gas turbine for safe and optimal connection to the steam system. The model of the reference case of the steam turbine was built, which was later supplemented with a gas turbine.

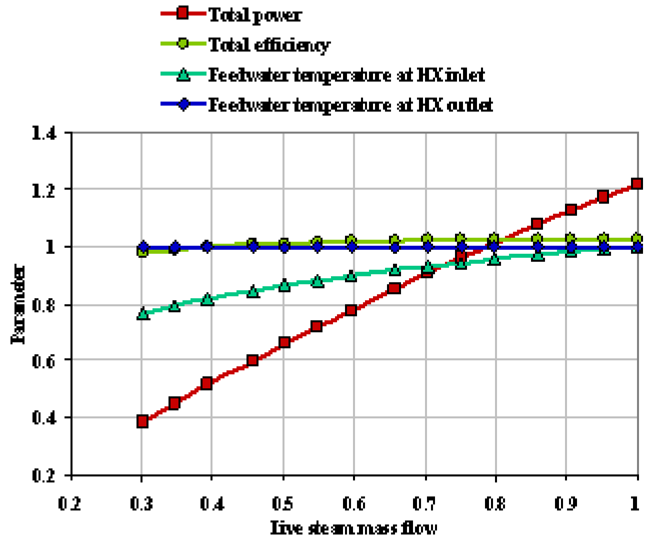

Figure 10: Characteristics of the steam cycle with feedwater repowering

The repowered steam cycle enjoys greater power and efficiency than the reference system. The power increase is due to the extra power generated by both the gas turbine and steam turbine (higher power by increasing the flow of steam through the turbine—closed extraction to bypassed high-pressure regeneration heat exchanger). System power is changed linearly with the steam flow and reaches the nominal point 20% higher than without the addition of the gas turbine (fig. 10).

Fig. 12 presents a comparison of the two systems' efficiency (reference and after repowering). It can be seen that the efficiency of the repowered system is higher across the whole range. In the nominal point the difference is about 1% and rises from 43.5% to about 44.5%.

The investment costs of the steam cycle repowering are provided based on the reviewed installation of General Electric. An economic analysis lay outside the objectives of this work and will form the subject of further studies.

A review of the literature suggests that a 5% increase in efficiency is achievable, but this study failed to confirm it. This may be due to the fact that only one of the regenerative heat exchangers was bypassed and that the gas turbine has relatively low efficiency. In addition, gas turbine power is about 1/6 of the steam power system—the literature states that 1/4 is

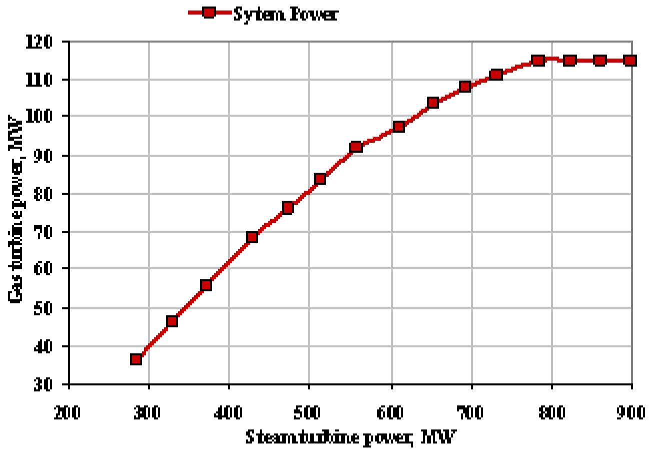

Figure 11: Power achieved by the gas turbine, depending on the power generated by steam turbine

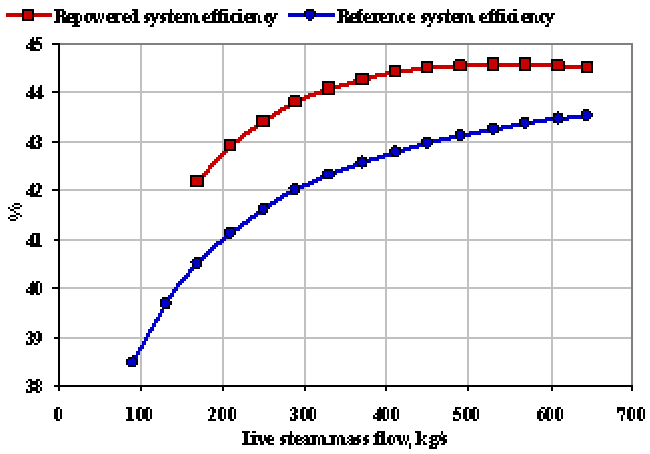

Figure 12: Comparison between steam cycle efficiency and repowered steam cycle efficiency

the optimum value, which in the case of a block of an 800 MW gas turbine means power of 200 MW. These aspects, as well as economic aspects, will be subject to further analysis.

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