Int.J. Applied Thermodynamics, **ISSN 1301-9724**
Vol.4, (No.2), pp.111-118, June-2001

The Impact Of Blade Materials On Long-Term Gas Turbine Profitability*

Kristin JORDAL#, Tord TORISSON
Department of Heat and Power Engineering
Lund University
P.O. Box 118, S-221 00 Lund, Sweden
Tel: +46-(0)46 222 31 91, Fax: +46-(0)46 222 47 17
E-mail: kristin.jordal@vok.lth.se, tord.torisson@vok.lth.se

Ulf LINDER
ALSTOM Power Technology Centre
Cambridge Road, Whetstone
Leicester LE8 6LH, England
Tel: +44-(0)116 201 5611, Fax: +44-(0)116 201 5468
E-mail: ulf.linder@power.alstom.com

Abstract

Thermal efficiency alone is an insufficient measure of the profitability requirement that electric power companies have on their power plants, in particular with the advent of deregulated electricity markets. In the present paper, this issue is illustrated with a study on the combined-cycle plant, where the benefit of various turbine entry temperatures and various materials for the first stage of the gas turbine is studied. The deviation in net present value is calculated, and it is shown how the possible profit to be made from more advanced materials and cooling is highly dependent upon electricity and fuel prices, whereas, the intervals for blade replacement during planned stops have a smaller impact on power plant profitability.

Key words: marginal net present value, fuel cost, electricity price, gas turbine blade materials

1. Introduction

One way of increasing the power output from a gas turbine is to increase the turbine entry temperature (Bathie, 1996). Gas temperatures in current advanced gas turbines are far above the maximum permissible material temperatures, and hence, the cooling of hot parts (blades, vanes, disks) is necessary. The coolant employed is usually air that is extracted from the compressor, such that part of the compressed air does not pass through the combustion chamber and it does not take full part in the expansion process. Also, the mixing of coolant and hot gases results in losses in work output. Nevertheless, these losses in a carefully designed gas turbine are not large enough to counteract the increase in net work output that is obtained from the high turbine inlet temperature, and in general, also an increase in engine thermal efficiency, η_{th}, can be obtained due to an increase in temperature.

The thermal efficiency, η_{th}, has traditionally been in focus as power plant manufacturers present their products on the market. Indeed, η_{th} is of major importance when buyers evaluate the performance of a power plant concept in order to decide what investment to make. However, the goal for those electric utility companies, especially when acting on a deregulated market, is not simply to own power plants with high thermal efficiencies, but to get a

---

* This paper was presented at the ECOS2000 Conference in Enschede, July 5-7, 2000
# Author to whom all correspondence should be addressed.

maximum profit out of their investment. Hence, the design procedure of a new power plant must be oriented towards the needs of the end-user with respect to the operating schedule (base load, intermediate load, peak load), taxes and expected fuel and electricity prices. This means that both buyer and seller must be aware of the impact that various technical solutions have on the profitability of the particular power plant under consideration.

As mentioned above, blade and vane cooling enable high specific power and increased thermal efficiency, but the advanced materials and complex cooling configurations also bring about additional costs. Furthermore, it depends on fuel and electricity prices whether an increase in thermal efficiency is beneficial or not. The objective of the present work is to present a method for estimating the financial cost or benefit of various gas turbine materials for the first stage of a modern mid-size gas turbine. In order to do so, common capital investment theory is reviewed and, thereafter, the method is applied for the comparison of various blade materials. The materials that are studied for the first stage blades and vanes are single-crystal blades and more conventional polycrystalline superalloys. Also, ceramic uncooled blading for the first stage is studied. These three different materials are evaluated at two different values of turbine entry temperature (TET), that is the total gas temperature immediately upstream of the first stator vanes. To illustrate the impact of electricity price, fuel price and blade life, sensitivity analysis is performed.

2. Power Plant Model

The studies are based on a model of a conventional dual-pressure combined cycle (540°C, 8 MPa/0.8 MPa) with a fully air-cooled gas turbine (compressor pressure ratio 20). The same configuration has been used in a previous study (Jordal and Torisson, 2000) and is more thoroughly described there. It is assumed that the HRSG and the steam cycle do not change, regardless of the changes made to the gas turbine blading in the first stage of the gas turbine. A compressor inlet mass flow of 100 kg/s is assumed throughout the calculations.

3. Economic Model

In the field of economic optimisation of entire power plants, tremendous and extensive efforts have been made and are continuously being made with a range of different methods applied to analyse various processes, with the purpose of studying such aspects as design, operation, maintenance or retrofit of energy-related processes. Some recent examples of this research are the application of neural networks to suggest optimum operating conditions for a pulp and paper factory (Tucci et al., 1996), a study of the maintenance requirements of an entire steam power plant from a thermoeconomic point of view (Carvalho and Horta Nogueira, 1996), an iterative thermoeconomic optimization technique for a cogeneration system (Tsatsaronis and Moran, 1996), and El-Sayed (1998), present a methodology for a cost-efficient design-process and operation of energy devices.

However, when studying various technical solutions for a well-defined point in the power plant, such as the first stage in the gas turbine, it is not necessary to consider the cost of the entire plant. Instead, it is sufficient to study the marginal cost and marginal income of the different solutions.

The net present value (NPV) of any investment is the present value of all the money inflows and outflows of the investment (Northcott, 1998). The method applied here is to calculate the “marginal” NPV; that is, the part of the net present value that deviates from a reference case due to changes in design of the first stage of the gas turbine and in TET.

For a power plant, the inflow of money, I, occurs from sold electric power, EP, which, over the economic lifetime of the plant (n years), is the sum of present value (PV) of the power output, P, times the annual operational time, ot, and specific electricity price, ep:

$$I_{PV} = EP = (P \cdot ot \cdot ep) \cdot \frac{(1+r)^n - 1}{r(1+r)^n} \tag{1}$$

where r is the rate of return.

The PV of the cost (or money outflow) K is the capital cost, CC, plus the present values of the total fuel cost, FC, maintenance cost, MC, other operational costs, OC, and, for a full economic evaluation, the environmental cost EC:

$$K_{PV} = CC + (FC + MC + OC + EC)\frac{(1+r)^n - 1}{r(1+r)^n} \tag{2}$$

“Marginal” NPV for the cooled gas turbine

A change in blade materials or design will not affect the price of the gas turbine when it is first being offered on the market, and hence, there is no change in CC for the various alternatives considered in the present paper. Furthermore, it is assumed that the only part of the maintenance cost that will change as the blading is altered is the materials cost of the blading itself; the labor cost for the replacement is assumed to be equal, regardless of materials. The fuel consumption and, hence, the fuel cost, will change with varying TET and varying coolant mass flow requirements. All operational costs, such as staff, are assumed not to be affected by blading or temperature level modifications. All calculations are made without taxes, which means that there will be no difference in environmental cost between the different cases.

The fuel cost, fc, is an input parameter that is allowed to vary in the present study. Furthermore, the fuel mass flow, $\dot{m}_f$, will change with varying turbine inlet temperature and required coolant mass flow. Under these conditions, for a year with the operational time, ot, the marginal fuel cost ΔFC is:

$$\Delta FC = \left(\dot{m}_f \cdot fc - \dot{m}_{ref} \cdot fc_{ref}\right) \cdot LHV \cdot ot \qquad (3)$$

since the fuel cost is given in SEK/kWh, based on the fuel lower heating value, LHV.

The electricity price is another input parameter that will be varied, and the power output, P, will vary depending on the cooling technology and TET. Hence, the marginal income of produced power during one year is:

$$\Delta EP = \left(P \cdot ep - P_{ref} \cdot ep_{ref}\right) \cdot ot \qquad (4)$$

The marginal maintenance cost under the above described conditions is for the replacement of one set of blades that is paid at the end of year n:

$$\Delta MC = \frac{FV_b - FV_{b,ref}}{(1+r)^n} = \frac{\Delta FV_b}{(1+r)^n} \qquad (5)$$

The input for the economic calculations is given in TABLE I.

TABLE I. INPUT FOR ECONOMIC ASSESSMENT OF VARIOUS FIRST STAGE CONFIGURATIONS.

Economic lifetime, n	20 years*
Rate of return, r	4%, 8%*
Operational time, ot	6000 h/year*
Blade lifetime	30 000 h
Specific fuel cost, fc	0.10 SEK/kWh*
Specific electricity price, ep	0.15 SEK/kWh
Single-crystal blades	1.5 MSEK
Polycrystalline blades	1.0 MSEK
Ceramic blades	1.5 MSEK

In TABLE I, values marked with * are set according to data given by Elforsk (2000), the Swedish electric power research and development society. A natural gas price of 0.10 SEK/kWh is very high, compared to prices in many other countries, but due to the lack of competition on the Swedish natural gas market, this is the estimated average cost for a plant of this size in Sweden. The electricity price of 0.15 SEK/kWh is what is currently being paid to the producer for electric power on long-term contracts on the deregulated market in Sweden. This price will most probably remain unchanged during at least year 2001. In the long term, it is of course more difficult to predict the development of the electricity price, but it is probable that it will rise, as power plants that deliver electricity to the grid grow older and need more maintenance or need to be replaced.

The price of the blades that is given in TABLE I is based on experiences for engines of this size, and include only material costs for the blades that are being inserted in the first stage when the previous blading is replaced during maintenance stops. No manufacturing costs are considered since the cost of the manufacturing itself is assumed to be equal for all blade types in this study.

A real rate of return of 8% reflects a business situation where concern is taken to risk, whereas, a real rate of return of 4% can be said to reflect a situation without risk (Elforsk, 2000).

With the assumptions above, the blading will be replaced during years 5, 10, 15 and 20, and, hence, in this case the marginal net present value, ΔNPV, becomes:

$$\Delta NPV = \left(\Delta EP - \Delta FC\right)\frac{(1+r)^n - 1}{r(1+r)^n} + \Delta FV_b\left(\frac{1}{(1+r)^5} + \frac{1}{(1+r)^{10}} + \frac{1}{(1+r)^{15}} + \frac{1}{(1+r)^{20}}\right) \qquad (6)$$

If there is no change in material costs between the different cases that are compared, ΔFV_b in Eq. (6) will be zero. It should be pointed out that the application of Eq. (6) does not show whether the investment in a power plant as a whole will bring a profit; it just shows how much more or less profit can be made for a particular alternative compared to the reference case. The very simple principle of the use of ΔNPV is illustrated in *Figure 1*, where an arbitrary case X has a net present value superior to the reference case, and another arbitrary case, Y, has a net present value inferior to the reference case.

When using the concept of ΔNPV, care must be taken not to interpret too much from the results. A positive value of ΔNPV for a case does not necessarily mean that this case will bring a profit. The meaning is that it will bring a larger profit *or* a smaller loss than the reference case. Using the thermal efficiency, the heat input to a plant can be expressed as:

$$\dot{m}_f LHV = \frac{P}{\eta_{th}} \qquad (7)$$

This means that the term ΔEP-ΔFC in Eq. (6) can be expressed as:

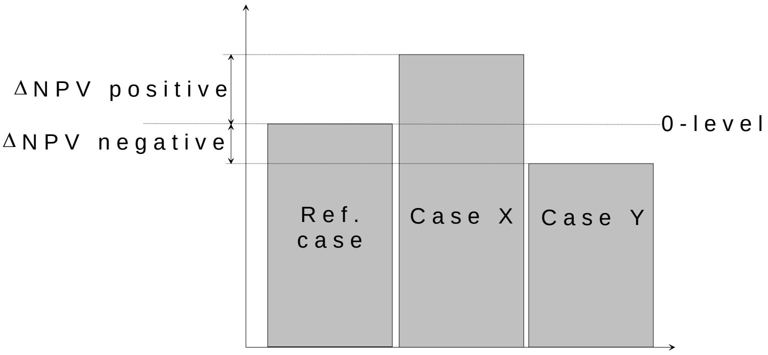

Figure 1. The principle for the use of the "marginal" net present value ΔNPV.

$$\Delta EP - \Delta FC = \left[P\left(ep - \frac{fc}{\eta_{th}} \right) - P_{ref}\left(ep_{ref} - \frac{fc_{ref}}{\eta_{th,ref}} \right) \right] ot \qquad (8)$$

The expression in Eq. (8) illustrates the above statement concerning the meaning of the ΔNPV: Power output P is always positive and, hence, as long as the value of $ep\text{-}fc/\eta_{th}$ is larger for a studied case than for the reference case, ΔNPV is positive. However, the difference between electricity price and fuel cost must be large enough if a profit is to be generated. With increasing plant thermal efficiency, this necessary difference can be reduced. Any modifications to a power plant should take into account the importance of changes in P and η_{th} in Eq. (8), if an increase in profit is to be obtained from a modification of a power plant concept.

4. Cases Studied

Three different blade materials were considered for the first stage, at two different values of TET which means that altogether six cases were studied.

The three blade materials studied are:

1) Single crystal
2) Polycrystalline superalloy with Thermal Barrier Coatings (TBC)
3) Ceramics, i.e. uncooled blades and vanes

Single-crystal blades and vanes are current state-of-the-art, and less temperature resistant polycrystalline superalloys with TBC are being employed in many gas turbines that are in service today. Ceramic blades and vanes for gas turbines of the size that is being considered here (~40 MW) are currently not possible to manufacture, but they are investigated here to see under what conditions they could be an interesting alternative, once they become available.

The turbine inlet temperature (TIT) is defined as the combustor outlet temperature that would be obtained if the entire compressor inlet mass flow (without leakage and extractions for cooling and sealing) entered the combustor, and at the same time the fuel flow, heat release and combustor inlet temperature are maintained at the values of the actual engine. Two values of TIT were chosen for case 1: case 1a, where TIT=1200°C and case 1b where TIT=1240°C. The two corresponding values of TET that are obtained in this way were maintained for the calculations of cases 2 a, b and 3 a, b.

A detailed description of the model employed for the cooled gas turbine is given in Jordal (2001). The model is thermodynamic and non-dimensional and uses a uniform blade temperature for the calculation of the coolant mass flow requirements. The model includes a linear correlation between gas turbine hot gas temperature and maximum blade temperature, which leaves the temperature difference between maximum and uniform blade temperature as the main parameter. For the single-crystal blading, this temperature difference was set to 200°C, and for the polycrystalline blading, it was increased by 50°C, meaning that the cooling of the blades must be increased to obtain this lower blade temperature.

TABLE II. RESULTS OF PERFORMANCE CALCULATIONS WITH INPUT ACCORDING TO TABLE I

Case	η_{th} [%]	P [MW]	$\dot{m}_f$ [kg/s]	m_{CO2} [kg/MJ$_e$]
1a	54.3	55.9	2.11	0.106
1b	55.3	60.2	2.23	0.104
2a	53.4	52.8	2.03	0.108

2b	54.4	57.1	2.15	0.106
3a	56.3	65.9	2.40	0.103
3b	57.2	71.0	2.54	0.101

5. Results

The performances of the various combined cycles are given in TABLE II. Although CO_2-taxes are not considered in the economical studies, CO_2-amounts are included in the table for the discussion of the results.

It can be seen from the results that an increase in thermodynamic efficiency of one percentage point is possible as TET is raised according to the principle described above, going from cases a to cases b, but also a small increase in CO_2 emissions, since more fuel is used for combustion. Also, there is an increase in thermal efficiency of almost one percentage point when the material temperatures are increased by 50°C, as one moves from case 2a or b to case 1a or b. Furthermore, it is evident that it would be possible to obtain a significant increase in power output of about 2 percentage points if it were possible to insert ceramic materials in the first stage of a gas turbine. As a comparison, a 2-percentage point increase in simple cycle efficiency is what is reported to be possible to obtain within the US DOE ATS program for simple cycle efficiency (Layne and Hoffman, 1999).

For the economic calculations, case 1a was chosen as the reference case and the values in TABLE III show the deviation between the net present value for a particular case and case 1a.

TABLE III. "MARGINAL" NET PRESENT VALUE (ΔNPV). ALL VALUES IN MSEK

Case	r = 4%	r = 8%
1a	0	0
1b	4.05	2.93
2a	-4.10	-3.03
2b	-0.10	-0.14
3a	7.44	5.37
3b	12.2	8.83

With an approximate investment cost of 220-250 MSEK for an entire combined cycle power plant of this size, it can be seen that the difference in the net present value between the various cases is of rather marginal importance, with the exception of case 3b and perhaps also 3a. The deviation between the various cases is smaller for a higher required rate of return, r, which illustrates the fact that a more risky power plant project must show a significant improvement in performance to be of interest, when compared to more conventional technologies.

Nevertheless, the difference in NPV is rather small between the various cases, regardless of the rate of return. The reason for this small difference is explained in the following sensitivity analysis.

6. Sensitivity Analysis

Some of the parameters that were set in the calculations above can be affected by the power plant owner (operation schedule, operation time, TET and, in a way, the required rate of return), whereas others, in particular fuel and electricity prices, cannot be affected.

Impact of varying fuel and electricity prices

The fluctuation in fuel and electricity prices is very difficult to predict and, hence, the impact of these two parameters on power plant profitability must be studied and understood when evaluating different technical solutions for the gas turbine or any other power plant component.

The impact of varying fuel and electricity prices on the ΔNPV is shown in *Figures 2* and *3*. Case 1a is maintained as the reference case. The difference between case 1a and the other cases is shown for each value of the electricity price and the fuel price, respectively, which means that the curve for case 1a coincides with the x-axis.

The reason for the small differences in TABLE III can be seen in *Figures 2* and *3*. With the input given in TABLE I, where the difference between fc and ep is rather small, it is definitely true that there is not much difference among the various bladings and turbine inlet temperatures. However, it can be seen that with increasing electricity price or decreasing fuel price, the economic benefit of increased efficiency is enhanced and vice versa. This means that with input data like those in TABLE I, that give a minor difference in NPV between the cases, refer to TABLE II, the investment should be made in the available technical alternative that gives the highest thermal efficiency, if it is believed that electricity prices will rise more than fuel prices in the future.

Over a period of 20 years, it could be realistic to have an electricity price equivalent to that of an average of 0.20 SEK/kWh. In that case, the benefit of case 1b compared to 1a, single-crystal blading in both cases but higher TET in case 1b would be approximately 15 MSEK, and compared to case 2b, polycrystalline blades, high value of TET, it would be approximately 10 MSEK. On the other hand, as can be seen in *Figure 3*, this benefit would be erased if, at the same time, fuel prices were to increase from 0.10 to 0.15 SEK/kWh.

Impact of varying blade lifetime

The operating schedule will affect the life of the blading, and hence, the interval between the replacements. The blades are designed for 40 000 equivalent hours; the actual blade lifetime is affected by the number of starts and shutdowns. In the calculations above, it was assumed that this would result in an actual blade life of 30 000 hours. In order to illustrate what impact this has on the economy of the power plant, the cases of blade lifetime of 20 000 and 40 000 hours were calculated. For these different calculations it is necessary to include the labor cost for the replacement of the blades which has been assessed to be 1.5 MSEK per replacement.

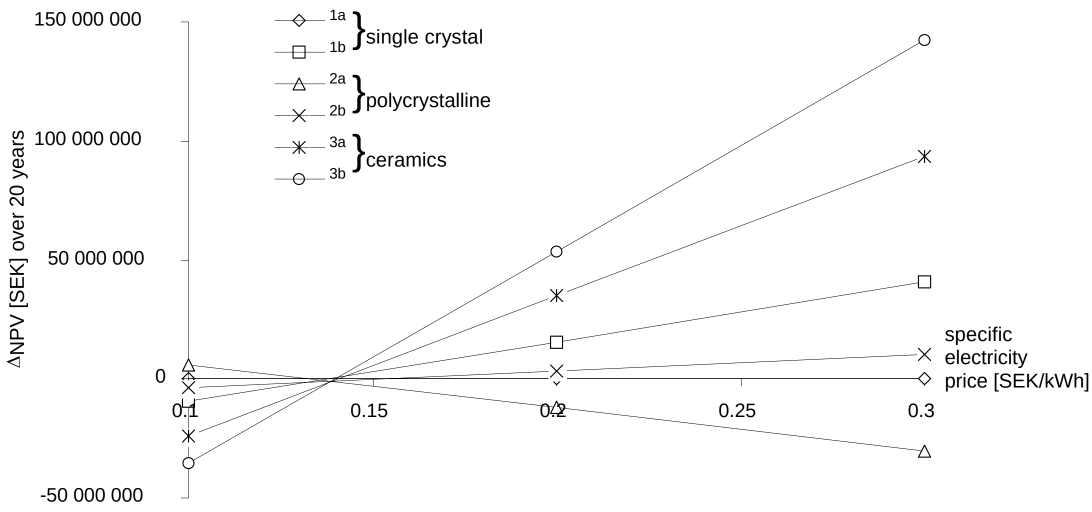

Figure 2.Variation of ΔNPV with electricity price, fc=0.10 SEK/kWh

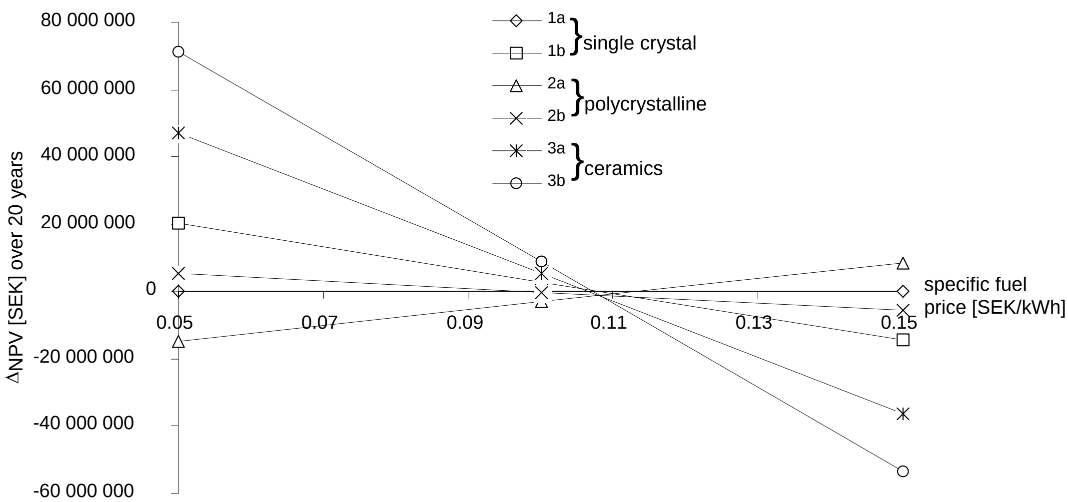

Figure 3. Variations of ΔNPV with fuel price, ep=0.15 SEK/kWh

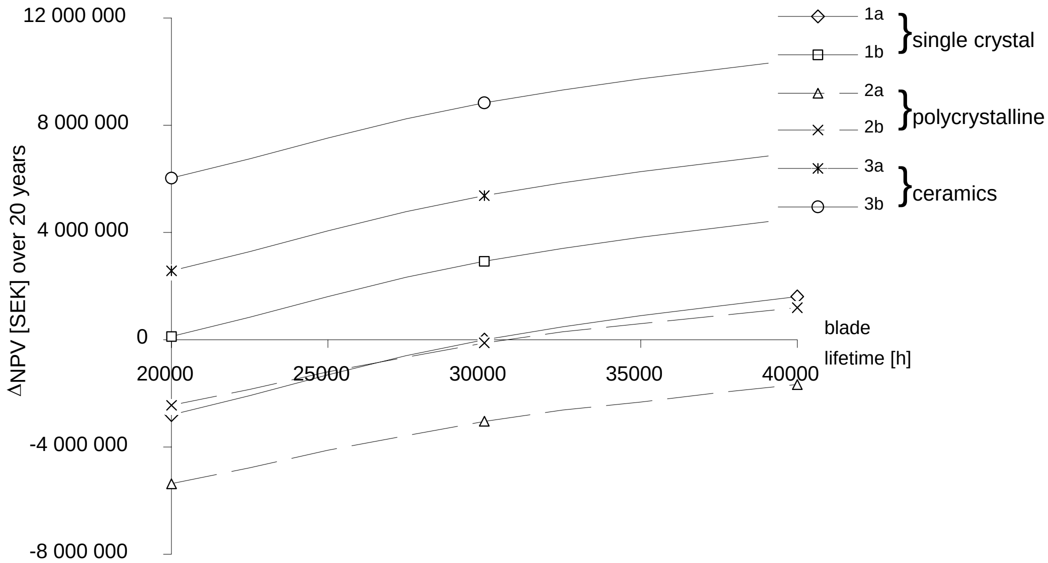

Figure 4. Impact of blade lifetime on plant ΔNPV

Furthermore, it is estimated that the replacement of the blades can be made during planned stops. The result is shown in *Figure 4*.

It can be seen that the deviation between various blade lives is rather small for any case; the increase or decrease in blade life in itself will cause an additional benefit or loss of approximately 3 MSEK over a period of 20 years.

In fact, the large loss of income that might occur if the operational schedule is such that blade life is shortened is the loss of income of unplanned stops for blade replacement. However, the economic impact of this was beyond the scope of this study.

7. Conclusions

A general method to estimate the difference in economic outcome among different technical solutions has been described with the purpose of illustrating that thermal efficiency alone is not sufficient for evaluating a power plant concept. The method is based on the calculation of the difference of the Net Present Value (NPV). In the present study, the long-term cost or benefit of various gas turbine first stage blading technologies was studied.

Under the given conditions, it is estimated that a combined cycle with a gas turbine with single-crystal blading, instead of polycrystalline blading, could increase the benefit of the power plant by an order of magnitude of 15 MSEK over its economic lifetime of 20 years, as the net power output is increased from 57 to 60 MW. The corresponding figure for ceramic blading in the first stage of the turbine would be around 50 MSEK, as the net power output could be raised to 71 MW. CO_2-taxes on electric power production would give additional economic benefit to techniques that increase the thermal efficiency.

Nomenclature

CC	capital cost (SEK)
EC	environmental cost (SEK)
EP	value of sold electricity (SEK)
FC	fuel cost (SEK)
FV	future value (SEK)
I	income (SEK)
K	cost (SEK)
LHV	lower heating value (J/kg)
MC	maintenance cost (SEK)
NPV	net present value (SEK)
OC	operational cost (SEK)
P	electric power (W)
PV	present value (SEK)
TET	turbine entry temperature (°C)
TIT	turbine inlet temperature (°C)
ep	specific electricity price (SEK/kWh)
fc	specific fuel cost (SEK/kWh)
$\dot{m}$	mass flow rate (kg/s)
n	year after investment
ot	operational time (h)
r	rate of return [-]
Δ	difference [-]
η	efficiency [-]

Subscripts

b	blade or blading
e	electricity
f	fuel
PV	present value
ref	reference
th	thermal

Acknowledgements

This work was sponsored by the Swedish National Energy Administration within the frame of the research program “Thermal Processes for Electric Power Production”. Adjunct Professor Lars Sjunnesson, Sydkraft, is greatly acknowledged for the information concerning prices on the deregulated electricity market.

References

Bathie, W. W., 1996, *Fundamentals of gas turbines*, John Wiley and Sons, New York.

Carvalho, F. R., Horta Nogueira, L.A., 1996, “Thermoeconomic studies applied to maintenance of power plants”, *Proceedings of ECOS’96*.

Elforsk, 2000, El från nya anläggningar (Electricity from new plants). Report No. 00:01.

El-Sayed, Y. M., 1998, “Revealing the cost-efficiency trends of the design concepts of energy-intensive systems”, *Proceedings of ECOS’98.*

Jordal, K., 2001, “Modelling and Performance of Gas Turbine Cycles with Various Means of Blade Cooling”, PhD Thesis No. ISRN LUTMDN/TMVK—1027—SE, Lund University, Sweden.

Jordal, K., Torisson, T., 2000, “Comparison of gas turbine cooling with dry air, humidified air and steam”, *Proceedings of ASME TurboExpo 2000*, Paper no. 2000-GT-0169.

Layne, A. W., Hoffman, P.A., 1999, “Gas turbines for the 21st century”, *Proceedings of ASME TurboExpo 1999*, Paper No. 99-GT-367.

Northcott, D., 1998, *Capital investment decision-making*, International Thomson Business Press, London.

Tsatsaronis, G., Moran, M., 1996, “Exergy-aided cost minimization”, *Proceedings of ECOS’96*.

Tucci, M., Rinaldo, R., Romoli, S., 1996, “General regression neural network in energy cost analysis”, *Proceedings of ECOS’96*.