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ANALYSIS OF COGENERATION ALTERNATIVES

M.A. Korobitsyn, G.G. Hirs

Department of Mechanical Engineering
University of Twente
Enschede, The Netherlands

ABSTRACT

Cogeneration plants in industries employ various schemes to satisfy the process needs. To determine the most efficient concept for process steam production, five different steam and power generating alternatives were compared on the basis of a constant process heat demand. The plants under consideration include both conventional boiler and gas turbine schemes with and without a back-pressure steam turbine. In the case of the gas turbine, additional options with supplementary firing were also examined. The alternatives were compared with the help of fuel saving analysis and exergy analysis. A comparison of CHP options with a conventional boiler leaded to a definition of the critical electric efficiency that indicates when fuel saving is zero. The results of exergy analysis of the plants are shown.

INTRODUCTION

Combined production of heat and power (CHP) is widely used for the process and space heating needs. The last decade has been marked by the rapidly growing number of cogeneration units. For example, in the Netherlands the amount of electricity produced at the CHP installations has grown from 9% of the total generated power in 1980 up to 18% in 1993 (Energiegids, 1994). Further increase of the cogeneration share in the total power production is expected. The Dutch Energy and Environment Agency NOVEM predicts a share increase of up to 25% by the year 2005. It is obvious that this considerable amount of power should be generated efficiently. To evaluate performance of a CHP plant an objective criterion is required.

Combined generation of heat and power implies production of two different kinds of energy. To analyse the efficiency of a plant they should be brought to a common denominator. Avoided fuel costs, or fuel consumption saving, can be one of the criteria to compare different CHP options (Timmermans, 1978). Efficiency calculations based on energy balance can be another measure, but the First Law approach, dealing only with the quantitative side of energy, can provide inadequate results. This was shown by F.F. Huang (1990) for a single-pressure HRSG cogeneration plant. Introducing the Second Law analysis to compare cogeneration options has proved to be a valuable methodology. M.A. Rosen and D.S. Scott (1986) defined and compared energy and exergy efficiencies for cogeneration systems, applying the analysis to several fuel-cell plants. M.A. Habib (1994) showed exergy advantage of a simple cogeneration plant over a conventional steam plant. A general overview of thermal plant configurations and their efficiencies was given by E.I. Yantovskii (1994). However, little work has been done on a detailed analysis of cogeneration alternatives.

The present paper focuses on typical cogeneration schemes. The aim of the study was to quantify the differences between the various options with the use of different methodology.

NOMENCLATURE

B = exergy, kW_{ex}
H = fuel consumption, kW_{th}
ΔH = fuel saving, kW_{th}
P = electric power production, kW_e
η = efficiency, %

Superscripts

crit = critical
el = electric
ex = exergetic

Subscripts

i = *i*-th alternative
ref = reference plant
ut = utility

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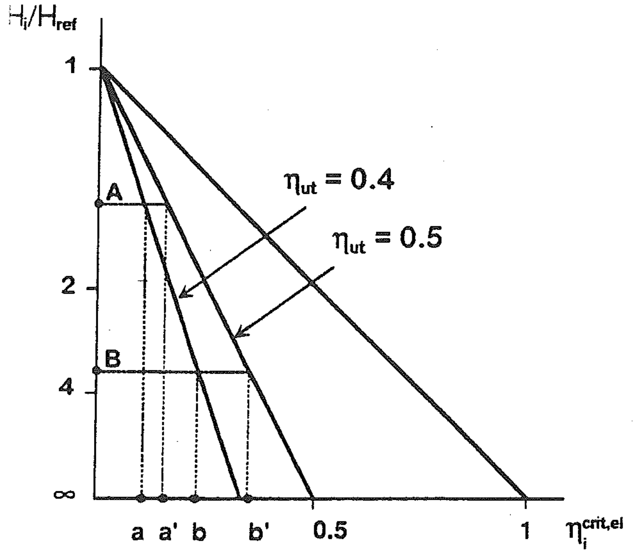


FIG. 1 CRITICAL ELECTRIC EFFICIENCY

FUEL SAVING ANALYSIS

To evaluate fuel saving of a cogeneration scheme, it is ompared with a conventional boiler as a reference. Electrical fficiency, with which power is generated by a cogeneration nit, is compared with that of a utility. The fuel saving of an lternative based on an equal heat production can be defined as difference between two terms. The first term is a sum of the mount of fuel consumed by the reference boiler plant H_{ref}, and ne fuel that would be consumed by a utility to generate power qual to that of the CHP plant, H_{ut}. The second term is the fuel onsumed by the cogeneration plant, H_i.

$$\Delta H_{i-ref} = \left(H_{ref} + H_{ut}\right) - H_i \tag{1}$$

Substituting H_{ut}, it becomes:

$$\begin{aligned} \Delta H_{i-ref} &= \left(H_{ref} + P_i/\eta_{ut}^{el}\right) - H_i = \\ &= \left(H_{ref} + H_i \eta_i^{el}/\eta_{ut}^{el}\right) - H_i = \\ &= H_i\left(\eta_i^{el}/\eta_{ut}^{el} - 1\right) + H_{ref} \end{aligned} \tag{2}$$

Fuel saving is zero, if the following condition is true:

$$\eta_i^{crit,el} = \eta_{ut}^{el}\left(1 - H_{ref}/H_i\right) \tag{3}$$

This critical electrical efficiency of an alternative at different vels of utility efficiency can be presented in a graph (Fig. 1).

A typical gas turbine CHP plant uses 2 to 4 times more fuel than the reference plant. To provide fuel savings the gas turbine plant is to be operated with electric efficiency close to that of utility. At the same time, a conventional boiler plant with a back-pressure steam turbine, that consumes 10-20% more fuel than the reference plant, can provide the savings at a rather low electric efficiency. It is shown in Fig. 1, where variant A represents a conventional boiler with a steam turbine and ratio H_i/H_{ref} of 1.15, and variant B as a gas turbine plant featuring the ratio of 3. It can be seen how a change in utility efficiency from 0.4 to 0.5 influences the critical efficiency for these CHP plants. For alternative A it leads to a small change from 0.05 to 0.06, while for alternative B the threshold value is increased from 0.27 to 0.33. Therefore, to provide fuel savings during its operational lifetime, a new CHP plant has to be designed either as a conventional boiler with a back-pressure turbine, or as a gas turbine plant with a high electric efficiency.

CONFIGURATION

The fuel saving analysis was applied to five initial alternatives:

1. Conventional boiler [10 bar]
2. Conventional boiler [80 bar] with back-pressure steam turbine
3. Gas turbine with single pressure HRSG [10 bar]
4. Gas turbine with single pressure HRSG [80 bar] and back-pressure steam turbine
5. Gas turbine with dual pressure HRSG [10/80 bar] and back-pressure steam turbine

Each of them delivers 40 t/h of superheated process steam [10 bar, 203°C]. The steam turbine has isentropic efficiency of 80% and expands steam from 80 bar/430°C to 10 bar/203°C. A heat recovery steam generator features the approach and pinch temperature of 10 K. All systems comprise a deaerator [1.2 bar]. It was assumed that there were neither the boiler blow-down, nor deaerator vent flows, and the return flow constituted 100% of the process flow. The flow diagrams of the plants are presented in Figure 2.

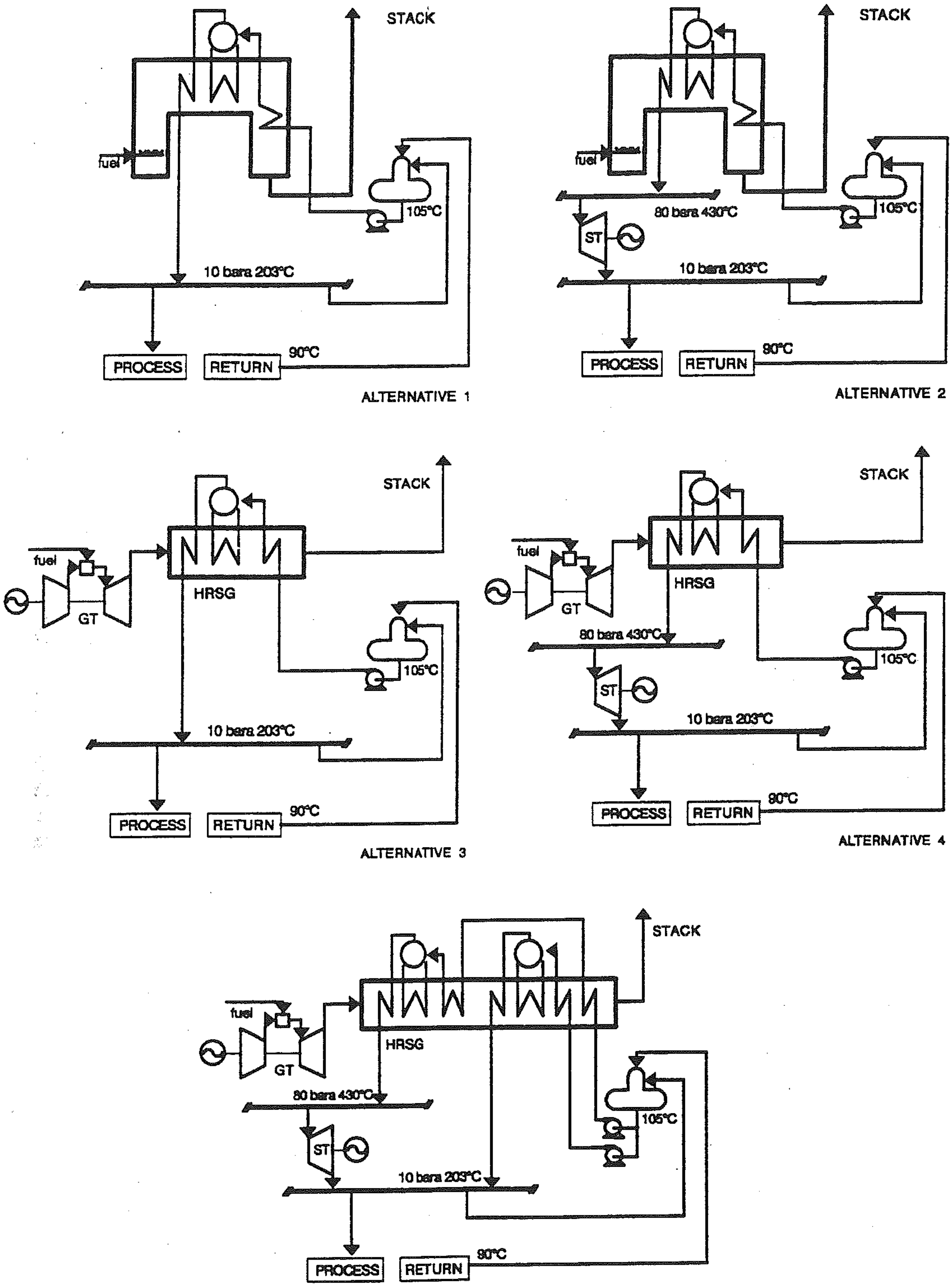
Three modifications with a duct burner were also considered:

3A. the same as 3, with supplementary firing
4A. the same as 4, with supplementary firing
5A. the same as 5, with supplementary firing

Thermal efficiency of the reference conventional boiler was set to 95%. Calculations were made using the Dutch natural gas as a fuel with the lower heating value of 38 MJ/kg.

The gas turbine simulation was based on the performance data of General Electric LM6000 engine:

Electric power	38.4 MWe
Exhaust flow	125.1 kg/s
Exhaust temperature	462°C
Simple-cycle efficiency	37.88%



ALTERNATIVE 1

ALTERNATIVE 2

ALTERNATIVE 3

ALTERNATIVE 4

ALTERNATIVE 5

FIG. 2 FLOW DIAGRAMS OF THE CONFIGURATIONS

TABLE 1. PERFORMANCE DATA AND FUEL SAVING

Alternative		1(ref)	2	3	3A	4	4A	5	5A
Total power production	MW_e	0.00	4.23	24.28	12.10	42.70	23.50	30.75	17.70
Fuel consumption	MW_{th}	28.73	33.29	64.14	45.40	101.59	65.00	73.11	52.20
Electric efficiency	%	-	12.71	37.85	26.65	42.03	36.15	42.06	33.91
Stack temperature	°C	114	124	148	141	235	208	155	144
Ratio H_i/H_{ref}		1.000	1.159	2.233	1.580	3.536	2.262	2.545	1.817
Additional power production compared to the reference	MW_e	0.00	4.23	24.28	12.10	42.70	23.50	30.75	17.70
Additional fuel consumption compared to the reference	MW_{th}	0.00	4.56	35.41	16.67	72.86	36.27	44.38	23.47
Fuel saving (η_{ut}=40%)	MW_{th}	0.00	6.02	25.29	13.58	33.89	22.48	32.50	20.78
Fuel saving (η_{ut}=50%)	MW_{th}	0.00	3.90	13.15	7.53	12.54	10.73	17.12	11.93

Exhaust gas composition:

O_2	14.29%
CO_2	2.97%
N_2	75.19%
Ar	0.89%
H_2O	6.66%

ANALYSIS OF THE ALTERNATIVES

The fuel saving analysis was based on a constant steam demand of 40 t/h. When a simulation model had a different steam production, fuel consumption and generated power were linearly scaled to fulfil the steam demand. Then, all options were compared with the conventional boiler as a reference. Fuel saving was calculated for different values of national efficiency. This analysis was also applied to a case of doubling steam production by means of supplementary firing (HRSG options). In this case, the working parameters were also scaled down to the constant steam supply of 40 t/h.

It can be seen from Table 1 that in the case where 40% was taken as average national efficiency, options gas turbine with unfired HRSG save 25-34 MWth of fuel compared to the conventional boiler, and 4 to 5 times more fuel compared to alternative 2 (conventional boiler with a steam turbine). The most economical option in this case is option 4, although, if national efficiency is assumed to be 50%, this is not the case. The fuel saving of alternative 4 is decreased by 60%. This can be explained by the highest H_i / H_{ref} ratio of the alternative, which indicates the scheme that is the most sensitive to an improvement in utility efficiency. Such a high ratio is resulted from exclusively generating high-pressure steam in HRSG.

The table also shows that the schemes with an unfired HRSG save 1.4 - 1.9 times more fuel than a plant with supplementary firing. This effect is especially noticeable in alternative 3. Among the firing cases, it is seen that at 40% as a value of utility efficiency, option 4A is most advantageous. But when η_{ut} improves, alternative 5A saves 12% more fuel than alternative 4A. Supplementary firing has some positive effect on option 4A in reducing the stack temperature to 208°C.

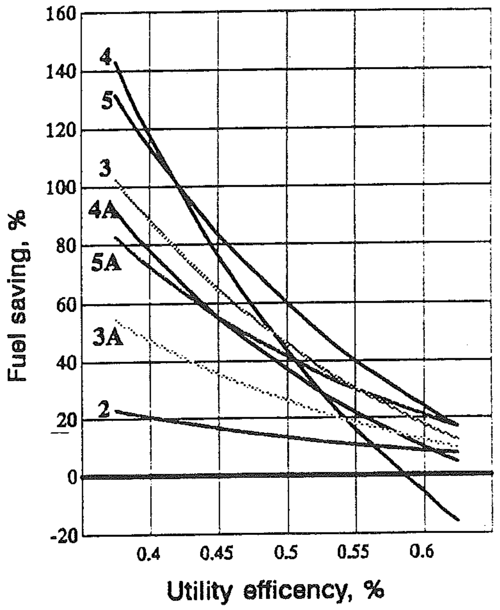
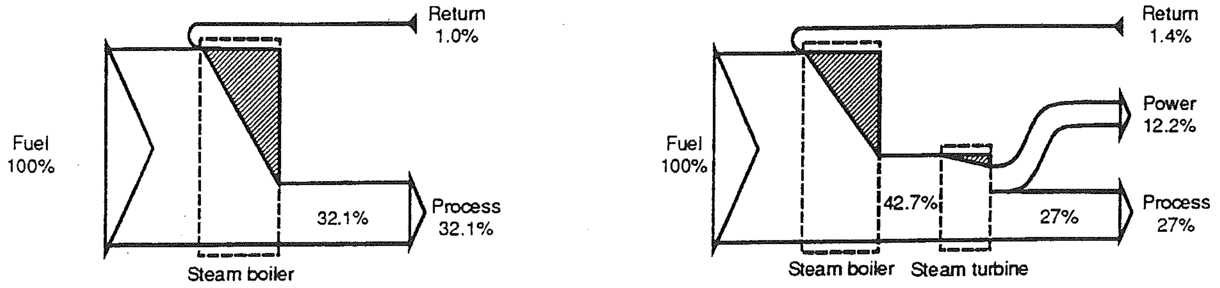
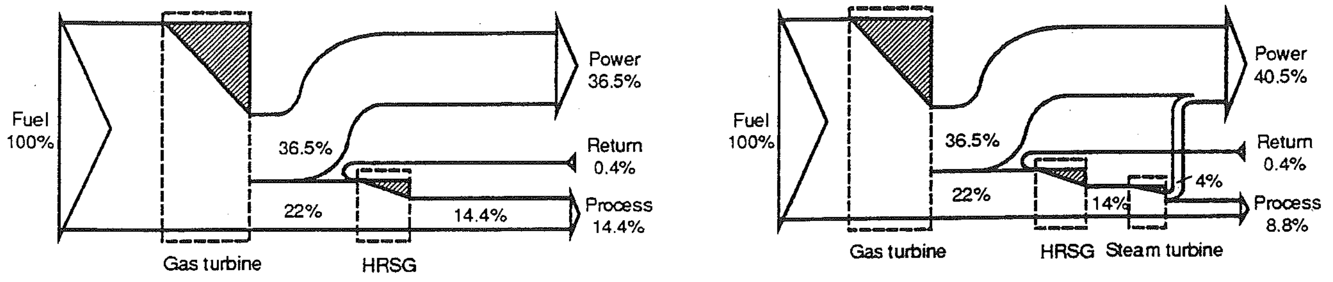


FIG.3 THE FUEL SAVING AS PERCENTAGE OF THE REFERENCE PLANT FUEL CONSUMPTION

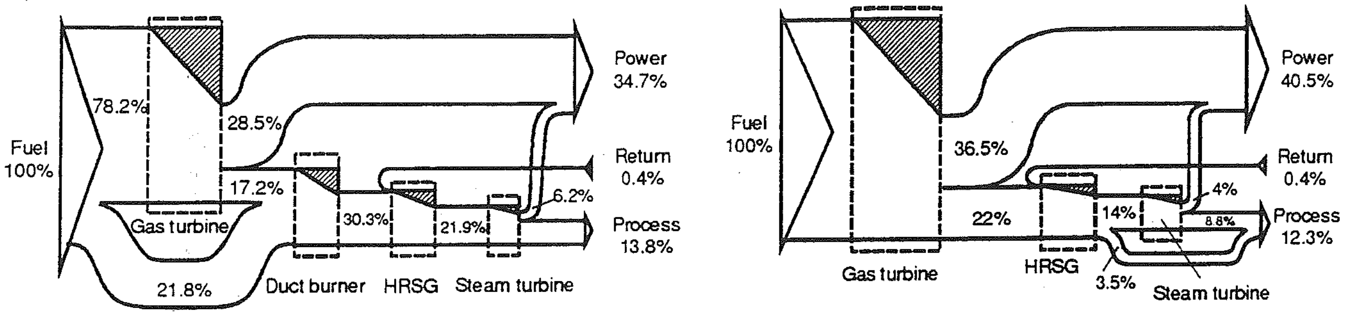
The influence of utility efficiency on the fuel saving is presented in Figure 3. The sensitivity of option 4 can be noted; the option's savings become zero when utility efficiency approaches 55.7%.



ALTERNATIVE 1 **ALTERNATIVE 2**



ALTERNATIVE 3 **ALTERNATIVE 4**



ALTERNATIVE 4A **ALTERNATIVE 5**

FIG. 3 GRASSMANN DIAGRAMS

EXERGY EFFICIENCY

Exergy efficiency of a process can be defined as:

$$\eta^{ex} = \sum \dot{B}_{out} \Big/ \sum \dot{B}_{in} \qquad (4)$$

that characterises the ratio of the desired output to the necessary input (Kotas, 1985).

For a combine heat and power plant it can be written as:

$$\eta^{ex} = (\sum \dot{B}_{out}^{power} + \sum \dot{B}_{out}^{heat}) \Big/ \sum \dot{B}_{in}^{fuel} \qquad (5)$$

where stack losses and blow-down flows are excluded from the desired output.

To analyse performance of separate components of a power plant, it was divided into black boxes, such as: a gas turbine, a duct burner, HRSG, or a steam turbine. The efficiency was calculated per black box and per system as a whole. The following assumptions were made: (1) only chemical exergy was used for fuel, (2) only physical exergy was used for flue gas and water/steam flows.

Exergy flow through a power plant can be presented in a Grassmann diagram. The diagram allows to visualise the exergy flows and irreversibilities. That was made for the plants under consideration (Fig. 4). Substantial exergy losses can be seen to occur in the conventional boiler. Depending on the steam pressure, the losses vary from 57% to 67%. In a gas turbine the losses amount to 41.5%. Introducing supplementary firing deteriorates exergy efficiency for all gas turbine plants.

Regarding the performance of HRSG, an equal exergy ratio for HRSG is noted in options 3 and 4, whereas option 4 generates steam of a higher exergy value. That is explained by the lower steam production of alternative 4. Although the mass flow of high-pressure steam in option 4 accounts for 63% of the flow in alternative 3, the higher exergetic quality of this stream makes it comparable with the low-pressure steam flow in option 3.

The final chart (Fig. 5) presents a comparison of overall exergy versus energy efficiencies of the alternatives under consideration. It confirms an evident advantage of the gas turbine plant in general, and, of the unfired double-pressure HRSG scheme, in particular. The efficiencies of the gas turbine alternatives lie in the range of 50% with two extremes: option 3A (single-pressure HRSG with supplementary firing and without steam turbine), which has efficiency of 45%, and option 5 (double-pressure unfired HRSG and steam turbine) with efficiency of 52.4%. The lowest energy efficiency among the gas turbine configuration has alternative 4. This is caused by producing high-pressure steam which results in larger stack losses (Table 1).

A remarkable difference can be seen between energy and exergy efficiencies, and even an opposite trend for most of the options should be noted: while exergy efficiency rises, energy efficiency decreases.

CONCLUSIONS

Fuel saving and exergy analyses both showed apparent benefits of the gas turbine plant featuring dual-pressure unfired HRSG concept in comparison with the other alternatives chosen. As long as average utility efficiency remains at the 40% level, this scheme saves a little less than a configuration based on a single-pressure HRSG with steam turbine. However, if utility efficiency is improved to a level of 50%, the double-pressure HRSG concept proves to be the most efficient one.

Examining the influence of an improvement of utility efficiency on the fuel saving, it was concluded that a gas turbine CHP plant is more sensitive to the growth of utility efficiency than a conventional boiler CHP installation. Considerable fuel consumption at a gas turbine plant can be justified only if the plant's electric efficiency is comparable to that of utility.

It was demonstrated that the use of supplementary firing was not attractive either from an operational, or a thermodynamic point of view: none of the firing alternatives could save more fuel than the corresponding unfired HRSG option. The same holds good for the exergy efficiency: the unfired schemes proved to be better in all cases.

It was shown that energy efficiency failed as a means for comparing different CHP configurations. The high energy efficiency of the conventional boiler option, for example, reflects only the quantitative, but not the qualitative side of the process, and only exergy criterion can demonstrate imperfections of this configuration.

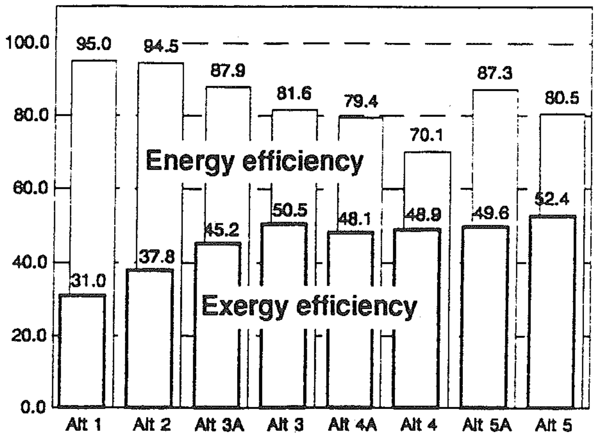


FIG. 5 COMPARISON OF ENERGY AND EXERGY EFFICIENCIES

The results of the fuel saving analysis and the exergy analysis prove that the options with better exergy efficiencies save more fuel.

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