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EVALUATION OF ENERGY PROCESSES THROUGH ENTROPY AND EXERGY

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PREFACE

Energy systems studies ordinarily make use of the concept of efficiency to characterize the effectiveness of energy conversion or use at the various stages of energy flow, from the gaining of primary energy through the stage of secondary energy to the energy finally used by the consumer or what has been called energy service. These efficiencies, defined as the ratio of energy output over energy input, do not take into account different qualities of energy, and one may be led to believe that the ratio of one (one hundred percent) were the ideal limit. These problems have been treated extensively in classical thermodynamics and textbooks, but are rarely taken up in practice, probably because there is no formalism that is simple enough but no less general than efficiency.

The work of the Energy Systems Program at the International Institute for Applied Systems Analysis is very closely related to these problems, especially the considerations on nuclear and solar energy, "negentropy supply", synthetic fuels, and of energy services; they take into account thermodynamic principles, each in its own way. The following publications are illustrative of this work (see Reference literature):

Marchetti:	Transport and Storage of Energy. RR-75-38.
Häfele:	On Energy Demand, IAEA Bulletin, 1977.
Thoma:	Energy, Entropy, and Information. RM-77-32.
Grümm:	Thermal Radiation and Entropy. RM-78-2.
Voigt:	Nuclear Entropy. IIASA internal notes.

This memorandum offers a very simple scheme for evaluating arbitrary stationary energetic systems and comparing systems that differ greatly in scale and type in terms of thermodynamic quality.

ABSTRACT

The measure of effectiveness with which energy is transformed or used in processes requires consideration of properties other than energy alone. Entropy is the most important quantity in this context. It permits to localize sources of ineffectiveness and calculate thermodynamic upper limits of efficiencies. Exergy is closely related to entropy and can be used for similar purposes; it also has the same dimension and order of magnitude as energy, but is not a variable of state in a thermodynamic sense. In this memorandum, the formalism is introduced and discussed for a (coal-fired) electric power plant, methanol production, and negentropy technologies. It is proposed to favor entropy production or exergy consumption over the concept of wasted or "consumed" energy as a measure of the effectiveness of energy use or conversion.

Evaluation of Energy Processes Through Entropy and Exergy

Description of a System and Its Thermodynamic Limits

The measure of effectiveness with which energy is transformed or used in processes requires consideration of properties other than energy alone: For example, every engineer knows that a joule of enthalpy carried by the coolant water of a power plant has less value than a joule of enthalpy carried by the high temperature steam. Similarly, it is obvious that a cold but fully charged storage battery is more useful than a discharged battery which, since it is hot, has the same total energy.

Thus a yardstick other than energy is needed to assess the minimum fuel requirements of any process. The laws of thermodynamics indicate that the relevant quantity is entropy.

Consider Figure 1. Efficiency is defined as the ratio of some "yield" to some "expense", η = yield/expense. It is

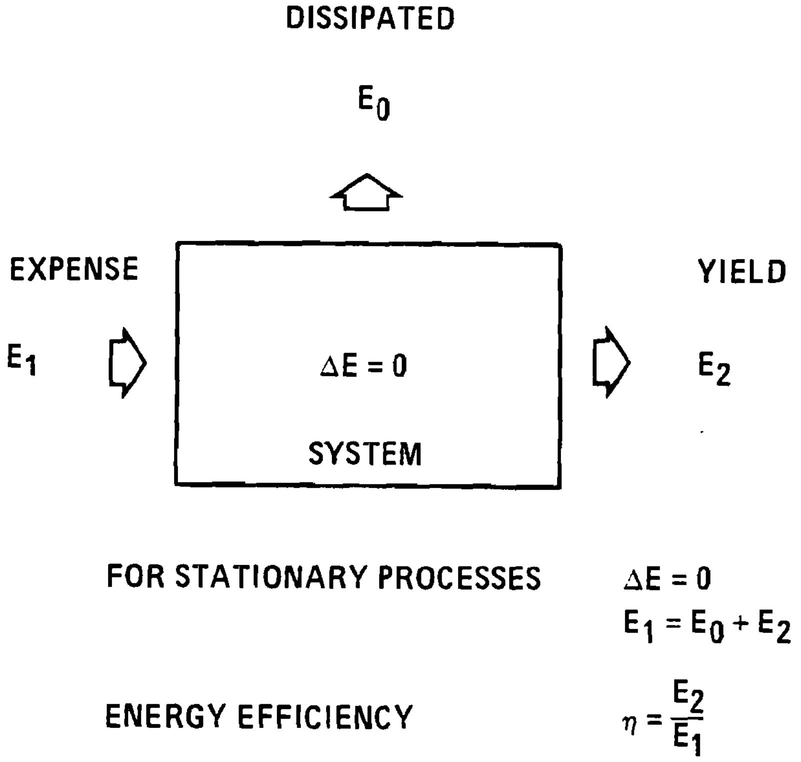


Figure 1. Nomenclature of Energy Flows that are Exchanged with a System.

preferable to measure both terms in energy and in the same units (for stationary processes in energy flow, i.e. power, Watts) obtaining a dimensionless quantity. Other choices are also possible: kWh/Btu, or gallons of hot water/barrels of oil, but these are more difficult to handle.

The expense E_1 (coal, for example) is supplied to the system, and the yield E_2 (electricity, for example) is withdrawn. For stationary processes the energy content of the system is constant over time, so that, according to the law of energy conservation, the difference $E_1 - E_2 = E_o$ has to be dissipated to the environment.

Combination of the different energy flows a system exchanges into these three groups: expense, yield, and dissipation is arbitrary and cannot be derived from thermodynamics, for instance; it is only determined by suitability and the purpose of the system.

Some energy carrying flows into and out of a (coal-fired) electric power plant, for example, are shown in Figure 2. Not all the inputs (air, coal, water, electrons) are counted as expense and not all the outputs as yield; the enthalpy difference of $(C + O_2) - CO_2$ (the so-called heat of combustion) is counted as expense, the term $(V_{high} - V_{ground}) \cdot I$ (electric energy) as yield, and all the other flows as dissipation (Figure 3).

It is essential to combine all these energy flows into exactly these three groups, since otherwise the related efficiency could not be defined uniquely.

What then does this efficiency imply in terms of a conceivable potential of the system for improvement according to thermodynamic principles, or in other words: "How big could the yield become if the expense remained the same?"

Especially if the efficiency is expressed in percentage the limit of 100 percent suggests itself. However, the thermodynamical limit need not be 100 percent, but may be more or less as is the case with a heat pump or a geothermal power plant.

It is not enough to know the energy flows or the energy efficiency of a system in order to evaluate its potential for improvement. Furthermore, this knowledge does not generally suffice for localizing the sources of ineffectiveness in the system.

In Figure 4 the electric power station is described by its main system components and its main internal energy flows. The burner is 92 percent efficient if the enthaly $(C + O_2) - CO_2$ and some electric energy for mills and blowers are counted as expense, and if the enthalpy supplied to the steam-generator is counted as yield, the rest being considered as dissipation.

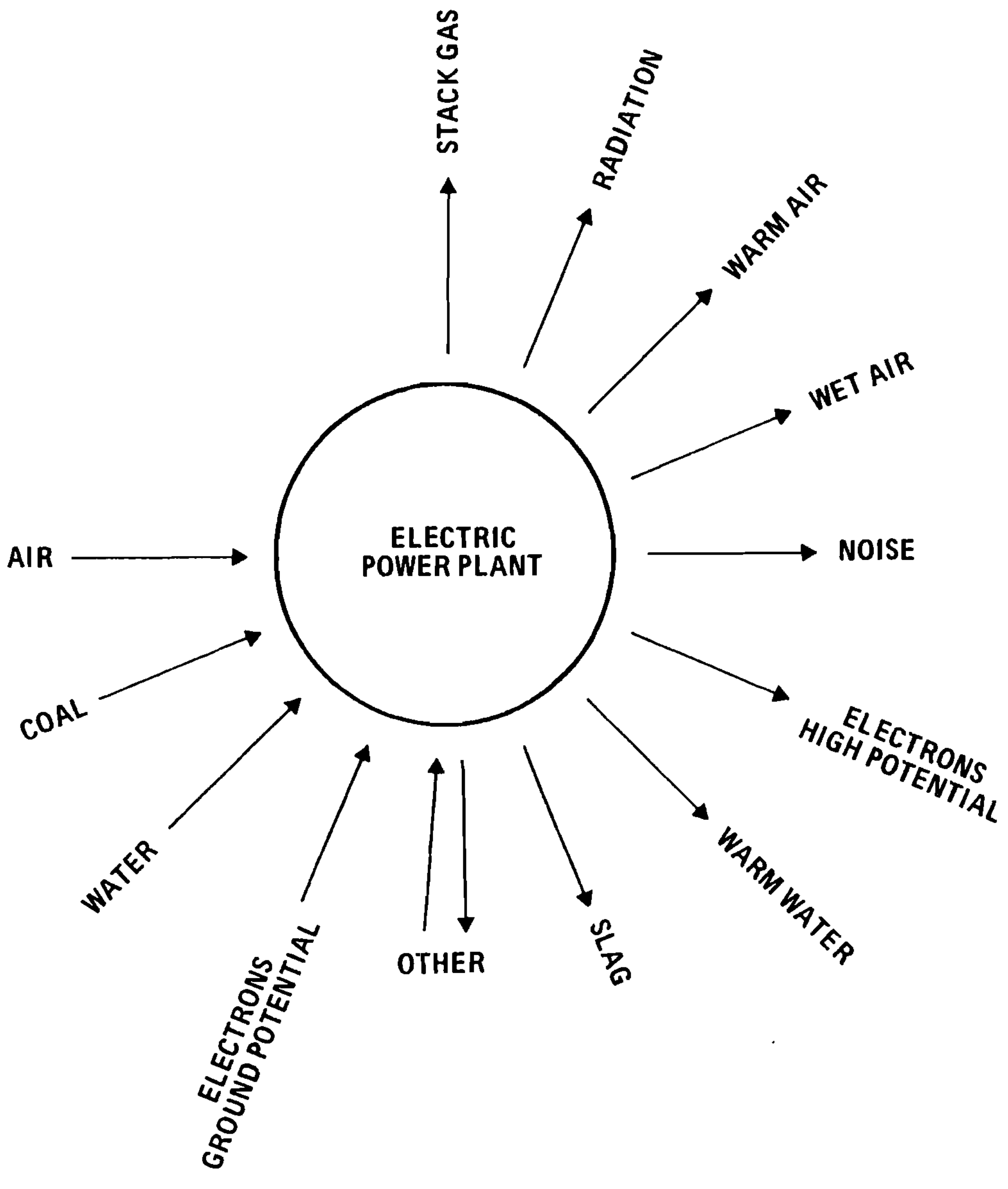


Figure 2. Main Flows that a Coal-Fired Electric Power Plant Exchanges with its Environment

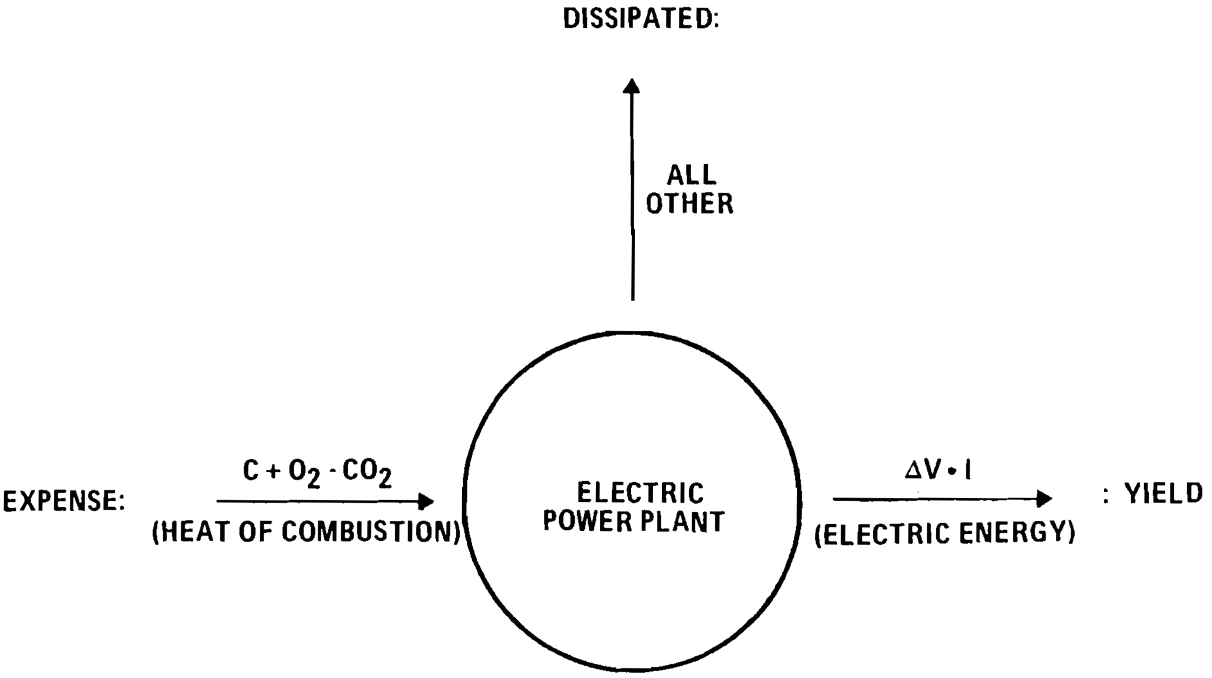


Figure 3. Flows of a (Coal-Fired) Electric Power Plant Grouped under the Aspects of Expense, Yield, and Dissipation.

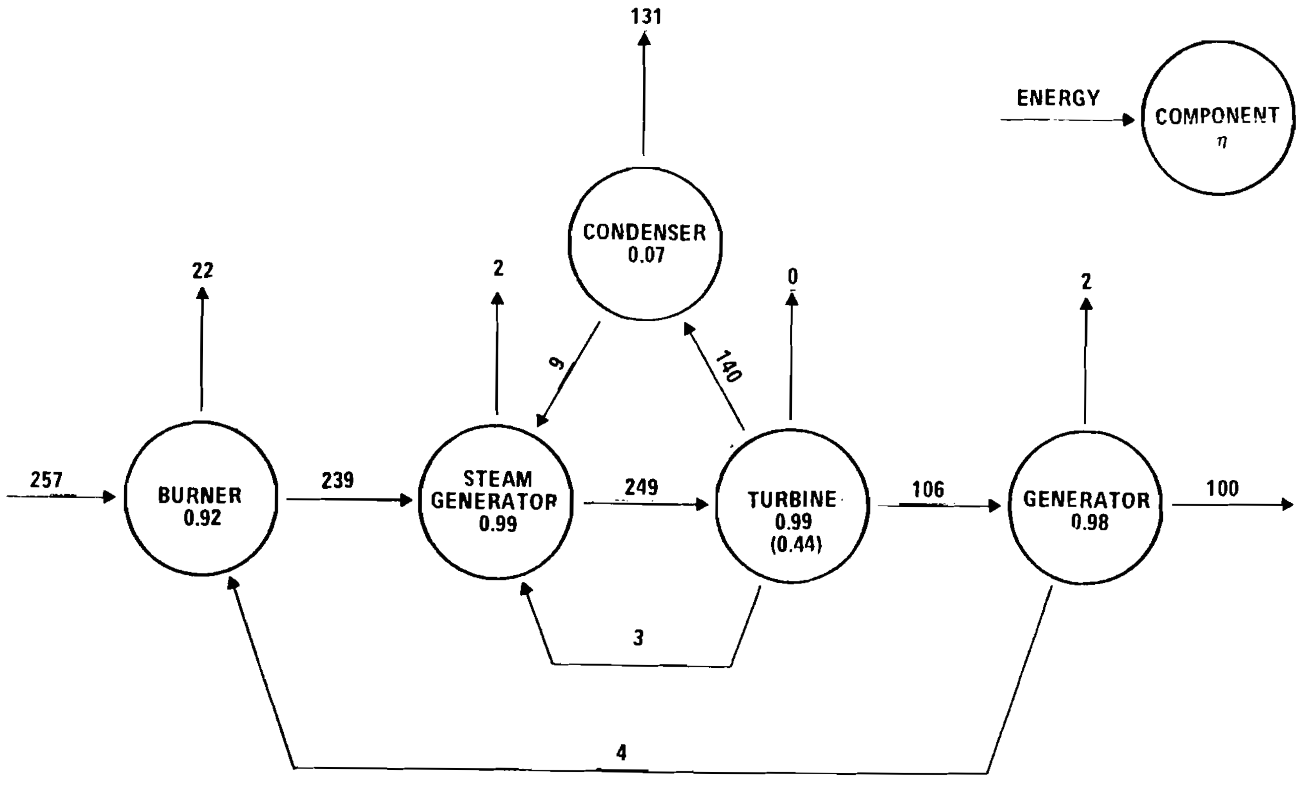
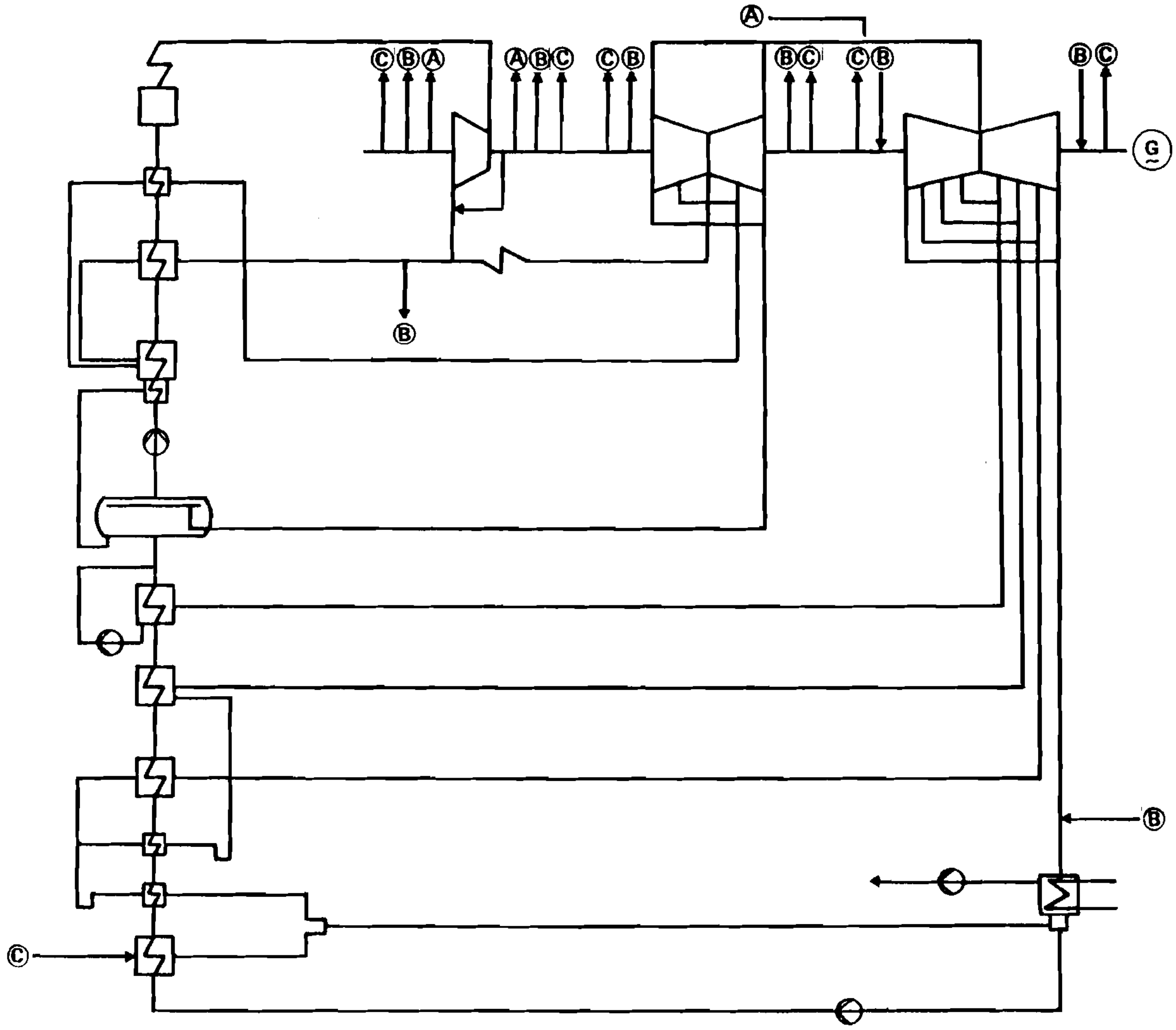


Figure 4. Main Energy Flows in a (Coal-Fired) Electric Power Plant with an Energy Efficiency of $\eta = 0.39$.

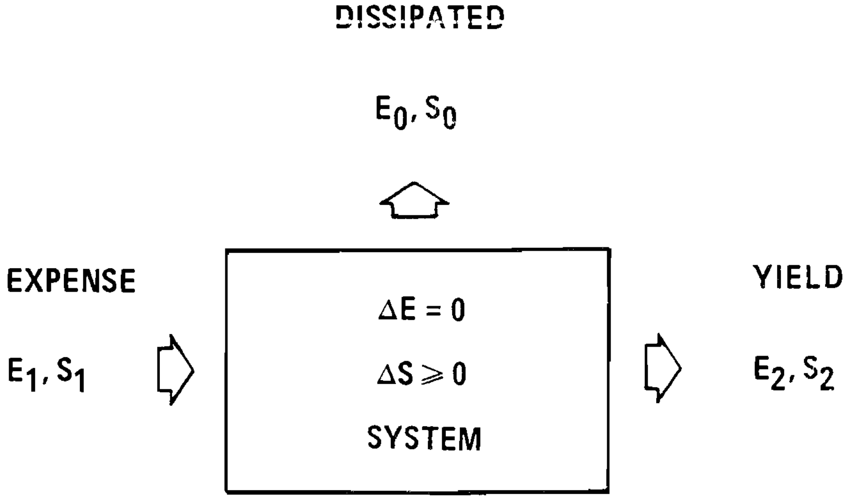


A, B, C ADDITIONAL PIPE CONNECTIONS

Figure 5. Flow Chart for a (Coal-Fired) Electric Power Plant (After: Kraftwerk Union AG, Erlangen).

The arbitrariness in labeling such flows expense or yield becomes evident for the steam generator and steam turbine (see Figure 4 and compare Figure 5 for the complex piping arrangement). The low-pressure steam passing from the turbine to the condenser (see Figure 4) could be regarded as yield (since it flows to another system component) or as waste (since its energy content is essentially not used, leading to 0.99 or 0.44, respectively, energy efficiency for the turbine. This low-pressure steam could also (energetically) be subtracted from the high-pressure steam, passing from the steam-generator to the turbine, which itself is a manifold of foreward and backward flows. The real heat loss dissipated to the environment is negligible, so that the turbine should be regarded as being efficient at more than 99 percent. The cooling tower, on the other hand, seems to be the most inefficient component of the plant, wasting 97 percent of the incoming energy--if one disregards that this is its very purpose.

The turbine or the condenser could be considered as the main sources of inefficiency of this 39% power plant, but as this, of course, requires evaluation of the quality of the energies. The thermodynamic measure of the value of energy is entropy S. Thus a complete thermodynamic description of a system also includes the entropy flows (Figure 6). For a stationary system, the energy production ΔE is zero and the entropy production ΔS is not negative. All these quantities should be dotted, e.g. $\dot{E}$, to indicate that they are flow rates; this is avoided for simplicity only.



$$E_1 = E_0 + E_2$$

$$S_1 + \Delta S = S_0 + S_2 \,, \quad \Delta S \geq 0$$

Figure 6. Balance of a System for Stationary Processes.

It follows from the first and second laws of thermodynamics by simple algebra that energy efficiency can be expressed as:

$$\eta = \frac{E_2}{E_1} = \frac{E_2(\beta_o - \beta_1)}{E_2(\beta_o - \beta_2) + \Delta S} ,$$

with

$$\beta_o = \frac{S_o}{E_o} , \quad \beta_1 = \frac{S_1}{E_1} , \quad \beta_2 = \frac{S_2}{E_2} ,$$

the latter being reduced measures of the entropy flows. This kind of notation makes obvious that the entropy generated, ΔS, i.e. the irreversibility of the system causes the reduction in efficiency. η attains its maximum if $\Delta S = 0$, i.e. if the process is reversible:

$$\eta_{\text{reversible}} = \frac{\beta_o - \beta_1}{\beta_o - \beta_2} .$$

A well known special case is this: With E_2 and $E_o \mathrel{\hat{=}}$ heat, $E_2 \mathrel{\hat{=}}$ work, leading to $\beta_1 = \frac{1}{T_1}$, $\beta_o = \frac{1}{T_o}$, and $\beta_2 = 0$, one attains the well known Carnot efficiency. The expression for η given above is generally valid, however; the flows may be heat or work, fuels, chemicals, etc., and any combination of them (this is important for gasification processes, for example): Add up the energies and add up the entropies for each flow of the <u>real</u> process, take their ratio, β, and you receive the maximum possible energy efficiency of the adequate <u>reversible</u> process!

From this we can also see that

$\eta_{rev} > 1$ if $\beta_2 > \beta_1$ (yield of less quality than expense)
$\eta_{rev} = 1$ if $\beta_2 = \beta_1$ (yield of same quality as expense)
$\eta_{rev} < 1$ if $\beta_2 < \beta_1$ (yield of higher quality than expense).

$\eta_{\text{reversible}}$ is the maximum energy efficiency obtained if the process is defined by the β's only, i.e. by the qualities of its energy flows. This concept provides one with a measure for the potential improvement of a given real process with an actual efficiency η. This measure is the ratio $\eta/\eta_{\text{reversible}}$, which we call ε (reversibility, or second law efficiency, or exergy efficiency):

$$\varepsilon = \frac{\eta}{\eta_{\text{reversible}}} \quad ,$$

$$\varepsilon = \frac{E_2(\beta_o-\beta_2)}{E_2(\beta_o-\beta_2) + \Delta S} \quad ,$$

$$\varepsilon = \frac{E_2-T_oS_2}{E_2-T_oS_2 + T_o\ S} \quad , \quad \text{if } \beta_o = \frac{1}{T_o} \quad ,$$

$$\varepsilon = \frac{E_2 - T_oS_2}{E_1 - T_oS_1} = \frac{\text{Exergy Yield}}{\text{Exergy Expense}} \quad .$$

All these forms are equivalent and differ from each other by the choice of variables only. The second line, which is generally valid, shows clearly that $\varepsilon = 1$ for a reversible process, i.e. $\Delta S = 0$, and that $0 < \varepsilon < 1$ for any real process, i.e. for $\Delta S > 0$. In the next line, a similar expression is used; the entropy of the dissipated energy E_o is assumed to be $S_o = E_o/T_o$, or $\beta_o = \frac{1}{T_o}$, with T_o being the temperature of the environment. This includes the assumption that E_o is heat at the temperature T_o. This is not so generally, where E_o is, e.g., heat at some higher temperature, radiation, or work. However, we regard the boundary of the system as being so wide that these flows have come into an equilibrium with the environment. It is only because of the imperfections of the system that this did not happen internally.

Exergy

In the last expression the influence of entropy production is not so obvious but the equation is more symmetric, being exactly the quotient of two exergies: exergy yield and exergy expense.

Exergy is defined as energy minus entropy times the temperature of the environment

$$Ex = E - T_oS \quad .$$

This quantity is equal to the work that can be obtained from a given energy in a reversible process if heat can be exchanged at T_o. This is quite obvious: If the energy E should be converted into work the related entropy S must be removed. This entropy can be given to the environment, linked to energy T_oS (heat), and only the remainder becomes available as work.

The term "exergy" was introduced by Rant in the 1950s, other labels for essentially the same quantity are "available useful work" or "maximum available work". For reason of brevity exergy is preferred. More exactly, E and S are meant to be the differences in energy and entropy of a medium or a system, between its actual state and its state of equilibrium with the environment, so that E in most cases is the difference in enthalpy between actual and reference states.

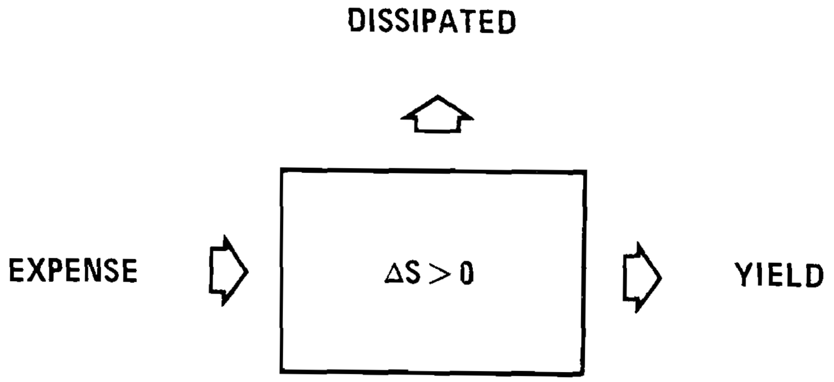
Exergy is no variable of state in a thermodynamic sense (it depends on two states, in a nonadditive manner); it is not identical with free energy or Gibbs' free enthalpy, $H - TS$, but it is equal to Gibbs' free enthalpy in the case where fuel is supplied at temperature T_O; then $H_O - T_OS_O$ is both free enthalpy and exergy.

Exergy is a measure of the quality of energy; it is the upper limit for the share that can be transformed to work, given a certain environment. The state of the environment is very important for that quantity.

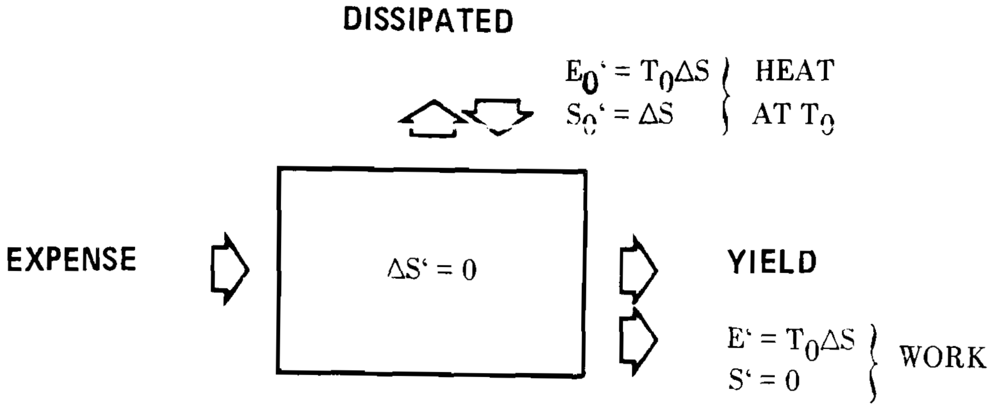
There is no law of conservation for exergy, it changes as the state of the environment changes; even with the environment fixed it can be annihilated or consumed (as entropy can be generated). It is advantageous compared with entropy, in that it has both the same dimension and units and the same orders of magnitude as energy. It is clear, however, that exergy cannot provide any new thermodynamic insight above what is known on account of energy and entropy.

As outlined, the definition of an energy (η) or exergy efficiency (ε) makes it necessary to combine the flows into and out of a system into exactly three groups, allowing for more or less arbitrariness. One univocal property in any system, however, is its entropy production ΔS (or production rate $\Delta\dot{S}$). This is independent of what is regarded as "expense", "yield", or "dissipated flow". Entropy production is the authentic (but absolute) measure of the thermodynamic quality of a system; one can also refer to it as negentropy consumption, there is no objective difference between the two.

In fact, some skill is necessary to formulate an opinion on a system only on the basis of its entropy production. I suggest multiplying the entropy production by the temperature of the environment to obtain $T_O \Delta S$. The connotation is obviously twofold: it is still entropy production, but expressed in convenient energy units, and it is equal to the exergy annihilated or consumed by the system. Or to put it another way: If the real process generated entropy ΔS (Figure 7, top), the same process as seen from the outside (i.e. with all the same inputs and outouts) made reversible (better appliances are used inside the system), could, in addition, completely convert the amount of $T_O\Delta S$ of environmental heat into work. In the reversible process



$T_0 \Delta S$ = EXERGY CONSUMPTION IN IRREVERSIBLE PROCESS



$T_0 \Delta S$ = ADDITIONAL WORK AVAILABLE
IF PROCESS IS REVERSIBLE

Figure 7. Irreversible Process and Respective Reversible Process.

(Figure 7, bottom), the entropy ΔS is not produced but taken from the environment together with the heat $T_0\Delta S$. This energy has to be released without entropy, i.e. as work. This should clearly illustrate the meaning of entropy production in an irreversible process.

Two Examples: Power Plant and Methanol Production

Let us now consider the example of a coal-fired electric power plant and its components or subsystems in terms of this formalism. If all flows (Figure 2) are given quantitatively, the entropy production can be determined; it is $\Delta\dot{S} = 0.53$ MW/K for a 100 MW net coal-fired electric power plant. Accordingly a plant that is similar (as seen from the outside and in terms of the flows) but fully reversible could completely transform an additional amount $T_0\Delta\dot{S} = 298$ K x 0.53 MW/K = 158 MW of environmental heat into work (or not dissipate this heat in the first place). This statement is independent of what flows are considered as expense or yield.

Combining these flows into such groups (Figure 3) we choose $C + O_2 - CO_2$ as expense, electric energy $\Delta V.I$ as yield, and all other flows as dissipated. The balance of energy, entropy, and exergy is given in Figure 8.

The exergy of carbon oxidation is a little bit larger than the energy, since the entropy flow is negative. Therefore, the thermodynamic value of coal is slightly greater than that of work, and the efficiency of converting coal to electricity would be slightly greater than one if it could be done reversibly!

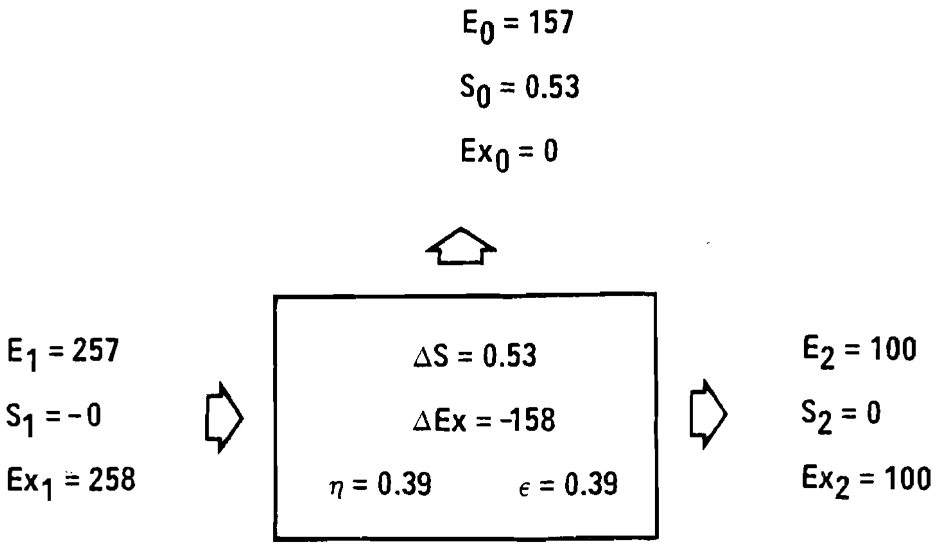


Figure 8. Energy, Entropy, and Exergy Balance of a Power Plant.

Figure 9 gives the exergy flows in the same scheme as for the energy flows. From it we see more clearly where the inefficiencies have their origin: in the burner and the steam-generator although their energy losses are only 22 and 2 MW, respectively.

In the burner the entropy production or exergy consumption is 80 MW since the heat of combustion deteriorates from more than 2000 K to 500 - 600 K of heat supplied to the steam-generator.

In the steam-generator another 60 MW of exergy are annihilated, the energy loss being only 2 MW. This is due to the temperature differences and flow resistances in the heat exchangers for condensate preheating and steam-generation and conditioning.

Compared with this figure (140 MW), the amount of 15 MW used up in the turbine is small. In the same way, condenser and cooling tower turn out to be among the most reversible components of that plant. It consumes only 4 MW of exergy while, in serving its purpose, it releases 131 MW of energy in the form of heat to the environment.

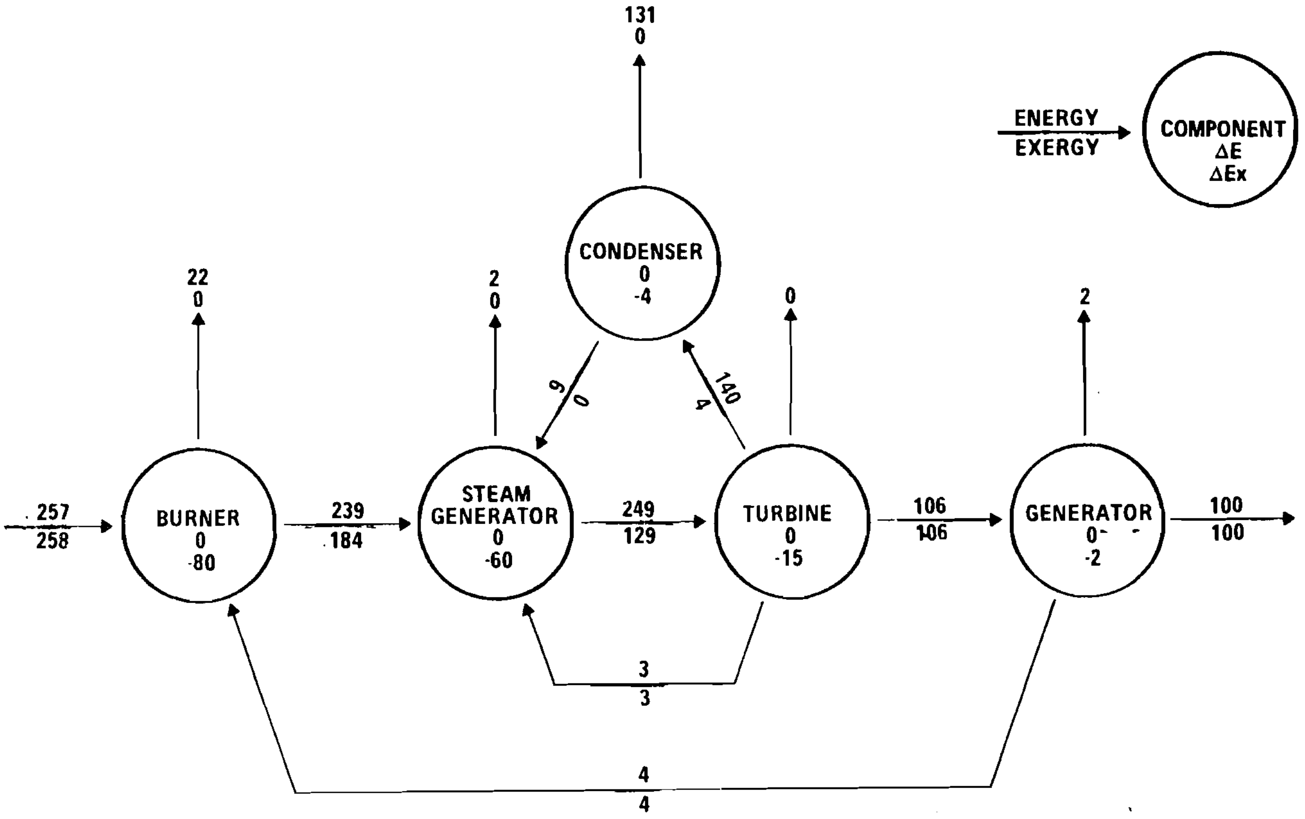


Figure 9. Main Energy and Exergy Flows in a Coal-Fired Electric Power Plant.

It is also possible to define the exergy efficiencies of these components (Figure 10), but for the arbitrariness of the classification this does not provide new insight with respect to some of the components.

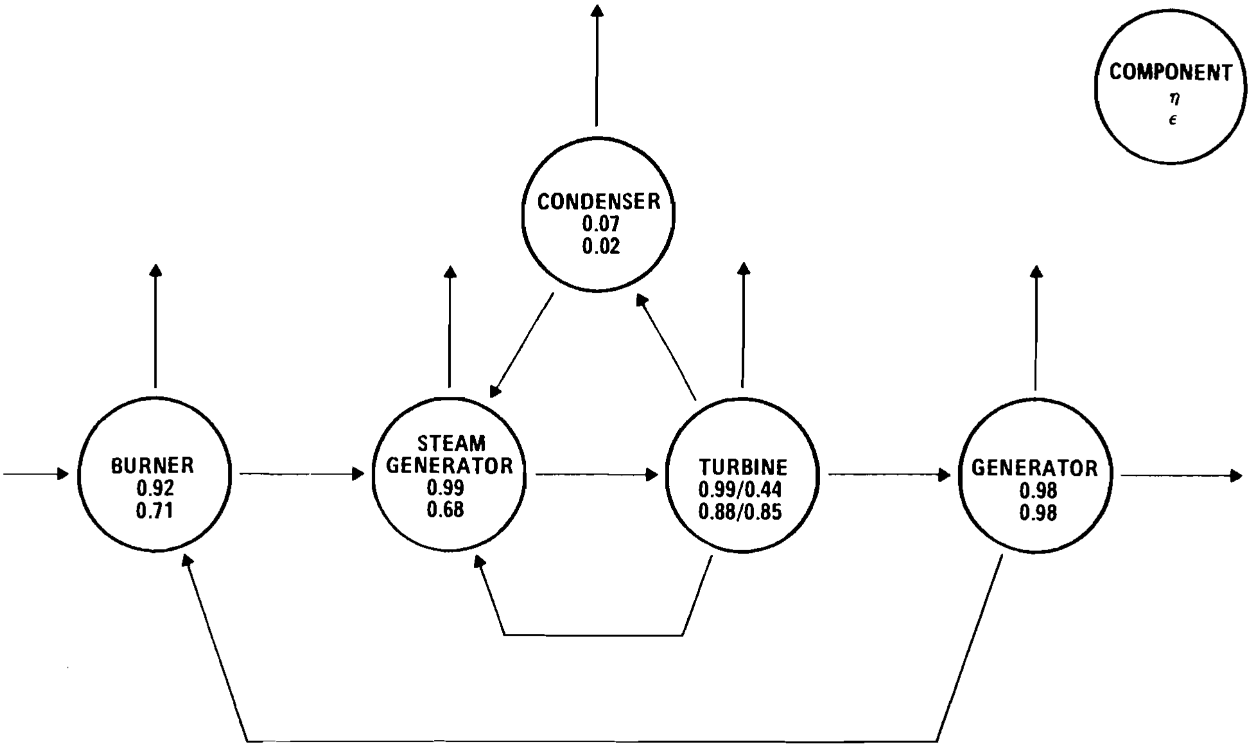


Figure 10. Energy Efficiency η and Exergy Efficiency ε of Main Components of a Coal-Fired Electric Power Plant.

Another example, more important for our work at IIASA, is the gasification or liquefaction of coal with nuclear energy. Consider a system that is fed with coal, water, and energy and produces methanol, the waste of which consists of heat at T_o and oxygen, but contains no carbon in any form (CO_2, etc.).

Figure 11 depicts such a scheme. In order to obtain $E_2 = 100$ energy units of methanol one would have to supply $E_1 = 54$ energy units of carbon plus 42 units of work if the process could be done reversibly, i.e. $\varepsilon = 1$. Again, the energy efficiency is slightly greater than 1, E_o is negative, and heat is supplied from environment.

If instead of work, heat of, for example, 800 K were supplied (Figure 12), entropy would also be introduced. For the same output, entropy has to be withdrawn at T_o, i.e. heat is released at T_o. Therefore, more heat (than work in the former case), namely 68 units, has to be supplied for the production of 100 units of methanol, the energy efficiency for this reversible process being reduced to 82 percent.

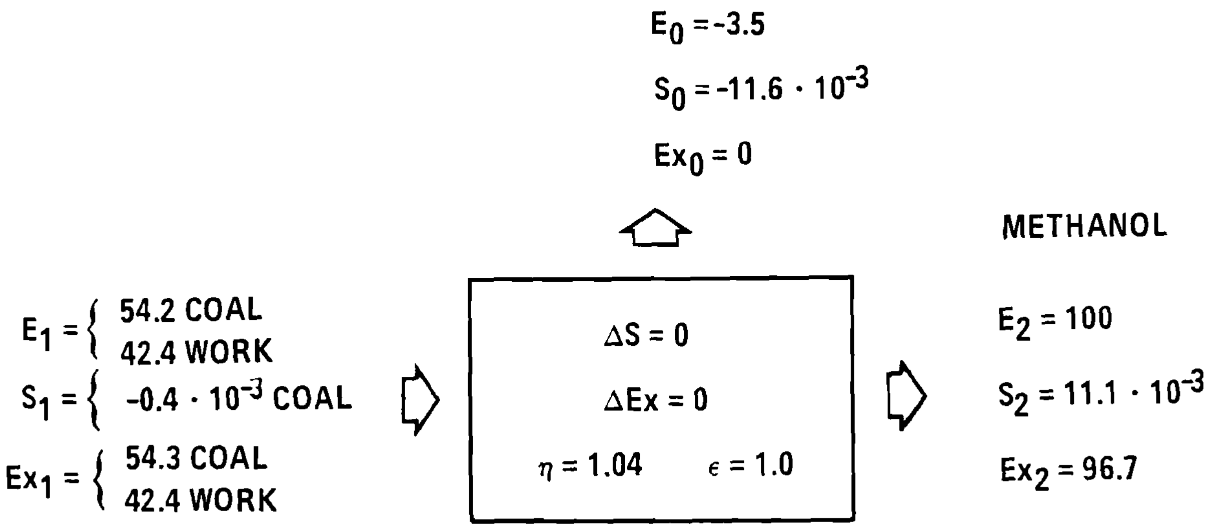


Figure 11. Energy, Entropy, and Exergy Balance for Reversible Methanol Production from Coal and Work.

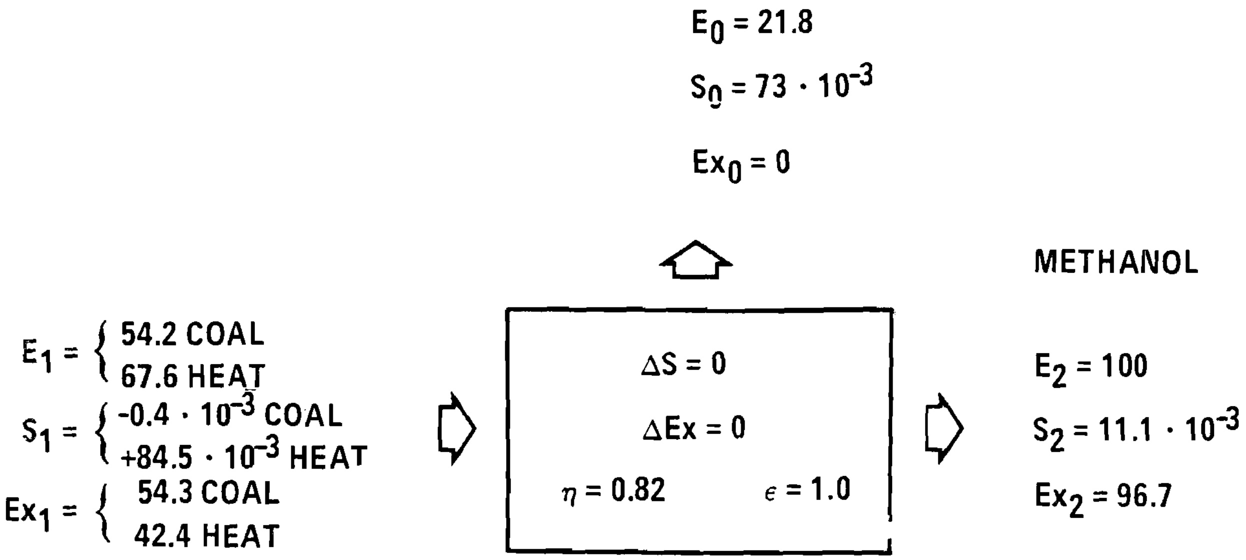


Figure 12. Energy, Entropy, and Exergy Balance for Reversible Methanol Production from Coal and Heat (800K).

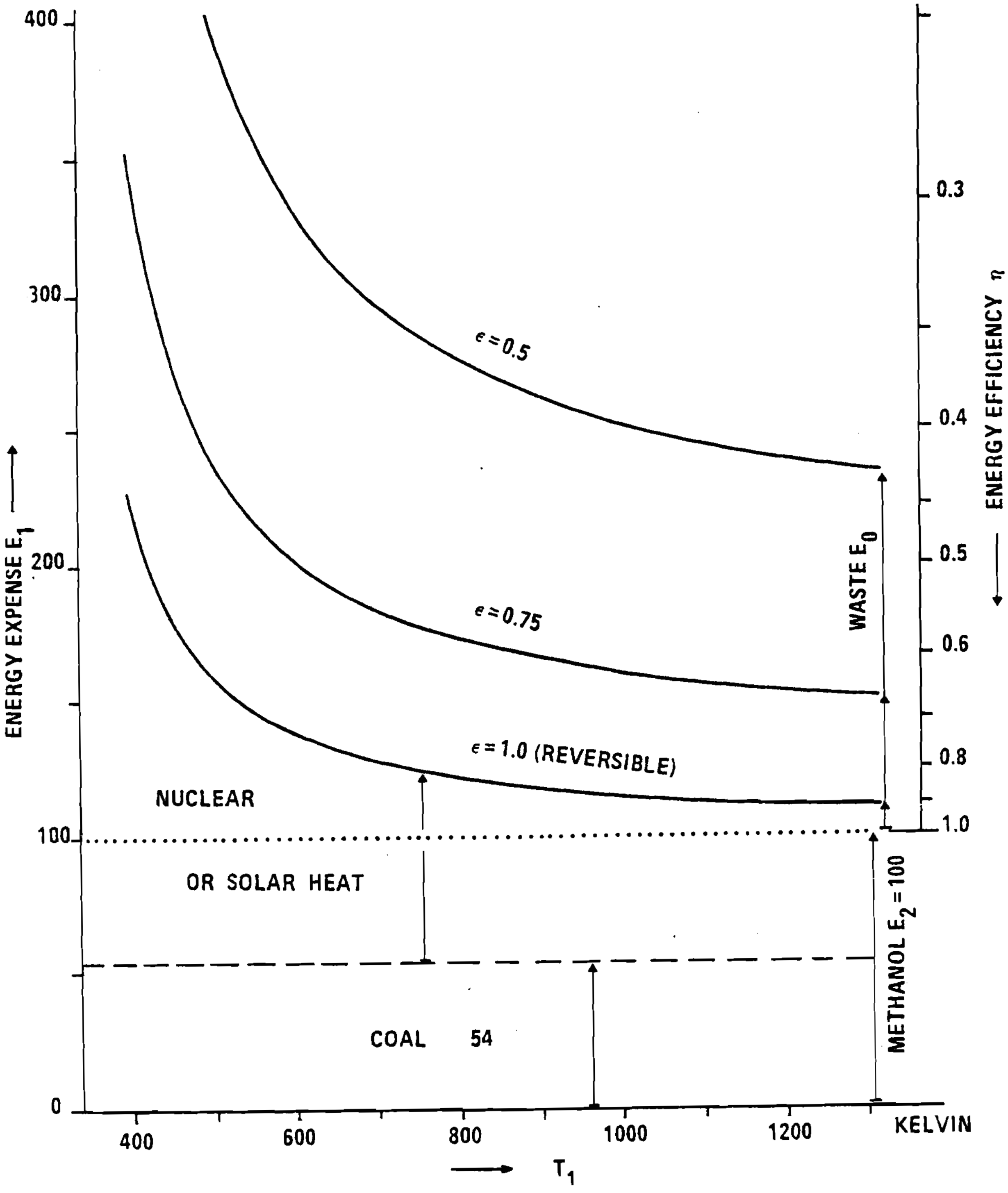
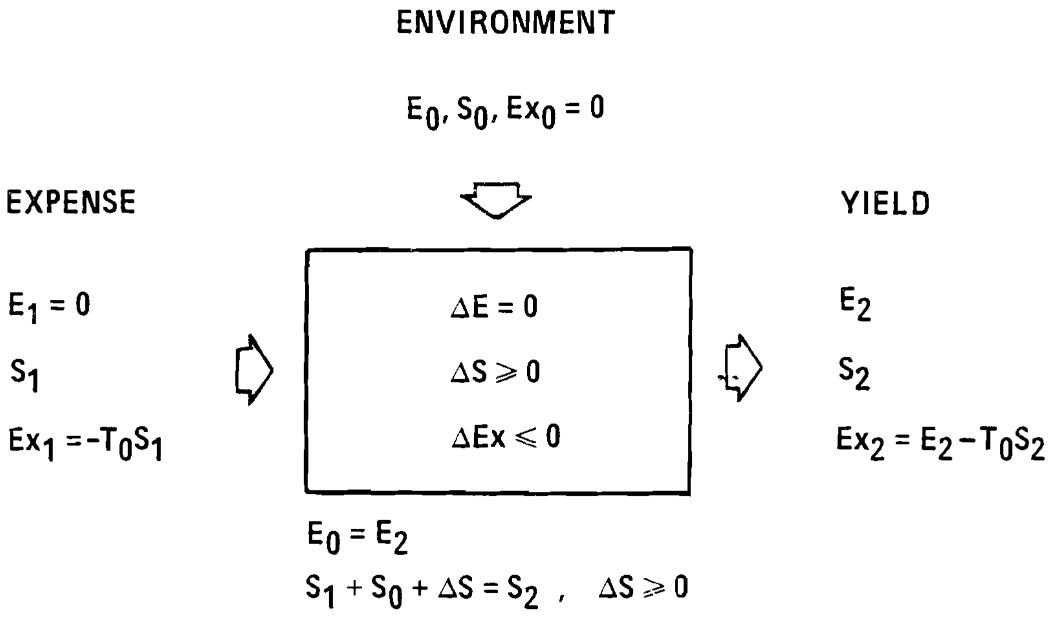


Figure 13. Energy Expense E_1 (Heat + Coal) for the Production of 100 Units of Methanol, for Reversible ($\varepsilon=1$) and Irreversible ($\varepsilon<1$) Processes.

In Figure 13, the energy expense for the production of 100 energy units of methanol is plotted as a function of the temperature of the heat supplied. The bottom section gives the amount of carbon required (54 units) if nothing is wasted. The distance from the broken line to one of the curves gives the amount of heat required. The lower curve, $\varepsilon = 1$, is valid for reversible processes. We recognize again that the energy efficiency (right-hand scale) is well below 1, even for reversible processes. The distance from the dotted line to the curve is the heat to be dissipated. The upper curve is valid for irreversible processes with $\varepsilon = 0.5$. 54 units of carbon plus 222 units of heat at 800K yield 100 units of methanol plus 176 units of waste heat. The overall energy efficiency then is 0.36. This diagram certainly tells one nothing about the technical feasibility of such processes, but it may serve to determine their reversibility, ε, i.e. to what an extent reversibility is reached for any process where energy requirements are known. This also indicates the scope of any further improvement that is conceivable.

Negentropy Systems

Finally a remark on negentropy technologies. Consider a system (Figure 14), that provides a consumer with energy E_2 accompanied by entropy S_2 (which would be zero if E_2 were work). This conversion system shall be run by the expense of negentropy (from an oceanic plant, for example), $-S_1$ (entropy supplied is given a + sign and negentropy a - sign).



Note: S_1 is the entropy supplied. If $S_1 < 0$ (entropy withdrawn), $-S_1 > 0$ is the negentropy supplied.

Figure 14. Balance of a Stationary System Run by the Expense of Negentropy $-S_1$.

The demand for negentropy therefore is:

$$-S_1 = S_o - S_2 + \Delta S \quad ,$$

or

$$= \frac{E_2}{T_o} - S_2 + \Delta S \quad ,$$

in the realistic case ($\Delta S > 0$). In the reversible case, where $\Delta S = 0$, the negentropy demand is $-S_{1\ rev} = S_o - S_2$.

Of course, it is impossible to define any energy efficiency since there is no energy expense at all, $E_1 = 0$ (or $\eta \to \infty$). However, just as above, one can define a reversibility ε with the exergy yield $E_2 - T_oS_2$ over the exergy expense $-T_oS_1$.

Reversibility then is expressed as:

$$\varepsilon = \frac{E_2 - T_oS_2}{-T_oS_1} \quad ,$$

$$\varepsilon = \frac{S_o - S_2}{S_o - S_2 + \Delta S} \quad ,$$

$$\varepsilon = \frac{-S_1 \text{reversible}}{-S_1} = \frac{\text{reversible negentropy demand}}{\text{actual negentropy demand}} \quad .$$

The second line gives the influence of entropy production, and the third gives ε as reversible negentropy demand over actual negentropy demand.

This formalism also holds if the yield is only negentropy unaccompanied by energy ($E_2 = 0$). Then E_o and S_o too are zero, and the second law reads as

$$-S_2 + \Delta S = -S_1 \quad ;$$

the reversibility is simply

$$\varepsilon = \frac{-S_2}{-S_1} = \frac{-S_2}{-S_2 + \Delta S} \quad .$$

Hence consider a pure "negentropy conversion plant", for example, i.e. an oceanic plant fed with negentropy of the thermal gradient ("primary negentropy") as the expense, and yielding compressed air as "secondary negentropy carrier" (carrying no energy); it follows that the exergy efficiency is identical to the "negentropy efficiency", i.e. the negentropy yield over the negentropy expense. The exergy or negentropy efficiency is the significant measure of effectiveness with which negentropy is transformed in processes, and the entropy production ΔS (i.e. negentropy consumption) enables one to localize the sources of inefficiency.

The present formalism is applicable to any stationary energetic system or process. The first step, of course, is to univocally define the system, especially its boundaries. This boundary need not be the fence of the plant or so, and not even a physical boundary, as outlined in connection with the dissipated energy. It is essential that all flows across the boundary can be defined and, in principle, be measured. At least the entropy carried by these flows has to be determined, which suffices for calculating the entropy production (or production rate) of the system. This entropy production (or negentropy consumption, or, at one's convenience, multiplied by T_O as exergy consumption) is the absolute measure of the thermodynamic quality of the system. It is not the energy demand or "consumption" that should be ultimately considered in all the energy discussions, it is rather entropy production that counts. It would be more reasonable to measure energy waste, environmental load, and similar concepts in terms of entropy production. Only because most of our present energy utilization facilities are inadequate is energy "consumption" still a good measure; almost all primary and secondary energy is exergy and almost all of this exergy is irreversibly annihilated. For wider penetration of "low grade" primary energies (e.g. geothermal heat) secondary energies (e.g. district heat) or negentropy technologies (e.g. ocean thermal gradient plants and pressurized air), however, it would be inevitable to use entropy production or exergy consumption (which may differ greatly from the energy turnover) as a measure. Moreover, entropy production is the unique tool to locate sources of inefficiency.

As mentioned, entropy production is an absolute measure, in the sense that a system of double the size but equal quality also has double entropy production. For a relative measure one must, as a last step, combine all flows into the groups of expense, yield, and dissipation. This allows one to calculate both the energy efficiency and the maximum conceivable energy efficiency or their ratio, i.e. the reversibility. This reversibility is a measure of approximation to an ideal, i.e. reversible, process and is therefore suitable for evaluating and comparing systems that are different in scale or type with regard to their thermodynamic qualities.

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