TOWARDS SUSTAINABLE ENERGY SYSTEMS

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Abstract
To improve the degree of sustainability of our energy supply the abundant use of fossil fuels has to be reduced. Therefore possibilities for a more sustainable production of electricity and heat in "developed countries" are investigated. Obviously the use of renewable energy sources must be considered. Large scale use of wind and solar energy however require storage of large amounts of energy in order to match production with demand; the effect on overall costs is tremendous. The use of biomass presents a more economic alternative. High efficiency power plants are possible through improved combined cycle plants or integration with high temperature fuel cells. Thermal efficiencies of gas fuelled plants can go up to 75 %; in case of solid fuels (e.g. biomass) efficiencies will be several percentage points lower. However, reductions in overall fuel consumption that can be achieved by this type of plants are limited. Further reductions in overall fuel consumption are able through application of CHP and heat pumps. Large savings can be realised with electrical heat pumps for the production of low temperature heat, but overall costs will increase considerably. Since due to costs the use of wind and solar energy will be limited, improved conversion techniques (gasification, advanced gas turbine cycles, fuel cells and heat pumps) will be necessary for efficient use of biomass and additional fossil fuels. It is expected that sustainability will require large reductions in final energy consumption.

Nomenclature

E	energy (J)
E_F	energy of fuel (J)
Ex_{fuel}	exergy of fuel (J)
f_{ex}	exergy factor (-)
$H_{fuel,\ low}$	lower heating value of fuel (J/kg)
P	power (W)
Q	heat (J)
Q_{HT}	high temperature heat (J)
Q_{LT}	low temperature heat (J)
T	temperature (K)
T_0	environmental temperature (K)
!	thermodynamic mean temperature (K)
W	work (J)
$\mathbf{0}$	efficiency (-)
$\mathbf{0}_{ex}$	exergy efficiency (-)
$\mathbf{0}_{th}$	thermal efficiency (-)
$\mathbf{0}_{int}$	internal efficiency (-)
$\mathbf{M}_m$	mass flow (kg/s)

subscripts

el	electric
ex	exergy
in	inlet
out	outlet
rev	reversible
tot	total

Introduction
There is a general understanding that regarding the use of energy and raw materials the so-called “developed countries” live in strong disharmony with environment. Possibilities to achieve a more

sustainable production of electricity and heat on a national level are investigated here. For this investigation it is assumed that the degree of sustainability is determined by the amount of fossil fuel required for the national energy supply. Today the production of electricity and heat is mainly based on finite primary energy sources; fossil fuels are combusted in such large amounts that flue gas emissions might effect our environment. A general approach to improve the degree of sustainability of our energy supply is layed down in the so called "trias energetica". It says that we should: reduce final energy consumption, make use of renewable sources and improve overall conversion efficiencies.

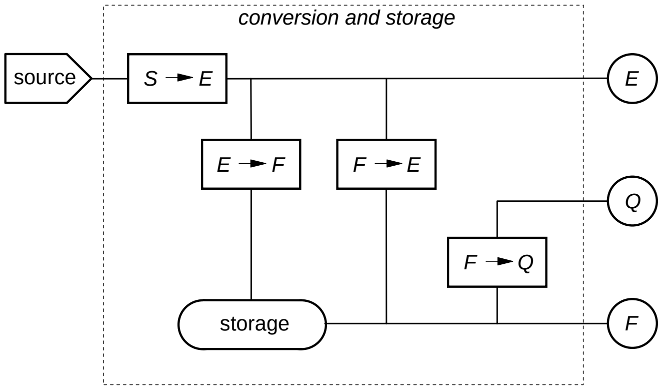

Figure 1
Simple energy supply system with storage to match variations in energy production and demand

Energy consumption is defined here as the demand of electricity and heat; in some cases the demand of fuel for transportation is also included. For more specific analyses the demand of heat is split up roughly in low temperature heat and high temperature heat. "Low temperature" heat is supposed to be required in residential areas while heat for industrial purposes is assumed to be "high temperature heat". In the developed countries large amounts of energy are wasted or unnecessarily used and significant improvements in the efficiency of final users are possible. Hence in the area of energy consumption an enormous potential for savings is still available. This investigation however will deal with possible savings through the use of renewable sources and conversion systems with improved efficiencies.

Renewable sources

Hydro-power, biomass, wind and solar energy are supposed to be the most important renewable sources. In flat countries, like the Netherlands, hydro-power will not play a substantial role. Biomass appears to be an attractive option for many countries. Besides specific problems with regard to cultivation, transport and storage of biomass, technologies for the conversion biomass into electricity and heat are highly similar to technologies for other solid fuels.

Wind and solar energy are strongly fluctuating sources. In Western Europe the amount of electricity and heat delivered by solar or wind driven systems will vary during the day as well as during the seasons. Also the energy demand is not constant during time. To illustrate the problems of fluctuating energy demands and energy sources in Western Europe, a strongly simplified system for the conversion of primary energy into electricity (E), heat (Q) and fuel (F) is presented in figure 1. In this figure the rectangles present energy conversion steps, e.g. $F \div E$ for the conversion of fuel into electricity. The system is supposed to be an option for the national supply system of the Netherlands for the future at the time that natural gas and oil are no longer available; heat is supposed to be necessary for domestic purposes as well as industrial processes and fuel is required for transportation. The system should not be seen as a serious option for the future but as an extreme case, suitable to analyse the strength and weaknesses of possible solutions. Energy from the primary source is transformed into electricity ($S \div E$), which can be used to fulfill the electricity demand. If the production of electricity is lager than the demand, the surplus is converted into a fuel (hydrogen) ($E \div F$). If the produced electricity is less than the demand, additional electricity is delivered by the conversion of fuel from the storage into electricity ($F \div E$). Hydrogen is also used for the production of heat and the supply of transport fuel, assuming that direct use of hydrogen by vehicles is possible. Source and demand patterns as well as total yearly demands were estimated based on historic data for a specific year. For three different energy sources, coal, wind and sun, storage capacity and installed powers of all energy conversion steps are calculated. The results are presented in table 1. All computations are made assuming that the storage content at the end of the year is the same as at the begin; in case of coal the installed power is minimized by assuming that coal fired plants can operate at design power during the year. For reference a comparison is made with a more traditional supply system, also based on coal. In this reference case coal is used directly (without storage of secondary fuel) for the production of respectively electricity, heat and fuel for transportation. It appears that the use of renewable sources requires much larger installed powers for the primary conversion - the conversion of primary energy into electricity (S ÷ E) - than the use of fossil fuel: 301 GW_e respectively 547 GW_e for wind and sun instead of 68 GW_e in case of coal. This is due to the limited availability of wind and sun during the year. Looking at the electricity production, wind has a load factor of approximately 25 % and sun about 12 %.

Table 1 Installed conversion capacities of system alternatives

system with direct use of coal			systems with energy storage				
conversion			conversion		primary source		
					coal	wind	sun
F_C 6 E	GW_e	9.7	S6E	GW_e	68	301	547
F_C 6 Q	GW_{th}	107	E6F	GW_e	63	298	539
F_C 6 F_C’	$GW_{f\text{-}out}$	12.7	F6E	GW_e	-	9.5	9.5
			F6Q	GW_{th}	107	107	107
			storage	PJ	327	346	772

Most of the produced electricity must be converted into hydrogen; therefore installed power of the conversion of electricity into fuel (presented as input power) almost equals the power of the primary conversion. With coal as energy source the storage capacity is determined by variations at the demand side only. In case of wind, the required storage capacity is hardly larger, 346 PJ instead of 327 PJ. The very large storage capacity required if sun is used as primary source (772 PJ), is caused by seasonal effects; the peak in electricity and heat demand occurs during the winter while maximum production is realized during the summer period.

In table 2 total yearly costs are given for the considered system alternatives. Costs are based on specific investment costs of assumed mature conversion technologies and a coal price of 8 Dfl/GJ. It is supposed that hydrogen can be stored in depleted natural gas fields. As a consequence of the large number of questionable assumptions, the meaning of the absolute values is very limited. However the ratio between costs is seen as meaningful. For the costs ratio the system with direct use of coal is considered as the reference case. Comparing the two coal based systems it appears that the application of energy storage multiplies the total yearly costs by a factor 2.5. It must be noticed that in this number additional costs of transport and distribution of hydrogen are neglected. In case of wind and sun as primary sources the costs ratios are respectively 3.6 and 4.4. From these numbers it appears that large scale use of renewable sources can become very expensive if large amounts of energy have to be stored. Obviously the combined use of renewable and fossil fuel sources should be considered. However, investigations of a large number of alternative options (Woudstra, Heil, Hartman [1], [2], [3], [4]) have shown that total yearly costs are almost increasing linear with the installed power of renewable sources. Of course these computations don’t give a final answer with respect to the use of wind and sun in Western European. But they show that serious attention is required for matching energy production with energy demand.

Table 2 Total yearly costs of system alternatives

	system with direct use of coal	systems with energy storage		
		primary source		
		coal	wind	sun
yearly costs (Dfl/a)	27×10^9	67×10^9	97×10^9	118×10^9
costs ratio	1	2.5	3.6	4.4

Also a large number of additional or alternative technologies have been considered. Some of them do result in significant cost reductions, but the noticed trend remains unchanged. The additional investigations do confirm that universal use of renewable sources like wind and sun results in much higher total costs, mainly due to additional losses and costs of energy storage. Since the use of sun and wind is seen as necessary for a more sustainable energy supply, application of these sources should occur in combination with energy demands that are able to eliminate the need for energy storage; e.g. the combination of photovoltaic conversion and air conditioning.

Improved efficiencies of power plants

Because of difficulties accompanied with the use of wind and sun, additional use of fuels (biomass and/or fossil fuels) for electricity production is supposed to be necessary. These fuels must be used in the most efficient way, thus overall exergy loss of electricity production must be minimized. Gas fuelled systems are considered here, assuming that similar technologies can be used for solid fuels after gasification. Today, almost without exception, thermal processes are used for the conversion of fuel into electricity. Regarding thermodynamics, such processes can be seen as power cycles receiving heat from a reservoir at high temperature (T_1) and discharging heat to a reservoir at low temperature (T_2), as shown in figure 2. Thermal efficiencies of reversible power cycles, cycles without internal losses, are determined only by the temperatures of heat supply and heat discharge, thus:

$$\eta_{th,rev} = \frac{W_{rev}}{Q_1} = 1 - \frac{T_2}{T_1} \tag{1}$$

In a real cycle internal losses will always occur. These internal losses can be accounted for by introducing the internal efficiency η_{int}. Then, for the thermal efficiency of a real cycle can be written:

$$\eta_{th} = \frac{W}{Q_1} = \eta_{int} \cdot \left(1 - \frac{T_2}{T_1}\right) \tag{2}$$

In this relation it is assumed that heat is supplied and discharged at constant temperatures. In general exchange of heat occurs at increasing and decreasing temperatures. With $\bar{T}_1$ and $\bar{T}_2$ as the thermodynamic mean temperatures of heat supply and discharge, Eq. (2) can be written as:

$$\eta_{th} = \frac{W}{Q_1} = \eta_{int} \cdot \left(1 - \frac{\bar{T}_2}{\bar{T}_1}\right) \quad \text{or}$$

$$\eta_{th,plant} = \frac{P_{el}}{\Phi_{m,fuel} \cdot H_{fuel,low}} = \eta_{int} \cdot \left(1 - \frac{\bar{T}_2}{\bar{T}_1}\right) \tag{3}$$

To explain the meaning of the internal efficiency, the use of exergy efficiencies might be helpful. Hence from Eq. (3) it can be derived that:

$$\eta_{ex,plant} = \frac{P_{el}}{Ex_{fuel}} = \eta_{ex,int} \cdot \left(1 - \frac{\bar{T}_2}{\bar{T}_1}\right) \quad (4)$$

In this equation the "internal exergy efficiency" ($\eta_{ex,intr}$) represents all exergy losses of the plant without losses due to the exchange of heat with the environment. Maximum conversion efficiencies are achieved today in large scale power plants with steam turbine cycles and combined cycles (combination of gas turbine with steam turbine). The efficiencies for three plants are presented in table 3; combined cycle plants with heavy duty gas turbine as well as with aero derivative gas turbine are considered. The thermal efficiencies as published by the plant manufacturer are given in the first column of table 3. These thermal efficiencies are converted into exergy efficiencies, as presented in the second column, assuming an exergy factor of 1.04. The exergy factor $f_{ex,\,fuel}$ represents the exergy to heat ratio of the fuel (based on the lower heating value):

$$f_{ex,fuel} = \frac{Ex_{fuel}}{\Phi_{m,fuel} \cdot H_{fuel,low}}$$

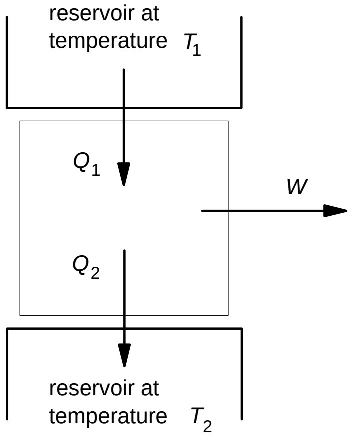

Figure 2
Cycle transforming heat into work with hot reservoir at temperature T_1 and cold reservoir at temperature T_2

In the third column the thermodynamic mean temperature of heat supply ($\bar{T}_1$) is given. For the combined cycle plants this temperature is based on estimated temperature values at in- and outlet of the gas turbine combustion chamber.

Assuming the steam condensation temperature as the temperature of heat discharge, the factor $1 - \frac{\bar{T}_2}{\bar{T}_1}$ can be calculated. The resulting internal exergy efficiencies are shown in the last column. It appears that differences in the calculated values are limited; the lowest value is calculated for the combined cycle plant with aero derivative gas turbine.

Table 3 Internal exergy efficiencies of three different power plants

	$\eta_{th,plant}$	$\eta_{ex,plant}$	$\bar{T}_1$ [K] ([°C])	$1 - \frac{\bar{T}_2}{\bar{T}_1}$	$\eta_{ex,int}$
steam turbine plant	0.435	0.418	646 (373)	0.54	0.77
combined cycle plant (heavy duty GT)	0.580	0.558	1083 (810)	0.73	0.77
combined cycle plant (aero-der. GT)	0.533	0.513	1097 (824)	0.73	0.70

The power output of this plant is much lower than for the combined cycle plant with heavy duty gas turbine; probably the internal efficiency is strongly effected by the plant power output. Furthermore it confirms that overall plant efficiency is dominated by the mean thermodynamic temperature of heat supply.

Higher efficiencies will be possible in the future by increasing the temperature of heat supply. For this purpose several improvements in gas turbine technology, such as steam cooling of high temperature parts, ceramic blades and flue gas reheat, are under development or recently introduced. In figure 3 the effect of increased supply temperatures is shown. The thin dotted line in this figure gives the efficiency of a reversible cycle while the thick line gives the thermal efficiency of a power plant with an "internal exergy efficiency", as defined by Eq. (4), of 75 %. The figure shows that increasing the heat supply temperature will improve plant efficiency; at high temperatures however (> 1000 °C) the

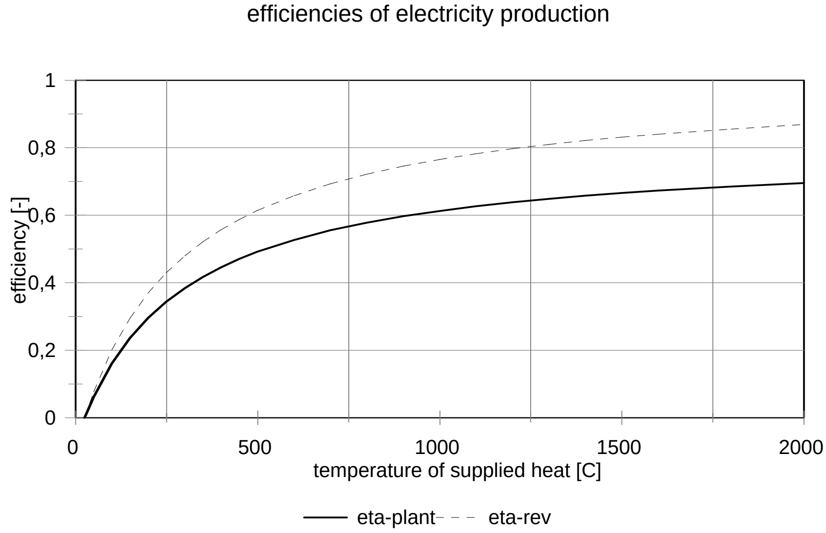

Figure 3
Efficiencies of electricity production as a function of the temperature of supplied heat (eta-rev = thermal efficiency of system with reversible cycle eta-plant = thermal efficiency of system with internal losses ($\eta_{ex,int}$ = 0.75))

effect is limited. In that case reduction of exergy losses as included in the “internal exergy efficiency” will become more important.
A new option to improve the conversion efficiency is the application electrochemical conversion processes. During the passed years large progress has been made with the development of several types of fuel cells and fuel cell systems. In particular high temperature fuel cells, as MCFC (Molten Carbonate Fuel Cell) and SOFC (Solid Oxide Fuel Cell), are supposed to be suitable for stationary power production.
The electrochemical conversion process as applied in fuel cells can replace the combustion process of thermal power plants and thus reduce the large exergy losses due to combustion. In thermal power plants, about 30 % of the exergy supplied by the fuel is lost during combustion. These losses can be largely avoided by the application of fuel cells. However, only well designed fuel cell systems will benefit from the low exergy loss of fuel cells (e.g. de Groot [5]). This can be illustrated by an example. In figure 4 results are presented of a 1 MW_e MCFC plant for combined heat and power production. Fuel cell stacks operate at elevated pressure and fuel processing occurs with integrated external reforming. The calculated exergy losses are distinguished with regard to origin and causes and are presented as percentages of the exergy supplied by the fuel. For this analysis the system is divided into a limited number of sub-systems. In spite of the small exergy losses within the fuel cells (< 10 %) overall exergy losses appear to be over 50 %. All sub-systems do contribute substantial to the overall exergy loss. Furthermore, it appears that heat transfer is the dominant cause of exergy losses in the system. Hence reduction of heat

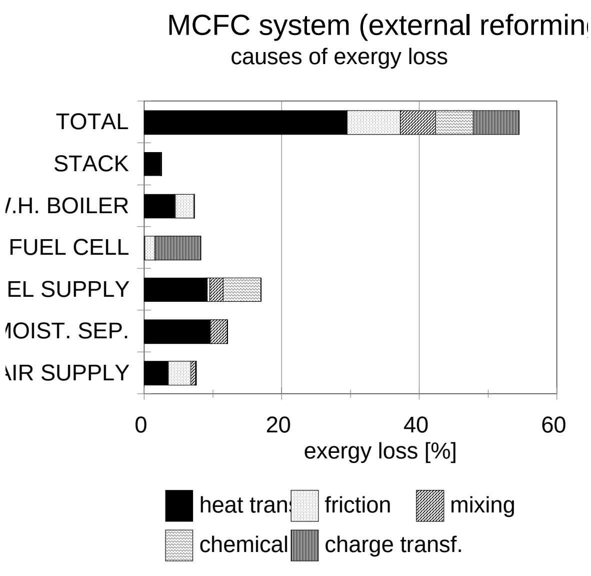

Figure 4
Origin and causes of exergy loss in a MCFC-CHP system

transfer, should be a major objective when designing fuel cell systems. This can be realised for instance with internal reforming or by integrating high temperature fuel cells into combined cycle plants. With integrated SOFC combined cycle plants thermal efficiencies up to 75 % can be achieved with present gas turbine technology (e.g. Campanari [6]).
Efficiencies as discussed here are derived for natural gas fired systems. In case of solid fuels roughly the same technologies can be applied after gasifying the fuel, but due to the high exergy losses during gasification and gas treatment (e.g. Woudstra [7]) plant efficiencies will be several percentage points lower. Therefore power plants based on biomass will be more expensive and have lower efficiencies than natural gas fired plants. But, if biomass will be sufficiently available, electricity from biomass fired plants will be cheaper than electricity derived from wind and sun at large scale.

Application of combined heat and power and heat pumps
The effects of combined production of electricity and heat will be investigated here also on a national basis. Therefore, the electricity and heat demand as well as the corresponding fuel consumption of a hypothetic country are given in figure 5. The ratio between electricity demand, high temperature heat and low temperature heat demand do reflect roughly the situation in the Netherlands. To translate the energy demands into fuel consumption, a thermal efficiency of 50 % is assumed for electricity production and thermal efficiencies of 90 % for the generation of low and high temperature heat. To explain the advantages of combined production of electricity and heat the exergy of the different types of energy must be reflected too. For a graphical representation of the exergy a kind of value diagram will be used. The value of a certain type of energy is defined as the exergy fraction of this energy, which means that the product of the amount of energy and the value of this energy equals the amount of exergy. In figure 6 the amounts of energy (fuel, electricity, low temperature and high temperature heat) as presented in figure 5 are extended with their value. Then the area's in figure 6 do represent the amount of exergy of respectively fuel, electricity, low temperature and high temperature heat. Here it is assumed that the value of fuel equals 1. The accurate value depends on the type of fuel, but will differ only some percentage points from the assumed value. As such small deviations will not affect the conclusions of this investigation seriously, this inaccuracy is acceptable. Also the values of low temperature and high temperature heat are rough approximations. In practice heat is generated at a range of temperatures. For convenience it is assumed here that all heat is generated at only two temperature levels, resulting in two different values for the heat. High temperature heat is supposed to be generated for industrial purposes while low temperature heat is generated for residential use.

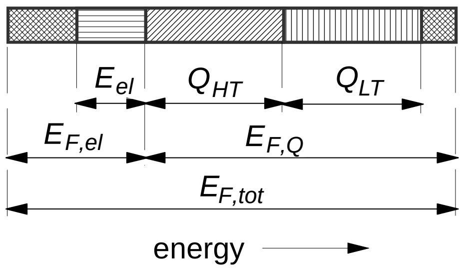

Figure 5
Electricity demand, heat demand and corresponding fuel consumption of a hypothetic country (η_{el} = 0.5; η_Q = 0.9).

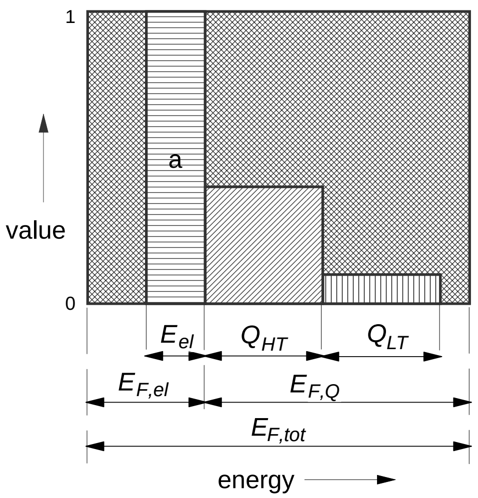

Figure 6
Fuel consumption and energy demand including their value (Reference case, fuel consumption = 100 %)

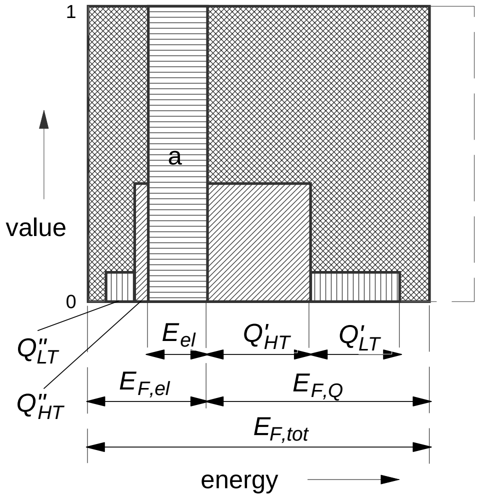

Figure 7
Maximum use of combined heat and power (CHP) (Alternative 1 (η_{el} = 0.5; η_Q = 0.9), fuel consumption = 88 %)

With these assumptions the total area of the figure represents the exergy of the fuel, necessary for the production of all electricity and heat. The horizontal shaded area “a” corresponds with the exergy of the generated electricity, while the area’s shaded with sloping and vertical lines correspond with respectively the exergies of high temperature and low temperature heat. For comparison with further alternatives figure 6 is considered to present the reference case and fuel consumption of this case is supposed to be 100 %. The value diagram in figure 6 shows that overall exergy loss of the reference case is large. There are several possibilities to reduce these losses. The application of high efficiency power plants for instance will reduce the exergy loss attended with electricity production. If the overall efficiency of electricity production can be increased up to 75 %, overall fuel consumption will be reduced by approximately 10 %. Thermal efficiencies of heat production are supposed to be 90 % and can hardly be improved. However figure 6 shows that in particular low temperature heat production is attended with very high exergy losses. Reduction of these exergy losses can be achieved only through application of Combined Heat and Power (CHP) or Heat Pumps (HP).

In practice CHP is used for the generation of low temperature heat as well as high temperature heat. In figure 7 maximum use of CHP is assumed, which means that all electric power is generated by CHP plants. The fuel consumption for this case (alternative 1) is determined assuming that the electrical efficiency of the CHP plants is the same (50 %) as for the power production in the reference case. Compared with the reference case a reduction in fuel consumption of approximately 12 % can be achieved.

In general the electrical efficiency of CHP plants is somewhat lower than for power stations. However electrical efficiency has only little effect on total fuel consumption as long as the overall thermal efficiency of CHP plants remains unchanged and heat to power ratio’s are within normal limits. The total reduction in fuel consumption that can be realised with CHP is mainly determined by the electricity demand and the efficiency of electricity production in the reference case. This means that the effect of CHP will decrease as the efficiencies of power plants increase.

Application of heat pumps can be considered for the generation of low temperature heat. In figure 8 it is supposed that all low temperature heat can be generated with electrical driven heat pumps. A mean value of 2.7 for the Coefficient Of Performance (COP) of all heat pumps together is assumed. The electrical power to drive the heat pumps increases the required power production with an amount represented by area "b" in figure 8. The higher power production increases also the available capacity for CHP plants and consequently the amount of heat that can be produced with CHP. Assuming that all low temperature heat is generated with heat pumps, then the available capacity for CHP can be used for generating high temperature heat only.

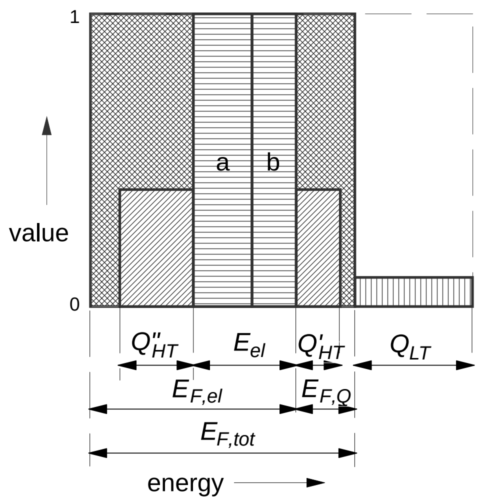

Figure 8
Maximum use of CHP for HT heat and heat pumps for LT heat (Alternative 2 (η_{el} = 0.5; COP = 2.7) b = additional electricity production to drive heat pumps, fuel consumption = 69 %)

Under these conditions overall fuel demand can be reduced till 69 % of the reference case. This value must be seen as a lower limit because fuel consumption has been determined by neglecting the problems that might occur due to matching power production related to the generation of low temperature heat and the generation of high temperature heat with CHP plants. The demand of low temperature heat is fluctuating strongly during the year; variations in the demand of high temperature, industrial, heat are far less. Due to these matching problems the real benefits of this alternative system concept will be smaller.
The calculated total fuel consumption of alternative 2 is based on an assumed overall efficiency of power production of 50 % and a overall COP of heat pumps of 2.7. The performance of these conversion technologies will improve in the future. Alternative 3 (figure 9) gives an impression of the effect of improved performances. For alternative 3, with the same system concept as for alternative 2, an overall efficiency of 75 % for power production and an overall COP of 4.0 for heat pumps is assumed. Then the overall fuel consumption is reduced to 62 % of the reference case.

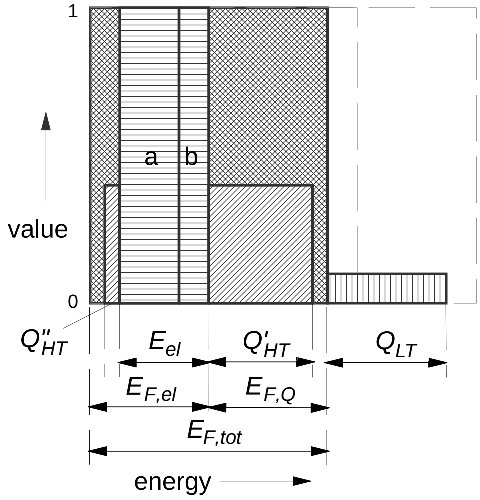

Figure 9
Maximum use of CHP for HT heat and heat pumps for LT heat. (Alternative 3 (η_{el} = 0.75; COP = 4), fuel consumption = 62 %)

It is clear that such investigations cannot accurately predict future fuel consumption. But they are useful to discuss advantages and disadvantages of future supply concepts. The results show that overall fuel consumption is strongly affected by the application of electrical driven heat pumps for the production of low temperature heat. Up to now the high investment costs of heat pump systems are limiting their introduction. In case of application on large scale also the capacity of the electrical grid must be increased significantly; for alternative 2 the increase of capacity is roughly 75 %. The required adaptation of the electrical grid will result in high additional investments.
In general the use of CHP for the production of low temperature heat is more efficient than the application for high temperature heat. However, if heat pumps are used for the production of low temperature heat, CHP is available for the production of high temperature heat.

Conclusions
The application of renewable primary sources like sun and wind can eliminate the use of fossil fuels completely. However in case of large scale use of sun and wind energy storage is required to match energy demand with production. Energy storage is attended with additional losses as well as high investment costs. As a consequence overall costs of supply systems based only on sun or wind are much more expensive than systems based on fossil fuels. Under (not pessimistic) conditions as used in the studies referred here, overall costs of systems based on sun and wind are about 4 times higher than costs of fossil fuel based systems. Combining sun and wind with fossil sources or biomass will not really solve this problem, since in case of large scale application of sun and wind total yearly costs appear to be almost linear with the installed power of renewable sources. The application of wind and sun should occur in combination with energy demands that are able to eliminate the need for energy storage.
Efficiencies of power plants can be increased by improved gas turbine processes and by integrating high temperature fuel cells into combined cycle plants. It seems that thermal efficiencies up to 75 % for gas fuelled power plants are not unrealistic for the future. Savings in overall fuel consumption that can be achieved with improved efficiency power plants as well as application of combined heat and power are limited. However, these savings can be realised without large additional investments. A substantial increase of production costs is not expected. In case of biomass gasification, biomass fuelled plants can also benefit from these technologies; due to additional losses of gasification efficiencies will be several percentage points lower.

Application of electrical driven heat pumps for the production of low temperature heat can significantly reduce overall fuel consumption. The use of heat pumps will increase electricity demand and therefore the capacity available for CHP plants. Application of heat pumps and CHP together will result in the maximum reduction of fuel consumption. If low temperature heat is generated by heat pumps CHP can be used for generating high temperature (industrial) heat. Heat pumps, however, still require high investment costs. Large scale application of electrical driven heat pumps will require higher capacities of the electrical grid and consequently increased costs of the grid. Hence the introduction of heat pumps is hampered by the high overall costs.

The way towards sustainable energy systems will require strong reductions of the consumption of fossil fuels. If the introduction of alternative options is dominated by economic rules, application of sun and wind is probably limited in order to avoid the need for large capacity storage systems. Large scale use of renewable sources without excessive increase of energy costs seems only to be possible through the application of biomass. Additional use of fossil fuels is expected to be necessary for several decades. High conversion efficiencies for the whole conversion chain are advantageous for the reduction of primary fuel consumption or the installed capacity for the conversion of renewable sources. The increase in overall conversion efficiencies strongly relies on the continued development of advanced gas turbine processes, fuel cell systems, biomass gasification, and heat pumps. It is hard to believe that our energy supply can be made sustainable with improved conversion and use of renewable sources only. A substantial contribution has to be delivered by reduced final energy consumption.

Acknowledgements
This paper was based in large part upon studies supported by the Dutch Technology Foundation (Stichting voor de Technische Wetenschappen).

References

1. Woudstra N., Heil C., Hartman M. De BB-CEL, methode van onderzoek en voorlopige resultaten. Report no. EV-1336, TU Delft, 1984 (in Dutch)
2. Woudstra N., Heil C., Hartman M. De BB-CEL, verkennende systeemstudies. Report no. EV-1346, TU Delft, 1985 (in Dutch)
3. Heil C., Hartman M. De BB-CEL, een systematisch onderzoek. Report no. EV-1418, TU Delft, 1986 (in Dutch)
4. Hartman M. Lange termijn energievoorziening, inzet van windturbines en energie-opslag. Report no. EV-1492, TU Delft, 1988 (in Dutch)
5. Groot A. de, Woudstra N. Exergy analysis of a fuel cell system. Journal of the Institute of Energy, March 1995, 68, p. 32-39
6. Campanari S., Macchi E. Thermodynamic analysis of advanced power cycles based upon solid oxide fuel cells, gas turbines and rankine bottoming cycles. ASME 98-GT-585, 1998
7. Woudstra Th., Woudstra N. Exergy analysis of hot-gas clean-up in IGCC systems. Journal of the institute of Energy, September 1995, 68, p.157-166