Int. J. Therm. Sci. (2001) 40, 338–343

S1290-0729(01)01229-7/FLA

Efficient energy systems on the basis of cogeneration and heat pump technology ☆

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(Received 15 September 2000, accepted 15 October 2000)

Abstract — Standard energy systems of communities, in particular industrialized areas, are characterized by a considerable amount of avoidable primary energy consumption. It can be shown that this potential can be realized by energy systems that are based on cogeneration and electrical heat pump technology. The typical features and components of such systems are discussed and a closed formula for their primary energy demand is presented. Results for a particular system demonstrate that the primary energy demand of the existing standard energy systems can be reduced to about 50 % by switching over to the efficient energy systems. © 2001 Éditions scientifiques et médicales Elsevier SAS

cogeneration / heat pump / thermodynamic analysis / exergy loss / energy system

Nomenclature

$\dot{S}_i$ internal entropy production
T thermodynamic temperature
$\dot{Q}$ heat flux
P power
PE primary energy

Greek symbols

η efficiency
σ power-to-heat ratio
ε coefficient of performance
γ contribution of heat pump heat to total heat

Subscripts

h hot
c cold
el electrical
C cogeneration
B boiler

1. INTRODUCTION

Industrialized community areas consisting of private settlements, buildings for administration and related services as well as production locations require various energy forms, such as electrical power, heat and cooling. While electrical power and cooling are usually produced by adequate thermodynamic processes, although associated with waste heat, heat in most practical cases is obtained from a primitive process, i.e. fuel combustion at high temperature with subsequent heat transfer to the desired temperature. This latter process is primitive in the sense that it does not take advantage of the various thermodynamic and technical solutions to provide heat with less primary energy input.

It will be shown here qualitatively and quantitatively that energy systems can be built up, using available technology, that lead to a reduction of primary energy demand of about 50 %. These energy systems are based on a synthesis of combined gas and steam cogeneration plants with electrical heat pumps, thus, essentially eliminating the primitive generation of heat and the waste heat production of power plants in most contemporary systems.

☆ This paper was selected from among the works presented within the framework of the interdisciplinary research project on "Waste energy utilisation strategies" of the Berlin-Brandenburg Academy of Sciences and Humanities.

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2. STANDARD ENERGY SYSTEMS

The structure of a standard energy system, as found in most community areas, is shown in *figure 1*. We can discern three levels of action, the user level, the region level and super-region level. The user level comprises all users of energy forms, such as private homes, administration buildings and production locations. It is this level which defines the quantities and qualities of the energy streams that have to be delivered from the other levels. The region level may be represented by a local supplier, who delivers electricity and gas to the user level. Frequently, production of these energy utilities does not take place in the region area but instead is realized in a super-region level. Here a large, central power station produces electrical power from any type of fuel which is transmitted to the other levels by the electricity grid. Gas is also produced or, more frequently, transmitted to the local supplier through this region from worldwide distributed gas fields.

This energy system is associated with strong exergy losses in various parts of the technology. We here concentrate on the most important avoidable contribution due to the transfer of heat over a temperature difference. Bearing in mind that [1]

$$\dot{S}_{\mathrm{i}} = \dot{Q}\,\frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{T_{\mathrm{h}} T_{\mathrm{c}}} \qquad (1)$$

is the entropy production associated with a transfer of heat $\dot{Q}$ from a high temperature level T_{h} to a low temperature level T_{c}, we discover a significant and avoidable contribution to the total exergy loss. In a primitive generation of district heat T_{h} is the temperature of the hot combustion gas and T_{c} is the temperature needed by the heating system. Clearly, this temperature difference is rather high, considering a combustion gas temperature of about 1 500 °C and a heating system temperature of about 50 °C. Established technologies are available that permit heat production with much lower temperature differences. Further, in standard power generation there is a considerable amount of waste heat the generation of which is also associated with an exergy loss due to (1) in addition to that of the combustion process. In that connection, T_{c} is the temperature of the cycle heat intake.

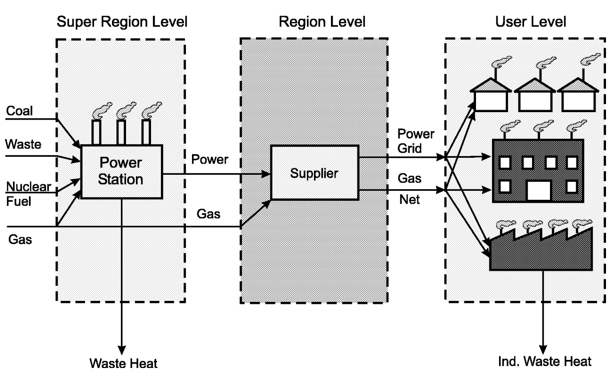

Figure 1. Structure of a standard energy system.

3. EFFICIENT ENERGY SYSTEMS

Since the dominant source of unnecessary entropy production in the standard energy system is associated with the primitive heat generation, alternative technologies for warm water production are required. Obvious choices are cogeneration and heat pump technologies. In both technologies it is possible to adjust the temperature of the produced heat to the actual requirement without entropy production, at least in principle. In cogeneration, this is achieved by replacing the heat transfer from the heat intake temperature of the cogeneration cycle to the temperature required by the heating system through a power cycle. Herewith, the entropy production over this temperature difference is eliminated or, more precisely, reduced to that associated with the dissipation processes in the cycle. The entropy production between the hot combustion gas temperature and the temperature of the heat intake temperature of the cycle remains unchanged but is much smaller than that associated with a heat transfer according to equation (1). Further, the waste heat in standard power generation is essentially avoided. In a heat pump, the heat is produced at the required temperature by a process that can again be visualized as reversible, at least in principle. Clearly, there is entropy production in practical heat pump technology, but again much smaller than that in the primitive heat generation process. So, central elements to efficient energy systems will be cogeneration equipment and heat pumps.

Cogeneration equipment is available over a large range of power parameters, from about 10 kW to 1 000 MW. For the energy systems considered here, combined gas and steam technologies seem to be most adequate. Such equipment has a high electrical efficiency at relatively low costs. The total efficiency can practically reach the limiting value of unity, if the configuration of *figure 2* is realized. This configuration uses the fuel input in a very efficient way. The combustion gas has a temperature of about 1 200 °C and is expanded in the gas turbine (GT) under power production. The gas leaving the gas turbine has a temperature around 550 °C. It is

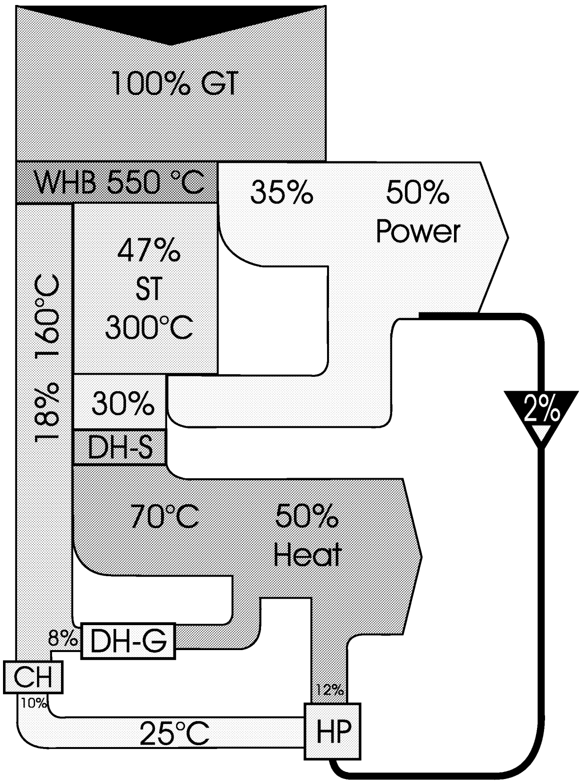

Figure 2. Combined gas and steam cogeneration system.

used in a waste heat boiler (WHB) to produce high pressure steam, which is expanded in a steam turbine (ST), again under power production. Heat production is realized from the steam leaving the steam turbine and from further cooling the combustion gas. This heat is transported via district heating system (DH-S) and (DH-G). The condensation heat (CH) of the vapour content of the combustion gas is regenerated by a heat pump which is driven by a small part of the produced electricity and delivers heat at the temperature required by the heating system.

Heat pumps in the efficient energy systems under consideration are electrical heat pumps. They are highly efficient for small temperature lifts and high electrical efficiency, the latter being guaranteed by the combined gas and steam power production equipment. Electrical heat pumps lead to a connection of the power with the heat demand. This has several positive effects. Load valleys in the electrical grid can be filled by turning on electrical heat pumps in combination with short time heat storage in the heat net. Further, electrical heat pumps can be switched off over short periods of time without serious consequences for the heat supply. They, thus, can serve to secure power supply in times of power station or net breakdown. Finally, heat pumps may be used to reduce the temperature level of the heating system reflux, thus making it available as a sink for low temperature heat, such as waste heat or solar heat.

Classical cogeneration systems usually have a primary energy demand which is considerably higher than at its optimum adjustment to the required quantities of power and heat, due to contributions of boilers and standard power stations [2]. This can essentially be improved by adding electrical heat pumps. The primary energy demand of a system based on cogeneration and electrical heat pump technology to produce the energy quantities required, i.e. the heat $\dot{Q}$ and the electricity $P_{el} = \sigma \dot{Q}$ can easily be shown to be [1, 3]

$$PE = \frac{\dot{Q}}{\eta_B}\left\{1 + \gamma\left(\frac{\eta_B}{\varepsilon\eta_{el,C}} - \frac{1}{\varepsilon\sigma_C} - 1\right) + \sigma\frac{\eta_B}{\eta_{el,C}}\left[1 - \frac{\eta_{el,C}}{\sigma_C\eta_B} + \frac{\Delta P_{el}}{P_{el}} \cdot \left(1 - \frac{\eta_{el}}{\eta_{el,C}} + \frac{\eta_{el}}{\sigma_C\eta_B}\right)\right]\right\} \quad (2)$$

Here η_B is the efficiency of a standard boiler, $\gamma = \dot{Q}_{HP}/\dot{Q}$ the ratio of the heat delivered by the heat pump to the total heat demand, ε the coefficient of performance of the heat pump, η_{el} the electrical efficiency and ΔP_{el} the electrical power obtained from a standard power station to match the total electricity demand. The index C indicates the cogeneration equipment. For $\gamma = 0$, equation (2) reduces to the energy demand for a cogeneration system [2]. The parameter γ may be optimized in such a way that primitive heating in a standard boiler is eliminated altogether. In this case the condition

$$\frac{1}{\sigma} - \frac{\gamma}{\sigma_C\varepsilon\sigma} - \frac{1}{\sigma_C} + \frac{\Delta P_{el}}{P_{el}}\frac{1}{\sigma_C} - \frac{\gamma}{\sigma} = 0 \quad (3)$$

must be fulfilled.

Figure 3 shows the basic structure of such an efficient energy system. On the user level, private homes and administration buildings get their heat exclusively from a heat net, eliminating all primitive heat generation in these applications. Industrial production sites receive fuel to satisfy their high temperature requirements in addition to the low temperature heat. All users receive electricity from the grid. The basic generation unit is a combined gas and steam equipment on the region level which delivers electricity into the grid and heat into the net. Industrial waste heat as well as possibly solar heat at low temperature are collected and lifted, if necessary, to the temperature level of the heat net

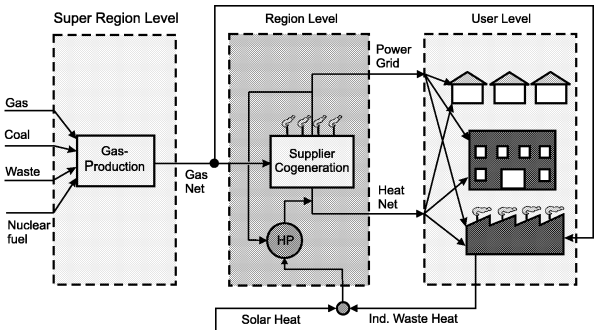

Figure 3. Structure of an efficient energy system.

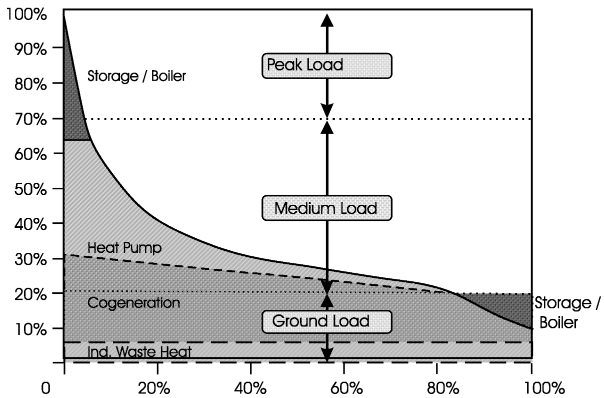

Figure 4. Heat load management in the efficient energy system.

by an electrical heat pump. The super-region level is reserved for the gas production to which fossil gas will contribute the dominant part but which can be augmented by coal and waste gasification. Clearly, for the electricity part, such an energy system has a more decentralized nature than the standard system. On the other hand, it is more centralized in comparison to the primitive heat distribution. This is reflected by the requirement of a heat net in addition to the electricity grid, and for industrial production locations, a gas distribution net. Clearly, this is a severe drawback to the economical attractivity of the new system. Calculations must reveal whether the reduction of primary energy demand in the efficient energy system can compensate the additional costs of the heat distribution net and the other equipment of the efficient system.

In *figure 4* a possible heat load management for the efficient system is shown. The heat load of the considered industrial area typically varies in the way shown between a ground load of about 20 %, a medium load and a short time peak load. The ground load is represented by the warm water demand and part of

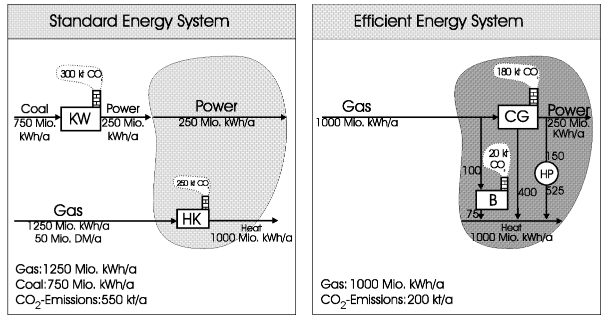

Figure 5. Gas demand of the efficient system with respect to a standard system.

the heating demand. It should generally be covered by highly efficient equipment, which is characterized by low primary energy demand, although possibly associated with high invest costs. Such technologies are industrial waste heat in addition to cogeneration heat. The medium load should be covered by the heat that can be adjusted rapidly and with little loss to the changing demand. This is typically a domain of the electrical heat pumps. For the cogeneration units this means, that during the winter period this equipment will be operated with twice the load of the summer months. This covers a 20 % increase of the electrical power demand and provides an increase of heat generation by a factor of 3 by means of the electrical heat pumps. Only the remaining peak load is generated in the usual primitive way, although this can in principle be eliminated entirely by use of heat storage.

An obvious question is whether enough gas is available to provide the energy forms in such an efficient energy system. Although gas can always be produced by gasification from any type of fuel, it may be interesting to investigate the gas demand of such a system. In order to address this issue we consider a simple example in *figure 5*. The system has an electricity demand of $250{\cdot}10^6$ $kWh{\cdot}a^{-1}$ and a heat demand of $1\,000{\cdot}10^6$ $kWh{\cdot}a^{-1}$, a typical ratio in many community systems. A standard power station with brown coal will need $750{\cdot}10^6$ $kWh{\cdot}a^{-1}$ and the primitive heating process will need $1\,250{\cdot}10^6$ $kWh{\cdot}a^{-1}$ gas. In the efficient energy system $1\,000{\cdot}10^6$ $kWh{\cdot}a^{-1}$ of gas will be used to produce $400{\cdot}10^6$ heat and $400{\cdot}10^6$ $kWh{\cdot}a^{-1}$ electricity in a combined gas and steam cogeneration equipment with an overall efficiency of 90 % and $75{\cdot}10^6$ $kWh{\cdot}a^{-1}$ in a standard boiler. From the $400{\cdot}10^6$ $kWh{\cdot}a^{-1}$ electricity, $250{\cdot}10^6$ $kWh{\cdot}a^{-1}$ are used to cover the electricity demand of the system and the remaining $150{\cdot}10^6$ $kWh{\cdot}a^{-1}$ are used in electrical heat pumps to produce $525{\cdot}10^6$ $kWh{\cdot}a^{-1}$ heat. The example shows that the efficient system needs even less gas input than the standard system, although both, heat and electricity demand, are covered without any additional fuel. *Figure 5* also shows the significant reduction of CO_2 emissions. The numerical results are open to changes with respect of the demand and generation parameters, the basic conclusions, however, remain the same.

4. RESULTS FOR A PARTICULAR SYSTEM

We consider a particular energy system. The demand of heat and electricity is defined by the demand lines of *figure 6*. The peak heat demand is about $\dot{Q} = 1\,300$ MW, the peak electricity demand about $P_{\mathrm{el,N}} = 400$ MW [3]. The time dependence is typical in the sense that the electricity demand is much more even than the heat demand. This leads to strong variations of the power-to-heat ratio with the typical difficulties in adjusting cogeneration equipment to this demand structure.

In order to cover the heat demand it is supposed that 90 % of the heat is delivered by a central heat distribution net and further 10 % by decentralized electrical heat pumps in areas too remote to be included in the central heat distribution. We assume a gas and steam cogeneration unit with an electrical efficiency of $\eta_{\mathrm{el,C}} = 0.50$ and a power-to-heat ratio of $\sigma_{\mathrm{C}} = 1.111$. The coefficient of performance of the heat pumps is taken as $\varepsilon = 2.88$. The standard energy system to which the efficient energy system will be compared is characterized by $\eta_{\mathrm{el}} = 0.40$ and $\eta_{\mathrm{B}} = 0.75$. This represents average values of established technology. With these values we find that the heat demand is covered as shown in *figure 7*. While the ground load is delivered from the cogeneration units a significant part of the total annual heat is contributed by the heat pumps. Due to the electricity demand of the electrical heat pumps the total electricity demand of the efficient system is higher than the net demand of the standard system, as shown in *figure 8*. In *figure 9*, it is shown that it can be covered almost completely by the cogeneration units, although not quite so. In the warm weather season the heat demand is so low that some cogeneration units have to be switched off in order to avoid an overproduction of heat. In such situations electricity must be obtained from standard power stations. Finally, in *figure 10*, we consider the primary energy demand, as documented by the exergetic efficiency, of various energy systems in comparison. The primary energy demand of the standard system is reduced to about 50 % by the efficient energy system based on a combination of cogeneration units and heat pumps (CG+HP). A cogeneration system (CG+B), although a major step is the right direc-

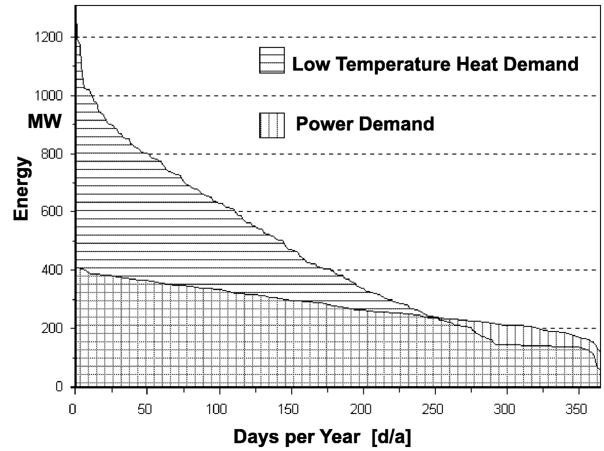

Figure 6. Demand profiles for low temperature heat and electricity for a particular community.

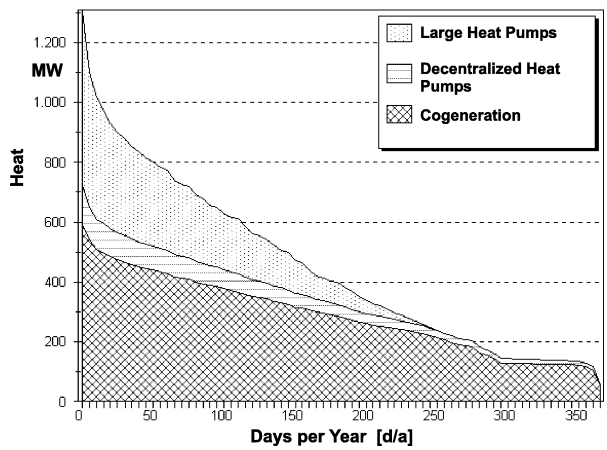

Figure 7. Coverage of the heat demand.

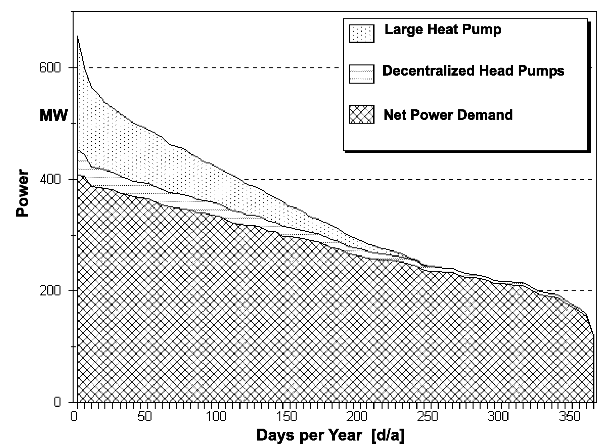

Figure 8. Total electricity demand.

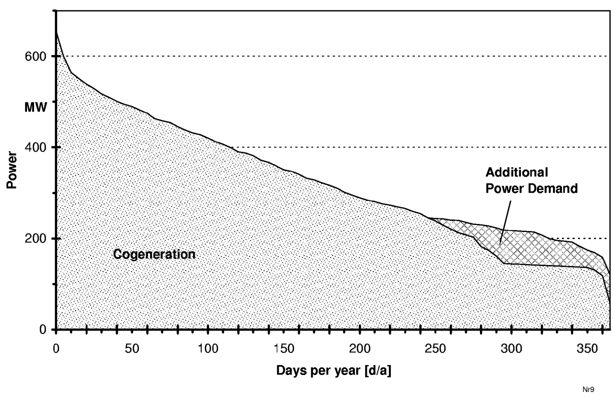

Figure 9. Coverage of the electricity demand.

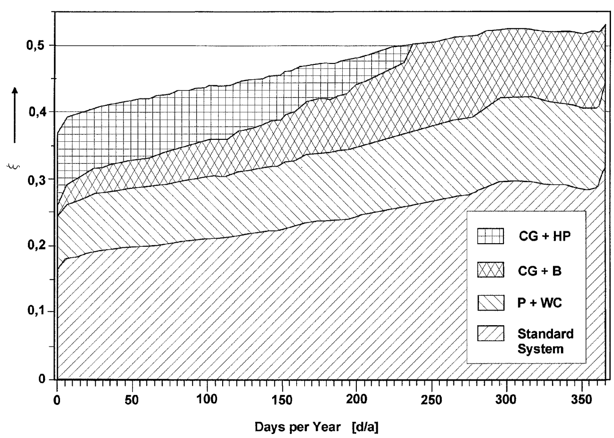

Figure 10. Primary energy demand for various supply alternatives.

tion, does not have the same reduction of primary energy demand. Still lower is the exergetic efficiency of a system using highly efficient power stations with $\eta = 0.55$ with modern boilers taking advantage of water condensation (P+WC).

5. CONCLUSIONS

We conclude that a considerable saving of primary energy is possible when standard energy systems are replaced by efficient systems on the basis of cogeneration and heat pumps. This originates from the fact that the large entropy production associated with the primitive heating process and the power plants of standard energy systems is diminished by introducing technologies in which the heat can be produced at the required temperature with less entropy production. The better energy performance will have to be balanced by the considerable costs of such a system, in particular for the district heat distribution.

Acknowledgement

The author wishes to acknowledge fruitful discussions with J. Besseling from the Niederrheinischer Verein für Energie und Umwelt.

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