CH9900008

OPTIONS FOR NEW SWISS ENERGY SUPPLY STRATEGIES

U. Gantner, S. Hirschberg, M. Jakob [1]

Ecologically neutral, cost efficient, without supply shortages, independent from foreign countries, risk- and waste-free - that is the image of an ideal future energy supply. But even if considerable ecological and economical improvements of various energy supply options can be achieved, the next generation of heat and power plants with the associated up- and down-stream parts of energy chains, will not comply with all such idealistic requirements. As research in the framework of the GaBE Project on "Comprehensive Assessment of Energy Systems" has shown, among the reasons for this are the limited medium term potential of renewable energy sources, and the necessity to employ primarily non-renewable energy carriers for the emerging more efficient energy conversion processes.

1 INTRODUCTION

Human interventions that disturb the natural processes and networks are unavoidable in a highly industrialised society. This also applies to the use and supply of heat and electricity. Apart from considerate usage by the consumer, the appropriate choice of energy sources and chains can promote developments towards maximum environmental and economic sustainability. In the frame of the project "Comprehensive Assessment of Energy Systems - GaBE" different future energy systems for the production of heat and electricity were studied [1]. This activity developed into a major part of the "Dezentral" project whose objective is to investigate possibilities, limits and impacts of a more decentralised energy production, by means of co-generation (combined heat and power - CHP) plants and the extended use of heat pumps (HP). The "Dezentral" project is an extension of "Vorschau 1995", which considered alternative means of centralised electricity production [2,3]. The contributions of PSI to both these projects were provided within the frame of research co-operation with the Swiss Association of Producers and Distributors of Electricity (VSE).

Chapter 2 introduces the methodology of the treatment of energy scenarios and associated problems arising from CHP plants. Chapter 3 deals with the technical and economic parameters of future energy systems. The Swiss electricity and heat demand for the year 2030 is modelled in chapter 4. Chapter 5 compares different energy supply options with respect to their ecological and economic performance.

2 METHODOLOGY

2.1 Overview

When CHP plants are considered as part of the analysis of the future electricity supply, it is necessary to split pollutant emissions and costs between the two products (electricity and heat) in order to assure a fair comparison. As these allocations between heat and electricity are subject to arbitrariness we adopt in the Project "Dezentral" a broader approach which lumps together the future demand for heat and electricity. Thus one avoids arbitrary allocations which would lead to considerable differences depending on the choice of specific criteria.

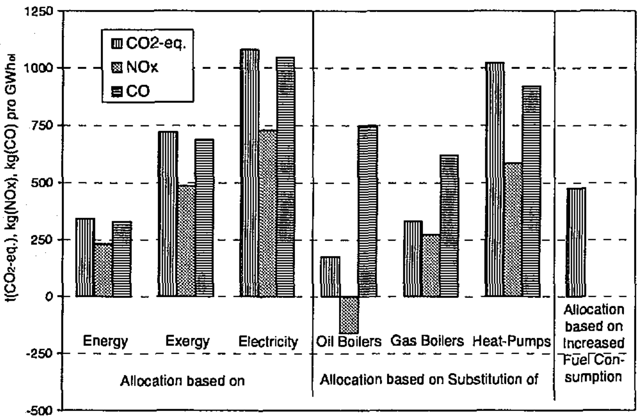

Fig. 1: Variation of results obtained for selected emissions to air using a number of allocation criteria. The emissions are normalised by produced energy and are based on a Life Cycle Assessment (LCA) of a current CHP plant operating in a residential area.

In the figure above the criteria "Energy" and "Exergy" split the total emissions of the whole energy chain according to the energy and exergy content, respectively. If the main interest lies in electricity as the product (e.g. the by-product heat is not used), all emissions and expenses are loaded onto electricity ("Electricity"). Another option which is often used is to consider the granting of bonuses for the substitution of existing plants. Depending on the ecological performance of the system to be substituted these merely fictitious emissions turn out to be higher or lower for the CHP plant (substitution of an oil boiler or of a heat pump). A third method, "Increased consumption", compares the production of useful heat from a conventional heating system and with a CHP plant. Because of their lower thermic efficiency CHP plants consume more fuel. This additional use of fuel is allocated to the electricity production. This method of comparison is subject to certain limitations, e.g. the same fuel has to be used.

From an ecological point of view, the use of allocation method for the comparison of energy systems has limited relevance. In the case of combined heat and power production other aspects seem to be much more important than the distribution of emissions and

[1] Energy Systems Analysis (ENE) PSI

costs between the products. Thus, the energy carriers used should be optimally transformed, the energy produced used effectively and the total emissions and costs minimised. Consequently, within the "Dezentral" project all energy scenarios were evaluated on the basis of the associated demand of both electricity and heat without any weighting between them.

Three steps can be distinguished in the approach used in the study [1]:

- Definition of boundary conditions for Switzerland: possible developments of the electricity supply and the heat production parks.
- Analyses of energy systems (regarding technical and economical developments and their market prospects), of the building park (regarding refurbishment and substitution rates) and of future supply options. The consistent comparison of plants and supply options reflects technological advancements expected to be fully available for the implementation in the period from 2020 to 2030.
- Discussion of results and of further criteria essential for decision-making.

2.2 Boundary Conditions

In addressing the future heat and electricity demand, a wide spectrum of boundary conditions is considered. These are, concerning electricity, the development of the current power plant park, lifetime of the plants, the availability and market expansion of new technologies and the development of the yearly consumption. These elements define the future electricity supply deficit due to retirement of the currently operating systems, which will be covered by one of the options being considered.

The future heat supply needs (space heat and hot water) can be assessed quite reliably, based on the current building park, the construction and refurbishment rates and specific improvements of the energy relevant features of these buildings. The demand for process heat depends on general economic developments, and is therefore more difficult to predict and is subject to larger uncertainties. The projected developments are based on studies made in connection with the "Energy Perspectives" activities of the Swiss Federal Office of Energy [4].

Thus, we first generate a consistent set of data which defines the electricity supply gap and the heat demand expected for year 2030, including the more detailed demand specification within the various categories in different energy consumption sectors.

2.3 Analyses

Starting from the structure of the building park, which is divided up into categories, the compatible future heat and CHP plants for covering the demand are defined and their technical parameters specified. The characterisations of central power plants for the pro-

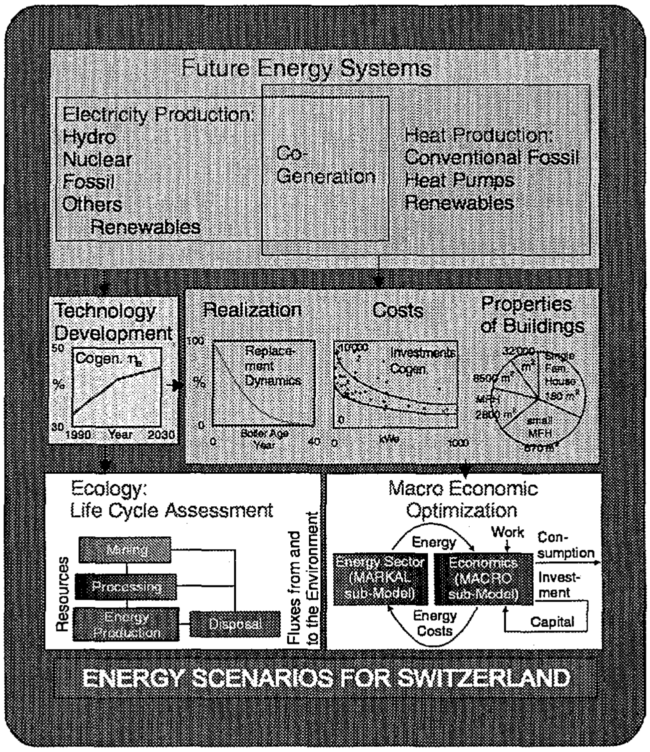

Fig. 2: Schematic presentation of the analysis.

duction of electricity can be taken over from earlier studies in the framework of the GaBE Project [2].

i) To guarantee fair ecological comparisons of energy systems, the whole energy chains are examined by means of a Life Cycle Assessment (LCA), whose scope stretches from the extraction of raw materials over their processing/refinement to the use in a power plant and the treatment of waste. An LCA aims at a comprehensive account of the flows of materials occurring within the various stages of the chain and their way into the environment. Therefore, not only the operation of the plant itself, but also the emissions caused during the construction and decommissioning phases must be taken into account. Furthermore, the direct and indirect emissions are integrated in the calculations. Direct emissions are generated by the operation of power plants and facilities processing the fuel, as well as by operation of machines used during plant construction and by transportation systems. Indirect emissions are mainly associated with the production of construction materials, with energy consumption in connection with the development of infrastructure, as well as with different industrial processes.

ii) On the side of economy, the full cost is calculated. Investments which have to be made at different points in time are expressed as costs per year, considering the specific lifetime of the components. The allocation of specific costs to the two products heat and electricity can be avoided in the examination of combined electricity and heat options by comparing the total costs of the alternative supplies. But also the comparison of specific electricity generation costs of different plants can be of interest. In this case the heat of the CHP plant is evaluated in relation to the marginal costs of heat generation, that is, using the full generation costs of a conventional heating system.

iii) When assessing the total supply options for Switzerland, especially when allocating plant shares to the specific categories, along with the construction and refurbishment rates, other parameters must be considered. These include not only the development of the investment and operation costs but also construction costs associated with the substitution of old heating systems by new technologies (e.g. co-generation). In the case of CHP, so-called cost-levels were defined, taking into account construction and implementation costs that can differ considerably depending on the building. Apart from that, the economic factors affecting the different categories must be considered. Evaluating all these factors, the quantities of CHP plants and heat pumps given by the top-down approach are apportioned, as realistically as possible, to the different building and industrial application categories. In this context one must not ignore that the assignments of thermal and electric power levels based on energy-relevant properties of buildings do not remain constant with time. A first simplified economic potential for CHP plants in Switzerland has been defined with the help of the energy-economy optimisation model MARKAL. The results are used to support definition of the options. Further, detailed analyses are planned in the framework of the GaBE Project.

2.4 Results and Decision Support

Although total emissions and residuals associated with the full energy chains are only a surrogate measure of environmental impacts, they give a hint as to the "ranking" of the different options. To be able to say more about the environmental effects, the situation at the place of emissions as well as local/regional and temporal influences such as topography and weather conditions must be considered. These aspects are all being considered in detail in the GaBE Project. Nevertheless, the comparison of total emissions of different energy supply options can be viewed as an instructive method for the strategic evaluation of future energy supply strategies. For the nine defined future options the greenhouse gas emissions (CO_2, CH_4, N_2O and CFC, expressed according to IPCC 1996 in CO_2-equivalent for a time horizon of 100 years) and the emissions of air pollutants CO, NO_x, SO_x, Non-Methane Volatile Organic Compounds (NMVOC) and particulate matter, were estimated.

Besides the environmental effects, the economic efficiency plays an important part in the planning of a future energy supply. Therefore, the annual costs of the supply options were calculated. The production costs together with other factors indicate in which direction it would be desirable to change the boundary conditions, in order to optimise the allocation of resources. A comprehensive assessment covers not only ecology and economy, but numerous other factors such as severe accidents risks, preservation of natural resources, security of supply, socio-economic aspects etc. Within the GaBE Project a large scale multi-criteria-analysis approach and tools are being developed, aiming at combining the criteria.

3 PARAMETERS OF FUTURE TECHNOLOGIES

3.1 Technical parameters

The ecological analysis of the energy supply options is based on 16 CHP plants; the performance scale covers smallest applications for use in one-family houses up to industrial plants of 30 MW_e. Natural gas and oil are used as fuels. For engine driven CHP plants one has to differentiate between lean and stoichiometric combustion as well as different ignition technologies, taking into consideration the corresponding abatement technologies which become legally required. Furthermore, LCA was carried out for a natural gas driven high temperature fuel cell, providing domestic heat and hot water.

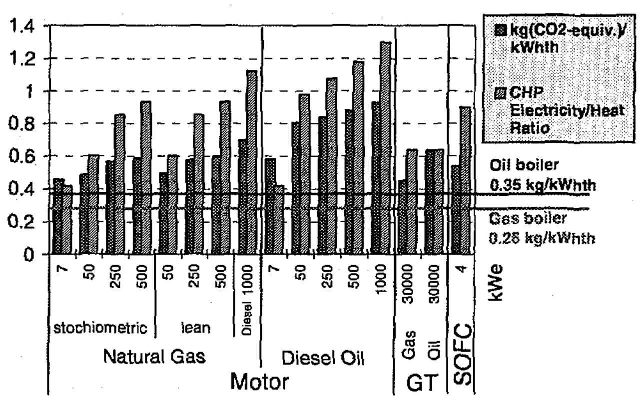

Fig. 3: Comparison of co-generation systems: greenhouse gas emissions and produced amount of electricity per unit of thermal useful energy [1].

Modern co-generation systems with an electrical power level of several hundred 100 kW upwards show a trend towards increased electrical efficiency of 40 to 50 % or more with total fuel utilisation factor of 80 to 90 %. Small engine driven systems, so-called "Mini-CHP-plants", will remain at a relatively low electrical utilisation of 25 %. For these systems a major innovation is a new control system which eliminates the need for a conventional back-up system (to cover the peak heat demand during only few hours per year). The high temperature solid oxide fuel cell (SOFC), still in test phase, combines several advantages. Despite low power level, electrical efficiency of more than 50 % and a total fuel utilisation of up to 100 % can be achieved. In addition, only traces of air pollutants, such as NO_x, CO, NMVOC and particles, are generated in the cells when the fuel is catalytically converted. The extremely low noise levels and the excellent load following performance are other attractive features of this system.

Apart from CHP plants, the project covers modern fossil boilers (with a yearly efficiency of 92 to 102 %) for the pure heat supply, and heat pumps with varying heat sources and maximum yearly performance coefficients of 4.2 (air), 5 (ground), 5.5 (water) and 6 (waste heat). Modern Gas Combined-Cycle (CC) plants with electrical efficiency of 60 % and advanced light water reactors are selected as central electricity supply systems included in the different supply options.

3.2 Economy

The focus of the economic study has been on two factors, i.e. (i) the influence of the relevant building characteristics on the costs (ii) the specific developments due to technical advancements.

i) Besides the costs for the CHP plant module, additional costs arise from the necessary periphery and the complete installation. These costs are typically about as high as the module costs. The influence of building parameters, such as the extent of refurbishment, the age of buildings and available space, on feasibility and costs of co-generation projects has been studied in detail. For this purpose the building categories were subdivided into three homogeneous groups with respect to co-generation costs. Some buildings are not classified since the feasibility of CHP plants is questionable; this applies to 20 to 25 % of the fully refurbished buildings and to 25 to 30 % of the non refurbished ones. Cost-level I corresponds to the lowest costs, cost-level II to intermediate and cost-level III to the highest. 25 % of the not refurbished and 30 % of refurbished buildings belong to cost-level I, while the corresponding figures for cost-level II are 30 % for both cases. The remaining buildings fall into cost-level III. These results (Tab. 1) are based on an evaluation of some hundreds of implemented or proposed CHP plants exceeding 70 kW_e [5].

In relative terms, the non refurbished buildings follow the same pattern. Slightly unexpectedly, the absolute level is lower by 10 to 15 %. This can be explained by the fact that in not refurbished buildings, the higher demand for heat, means that bigger and thus more cost-efficient (per kW_e) stations can be installed.

Table 1: Gross specific investment costs of gas-driven CHP plants for new and for three cost levels (CL) for refurbished buildings for the year 2030; REA: Reference Energy Area.

Building size REA (m²)	Cap. kWe (ca.)	Investment Cost (thsd sFr/kWe) new B.	refurbished Buildings CL I	CL II	CL III
8500	95	2.5	2.5	3.0	4.6
21000	250	1.9	2.0	2.3	3.1
60000	870	0.9	0.9	1.0	1.3

As far as heat pumps (HP) are concerned the influence of buildings indirectly impacts the economic parameters through the different outlet temperature of the heating distribution system. The attainable thermal power level and efficiency of an HP may decrease by as much as 40 % and 25 %, respectively. The investment and electricity costs rise correspondingly at these low efficiencies. Apart from that, there are big differences in the costs of tapping the heat source.

ii) When considering the evolution of costs with time technical improvements must be recognised. In a market characterised by growing competition, prices for power plants cannot be expected to rise. Customers (i.e. plant operators) can thus profit from the technical improvements (see section 3.1) and the corresponding cost elements are likely to decrease accordingly.

- For CHP plants increases in efficiency are expected to lower module, operational and maintenance costs, particularly since a dominant maintenance cost element is the replacement of the motor after about five years. The effect is bigger for smaller stations, because an increase in efficiency compresses the specific cost curve, which leads to bigger differences at the steep part of the curve.
- For heat pumps the efficiency improvements lead to corresponding cuts in electricity costs. For smaller heat pumps the cut in capital costs achieved by technical improvements and benefits of replication (about -15 % for the HP, [6]) is just as important.

Furthermore, it must be taken into account that the allocation of plants to building categories changes in time. The gross power level of the plant can be reduced slightly by improved insulation of the building: e.g. for CHP plants this slightly counteracts the above mentioned trend of the power-specific cut in costs.

When comparing generation costs it has to be kept in mind that the energy economic value of the generated electricity could vary from one technology to another. Electricity from CHP plants, but also CC based electricity that is produced mainly in winter season has a higher economic value than electricity from power plants with predominantly base load characteristics. Furthermore, electricity from CHP plants is produced at a lower voltage level which is closer to the consumers. Additionally, CHP plants are able to contribute to the network services. There is a variety of opinions about the economic value of these items, with a range from nearly zero up to 6 Rp/kWh_e.

The production costs of the central fossil plants are sensitive to fuel prices: an increase by 30 % leads to 20 % higher production costs. There is a similar sensitivity of the costs of nuclear power production to the investment costs: a variation by 1'000 CHF/kW_e results in changes in production costs by 0.8 Rp/kWh_e.

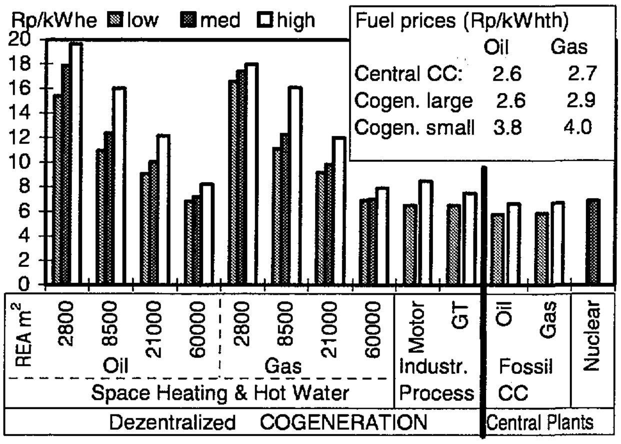

Fig. 4: Electricity generation costs in year 2030. Low: new buildings and CL I for existing buildings incl. hwg (hot water generation). High: CL III for refurbished buildings without hwg. Central fossil plants Low: 7'300 hours/year, High: 4'500 hours/year (comparable to CHP). Investment cost for central Combined Cycle (CC) plants: 750 CHF/kW, for Nuclear Plants: 3'500 CHF/kW.

4 MODELLING OF THE ENERGY SUPPLY FOR THE YEAR 2030

4.1 The model electricity

It is quite straight-forward to predict the electricity supply of the present plant park (operating plants) until the year 2030. The assumed base supply of about 38'600 GWh, consists of hydropower (32'300 GWh), smaller thermal plants (4'500 GWh) of which about one third are fuelled with renewable energy carriers, photovoltaic plants (100 GWh) and the remaining from import contracts (1'700 GWh). It is assumed that the currently operating nuclear power plants will be decommissioned at the end of their expected operation lifetime of 40 years and that no new import contracts with foreign countries will be signed. The technically realisable potential of new renewable energy sources such as wind, biomass and geothermal has been evaluated by PSI in the framework of the SATW study *CH 50%* for the time horizon 2020 [7]. 3'000 GWh is the estimated optimistic potential of these sources. Under favourable conditions this potential could be realised, with almost 60 % of it originating from the use of biomass, e.g. in waste incinerators. These figures were not fully used in the "Dezentral" project due to the underlying highly uncertain assumptions (e.g. geothermal plants are totally novel for Switzerland) and the magnitude of effort needed for the assumed expansion of photovoltaic and wind plants.

The efficiency improvements on the demand side, changes in the structure of economy, the increase of population and the further spread of automation processes in the industrial and commercial sectors are factors which influence the long-term development of the electricity demand in a complex way and which sometimes show competing effects. Under the assumption of a positive economy growth, the scenarios "high demand" and "low demand" have been studied in [3]. The consumption of electricity is assumed to grow by 2 % (1 %) per year until the year 2010 and then by only 1 % (0.5 %). Fig. 5 shows that even if the electricity consumption would stagnate on the today's level there will be a supply shortage starting from the year 2020.

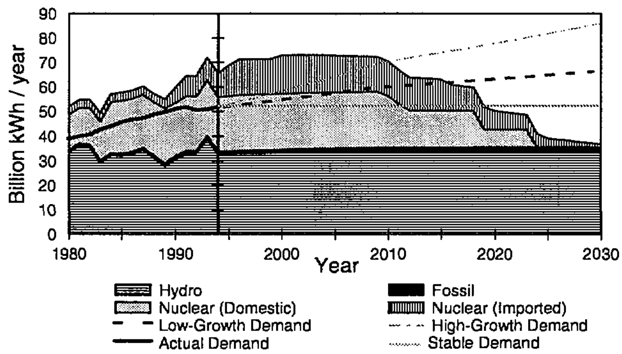

Fig. 5: Electricity supply (split up into hydropower, domestic nuclear & fossil plants and nuclear energy imports); Development of the effective electricity consumption of the last years as well as the development of supply and demand until the year 2030 according to [3].

The Project "Dezentral" uses the postulated "low demand" as the reference. This implies an electricity shortage of 27'000 GWh_e by 2030. Energy policy strategies and publicly acceptable solutions must be developed to cover this gap, especially if parts of the shortage are to be covered by smaller decentralised plants.

4.2 The model heat

While the current electricity demand is covered by a relatively small spectrum of power plants, the heat production occurs mainly by means of a wide variety of decentralised plants. This means that heat is primarily directly produced by the users. The relatively more complex structure of the heat supply makes the corresponding modelling more difficult and broader in scope than in the case of electricity supply.

In the first step the total yearly heat demand of about 340 PJ, where 1 PJ = 278 GWh, is divided into the process heat and low temperature heat. The space heat and hot water generation (260 PJ) is addressed by a bottom-up representation of the energy demand. The expected development of the relevant characteristics of the building park up to year 2030 is based on predicted Reference Energy Areas (REA), the refurbishment rates and the projected evolution of specific useful energy (MJ/m²/a) for buildings [8,9].

Thanks to the continuous refurbishments and energy-related improvements of new buildings, the total Swiss useful energy demand in year 2030 is expected to remain at the level of 1990, in spite of the projected REA increase by 38 %. The end energy consumption will be simultaneously reduced by 15 % due to the efficiency improvements [4].

In order to enable the allocation of appropriate heat systems, the building park was additionally divided according to sizes (expressed in REA), based on a number of statistical sources (Fig. 6) [8]. This leads to seven classes based on the energy-relevant areas and five classes based on the status of the buildings.

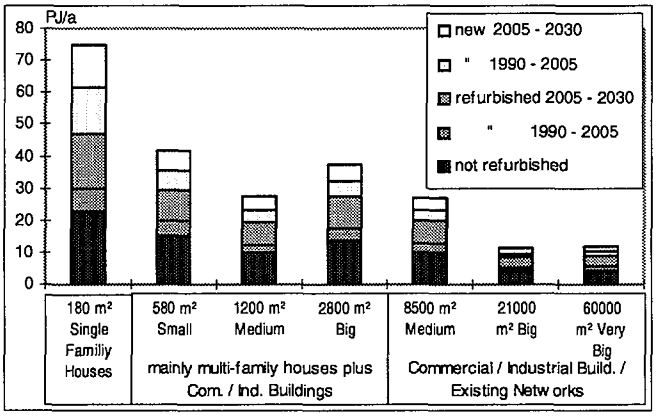

Fig. 6: The total Swiss useful heat demand (excluding conversion losses) for space heat and hot water in year 2030, according to REA and building status.

Since co-generation is of high interest for industrial applications, the process heat demands for various industrial sectors were considered, with more detailed division into various temperature and enthalpy bands [10]. Of the total 80 PJ, the "base" development already covers 18 PJ, of which about 10.5 is supplied by co-generation. The remaining process heat is open for new supply options.

A "base" development was also assumed for low temperature heat (space heat and hot water). The renewable sources are expected to take a larger part of the market consequently reducing the fossil share. Analogous to the electricity supply the SATW expert group addressed the feasibility of heat supply by means of enhanced use of renewable sources [7]. According to the PSI-study a maximal increase from the current 18 PJ to 61 PJ is feasible. The "base" development of space heat supply includes 20 PJ from biomass, 24 PJ from heat pumps, 5 PJ from solar collectors and 8 PJ from CHP plants. In addition, it is assumed that the contribution from electrical heat will be reduced by 50 % to 8 PJ. The remaining need for low temperature heat, potentially open to new supply options, corresponds to 195 PJ.

The total heat demand treated in connection with the studies of decentralised options as above is almost 258 PJ.

5 ANALYSIS OF SUPPLY OPTIONS

5.1 Definition of the future supply options

Starting from the basic data outlined in the preceding chapters it is possible to define various energy supply options and to compare the associated economic impacts and ecological burdens. A fundamental condition for this comparison is that the various options provide equal benefits in terms of useful energy. The electricity generation should follow more or less the same load characteristics.

The assumed base development (see section 4.1 and 4.2) is common for all options and therefore not included in their definitions. The options are divided into four groups:

- For the first three options the heat supply is based on conventional fossil systems. The electricity gap is covered by large central plants (A: 100 % Combined Cycle (CC); B: 100 % Nuclear; C: Nuclear as today, the remaining part CC).
- Within options D and E 5 TWh_e are supplied by co-generation. The remaining part of the electricity gap is covered by CC (D) or by nuclear (E) alone. The remaining heat demand is supplied by conventional fossil systems.
- Options F and G supply the same electricity contributions from CHP plants as options D and E. The goal is, however, that the CHP plants deliver so-called "CO_2-neutral" electricity. This is achieved through the substitution of conventional fossil heating systems by HP. The latter are driven with the electricity generated by CHP systems.
- Options H and I supply the same amount of heat from HP as F and G. The difference is that the corresponding electricity is supplied by central plants.

Within all options the oil and gas shares were specified according to common rules. Thus, the conventional fossil heating systems are driven by oil and natural gas (2/3 and 1/3, respectively), while for the CHP units the corresponding shares are reversed (1/3 and 2/3, respectively). The fossil CC plants use 75 % natural gas and 25 % oil.

While the electricity generating plants are to be substituted at few discrete points of time, the substitution of heating systems is a continuous process, affected by the ageing of the available systems and the refurbishment rate for buildings. When apportioning the CHP plants (total according to Table 2) to the specific building categories (Table 3), the heating systems replacement rates were taken into account along with the production costs. According to our findings, whether building refurbishment has been implemented or not is of secondary importance. In order to reach the assumed shares for year 2030, it is necessary that the new technologies (such as Mini-CHP or fuel cells) are introduced into the market in the near future, and that the implementation of the available ones is intensified. In the industrial sector there is a concentration of co-generation uses within energy intensive sectors while facilities exhibiting high energy demand are comparatively scarce [11].

Table 2: Useful energy (Heat, PJ) and generated electricity (TWh_e) of the assessed options. CHP: Co-generation, HP: Heat Pumps, CC: Combined-Cycle Plants, ->HP: Electricity consumed by HP.

	Options	A B C			D E		F G		H I	
Heat PJ	Fossil Boil.	258			226		185		230	
	CHP				32		45			
	HP						28		28	
	Total	258								
	Options	A	B	C	D	E	F	G	H	I
Electricity TWh	CHP				5					
	CC	27		5	22		22		27	5
	Nuclear		27	22		22		22		22
	CHP -> HP						1.9			
	CC -> HP								1.9	
	Total Net	27								

Table 3: Allocation of the assessed CHP to the various demand categories. Share of Heat Market (SoHM) indicates share of CHP in each heat market category. Shares and generated electricity of "Dezentral" options are to be read as additional to the base development.

	Base		Additional in Dezentral Options D E		F G	
	SoHM	GWhe	SoHM	GWhe	SoHM	GWhe
SFH	0%	20	1%	110	2%	160
Small MFH	0%	20	2%	110	4%	220
Med. MFH	1%	30	4%	100	8%	210
Big MFH	2%	110	8%	460	13%	740
Bld. 8500 m²	6%	310	32%	1'600	43%	2'200
Bld. 21000 m²	18%	410	31%	700	38%	900
Bld. 60000 m²	18%	510	31%	900	39%	1'100
Total Space Heat		1'420		4'000		5'500
Refinery	11%	210	11%	250	11%	250
Food	14%	100	16%	200	24%	300
Paper	42%	500	8%	100	13%	150
Chem./Pharm.	22%	400	14%	300	21%	450
Others		-		150		200
Total Industr. Proc.		1'210		1'000		1'350
Other cogeneration		670				
Total cogeneration		3'300		5'000		6'850

The bulk of the heat pump supply is predominantly allocated to one-family houses and small and medium multi-family houses. The share of HP supply declines with the growing building size. The highest share of HP (50 %) is to be found in new one-family houses. The building attributes have a significant impact on the economy of HPs. For this reason the variation of the shares within specific categories is of the order of factor two, depending on the status of the buildings (new, refurbished, not refurbished).

5.2 Ecological analysis

The criterion which is currently most used for the assessment of energy supply options is greenhouse gas (GHG) emissions. According to the Kyoto climate convention, Switzerland, together with other countries, committed itself until year 2000 to reduce GHG-emissions to the level of 1990; this should be followed by a further reduction by 8 % until year 2010. Thanks to the economic stagnation and mild winter weather the GHG-emissions were more or less stabilised in the middle of the nineties and now amount to 53 million tons per year, of which transport (without air plane fuel for international transport) makes up 15 million tons per year, and households, service and commercial industry 17.5 million tons per year. As the Swiss electricity is almost entirely generated by nuclear and hydropower plants, the electricity sector contributes only a negligible part to the overall Swiss GHG inventory. Contrary to the national GHG statistics, in the "Dezentral" Project the estimates of the emissions cover full energy chains and include both direct and indirect contributions. Therefore, the emissions calculated for the different options are not directly comparable to the statistics.

Figure 7 shows the contribution from each system for the nine postulated future energy supply options and the total GHG emissions. The specific contributions from electricity generation, CHP and heat generation are illustrated.

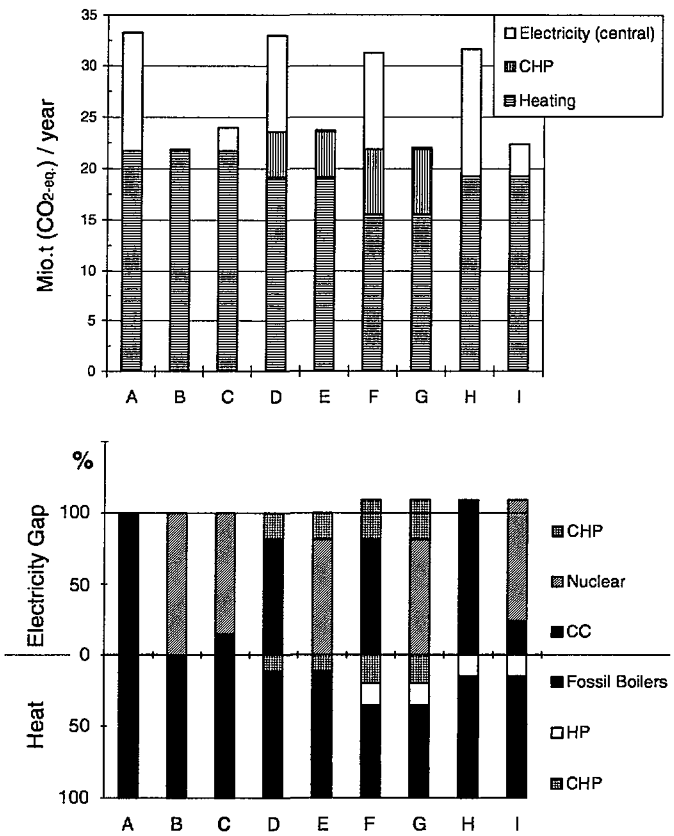

Fig 7: Option-specific greenhouse gas emissions per year according to (IPCC 1996).

Options A, B and C with conventional fossil heating systems exhibit the expected dependence on the choice of central electricity generation source, with B closely corresponding to the present situation.

Provided that electricity production is based on fossil sources, CHP plants can slightly reduce the GHG emissions. However, the positive influence of additional HPs is much stronger.

Given a continued coverage of the electricity demand by nuclear complemented by CHP plants the GHG emissions grow by almost 10 % compared to the nuclear electricity combined with conventional fossil based heating. In the "CO_2-neutral" CHP-HP options the amount of GHG from CHP plants and conventional heat plants was fixed at the level of option B. Therefore, for these scenarios the primary interest is to calculate the additional electricity needed and the corresponding burdens due to other air pollutants.

If options with mainly fossil based generation are compared to nuclear options (CHP included) the GHG emissions are between 30 and more than 50 % higher.

If the amount of HPs needed to reach the "CO_2-neutrality" of CHP plants is not changed and electricity is generated with central stations solely (options H and I), the GHG emissions are increased slightly (option H), compared to option F. A mixed electricity generation (option I) results in emissions higher by 2 % than option B, even with an electricity generation of 6.9 TWh by CC-plants.

Although the ranking of options is not influenced, the results of LCA calculations show that contributions of up- and down-stream process steps can amount to up to 20 % and, therefore, are not to be neglected. This aspect becomes even more striking for the other examined pollutants for which the contributions that do not directly originate from the power plant can be quite high (NO_x, SO_x and CO), or even dominate the total emissions (NMVOC and particles). In these cases changes in ranking of the options occur.

The total SO_x and NMVOC emissions depend mainly on the proportion of oil in the defined options, while the major part of NMVOC emissions originates from oil extraction. Still, it can be noted that the direct NMVOC emissions from the plants in options that include cogeneration are about 50 % higher than in other options; this may have an impact on health relevant limits in heavily burdened areas with high population.

The emission limits for carbon monoxide (CO) and nitrogen oxide (NO_x) are specified in the Swiss clean air act (LRV). All systems addressed in the present analysis meet these criteria. Nevertheless, the yearly emissions of these air pollutants associated with the different options are studied, as their environmental and health relevance is given and the impacts of an intensified use of engine-driven CHP plants should be evaluated.

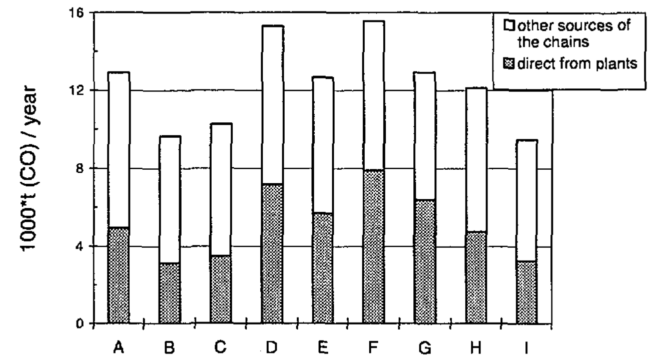

Fig. 8: Yearly CO emissions originating direct from the plants and other sources of the entire energy chains.

The direct CO emissions are clearly highest in those options with CHP plants. Even option A with fossil fuelled stations shows lower CO emissions than option E with 5 TWh electricity produced in CHP plants. The combination HP/central power plant mix imposes the lowest CO burden (option I). The contribution of direct emissions from the plants is between 32 and 52 %.

In contrast with the figures for GHG emissions, when the electricity production is based on fossil fuels, CHP plants can only contribute to the reduction of NO_x emissions if part of the conventional heating supply is replaced by heat pumps.

If the supply gap is continuously filled with nuclear energy and CHP plants (option E) NO_x emissions grow by 10 % relative to conventional heating and nuclear energy production. The purely fossil options show an increase by more than 40 %. Analogous to the figures for GHG, HPs and nuclear power also reduce the NO_x emissions.

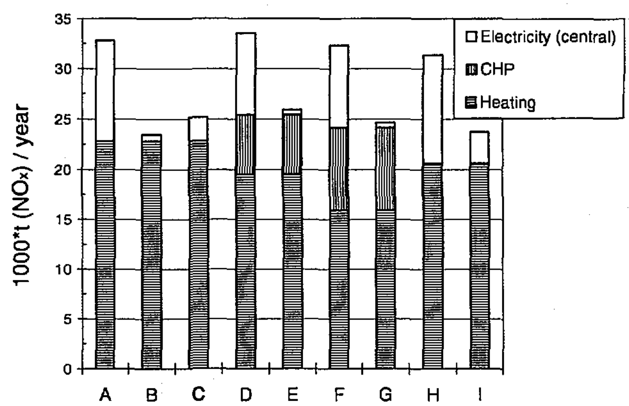

Fig. 9: Yearly NO_x emissions originating from central electricity production, pure heat supply systems and CHP plants.

5.3 Economic Analysis

The economic impact of the various options is analysed in terms of investment and operating costs. The investment costs are considered first.

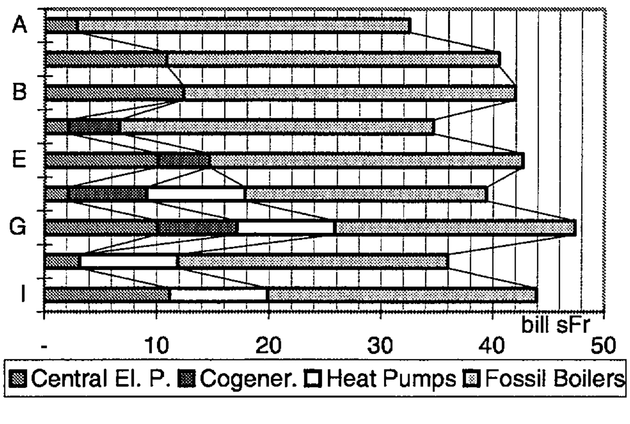

Fig. 10: Structure of the investment costs of the nine Swiss supply options A to I, with contributions from various types of supply systems.

A remarkable feature of the economic burden is that the investment costs into the electricity sector make only up between 10 and 25 % of the total investment costs of the various options. The investment costs are dominated by heating systems. Firstly, the amount of energy to be produced for heating is bigger than the electrical energy; secondly, the unit costs are high for small heating plants.

The biggest differences are between options with nuclear energy (B, C, E, G, I) and those without (A, D, F, H). Referring to the total costs this results in a need for additional investments of 20 to 25 % for options with nuclear component when the proportion of CHP plants and HPs are equal. On the other hand, comparing the options with (approximately) equal nuclear share, a steadily growing need of additional investments becomes evident for the options with CHP plants (D, E), with HPs (H, I) and with the combination of CHP-HP (F, G). However, the respective differences of 5 to 7 %, 9 to 11 % and 17 to 21 %, are smaller than the ones earlier noted between the options with and without nuclear energy.

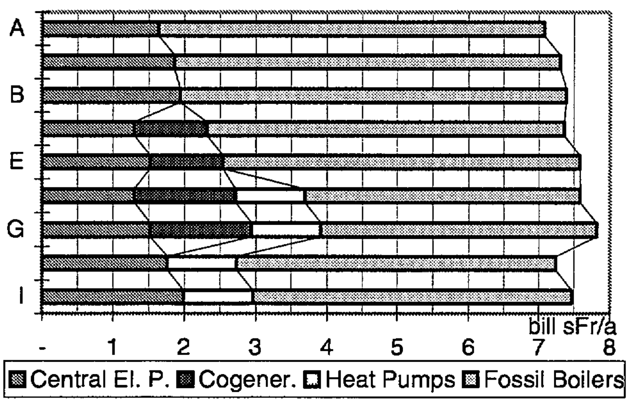

Fig. 11: Structure of annual costs of the nine Swiss supply options A to I, with contributions from various types of supply systems.

More important than the investment costs are the annual costs for capital, operation and fuels. Since the benefits of the options are more or less the same for all (e.g. economic differences due to the long term changes of the network structure were not taken into account), the annual costs are an indicator for economic efficiency.

The total yearly costs of the options are approximately 7.5 billion CHF/year. It is evident that the differences between the options are relatively small (10 % at most). The characteristics of the differences between the options are similar to the ones of investment costs: the options with nuclear electricity generation are more expensive than the comparable ones with central fossil-based electricity generation. Options with HPs, with CHP plants as well as combined CHP-HP options show uniformly higher annual costs. The options with CHP and options with HP swap places relative to the ranking according to the investment costs.

The levelling of differences is caused by the fact that the high investment costs of options with nuclear energy are discounted over a longer period than investment costs of central fossil fuelled power plants (40 and 20 years, respectively). Apart from that, power plants with low investment costs are more cost-intensive regarding fuel, as Fig. 12 shows (A/C, D/E, F/G, H/I are to be compared in pairs). The yearly costs in the central electricity production sector are between 17 and 27 % of the total for the considered options.

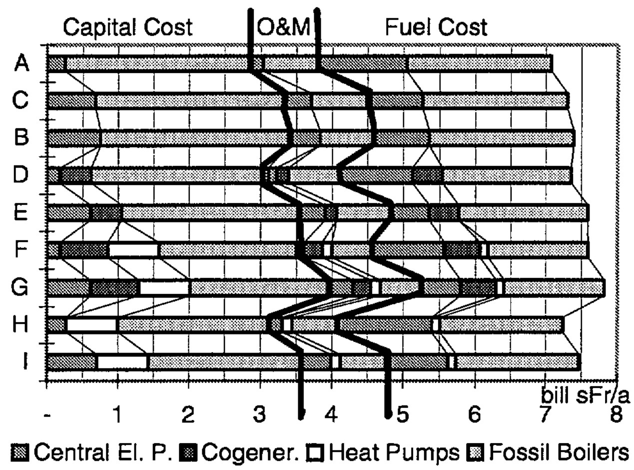

Fig. 12: Structure of annual costs of the nine Swiss supply options A to I, with contributions from various types of supply systems and specification of cost elements.

In all options capital costs make up almost half of the yearly costs (40 to 50 %). Fuel costs are also important; they account for one third up to 45 % of yearly costs. Operating and maintenance costs, making up around 15 %, are of relatively minor importance. As evident from Fig. 12, the differences between the totals of the different options are quite small as contrary trends tend to almost neutralise each other. This means that capital-intensive plants are less cost-intensive regarding fuel and vice-versa. As the differences of the specific generation costs of the considered systems are not very high, this is also reflected in the total result. In addition, the costs are levelled because the options have a common basis of plants, which makes up almost 40 % of the total. Moreover, the total cost of the options containing CHP could be possibly lowered when allocating more CHP to the industry with corresponding reductions in space heating of small buildings.

6 CONCLUSIONS

Given the Swiss commitments on the national and international level to reduce GHG emissions, the use of fossil fuels should not be subject to an expansion. The reduction of the uses of fossil fuels would be also favourable in view of the direct and indirect health and environmental impacts of such pollutants as NO_x, SO_x, CO, NMVOC and particulate matter. Some of these impacts which occur under specific conditions (tropospheric ozone during summer) are already considerable.

The differences between the annual costs of the nine options are relatively small. However, the investment costs differ substantially; this aspect is quite important with view to the degree of flexibility associated with the various options. Relatively low electricity production costs apply to the large space heating and industrial CHPs. The specific production costs are in the first place dependent on the power level and to a lesser degree on the properties of buildings. It is likely that the costs of CHPs will be further reduced - at low power levels more than at high. Also HPs exhibit a considerable potential for cost reductions once the industrial production of small but highly efficient HPs is optimised.

Fuel cells open new opportunities for energy supply. From the technical point of view the flexibility in load-following and the fact that high electric efficiency may be achieved independently of the installed power are the primary benefits of fuel cells. Given the economic break-through fuel cells could become an important factor in electricity generation. Simultaneously, for a given amount of heat more electricity would be generated due to the high electric efficiency, although also more fossil fuel is needed. So, if fuel cells are installed instead of CHPs in certain buildings, the additional electricity will replace either nuclear or fossil based power, and lead to a raise and a lowering of the fossil based emissions, respectively.

The analysis of the options for the future energy supply leads to the following conclusions:

- The various types of plants or their combinations must be always considered in the context of the national energy supply. Comparison on the individual plant level is an insufficient basis for supporting energy policy decisions.
- None of the considered options stands out as clearly superior to others in respect of every important parameter.
- A mix of technologies appears attractive. However, with respect to the decentralised options, the excessive expansion cancels some of the advantages and the drawbacks then dominate. Thus, in the case of renewable sources, CHP plants and HPs their potential benefit is limited and the costs strongly increase after the potential is realised.

Taking into account the currently expected technological advancements some recommendations can be made based on the findings in the "Dezentral" Project.

- Enhanced use of new renewable sources; significant contributions can be achieved particularly on the heating side.
- Increased use of heat pumps for the generation of space heating given suitably favourable conditions (low costs of small units, availability of distribution net for low temperature heat, and/or availability of heat source that can be easily tapped).
- Use of CHP plants in combination with modern boilers in large buildings and for the production of process heat.
- Use of heat pumps as a means of optimising the consumption of fossil fuels in CHPs and reducing the environmental burdens.

It should be noted that these statements cannot be directly extrapolated to options beyond the ones considered within the present study.

From an environmental point of view it is highly desirable to continue, to a large extent, with the present mix of sources for electricity production. The necessary seasonal additional capacities, resulting from expansion of heat pumps can be advantageously covered by modern CC plants or CHP plants; for the latter the conditions are favourable costs and high electric efficiencies. Among the fossil options, a combination of CC plants and highly efficient heat pumps is better than CHP-HP combination. However, the potential for highly efficient heat pumps is limited by the availability of suitable heat sources and favourable building conditions. Using heat pumps with lower or average future yearly coefficients of performance, the CHP-HP strategy may gain when best available technologies are employed at the higher power level (motor driven CHP) or when economic fuel cells become available.

Economic performance of the various options shows differences mainly concerning investment costs. The options with high share of nuclear have the disadvantage of high capital needs but the benefit of low sensitivity to fuel price changes. For the fossil based options the opposite picture is true.

Certain economic facts have yet to be considered, such as the effect on employment and the potential economic gains from exploiting innovative technologies.

Factors such as waste generation, risks of severe accidents and socio-economic aspects are pursued within the GaBE Project which also includes an integrated analysis based on a multi-criteria framework.

7 ACKNOWLEDGMENTS

The authors would like to acknowledge the support and input received from VSE and from representatives of the Swiss utilities acting within the Project "Dezentral". Special thanks go to Mr. K. Wiederkehr of NOK, Baden for initiating the Project and for the very useful interactions.

Finally we are grateful to our colleagues Roberto Dones and Socrates Kypreos for their contributions to the first phase of the project and valuable comments.

8 REFERENCES

[1] U. Gantner, M. Jakob, S. Hirschberg, *"Methoden und Analysen - Grundlagen sowie ökologische und ökonomische Vergleiche von zukünftigen Energieversorgungsvarianten der Schweiz"*, contribution to the VSE-Project *"Dezentral - Möglichkeiten, Grenzen und Auswirkungen einer verstärkt dezentralen Stromproduktion aus nicht erneuerbaren Energieträgern"*, to be published in 1999 as PSI-Report.

[2] R. Dones, U. Gantner, S. Hirschberg, G. Doka, I. Knöpfel, *"Environmental Inventories for Future Electricity Supply Systems for Switzerland"*, PSI-Bericht Nr. 96-07, Villigen (1996).

[3] Swiss Association of Producers and Distributors of Electricity (VSE), *"Vorschau 1995 auf die Elektrizitätsversorgung in der Schweiz bis zum Jahr 2030"*, VSE, Zürich (1995).

[4] Prognos AG, *"Energieperspektiven der Szenarien I bis III 1990 bis 2030 - Synthesebericht"*, Forschungsprogramm Energiewirtschaftliche Fragen, Bundesamt für Energiewirtschaft Bern, (1996).

[5] H. Reichenbach, J. Hubler, *"Investitionskosten Gas-WKK-Anlagen in bestehenden Gebäuden"*, by order of PSI, IWK, Zurich, (1997).

[6] M. Zogg, *"Modifizierte Anforderungsliste zur SRHP Swiss Retrofit Heat Pump für ein gemeinsames Projekt der drei erstplazierten Bewerber"*, Oberburg (1997).

[7] U. Gantner, S. Hirschberg, *"Entwicklung der Nutzung regenerativer Energiequellen in der Schweiz"*, contribution to the final report of the SATW working group *"CH 50 % - Eine Schweiz mit halbiertem Verbrauch an fossilen Energien"*, PSI, Villigen (1998).

[8] M. Jakob, *"Auswertung von Gebäudedatenbanken zwecks Bestimmung der Gebäudegrössen und exisiterenden Nahwärmeverbunde"*, PSI (1999).

[9] Wüest & Partner, *"Basisdaten und Perspektiven zur Entwicklung des Gebäudeparks 1990 - 2030"* working report, Zurich, (1994).

[10] W. Baumgartner, *"Energetische Grundlagen zur Ermitttlung der WKK-Potential in der Industrie"*, paper in attention of PSI, BASICS, Zurich, (1998).

[11] Dr. Eicher + Pauli, IWK and others; CHP studies on a company level for different Swiss Industries (1998).