10th International Symposium on District Heating and Cooling

September 3-5, 2006

Monday, 4 September 2006

Sektion 3

Technology trends – the prospects of dispersed energy: CHP and DH/DC

Multidimensional assessment of heat and power supply technologies with a special focus on CHP

P. Radgen, J. Oberschmidt,
Fraunhofer ISI, Karlsruhe/Germany

Multidimensional Assessment of Heat and Power Supply Technologies with a special Focus on CHP

Dr. Radgen Peter[*], Oberschmidt Julia
Fraunhofer ISI, Breslauer Straße 48, Germany, 76139 Karlsruhe, Tel.: +49 (0)721 6809-295, peter.radgen@isi.fraunhofer.de, www.isi.fraunhofer.de

Abstract

Heat and Power supply are an important element for today's societies. Energy supply plays a major role in the discussion for a competitive and sustainable economy. The liberalisation of electricity markets together with the fact that a large number of new power stations have to be build during the next 25 to 35 years makes it very important to select and identify the best energy technologies available on the market today and those who might play an important role in the near future.

However, the identification of "the best" technology is not as easy as it seems, as different dimensions have to be taken into consideration. In this context multi-criteria assessment is a methodology that can be applied. The main three dimensions which have to be considered are economy, ecology and technology. When trying to evaluate different technologies, all three dimensions have to be taken into account. The dimensions are further divided by different target criteria. Achievements of technologies in the different dimensions are measured in different units and a consensus needs to be found, how to standardize and weight the different dimensions. The paper presents a methodology for multi-criteria assessment of heat and power supply technologies as well as its application. The methodology is aiming at preparing a sound foundation for decision making in the energy sector.

1 Introduction

Heat and Power supply are an important element for today's societies. Energy supply plays a major role in the discussion for a competitive and sustainable economy. The liberalization of electricity markets together with the fact that a large number of new power stations have to be build during the next 25 to 35 years makes it very important to select and identify the best energy technologies available on the market today and those who might play an important role in the near future [1].

However, the identification of "the best" technology is not as straight forward as it seems, as different dimensions have to be taken into consideration [2]. The main three dimensions which have to be considered are economy, ecology and technology. The problem in the decision making process is based on the fact, that no "golden bullet" technology exists which scores best in all criteria. Moreover, there are other factors influencing the decision making process. One factor which has become a focal point in the last years is the security of supply and the dependency on fuel imports [1]. When trying to evaluate different technologies, all dimensions have to be taken into account. The dimensions are further divided into different target criteria. Furthermore, the achievements of technologies in the different dimensions are measured in different units and a consensus needs to be found, how to standardize and weight the different dimensions [2].

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[*] Corresponding Author

The latter will be addressed based on interviews with decision makers in companies producing electricity and heat, and companies developing and producing the required technology. Those interviews will be used to analyze the perspective of leading executives on the impact of technological, economic and ecological aspects. Additionally, the interviews conducted will serve to identify further social determinants that could possibly influence the decision making behavior and process.

The paper will highlight the methodology used within the study "Multidimensional Assessment of Heat and Power Technologies" as well as the preliminary results of this study, which is conducted in cooperation with different research institutions under the direction of the German District Heating Association. It is aimed at preparing a sound foundation for the decision making process to start the transition to a better supply of heat and power in the future.

2 Methodology

The multidimensional assessment of technologies can be represented in form of a matrix in which the assessment matrix is composed of rows with the technology alternatives *A* and columns with the target criteria *C* [3]. The matrix is filled with the valuation *a* of the technology alternatives with regard to the target criteria (figure 1). In the optimal case, one technology will perform best for all target criteria. In this case the problem can be simplified as the solution becomes independent from the valuation of the different criteria. However, in the case of heat and power supply technologies this is not the case.

$$
\begin{array}{ccc}
 & & \text{Target Criteria} \\
\begin{array}{c}\text{Technology}\\ \text{Alternatives}\end{array} & E = &
\begin{array}{c|ccccc}
 & C_1 & C_2 & C_3 & \cdots & C_n \\ \hline
A_1 & a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\
A_2 & a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\
A_3 & a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
A_m & a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mn}
\end{array}
\end{array}
$$

Figure 1: Assessment matrix [3]

The main dimensions to be considered within the underlying study are technical, economic and ecological. All dimensions are broken down to different target criteria. The selected target criteria build on the results of a previous study [3] focusing on the multi-criteria analysis of CHP systems. However, it is important not only to compare and analyze competing CHP technologies but also to evaluate them in the framework of other technologies which can be used either for heat and/or power generation. Table 1 lists the most important criteria used in the analysis. There are a large number of other target criteria that could be considered but to start with we limited the analysis to the most important ones. An extension to include other criteria is easily feasible, enabling a later addition if criteria are identified that prove to be of importance for the evaluation.

Table 1: Target criteria for the multidimensional assessment of heat and power supply technologies

Technical criteria	Economical Criteria	Ecological criteria
Energetic Efficiency	Investment Cost (CAPEX)	Global Warming Potential
Exergetic Efficiency	Operating Cost (OPEX)	Acidification
Part Load Efficiencies		Eutrophication
Flexibility of Operation		Ozone Depletion
Availability		Toxicity
		Radiation
		Land use

For the economic criteria it has to be kept in mind that the results obtained depend on the assumed boundary conditions such as fuel prices. In addition to the dimensions described in table 1 socio-economic issues need to be addressed. Using the methodologies of interpretative social research we try to find out, to which amount the perception of technologies as well as the evaluation of constellations of action and decision making are shaped by social factors. This includes factors such as specific professional norms and knowledge practices, organizational routines, embedding networks and organizational patterns.

Of special interest in this context is the way, in which problems of social acceptability of technological developments or of business strategies (on the level of social discourse as well as on the levels of professional communities and of academic peer groups) are perceived by the relevant stakeholders in this field. However this work is still ongoing and the results will be included at a later stage in the analysis.

Once the assessment matrix has been filled with the values for the different technologies and criteria, there are different methods for further processing and analyzing the data. Value benefit analysis is the most widely used method due to its applicability and accessibility [4, 5]. For those reasons value benefit analysis is also used in our work. Thereby, an overall value is calculated by summing up the standardized and weighted values of the single criteria [2, 3]:

$$P(A_i) = \max_i \sum_{j=1}^{n} f_i(a_{ij}) w_j \quad \text{with} \quad w_j \geq 0 \text{ and } \sum_{j=1}^{n} w_j = 1$$

$P(A_i)$	Overall value for technology alternative i
i	Index for alternative (i = 1, 2, …,m)
j	Index for target criteria (j = 1, 2, …, n)
$f_i(a_{ij})$	standardized value of alternative i for target criterion j
w_j	weight of target criterion j

Standardization and weighting are crucial factors as they have a high impact on the final results of the multi-criteria analysis [2]. Derived conclusions could be very different due to varying standardization and weighting. Therefore consensus needs to be found on the appropriate standardization methods and weighting criteria. Sensitivity analysis can help to identify useful and sensible methods as well as interviews with stakeholders as previously mentioned.

The following chapter will illustrate the methodology described above. Different technologies for supply of heat and/or power will be assessed and compared, demonstrating the methodology in detail. This paper will focus on a combined heat and power generation plant (steam extraction-condensation process, lignite, 90 MW_{el}), a nuclear power plant (pressurized water reactor, uranium, 1,000 MW_{el}), a wind turbine (1 MW_{el}, onshore) and a condensing boiler (natural gas, 50 kW_{th}).

3 Integrated Technology Assessment

The multi-criteria analysis is supposed to assess and compare different technologies for generation of heat and/or power. It should be as general as possible, so that it can be applied to the whole range of available technologies. The following examples will illustrate the proposed methodology and demonstrate the difficulties in comparing the different technologies, especially considering varying outputs with different values for the products such as heat and power at the same time.

Furthermore availability of reliable technology data presents a problem. Especially as cost data are not independent of plant location it is very difficult to select representative average data. Apart from obtaining data for past years, it is even more complicated to obtain good data for the future. Identified gaps in data availability had been filled with best guess. In addition learning curves will be applied to evaluate possible development in the future. However the selected values can easily be updated and the evaluation restarted for the datasets in question. Thus, the results shown for representative technologies shall primarily illustrate the methodology.

Due to complexity of the assessment matrix and diversity of data not all the technologies, which are dealt with in the underlying study, or all target criteria are presented here. The dimensions considered in this preliminary analysis are technical, economical and ecological. Social criteria are not included for the analysis as only few interviews have been conducted so far and no reliable conclusions can be drawn yet.

3.1 Combined Heat and Power Generation

For the example of the lignite fired steam extraction-condensing power plant the analysis is presented step by step in detail. Then the assessment of other technologies will be summarized and results of the different technologies will be compared with each other.

3.1.1 Technical Assessment

The main technological characteristics of the CHP plant under consideration are summarized in table 2.

Table 2: Main characteristics of CHP technology under consideration [3]

Technology	Steam extraction-condensing turbine
electrical power	90 MW_{el}
thermal power	173 MW_{th}
electrical efficiency	29.9 %
thermal efficiency	57.6 %
technical life time	35

Apart from the energetic efficiency exergetic efficiency is a main technical characteristic, accounting for the varying quality of the different forms of energy [6]. Electricity for example can be transformed into whatever other kind of energy, therefore its exergy equals its energy content. In contrast to this the exergy of heat is much lower as the energy content. While the overall energetic efficiency of the technology is given by summing up electrical and thermal efficiency, the overall exergetic efficiency can be calculated from:

$$\eta_{en} = \frac{W + Q}{\dot{m}_{Fuel} \cdot H_u}$$

$$\eta_{ex} = \frac{E_W + E_Q}{E_{Fuel}} = \frac{W + \eta_C Q}{\dot{m}_{Fuel} \cdot H_u} = \eta_{el} + \eta_C \eta_{th} \qquad \text{with} \qquad \eta_C = \frac{T_Q - T_U}{T_Q}$$

η_{en}	energetic efficiency
η_{ex}	exergetic efficiency
W	electric power
Q	thermal power
$\dot{m}_{Fuel}$	fuel input flow
H_u	heating value of fuel
E_W	exergy of produced electricity (equals energy)
E_Q	exergy of produced heat (lower than its energy)
E_{Fuel}	fuel exergy (equals its energy)
η_C	Carnot efficiency
T_Q	temperature of delivered heat
T_U	temperature of the environment

Carnot efficiency η_C can be calculated from the temperature difference between delivered heat T_Q and the temperature of the environment T_U. Assuming that $T_Q = 403K$ and $T_U = 288K$, the Carnot factor for the heat becomes:

$$\eta_C = \frac{403K - 288K}{403K} \approx 0.285.$$

The exergetic efficiency then becomes:

$$\eta_{ex} = \eta_{el} + \eta_C \eta_{th} = 0.299 + 0.285 \cdot 0.576 \approx 0.463$$

This means that even if 87.5 % of the energy content of the fuel is still available in the products electricity and heat, only 46.3 % of the exergy is incorporated in the products.

At this stage of work only these two criteria are used to describe the technical dimension. To summarize the technical evaluation, characterized by energetic and exergetic efficiency, values for these criteria first have to be standardized and then weighted. For standardization a linear function was chosen (see figure 2), with 1 being the best value (energetic efficiency and exergetic efficiency = 100%) and 0 being the worst (exergetic and energetic efficiency = 0%). Thus, the standardized value for energetic efficiency of the technology under consideration equals 0.875, the one for the exergetic efficiency 0.463.

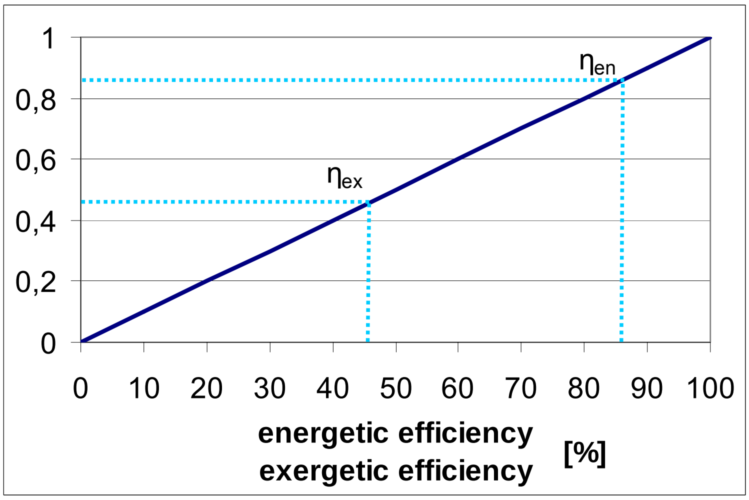


Figure 2: **Standardization of technical criteria**

After standardization the two criteria are weighted. Following previous work [3] weighting is done using the trade-off-method. Hereby, weights are derived from two alternatives with different efficiency and exergy, which are nevertheless considered to show the same overall technical performance. According to [3] these are the technology alternatives with an energetic/exergetic efficiency of 95%/53% and 80%/61%. Weights can then be calculated from:

$$w_1 \cdot 0.95 + w_2 \cdot 0.53 = w_1 \cdot 0.8 + w_2 \cdot 0.61$$
$$\Rightarrow w_1 \cdot 0.15 = w_2 \cdot 0.08 \Rightarrow w_1 : w_2 = 0.53 : 1$$
$$\Rightarrow w_1 = 0.35 \ , \ w_2 = 0.65$$

w_1	weight of target criteria 1 (energetic efficiency)
w_2	weight of target criteria 2 (exergetic efficiency)

For the CHP technology under consideration this leads to an overall technical valuation of:

$$0.35 \cdot \eta_{el+th(s\tan dardized)} + 0.65 \cdot \eta_{ex(s\tan dardized)} = 0.35 \cdot 0.875 + 0.65 \cdot 0.463 \approx 0.61 .$$

3.1.2 Economical Assessment

Underlying economical criteria of the CHP technology under consideration are shown in table 3. Only one overall criterion is used to assess this dimension, which is the specific cost in ct/kWh_{el+th}. This factor summarizes annualized capital cost as well as fixed and variable operating cost.

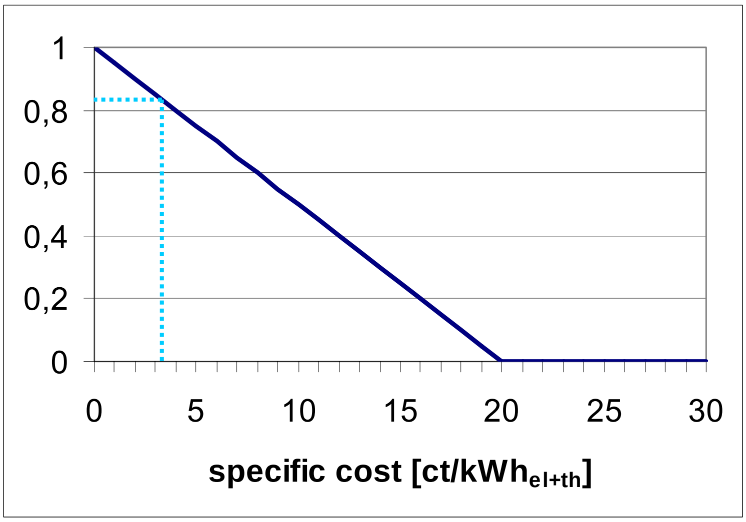
Table 3: Economical characteristics of CHP technology under consideration [3, own calculations]

Investment	2.367.50 11.74	€/kW_{el} €/kW_{th}
Fixed O&M	130.10 14.46	€/(kW_{el} a) €/(kW_{th} a)
Variable O&M	1.36 0.71	ct/kWh_{el} ct/kWh_{th}
Overall economic assessment	3.12	ct/kWh_{el+th}

For the overall economic assessment shown in table 3 data was calculated based on 6,000 full load hours per year and an interest rate of 8%, as well as on the technical data shown in table 2. Investment was annualized based on a technical life time of 35 years. The share of heat generation was estimated based on the assumption that heat generation makes up 10% of the total investment and O&M costs. Fixed O&M includes personal costs, taxes, insurance, administration and other costs. Variable cost includes mainly fuel cost [3].

For standardization of the specific cost again a linear function is used, with 0 ct/kWh_{el+th} valued best (= 1) and 20 ct/kWh_{el+th} and above worst (= 0) (figure 3). For the CHP technology analyzed together with the above mentioned assumptions this results in a standardized value of 0.84.

Figure 3: Standardization of economic criterion



3.1.3 Ecological Assessment

Table 4 shows ecological data for the lignite fired CHP plant.

Table 4: **Emission data for the CHP technology under consideration [3]**

CO_2-Emissions	1250.3 g/kWh_{el}
CH_4-Emissions	17.9 mg/kWh_{el}
N_2O-Emissions	33.7 mg/kWh_{el}
SO_2-Emissions	710.7 mg/kWh_{el}
NO_x-Emissions	863.8 mg/kWh_{el}

Different ecological impact categories can be defined [7]. The impact categories used here for the ecological assessment are global warming potential, acidification and eutrophication. The global warming potential is usually given in CO_2-equivalents describing the effect certain emissions have on global warming compared to CO_2. Acidification is measured in the same way using SO_2-Equivalents. Table 5 shows CO_2-Equivalents and SO_2-Equivalents for different substances. To account for eutrophication only NO_x-Emissions are taken into account.

Table 5: **Weighting factors for CO_2- and SO_2-Equivalents of different components [8]**

	CO_2-Equivalents
CO_2	1
CH_4	23
N_2O	296

	SO_2-Equivalents
SO_2	1
NO_x	0.7
NH_3	1.88

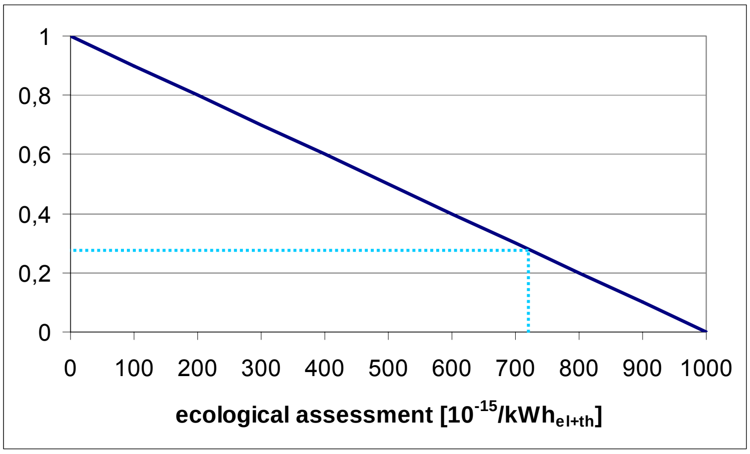
By summing up CO_2- and SO_2-equivalents ecological impact categories can be calculated. For an overall ecological assessment the different impact categories should be made comparable. Thus, the CO_2-equivalents, SO_2-equivalents and NO_x-emissions per kWh_{el+th} are all related to the overall CO_2-equivalents, SO_2-equivalents or NO_x-emissions respectively in one certain region. The region chosen here is Germany. Thus, the related value shows how high the contribution of one technology is to the overall emissions of the same kind in Germany. Table summarizes these calculations.

Table 6: **Ecological impact categories [3, 9, own calculations]**

Impact category	included Emissions	Overall Emissions for Germany	Emissions of CHP technology under consideration	
			specific	related to Germany
Global Warming Potential	CO_2, CH_4, N_2O	$974 \cdot 10^6$ t CO_2-Equivalents	$4.31 \cdot 10^{-4}$ t CO_2-Equivalents/kWh_{el+th}	$442.67\ 10^{-15}$ 1/kWh_{el+th}
Acidification	SO_2, NO_x, NH_3	$2,8 \cdot 10^6$ t SO_2-Equivalents	$4.49\ 10^{-7}$ SO_2-Equivalents/kWh_{el+th}	$156.78 \cdot 10^{-15}$ 1/kWh_{el+th}
Eutrophication	NO_x	$1,6 \cdot 10^6$ t NO_x-Emissions	$2.95\ 10^{-7}$ NO_x-Emissions/kWh_{el+th}	$186.35 \cdot 10^{-15}$ 1/kWh_{el+th}
				$717.17 \cdot 10^{-15}$ 1/kWh_{el+th}

Analyzing ecological threat of the different impact categories as well as their "distance-to-target", defining the difference between the actual and desired situation concerning this category, weighting can be derived. According to [3] global warming potential, acidifation and eutrophication are then to be weighted 1:0.8:0.8. This gives an overall ecological value of $717.17 \cdot 10^{-15}$ 1/kWh_{el+th}. Finally, this overall value is standardized for comparison. Again a linear function as described in figure 4 is used, leading to an overall standardized value 0.28.

Figure 4: **Standardization of ecological assessment**



3.2 Comparison with other technologies

In the following some technologies for generation of electricity or heat – as opposed to combined heat and power generation – are assessed. The comparison includes a wide diversity of technologies, illustrating the large differences that exist between technologies available, including centralized as well as decentralized options for heat and/or power supply, different fuels, different sizes etc. The technologies under consideration are one large nuclear power generation plant, one wind turbine and a small condensing boiler for generation of heat for domestic use. The main characteristics for those technologies as well as for the previously described CHP technology are shown in table 7.

Table 7: Data for all technologies under consideration (full load 6,000 h/a, interest rate 8%) [3, 10, 11, 12, 13, own calculations]

		CHP	Nuclear	Wind	Boiler
Technical					
electric power	kW$_{el}$	90,000	1,000,000	1,000	-
thermal power	kW$_{th}$	173,077	-	-	50
electric efficiency	%	29.9	33	35	-
thermal efficiency	%	57.6	-	-	107 (a)
exergetic efficiency	%	46.4	33	35	26.6
overall (standardized)	-	0.61	0.33	0.35	0.55
Economical					
Investment	€/kW$_{el}$	2,367.5	1,767	1,080	-
	€/kW$_{th}$	11.74	-	-	500
Fixed O&M	€/(kW$_{el}$ a)	130.1	38.55	32.4	-
	€/(kW$_{th}$ a)	14.46	-	-	0
Variable O&M	ct/kWh$_{el}$	1.36	0.07	0	-
	ct/kWh$_{th}$	0.71	-	-	5.61
overall	ct/kWh$_{el+th}$	3.24	3.18	2.37 (b)	6.58
overall (standardized)	-	0.84	0.84	0.88	0.67
Ecological					
Global Warming Potential	10^{-15}/kWh$_{el+th}$	442.67	5.82	143.7	923.77
Acidification	10^{-15}/kWh$_{el+th}$	156.78	10.39	4.07	182.07
Eutrophication	10^{-15}/kWh$_{el+th}$	186.35	8.84	5.05	45.45
overall	10^{-15}/kWh$_{el+th}$	717.17	8.16	58.07	374.88
overall (standardized)	-	0.28	0.99	0.94	0.63

(a) energetic efficiencies are based on the lower heating value

(b) theoretical value as 6,000 h/a can not be achieved in practice

Table 7 also shows the standardized values for each dimension (technical, economical, ecological), which have been derived using the methodology described before. First of all it has to be pointed out that data in table 7 has been calculated based on 6,000 full load hours per year for all the technologies under consideration (base case). Obviously this is an unrealistic assumption especially for wind generation, which is not available for so many hours a year. Therefore alternative data has been calculated based on 1,700 hours a year. The overall results for both alternatives are shown in figure 5.

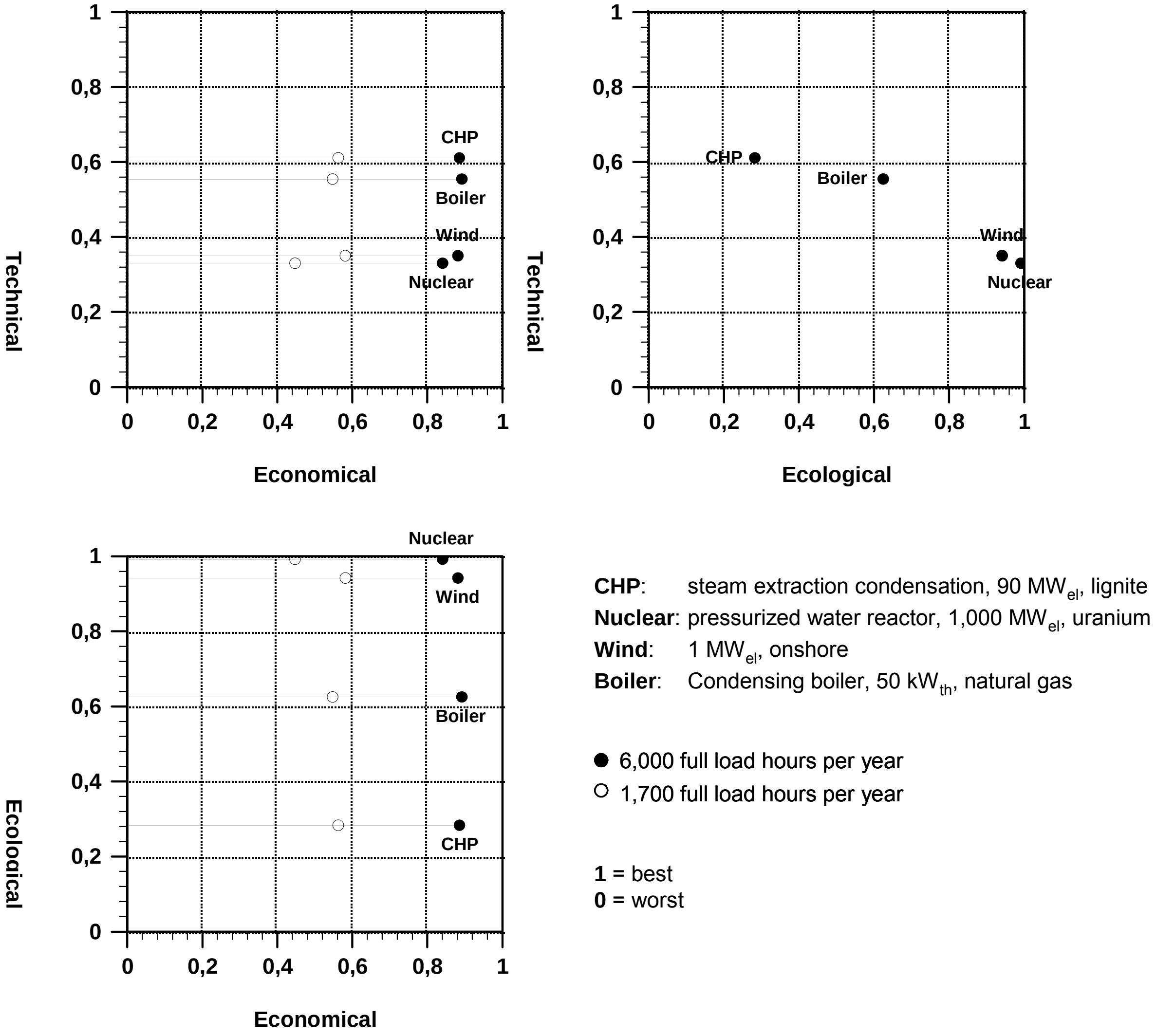


Figure 5: **Multidimensional assessment of different heat and power supply technologies**

3.2.1 Technical results

Technically speaking the CHP technology under consideration clearly performs best (see figure 5). This is due to its high overall efficiency. Also exergetic efficiency is very good for the CHP technology. Contrarily, nuclear power generation performs worst in technical terms due to its efficiency. Wind generation performs slightly better but still has a low efficiency. Technical performance of the condensing boiler lies between the other technologies. It is mainly influenced by its very high efficiency, which exceeds 100%. However, exergetic efficiency of the boiler is very poor compared to the other three technologies.

For future assessments the weighting of energetic and exergetic efficiency will be varied to evaluate its influence on the overall technical assessment. Also, other criteria, such as availability and part time efficiencies will be taken into account (see table 1). This will allow for a more realistic representation of technical performance.

3.2.2 Economical results

Figure 5 shows that overall economic performance of the technologies under consideration is in the same range for the base case with 6,000 full load hours per year. However, for wind electricity generation it is not possible to work at 6,000 full load hours due to the availability of wind. Thus, the alternative with 1,700 full load hours per year shows deterioration in economic performance for wind generation but an even stronger deterioration for the other technologies. This is due to their higher investment cost. Comparing the more realistic possibility, as to say 6,000 full load hours per year for other technologies, 1,700 full load hours per year for wind, it shows of that wind generation performs significantly worse than CHP, nuclear power and the boiler. Technologies which can operate year round and others, especially renewables, that can't should therefore be compared carefully.

This illustrates the problems comparing such a diversity of technologies. First of all comparison is based on standardized values relating to electricity and heat generation even though some of the technologies under consideration are not used to produce both. Furthermore different framework conditions have to be taken into account, especially considering renewable energies. For example, for photovoltaic technologies the same problem with availability such as for wind arises in assessment. Morover, for further assessment also the standardization function should be varied to analyze its influence on the performance of the economical dimension.

3.2.3 Ecological results

Looking at figure 5 it can be seen that the technology to perform best in ecological terms is nuclear power generation. However, this result must be interpreted very carefully as issues such as nuclear waste and toxicity are not included here. Wind performs nearly as good as nuclear power. In this context it should be mentioned that emission data available for wind do not only include those emissions for operation but also for decommissioning. This may deteriorate the results.

The CHP technology performs worst in overall ecological evaluation, whereas the condensing boiler performs better. The performance of those two technologies can mostly be assigned to fuel usage, where for example lignite (used in the CHP technology under consideration) has a much higher CO_2-emission factor as natural gas. However it should be kept in mind that CHP technologies perform much better compared to traditional fossil power generation.

For future assessment other ecological impact categories should be taken into account, to give a better picture of overall ecological performance. In particular issues such as nuclear waste, radiation and toxicity should be accounted for. Also factors such as cumulated energy usage should be included into the analysis.

4 Summary and Conclusions

A methodology has been introduced and applied to assess and compare different heat and/or power supply technologies. This methodology is a useful tool to get an overview of the overall performance of different technologies for heat and power supply and to compare them on a transparent basis. Nevertheless, the results presented here also demonstrate the difficulties in evaluation and comparison of different technologies with different outputs in multidimensional assessment. Better and new methods have to be found and tested for weighting and standardization. Future work will include an extension of the analysis to other technologies and criteria as well as sensitivity analysis concerning the underlying data and functions used for weighting and standardization. Moreover social issues will be included into future evaluations.

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Acknowledgments

This paper is based on preliminary results of the study "Multidimensional Assessment of Heat and Power Technologies". We thank the project partners EWI, Köln, Technical University of Dresden and the Institute for Social Research, Frankfurt, for their contributions. Financial support by the German District Heating Association (AGFW) and the Federal Ministry of Economics (BMWi) is gratefully acknowledged.