Alternative Methods of Simultaneous Production of Electrical and Thermal Energy

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Abstract: - This report describes different possibilities of simultaneous production of electrical and thermal energy (CHP - Combined Heat and Power) from gas. It mostly emphasizes advantages of using microturbines as devices producing energy. The document mentions already released products, shortly describes existing solutions and some new ideas, which are worth being considered. Some competitive solutions not using microturbines are also taken into consideration and briefly described. In the penultimate paragraph the maintenance costs of the two most promising solutions are calculated. Although the expenses reduction seems to be low and varies from 22 to 33%, there are other advantages of using the systems – they are environmental friendly and almost noiseless.

Key-Words: - CHP, Microturbine, Power Generation, Energy, Sterling Engine

1 Introduction

During the last few years environmental care has become one of the most important topics of our life. We all sort waste, bottles, papers and we choose less air-polluting cars, but not everybody knows how much electrical energy we use and simultaneously how much we pollute the environment. We have to realize that every single German citizen consumes about 6,000 kWh per year. In Germany electricity costs five times as much as natural gas. This is the reason to think about using gas as a main source of electrical and heating energy.

Current production of electrical energy is highly centralized. It means that there are only a few power plants in Germany producing energy. The centralization requires sending the energy for thousands of kilometers. It means that from 3 to 7% of the energy is lost. What's more, the power plant has to be run all over the year, producing at least 50 to 70% of nominal exhaust heat [1]. One solution, which can make the distribution more economical and clean, is to move the source of electrical energy to the location of the consumer and use biogas or natural gas as a primary energy. It has been proved that use of biogas is as environment friendly as fuel cells. Also a lack of unpleasant smell of waste exhausts from power plant is worth being mentioned. Use of our own small power plant can make us independent from disasters (15.06.2003 USA/Canada, 23.09.2003 Denmark/ Sweden, 28.09.2003 Italy) and let us administrate our small power plant by ourselves (for example it's possible to switch it off during our absence). Besides the production of electricity the same power plant can be used to produce heat. The combination of electricity and heat production is called CHP (Combined Heat and Power).

2 Current achievements

In order to reduce the cost it would be reasonable to use one CHP unit by more families, but knowing the flesh and blood of a human being, it is sometimes very easy to find the neighbours irritating. That's why it should be more convenient to have our own, small power plant (microturbine) and to be more independent.

There are a few companies producing microtubines. Most of the products they offer, can produce from 30 to 50 kW of power (for example Capstone C30 series), which is enough for three or four residences but is too much for one family.

The production of small CHP systems and therefore smaller turbines requires a high-tech approach. The main problem of building the small turbine is a necessity of use of high speed drives. It requires high quality components, more expensive bearing (gas-bearing) which simultaneously increases the price of the whole system [2].

Although there are just a few companies producing microturbines, there are many different approaches and technologies of producing electrical energy. Each of the ideas is based on the same principle presented below:

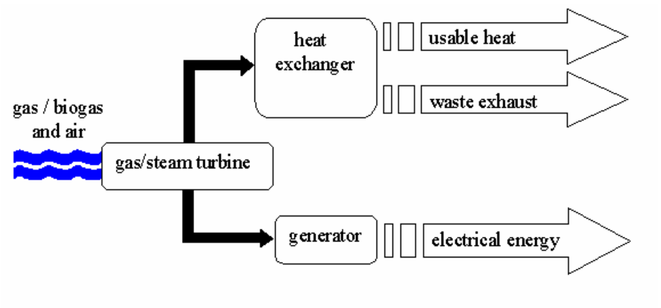

Fig. 1

All the ideas described below base on a CHP plant, which is an installation with simultaneous generation of usable heat and power.

2.1 Gas turbine

The most typical way of producing electrical energy is a system, which delivers gas (or biogas) to the turbine.
Due to the fact that the biogas consists of many derivatives of silicon, most of the system has to be made of stainless steel [3].
The gas turbine has the following working principle: air is compressed by a compressor and heated by combustion energy of gas (biogas) at first. The temperature and pressure of the working gas becomes very high. The energy of working gas is converted into the rotating energy of the blades. The blades are connected with a generator via a shaft. The generator changes mechanical energy into electrical energy. The easy construction implies a low efficiency varying from 25 to 35% [4], which is the main disadvantage of the whole system.
In case of using small turbines the total electrical efficiency may decrease to 17-30% [5].

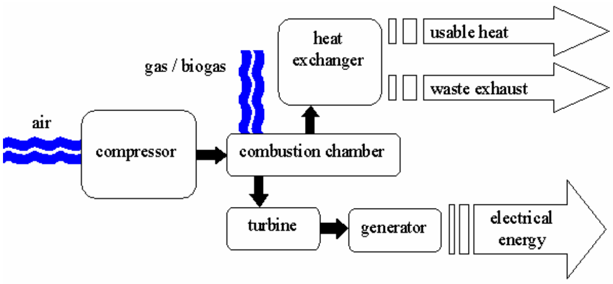

Fig. 2

The waste exhaust from the turbine can reach a temperature between 270 to 680^{O}C [6], so the warmth can be used to warm up water or for other heating purposes. The efficiency then increases up to 92% [7].

2.2 Steam turbine

The working principle of the system:

- steam is produced in a boiler
- the steam propels a turbine
- a generator situated on the turbine shaft produces the energy
- a waste heat boiler generates steam by capturing heat form the turbine exhaust
- the condensated steam can be redirected to the boiler

The electrical efficiency of a steam microturbine varies from 10 to 20%. When using heat exchanger the total efficiency may increase up to 85% [7].

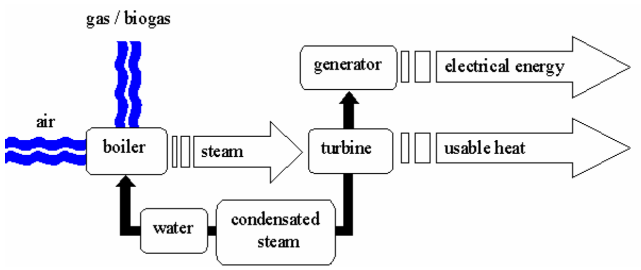

Fig.3

2.3 Steam injected gas turbine

As it was mentioned in the paragraph 2.1, the efficiency of a simple gas turbine is rather small. It can be increased by using STIG (Steam Injected Gas Turbine).
The working principle of STIG is similar to the working principle of the previously mentioned typical gas turbine. The only difference is that the waste exhausts are used to produce steam in an additional boiler (Heat Recovery Steam Generators - HRSG). Then, part of the steam is used to propel the turbine and some part is directed to the combustion chamber. Instead of using a waste heat boiler at the end of the cycle the efficiency of the cycle can be increased by installing a recuperator. The recuperator captures waste heat in the turbine exhaust stream to preheat the compressor discharge air before it's directed to combustion chamber.
The addition of compressor intercooling to the STIG cycle can raise both thermal efficiency and shaft power output. A system containing such intercooler is then called ISTIG (Intercooled STIG) [8].
The ISTIG increases the electrical power to 40% and the overall power cycle efficiency up to above 85%. [7]

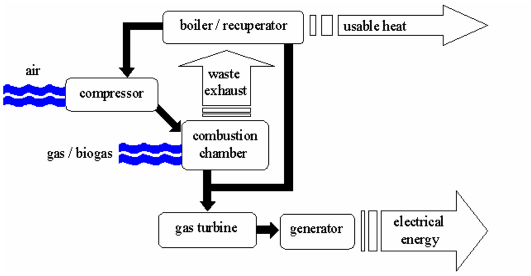

Fig.4

2.4 Gas turbine + steam turbine

This idea is based on two turbines connected into one system. The working principle of a gas turbine has been described above. In this solution, the waste exhaust from the gas turbine can be used to warm up water and consequently produce steam. The steam can be used to propel the blades of the steam turbine. The efficiency of the system increases to 55%. Furthermore, the hot steam coming from the steam turbine can be used in a central heating system for the house and it increases the efficiency up to 85%. [7].

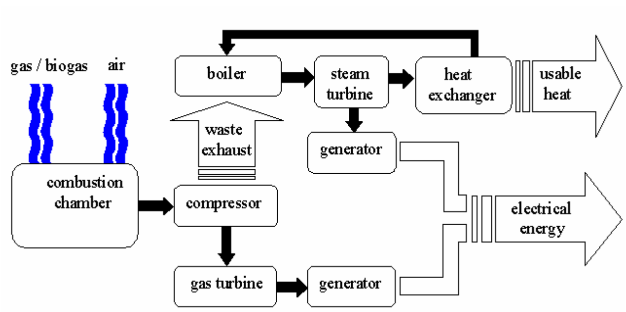

Fig.5

2.5 Fuel cell + micro gas turbine

The hybrid system consists of a combination of two advanced technologies – solid oxide fuel cell and a microturbine powered by gas. As it is a new technology it can't be said too much about the whole system efficiency, although the operators of the system believe that the technology could reach 70% of electrical efficiency.

There are two big disadvantages of using the cells. Firstly, the production cost of the fuel cell is incomparably higher than the cost of producing a combustion engine or a gas turbine. Another problem is a big size and a huge weight of the fuel cells. [14].

The working principle of the system bases on a solid oxide fuel cell, powered by natural gas, with hot waste exhaust gases used to drive a microturbine. The company producing the system claims that "producing an efficiency of around 53%, believed to be a world record for the operation of a fuel cell using natural gas". After applying some improvements, the efficiency of the technology could increase to 60% for smaller systems and 70% or more for large systems. [9]

3 Other ideas

3.1 Sterling engine

Almost all of the systems available on the market can recover waste exhaust heat. As it was described in previous paragraphs, it can be done by using recuperators, boilers or heat exchangers. All the methods have been used for many years and their efficiency is already known and proved. A good alternative to the heat recovery systems can be a Stirling engine.

The Stirling engine consists of a cylinder and a piston, the same as a combustion engine. The cylinder is filled up with air or hydrogen. When the cylinder is heated from outside, the temperature rises, the gas expands and drives the piston. Then, as a gas cooling system is incorporated, the engine accomplishes continuous reciprocating motion.

The new idea is to use a combination of a microturbine and the Sterling engine. Because the temperature of the microturbine waste exhaust is about 500^{O}C, it can be used as a source of energy for the Sterling engine.

The great advantage of such system is that its total efficiency would be significantly higher then the efficiency of a single gas turbine. The electrical efficiency of Sterling engine can reach 31% while the total efficiency of the engine is about 80% [10]. Another important advantage is, that the Stirling engine would produce almost no pollution. With a regenerator, the efficiency of the Stirling cycle approaches ideal efficiency and leads to better fuel economy than current IC engines. In addition, the engine is simple and quiet [7].

3.2 Geothermal energy

Most of existing solutions basing on the geothermal energy use a heat pump. The main advantage of the system is that it doesn't require deep drilling. The working principle of the pump bases on the same working principle as a refrigerator [11]. Because the pump is equipped with a compressor it requires electrical energy. In order to produce 100kW of heat, only 20-40kW of electrical power are required. The temperature, the pump requires to produce enough heat should be positive (typically 0-10^{O}C) and stable during the heating season [12].

The main advantage of using geothermal energy is its cleanness. The heat pump may produce only a clean steam. Another advantage is low costs per 1kWh.
The main disadvantage is that it uses electricity and as a result it depends on electricity prices and uses a lot of available maximum power.
Considering the need of generating electricity from geothermal energy, it would be better to drill deeper and get water of higher temperature. The high temperature could be used for producing steam for a steam microturbine and consequently electricity. Unfortunately, the prices of drilling are very high. In order to achieve a temperature of $150^{O}C$, a drilling of about 1,000 meters depth is required. The drilling costs estimated by companies vary from 1 to 2,5 million Euros and that is obviously too expensive for a one family house [13].

3.3 BHPP (Block Heat and Power Plant)

BHPP is a unit, equipped with an internal combustion engine (I.C. engine), for the decentralized supply of one or more plants with heat and electricity [15].
The main part of the system is a diesel or a gas engine propelling a generator. The exhaust heat from the engine can be used for producing steam in a boiler to propel a steam turbine. The great advantage of the BHPP is its overall efficiency reaching 85%. Another important virtue is a high popularity of this kind of systems, which should lead to reduction of production costs. Although the prices have decreased significantly during last few years, such installation is still expensive. One of the smallest units available on the market (EAW [16]) producing 5,5kW of electrical power and 12,5kW of thermal power costs about €30,000. The manufacturer claims its system to have the efficiency of about 90%. Another example is a product of Senertec [17] HKA-G S1 reaching efficiency of 87-88%.

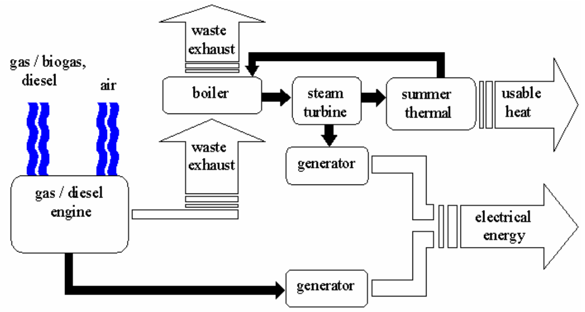

Fig. 6

4 Costs and efficiency comparison

Efficiency is the ratio of useful work to energy expended [18]. The efficiencies mentioned in previous paragraphs were based on the experience of companies producing CHP systems or turbine developers. The efficiency, which is used in our calculations, is always the highest currently achieved. The efficiency of a microturbine is usually about 20-25% lower than the efficiency of a similar size turbine. This has been also taken into consideration.
A typical one family house (4 people) consumes about 7,750kWh of electrical energy. 3,450kWh of the energy is used for cooking and heating water in a boiler.

	Power consumption [KWh]	TWO [19] [euro/year]	Energie [20] [euro/year]
Heating of water / electrical. oven / light, TV, fridge, etc.	7,750	1,233	1,137.59
Electrical oven / light, TV, fridge, etc.	3,750	597	603.32
Heating of water / electric oven	3,450	548.9	562.85
Light, TV, fridge, etc.	3,300	525	542.61

Table 1

Most of German households use an electrical oven instead of one running on gas. Moreover, most of them use gas for heating water. It means that a host of an average house pays about €600 on electricity. Considering all electrical devices of an average German house, it is reasonable to produce about 5-6 kW of maximum electrical power.

Total consumption of natural gas for a family house amounts to $1{,}410m^3$. Assuming that $1m^3$ of a natural gas gives about 10kWh of energy it results in 14,100kWh used. This gives €646 per year and results in total costs of:

€600 + €646 = €1,246,

In order to heat a house, energy of 60W per $1m^2$ is required. For an average house of $120m^2$ we need then 7.2kW. Another 2kW is required for a water boiler. As a result, the thermal power of our system should be about 10-12kW.
It is easy to notice that according to the following equation:

$$\frac{P_{\max thermal}}{P_{\max electrical}} = \frac{10kW}{5kW} = 2,$$

and in order to meet our requirements the maximum thermal power should be twice as much as the maximum electrical power.
We have to notice that about 83% of the thermal energy is used during 6 winter months (Nov, Dec, Jan, Feb, Mar, Apr) and the difference between the most energy consuming January and least consuming August is about 14 times. The 83% results in total gas consumption of 11,700kWh. The reason of the big differences is that during the summer time the gas is used only for heating water and not for heating the house. Also the electrical energy consumption is over 63% higher during winter (2,363kWh).

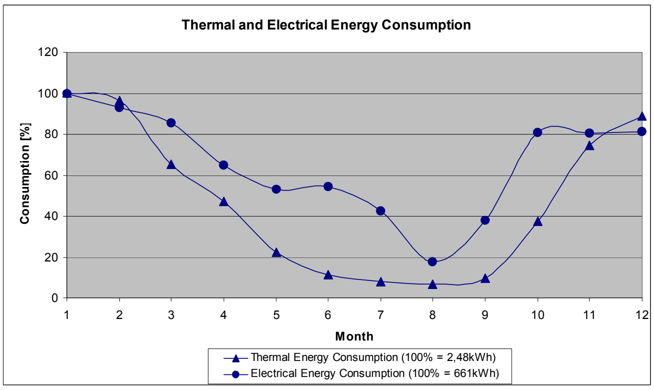

Fig. 7

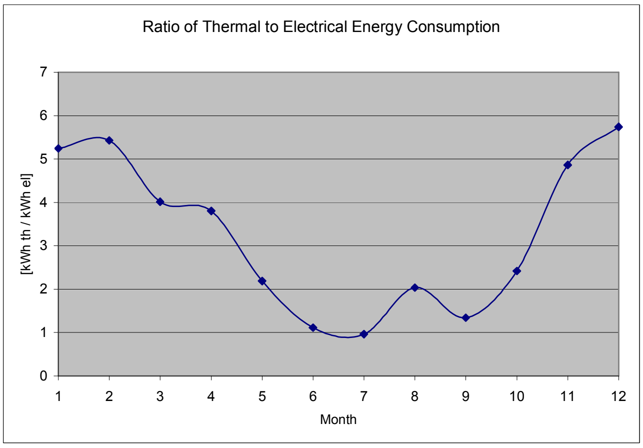

Fig. 8

When we compare the price of natural gas and electricity, it is easy to discern that the price of gas is 29% of the price of electricity. It means that if we don't consider the cost of purchase of the CHP system, already 29% of system efficiency is enough to make the system worth being installed. Almost all of the systems described in the previous paragraphs offer, beside at least 25% electrical efficiency, thermal power.

	Price of 10,000kWh [euro]
Electricity	1,591
Natural gas	458

Table 2

It may be noticed that the cost of the system has not been considered. We have to remember that we compare the CHP to a conventional gas heating (and electrical energy from the network) which also requires some investments at the beginning.
In sum, the system which will be chosen as the most suitable CHP for a one family house, should be able to change the proportion between thermal and electrical power easily and also be able to produce up to six times as much thermal energy as electricity. That is why there are only two systems, which should be taken into consideration:

- combination of gas and steam turbine

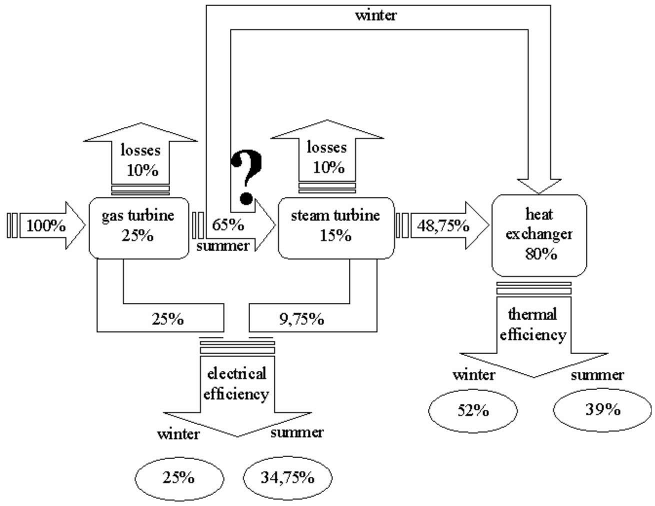

Fig. 9

In case of using two turbines the total cost of the system should increase drastically as the cost of a high speed turbine is the most significant in the system. On the other hand the system seems to be very flexible because of its easiness to change the balance between electrical and thermal energy. The final conclusions can be drawn after estimating the price of a turbine.
Also the total efficiency both in the summer and in the winter is relatively high.
The maximum electrical power should always reach the level of 5kW. Also the maximum thermal power can not be lower than 10kW in the winter and 2kW in the summer.
We can encounter two extreme situations:

- best case - when thermal and electrical power is used at the same time

Total energy = Thermal Energy = 14,100kWh (because the electrical energy can be produced simultaneously with the thermal energy from the same input energy)

- worst case - when electrical and thermal power is used independently

Total energy = Thermal Energy + Electrical Energy = 14,100 + 3,750 = 17,850kWh,

Assuming that the calculations of efficiencies are done correctly, we get the following results:

	Winter	Summer
Electrical efficiency [%]	25	34.75
Thermal efficiency [%]	52	39
Total efficiency [%]	77	73,75
Maximum electrical power [kW]	5	5
Maximum thermal power [kW]	10.4	4.5
Total power consumption/ production (worst case) [kWh]	14,815/ 19,241	3,035/ 4,145
Total power consumption/ production (best case) [kWh]	11,700/ 15,195	2,400/ 3,810
Cost (worst case) per year [euro]	1,071	
Cost (best case) per year [euro]	971	

Table 3

In case of using that kind of installation the energy cost can be decreased. The savings can amount from €175 to €275 annually. It means that we can reduce the cost up to 22%.

- gas turbine with sterling engine and heat recovery

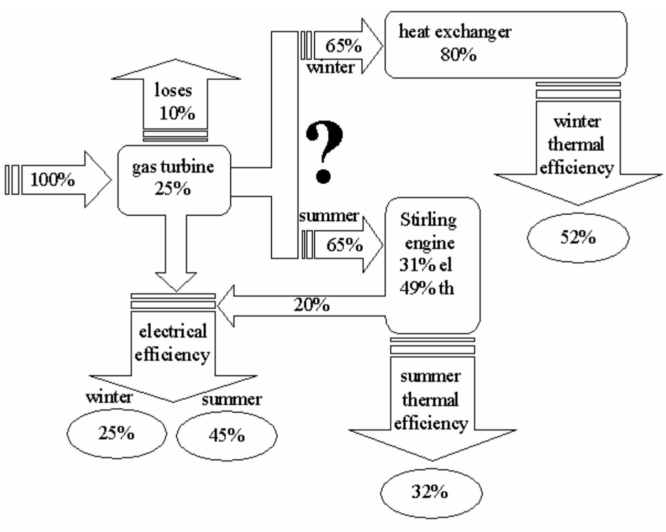

Fig. 10

The calculation result seems to be very promising. Unfortunately the technology of the Sterling engine is still being developed and there are only a few companies currently producing that kind of engine. Each of the manufacturers promises completely different efficiency of the Stirling engine. It can be only discerned that the efficiency increases with the increase of the maximum power.

	Winter	Summer
Electrical efficiency [%]	25	45
Thermal efficiency [%]	52	32
Total efficiency [%]	77	77
Maximum electrical power [kW]	5	5
Maximum thermal power [kW]	10.4	3.6
Total power consumption/ production (worst case) [kWh]	13,063/ 16,965	3,787/ 4,918
Total power consumption/ production (best case) [kWh]	11,700/ 15,195	2,400/ 3,117
Cost (worst case) per year [euro]	971	
Cost (best case) per year [euro]	838	

Table 4

In case of using the micro gas turbine combined with a high efficient Sterling engine, the expenses can be reduced up to 33%. It is hard to predict how the use of Sterling engine can increase the price of the whole system but it can significantly increase the efficiency of the system and furthermore, it increases maintenance expenses.

5 Conclusions

There is no doubt that microturbines combined with gas will be one of the best CHPs. Gas ensures cleanness and a low price while the microturbines ensure high efficiency of the system.

The already existing solutions offer either I.C. engine producing 5kW or turbines producing over 30kW. No manufacturer offers a turbine with low power output (3-5kW) as a source of energy while there are many advantages of using microturbine instead of combustion engine: cleaner exhaust gases, less vibrations, lower frequency of maintenance, lighter weight [21]. There are unfortunately two emerging problems, which have to be overcome: design of efficient high speed generator and high production cost. The currently developed turbines using ceramic technology will be able to reach about 40% of electrical efficiency [2].

The efficiency of microturbines is meaningly smaller compared to large conventional plants but the operating costs and total pollution volume are superior. The manufacturers of microturbines try to avoid discussing the efficiency of their microturbines but they prefer to present the overall efficiency reaching 50% to 70% when used in a CHP.

Currently, the savings that can be reached by using microturbine are not high.

Finally, gas turbines provide the highest efficiency and the lowest emissions of all combustion power generation technology that is available today. The best evidence of that is the first place in Business Week competition "21 ideas for the 21st century" [22].

References:

[1] Unitherm sp. j., http://www.unitherm.com.pl

[2] U.S. Department of Energy, Energy Efficiency Improvements Through the Use of Combined Heat and Power (CHP) in Buildings, *DOE/EE-0239*, October 2000

[3] Emily Burke, Macro problem – Micro solution?, *Power Engineering International Magazine*, 2002 November

[4] University of Alaska Fairbanks, http://www.uaf.edu/energyin/webpage/pages/heat_engines/steam_and_gas_turbines.htm

[5] Ted Bronson, Combined Cooling, Heating and Power Technologies (CHP), *Combined Heat and Power Symposium*, February 2003

[6] Arbeitsgemeinschaft für Sparsamen und Umweltfreundlichen Energieverbrauch E.V., Mikro-KWK Motoren, Turbinen und Brennstoffzellen, *Veröffentlichungen Blockheizkraftwerke*, 2001

[7] Energy Technologie Austria (energytech.at), Cogeneration (CHP) Technology Portrait, Vienna 2002

[8] R. H. Williams, E. D. Larson, Biomass Gasifier Gas Turbine Power Generating Technology, *Biomass and Bioenergy* Vol. 10. No. 2-3, 1996, pp. 149-166,

[9] Edie – The online Community for Water, Waste & Environment Professionals, World's first fuel-cell/micro-gas-turbine combination power plant, *Edie weekly summaries*, April 2002

[10] STM Power Inc., http://www.stmpower.com/Technology/Technology.asp

[11] R. Benstead, Industrial heat pumps, *Power Engineering Journal*, Volume 2, Issue 3, May 1988 pp. 173-178

[12] International Energy Agency, The world's leading information centre on heat pumps, http://www.heatpumpcentre.org/About_heat_pumps/HP_technology.asp, March 2004

[13] Geothermische Vereinigung e.V., http://www.geothermie.de/wa/2_drilling_cost.htm

[14] Hans von der Hagen, Brennstoffzelle, Kraftwerk zum Mitnehmen, Süddeutsche Zeitung GmbH, 23 October 2003

[15] M. Rauber, Script, Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt, Practical Course of the Lesson Enenrgy Technology, 2004

[16] EAW Energieanlagenbau GmbH, http://www.eaw-energieanlagenbau.de

[17] Kraft-Wärme-Energiesysteme GmbH, Senertec, http://www.senertec.de

[18] Brainy Dictionary, http://www.brainydictionary.com/words/ef/efficiency158491.html

[19] Technische Werke Osning, http:\\www.two.de

[20] Energie AG, http:\\www.energie-ag.de

[21] R. Isaksen, Eurodyn Gas Turbines in Yachts, Rolls Royce Ulstein Turbine AS, The Yacht Report, Project Seminar, 2001

[22] L. Armstrong, 21 ideas for the 21st century, *Business Week*, 30 August 1999