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APPLICATIONS OF MAGNETIC « POWER PRODUCTION» AND ITS ASSESSMENT

Annual report 2007

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SUMMARY

The main objective of this project is to search for different applications of heat utilization, where magnetic «power generation» may present a good alternative to conventional power conversion technologies. The annual report 2006 of this project briefly presented power conversion domains, which could have a potential for an application of magnetic «power generation» machines. Now, in this annual report, a selection of magnetic power conversion systems, which are most feasible and economic, is listed. Magnetic «power generators» based on permanent and superconducting magnets are analyzed for numerous heat source temperatures, magnetic field strength and rotational frequencies of a machine. The special analysis takes advantage of a new derived model, which permits to determine the thermodynamic efficiency, the exergy efficiency, the total mass and volume of a magnetic power conversion system.

Preliminary results show that systems based on permanent magnets are limited to approximately 140-160°C heat source temperature, whereas systems with superconducting magnets permit a much wider range of applications with an upper limit at approximately 600°C heat source temperature, if a magnetic field of 10 Tesla magnetic flux density is applied.

This study shows that magnetic power conversion beats conventional technologies in many aspects. This is especially the case for low exergy heat sources, where most of the conventional energy conversion technologies cannot even operate. In contrast the magnetic power generation technology for these sources leads to a high exergy efficiency of energy conversion. Despite of the low thermodynamic efficiency of these sources, the available energy potential is nearly unlimited large. Another advantage of magnetic «power generators» is that they work favourable with a temperature difference actually independent of the height of the temperature levels of the source and sink.

Objectives of the project

The basic phenomenon of magnetic power generation is the temperature dependency of magnetization. If additionally the material is magnetocaloric instead of only magnetisable, a more efficient thermodynamic cycle may be performed. To see this, one has to study a T-s diagram of the thermodynamic process. Now, if for example a material is in its ferromagnetic state, it will be attracted toward the higher magnetic field. In the case that there is heat added to it, its magnetization decreases. By the heating-up the attracting force field is reduced. As a consequence high-temperature magnetic or magnetocaloric material is less attracted by a spatial increasing magnetic field.

In a thermodynamic open system material is moving through a magnetic field. At its entrance it is attracted to the field and it moves in. If it is now heated in the magnetic field region its temperature is increased and its magnetization lowers down toward the exit. Therefore, the repulsion force to push it out of the magnetic field is smaller than the corresponding attracting force at the entrance. If the attraction on one side of the magnetic field is higher than the repulsion on the other side, the magnetic material feels a resultant force field that moves the body. In a machine with rectilinear motion, if the resistance of the machine to this movement is known, its velocity of movement is determined. The product of force times velocity determines the energy rejected per time unit, which is the obtained power of such a machine. In a rotary system the force field leads to a resultant moment. Resistance forces, which can be those of an electricity generator fixed to the axis of a magnetocaloric wheel, will determine the equilibrium angular velocity. And here the product of moment with angular velocity is identical to the converted power.

The advantage of applying this method of power conversion is that such systems may also utilize heat of low temperature from many kinds of different heat sources. If the temperature of the source is low, the heat is of low exergy. The advantage of such systems is that it is possible to have a direct conversion into electrical energy without a necessity of additional mechanical devices.

The magnetic power generation is a research domain, which dates back to the late 19th century when the two famous scientists Tesla [1] and Edison [2] deposited their ideas in patents and named the related machines pyromagnetic generators. Their inventions were based on the great discovery of Warburg [3], who observed an increase of temperature when he had brought an iron sample into a magnetic field and a decrease when the sample was removed out of it. At this ancient time the permanent magnets were not strong enough and the magnetocaloric materials available not enough performing to build economical and practical devices.

There was not much research and development activities until to the 1950’s when a large interest of scientists was created by the idea of performing magnetic power generators by applying magnetocaloric suspensions as working fluids. Most of this pioneering work was performed by Resler and Rosensweig (see Ref.’s [4] and [5]). However, some single earlier publications than those may be found in the Ref.’s [6] to [9]. In that period ideas and publications were mainly related to the idea to consider magnetocaloric suspensions as working substances. There is no evidence that any of these early ideas were transformed to real working prototypes.

Thirty years later most of the publications were related to studies of magnetocaloric power generators with solid working materials (Ref. [10] to [12]). In the context of an exponentially growing research and development activity in the domain of magnetocaloric materials and magnetic refrigeration the HEIG-VD group rediscovered the interesting idea of magnetic “power conversion”. A scientist working on the Curie wheel [13] got into contact with experts of magnetic refrigeration (see Ref. [14] and [15]). The Curie wheel is a small device which contains the characteristic properties of such machines. The input of heat is given by light radiation absorption on the surface of the wheel. Because this surface is very small, the heat input is negligible. And even if the cylinder is held by levitation in its upright position and it shows hardly any friction, it cannot be applied to obtain a reasonable “power conversion”. On the other hand it is an excellent device to study some basic phenomenon of this technology.

The development of permanent and superconducting magnets has been significantly improved compared to the time when first research activities in the domain of pyromagnetic generators occurred.

At present new developments in material science, concentrating on the creation of magnetocaloric materials, exhibit magnetocaloric effects and “giant” magnetocaloric effects which occur at different temperature levels (also above the level of refrigeration) with improved physical properties.

A great advantage of magnetic power conversion machines is that their operation is mainly based on the temperature difference of the temperatures of a heat source and a heat sink and not so much on the height of these two temperatures. Furthermore, in this report it will be shown that this kind of systems present an excellent possibility of converting low exergy heat into mechanical work or even electricity and this with a very high exergy efficiency.

The main objective of this project is to search for and identify different applications and their domains of heat utilization, where magnetic power generation may present a serious alternative to the conventional power generation technologies. The evaluation was performed on a very broad basis. It shows some interesting potential for some specific applications. The work of this study is structured by the following list:

1) Overview of the technology „Magnetic Power Conversion“
2) Advantages and drawbacks
3) Comparison with existing power generation technologies
4) A list and short descriptions of possible applications of magnetic power conversion
5) Models, analysis and presentation of results on technical characteristics for selected applications
6) The proposal for the design of a first prototype and its specifications
7) Cost estimation
8) World market potential for selected applications
9) Comparison of selected applications with the conventional ones
10) Proposal for future work.

Accomplished work and achieved results

Introduction

A comprehensive study of all power conversion technologies, which were briefly presented in the annual report 2006 of this project [16], led to a selection of possible application domains of magnetic power generators.

At the present stage of the development of permanent magnets, all the magnetic power conversion systems, which are operating with a large temperature span between the heat source and the heat sink, are not yet really feasible.

An alternative is to use superconducting magnets. However, they should be applied in very large units. They are especially efficient, if heat sources with temperatures of up to 600°C are taken into consideration.

In this study a new analysis has been applied to evaluate the different systems. The thermodynamic efficiencies and the exergy efficiencies of all the systems under consideration were calculated. A brief definition each will be given in the final report of this project. The method is based on a model, which was basically developed in another BFE project (see Ref. [17]) and was also applied in a modified version to the evaluation of magnetic refrigeration systems [18].

The present study and analysis reveals a very interesting result, namely that for systems with low-temperature heat sources the exergy efficiencies are very high. A first conclusion of this new insight is that probably no other energy conversion method can compete with magnetic «power conversion» in this area of application. But one has to be aware that low exergy heat sources cannot lead to very high thermodynamic efficiencies. This can immediately be seen by calculating the Carnot efficiency, which is the highest obtainable efficiency at all. Finally we must recognize that still new magnetocaloric materials with higher Curie temperatures are developed, so that also the high-exergy region becomes more and more feasible for this magnetic technology.

List of possible systems

In the following section the reader finds a comprehensive overview on the possible technical applications of «power conversion», even though this study has not been completely finalized. The upper limit of 600°C is related to a magnetic flux density of 10 Tesla and a heat sink temperature of 25°C. The up-to-present investigated systems are the following:

a) Small solar power generation devices

- Liquid solar plate collector with generator based on permanent magnets (high exergy efficiency but low thermodynamic efficiency)
- Liquid evacuated tube solar collector with generator based on permanent magnets (high exergy efficiency but low thermodynamic efficiency).

b) Large solar power generation devices

- Large evacuated tube systems (generators based on permanent and superconducting magnets, both are leading to high exergy, but low thermodynamic efficiency)
- Parabolic trough technology (application of high temperature superconducting magnets)
- Power tower technology (application of high temperature superconducting magnets)
- Solar dish technology (application of high temperature superconducting magnets, preferably with field inductions higher than 10 Tesla).

c) Small geothermal systems

- Small geothermal systems with temperature differences above 50 K between heat sink and heat source (generator with permanent magnets, high exergy efficiency, but low thermodynamic efficiency).

d) Large geothermal systems

- Magnetic power generators running at temperature levels of flash steam systems (special secondary liquids are required), application of high temperature superconducting magnets
- Magnetic power generators running at temperature levels of binary cycle systems (special secondary liquids are required), application of high temperature superconducting magnets.

e) Power of waste heat from internal combustion engines in transport

- Magnetic power generators using heat from internal combustion engines in large marine applications (application of high temperature superconducting magnets)
- Permanent magnet based magnetic power generators using heat from the cooling water of the engine in larger vehicles, e.g. trucks, buses, trains (evaluation still under consideration).

f) Power from cogeneration (poly-generation) plants

- Magnetic power generators with heat sources up to 600°C, special secondary liquids required, possible applications of hybrids with conventional production where a magnetic power generator is operating at lower temperature levels (application of high temperature superconducting magnets).

g) Nuclear power plants

- Magnetic power generators with heat sources up to 600°C, special secondary liquids required, possible applications of hybrids with conventional power conversion where magnetic power generator is operating at lower temperature levels (use of high temperature superconducting magnets).

h) Power from waste heat from fuel cells

- Possible application of permanent or high temperature superconducting magnet based generators (because of a rather low temperature level of the waste heat from the fuel cell, a small thermodynamic efficiency, but a very high exergy efficiency is expected to occur).

i) Power from waste heat from chemical exothermal processes

- Possible applications with generators based on permanent magnets or high temperature superconducting magnets (depending on the temperature level of the heat source).

j) Power from waste heat from waste incineration plants

- Magnetic power generators with heat sources up to 600°C, special secondary liquids required, possible applications of hybrids with conventional power conversion where magnetic power is operating at lower temperature levels (application of high temperature superconducting magnets).

k) Power from heat in food industry processes

- Possible application of generators based on permanent magnets or high temperature superconducting magnets (depending on the temperature level of the heat source).

l) Power from waste heat from process technologies

- Possible application of generators based on permanent magnets or high temperature superconducting magnets (depending on the temperature level of the heat source).

m) Special systems

The goal of some special systems is the utilization of pure natural sources by “power generation”. These systems in general do not enable high thermodynamic efficiencies to occur, but usually show high exergy efficiencies. Depending on the specific application permanent magnets as well as superconducting magnets are applied. Some examples of such systems are:

a) power conversion in a desert area using the temperature variation between the ambient (air or solar heated panel) and the soil. This system may also operate during night with inverse temperature levels of the heat source and heat sink

b) power conversion using the temperature difference between outside air as a heat sink (e.g. far north regions) and soil or sea as heat source

c) space applications, where heat is supplied or rejected by radiation (levitation possible).

Proposed application of magnetic power conversion

Two different types of favorable magnetic «power generators» were selected for a more detailed presentation. In both cases the electric output power is large, namely 1 MW. The analysis comprises different types of magnet assemblies. The first is a generator based on permanent magnets with a «magnetic field strength» of 3 Tesla. The second is an analogous system, but now equiped with superconducting magnets of 10 Tesla induction. As the study is still ongoing the two chosen examples, which are presented in more detail, may be not the most favorable. But already at this previous stage we want to demonstrate the possible occuring high performance of this technology. Furthermore, the following presentation will also reveal an important dependence on the heat source temperature.

It must be noted that a very small number of technologies enable power conversion with a heat source containing heat of 100°C or lower. One has to be aware that even if one assumes a perfect system operating at Carnot efficiency, e.g. operating between the two temperature levels 100/35°C, it only shows a thermodynamic efficiency of 17.4%. It is clear that the occurrence of the Carnot efficiency is identical to that of an exergy efficiency of 100%. This has to be emphasized especially when such a technology is presented to non-specialists in science and engineering (e.g. economists, managers, politicians, etc.) in order to make them clear what is realizable when we are treating, for example, waste heat. The exergy efficiency defines the ratio of what a system actually performs to the best possible operation which nature would allow us to perform.

High temperature superconducting magnetic power generator

Superconducting magnets are mostly applied in low temperature physics, high energy research (e.g. fusion) and - with the highest number of applications - in medicine (e.g NMR equipment, etc.). Special efforts in research are undertaken in the domain of superconducting motors and generators. They may operate with efficiencies of up to 98%. The high-temperature superconducting magnets require an external cooling of the superconducting material, e.g. by liquid nitrogen. This also implies a special supplementary cooling system. This auxiliary cooling system itself could be designed to be magnetic.

An application of superconducting magnets in the magnetic power conversion field is limited by the investment costs, especially when applying this technology to smaller systems. In large systems the relative costs do not present such a large contribution compared to the total system cost; so an application of this technology for large systems is more feasible.

The exergy efficiency obtained by the magnetic power conversion method may exceed that of any other known technology, if applied to the low temperature range. If cryocooling is available, this does not only allow an operation of superconducting magnets, but it also gives the possibility to operate a superconducting electric generator. This additionally improves the efficiency of the generator and its compactness. Figure 1 shows an example of a large solar trough system coupled to magnetic «power generation» with surrounding superconducting magnets. The analysis was performed in order to evaluate the thermodynamic efficiency and exergy efficiency of a 1 MW superconducting magnet power conversion system with a magnetic flux density of 10 Tesla. The analysis was made for numerous temperatures of the heat source and frequencies of operation. Figure 2 shows the thermodynamic efficiency, figure 3 the exergy efficiency, as well as the involved mass of the magnetocaloric material, which is presented in figure 4.

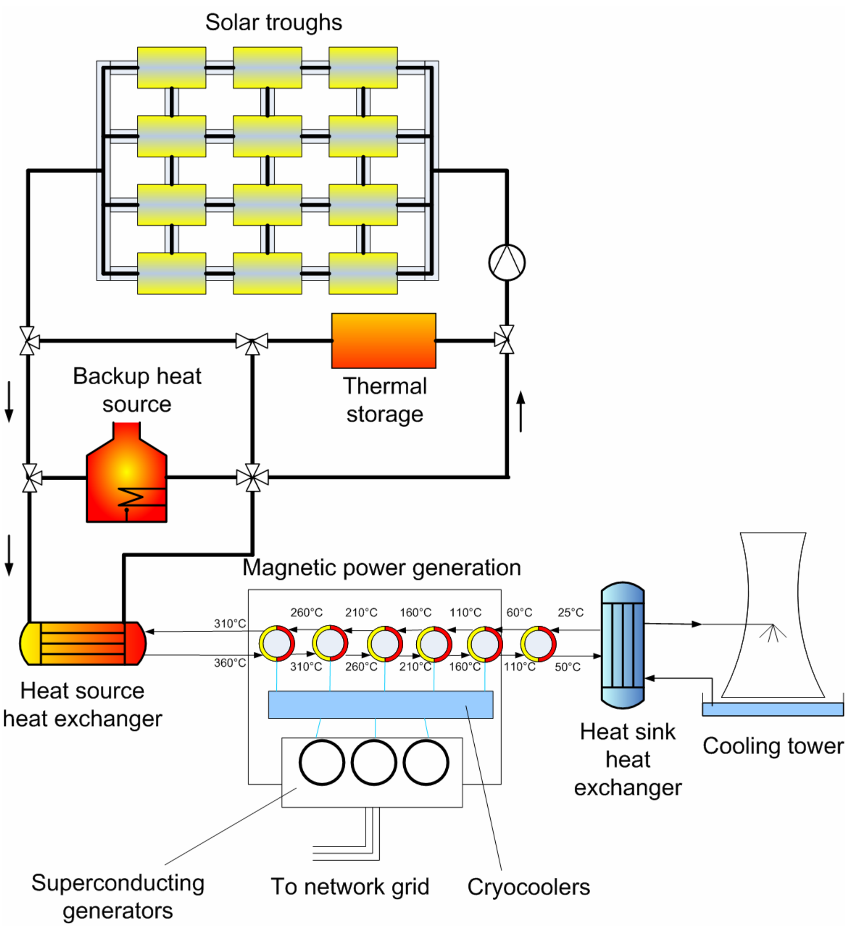

Figure 1: A parabolic trough power system with a magnetic power conversion containing superconducting magnets and generators is presented.

Parabolic solar trough technology is currently the most proven solar thermal electric technology. Such kind of plants, which continue to operate on a daily basis, range in size from 10 to 80 MW. Large fields of parabolic trough collectors supply thermal energy to produce steam for a Rankine steam turbine/generator. The temperature of the working fluid varies between 300 °C to 400 °C. Such temperature levels wouldpresent a perfect match to the superconducting magnetic power generators with magnetic flux density of 10 Tesla and above.

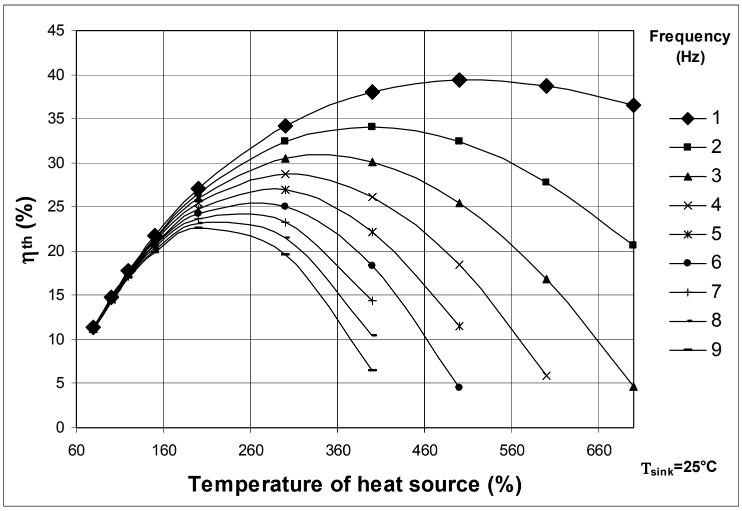

Figure 2: Thermodynamic efficiency of a 10 Tesla superconducting magnetic power generator.

The frequency of operation strongly influences the thermodynamic efficiency and exergy efficiency. One may see that such systems show very high efficiencies for rather low temperatures of the heat source, e.g. < 600°C. This leads to the conclusion that the most appropriate applications of superconducting systems with magnetic flux densities of up to 10 Tesla are geothermal power systems, solar systems, e.g. such with parabolic troughs, waste heat utilisation, etc.

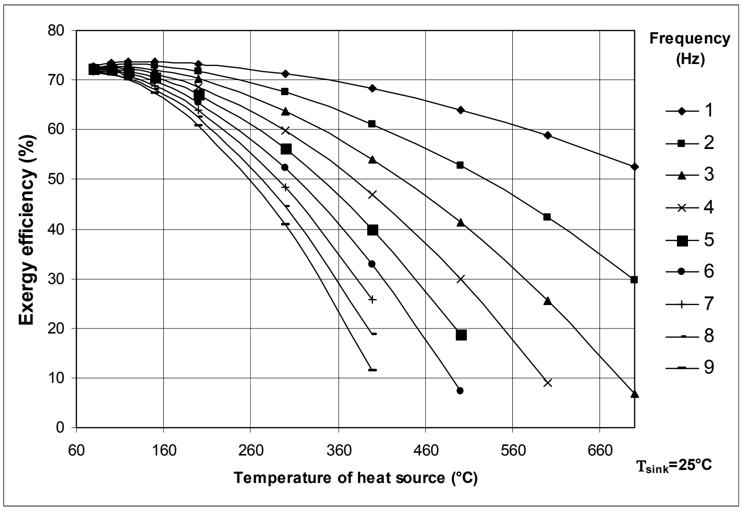

Figure 3: The exergy efficiency of a 10 Tesla superconducting magnetic power conversion plant.

However, it has to be emphasized, that machines with magnetic flux densities beyond 10 Tesla show a very high efficiency also at high temperatures of the heat sources. Such are occuring e.g. in thermal or nuclear power plants. A special liquid based system should be built rather than applying steam or gas as working fluid.

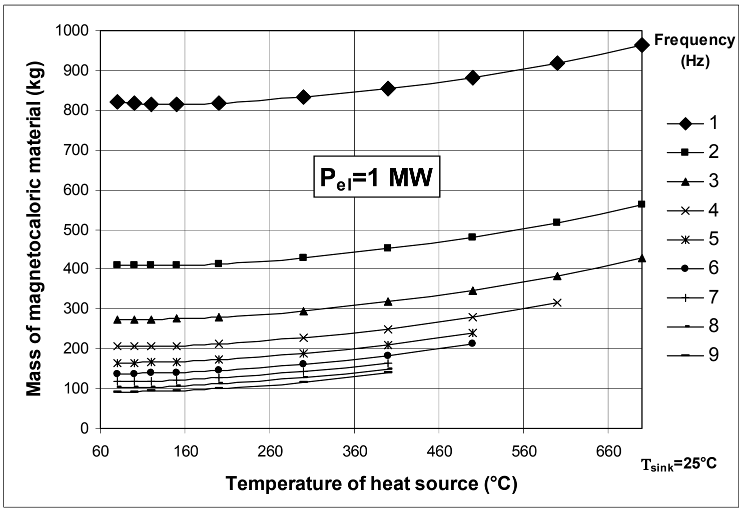

Figure 4: The magnetocaloric material mass of a 10 Tesla superconducting magnetic «power generator» is presented.

For the solar trough system - with a heat source temperature of 360°C and a heat sink temperature of 25°C (3 Hz) - the thermodynamic efficiency is higher than 30%. The exergy efficiency reaches 60%. The magnetocaloric material mass for a 1 MW electrical power conversion system would be around 300 kg. Such efficiencies for the same operating temperatures cannot be obtained by any other known conventional technology.

Permanent magnet based magnetic power generator

In general a system with permanent magnets, compared to one with superconducting magnets, would require a higher total volume and total mass of its device. Advantageous is that in systems with permanent magnets no additional power for cryocooling and work to perform a magnetization are required. Therefore, these systems lead to comparatively small units. However, the permanent magnets show a limited magnetic flux density and as a result of this the optimal temperature differences between the heat sources and the the heat sinks are limited in size.

An example shown in this annual report presents the utilization of low exergy heat from a geothermal power plant. Such plants are named binary-cycle plants. They are operating with a Rankine cycle and reasonable temperatures of the heat source may reach 180°C.

Figure 5 shows an example of a large geothermal power plant with mounted permanent magnets.

In an analysis with our evaluation method, a power plant with permanent magnets and an electric power conversion of 1 MW was investigated. A magnetic flux density of 3 Tesla was assumed to define the present upper limit for such a technology, despite higher magnetic flux densities were already reached, e.g. in special devices up to 6 Tesla. Just as in the study of systems with superconducting magnets also here the temperature of the heat source and the frequency of rotation of the machine were varied. A comparison with the conventional binary plant (see Ref. [19]) was made in order to demonstrate the potential of a power conversion based on a permanent magnet's assembly. Figure 6 shows the thermodynamic efficiency, figure 7 the exergy efficiency, figure 8 the total mass and figure 9 the total volume of such a plant.

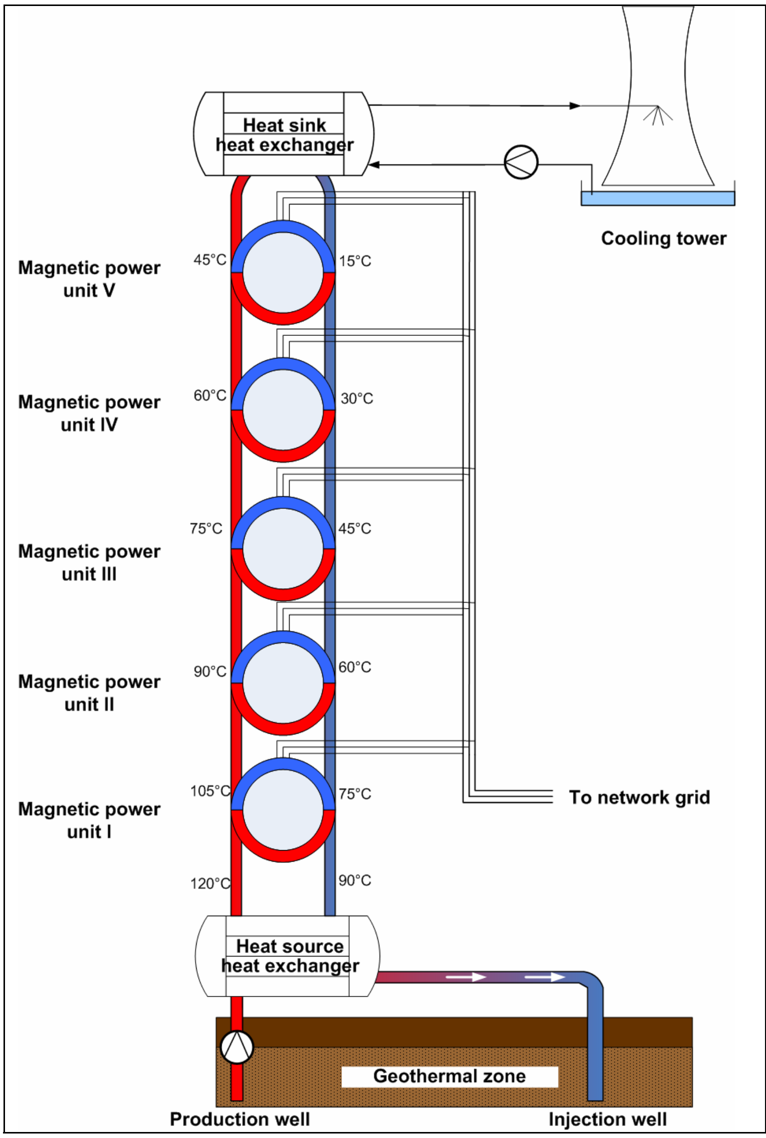

Figure 5: A rough design of a geothermal (low temperature source) magnetic power conversion plant is shown.

Most geothermal areas contain moderate-temperature sources with temperatures below 200°C. Usually energy is extracted from binary-cycle power plants. In conventional systems hot geothermal fluid and a secondary «binary fluid», with a much lower boiling point than water, is used. Heat from the geothermal fluid causes the secondary fluid to flash to vapor, which then drives the turbines. This presents a closed-loop system. Moderate-temperature water is the most common geothermal resource, and most geothermal power plants in the future are planned to operate as binary-cycle plants. The magnetic geothermal plant should not use the transformation of fluid into vapour, but rather a liquid/ liquid system. A magnetic «power generation» with permanent magnets is interesting in cases when the temperature of the heat source is rather low, e.g. 140°C. A special effort has to be made in order to perform compact devices with a low total mass. Systems with permanent magnets would also lead to low maintenance and operating costs.

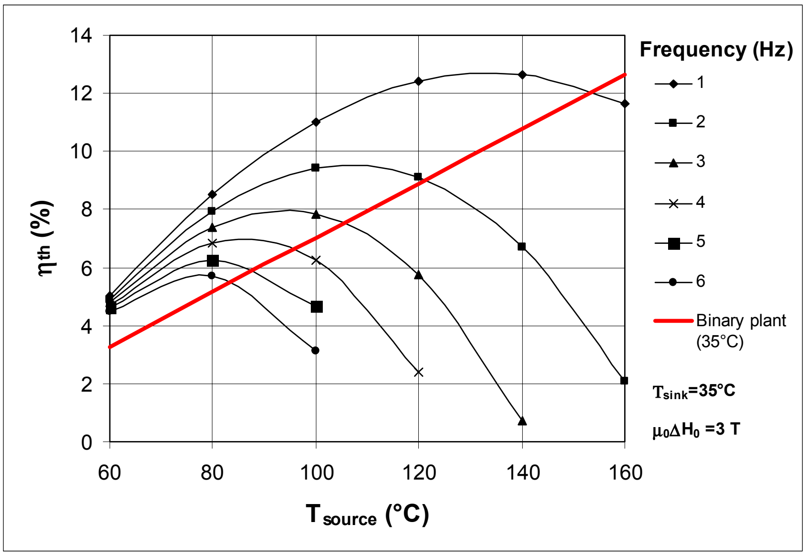

Figure 6: The thermodynamic efficiency of a geothermal power plant with permanent magnets is shown.

Results of figure 6 show that quite high exergy efficiencies may be obtained even with generators containing permanent magnets. Low exergy heat source systems lead to low thermodynamic efficiencies. This is of course a fact of nature and not of magnetic power conversion. The red line presents the thermodynamic efficiency of a conventionnal binary plant (taken from Ref. [19]).

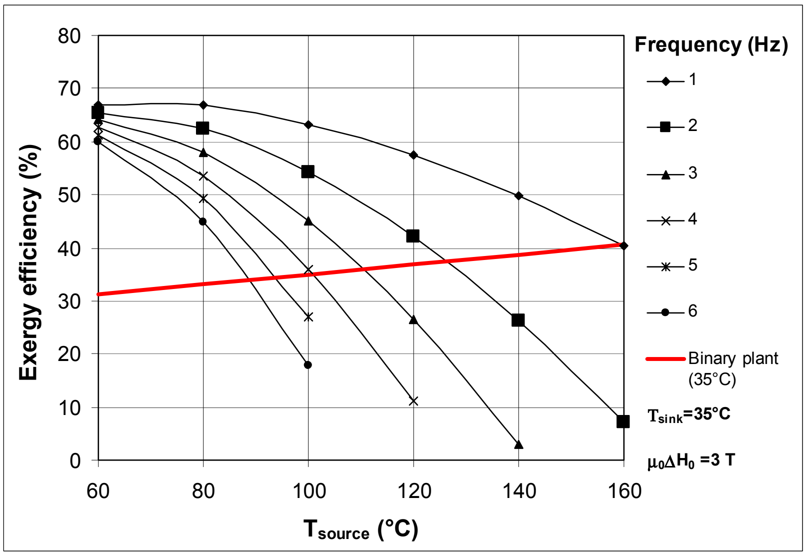

Figure 7: The exergy efficiency of a permanent-magnet-based geothermal power plant is shown.

The large advantage of magnetic power conversion becomes transparent, especially in the region of lower temperatures of the heat sources (e.g. <140°C). In the case that power generation with superconducting magnets instead of permanent magnets will be applied, the efficiency would be higher (see figure 2 in the range of lower temperatures of the heat source).

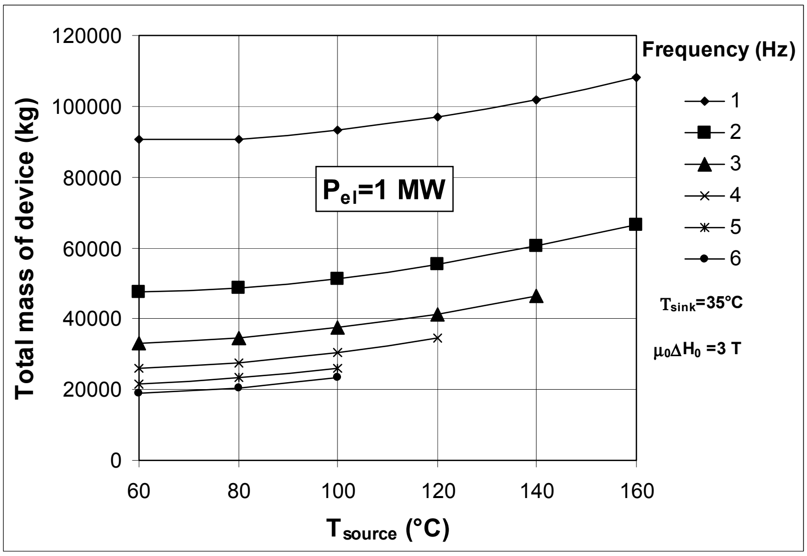

Figure 8: The total mass of a 1 MW magnetic power generator based on permanent magnets is presented.

Permanent magnet systems require a low degree of maintenance. However, their total mass and volume is rather high. That leads to the first impression that such systems will be rather robust.

On the other hand heat from low exergy heat sources may be successfully converted into electrical energy by systems based on permanent magnets, even if the production rate is low.

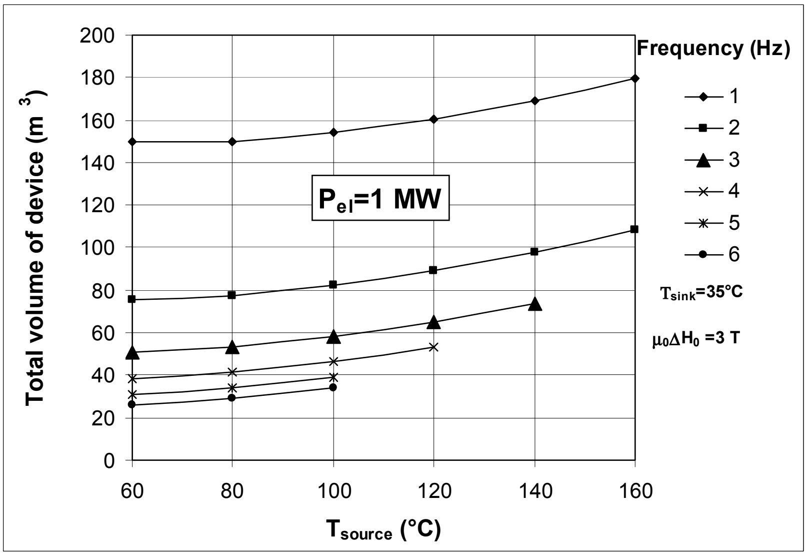

Figure 9: The total volume of a 1 MW magnetic power generator based on permanent magnets is presented.

Despite their low thermodynamic efficiencies related to low exergy sources, these systems may be operated below 120 °C, which in the case of applying other methods becomes practically impossible.

A rough estimation is that in the case of superconducting machines the power range will be in the Megawatt domain.

But this must be confirmed by more thorough studies.

Conclusions and outlook

This report presents different applications where the magnetic power conversion technology is a serious alternative to the conventional technologies. Results show that the utilization of heat sources is limited by their temperatures and magnetic field fluxes which the magnets of a power conversion generator can provide. On one hand a higher frequency of the operation reduces the investment costs and on the other hand it decreases the efficiency. Therefore, when designing such a system the optimal configuration should be determined by (numerical) optimization procedures.

Generators with permanent magnets should be applied in small-scale systems and superconducting magnets in medium-sized or large to very large systems. A further result of this study is that sites applying permanent magnets are limited to 140-160°C heat source temperature, whereas applying superconducting magnets shows a much higher limit of 600°C for 10 Tesla magnetic flux density. But one must notify that such materials, especially tailored for such an application, are not yet available. The temperature level of the heat source, in some special cases, could be increased above 600°C, if the magnetic flux densities could be increased up to 15 to 20 Tesla.

The final report will comprise the analysis for all the mentioned magnetic power technologies, which are presented here as possible applications. A selection of most feasible magnetic power conversion technologies will be made, based on market requirements and the market potential, also taking environmental aspects into consideration.

National and international collaborations

Because the work performed in this project and the efforts taken in the study of magnetic heating and refrigeration are related, all the national and international collaborations, which are described in Ref. [18], are also contributing to this project. Instead of repeating them here, we refer to this reference.

Additionally it must be mentioned that by P.W. Egolf a DUO diploma work was initiated. DUO means a collaboration between an engineering student and an economic student. The related diploma works, which have been performed with strong interrelations, will be finalized end of this year. It must also be mentioned that experts from Nestlé in Vevey participate in this DUO diploma work with their expertise. They have defined an example of waste heat treatment, which is evaluated for an application of the magnetic energy conversion technology by the two HEIG-VD diploma students.

At present a project proposal for the subject DUO/Nestlé has been deposited to the RCSO committee of the Hes-so (Haute Ecole d'Ingenieurs de Suisse Occidentale) to investigate the waste heat utilization by magnetic power conversion in greater detail. The two-step evaluation has led to a positive result in the first stage. A final decision on funding will be obtained before end of this year.

BASF, Divison Future Technologies, shows a large interest in magnetic power conversion technologies. Experts from this company are discussing a collaboration with the scientists from HEIG-VD/ SIT.

Acknowledgements

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Evaluation of 2007 and view of 2008

The project could be developed as it was planned. Interesting and important findings concerning thermodynamic efficiencies have been made, which require more profound investigations. The time till to the end of the project, which is planned to be at the end of April 2008, will be used to also make some more market-related studies. Some main results of the two DUO diploma works shall also be incorporated into the final report of the project.

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