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APPLICATIONS OF MAGNETIC »POWER PRODUCTION« AND ITS ASSESSMENT

ALTERNATIVE POWER PRODUCTION TECHNOLOGIES

Final report: Appendix 2

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1. INTRODUCTION

This appendix focuses on the existing alternative technologies of heat to power conversion, where heat is not available with a high exergy value but rather a low one, which is determined by the temperature level of the heat source. It also deals with technologies, where heat from the sun radiation is utilized for power production. The appendix therefore does not deal with any of the technologies, where as input fossil fuels, nuclear fuels, hydrogen, alcohols or bio fuels are used. However, a by-product of these technologies is heat as well. There exist plenty of different alternative technologies, which are discussed, researched and developed by researchers and industries. The most interesting are the Stirling Power Generators, the Organic Rankine Cycle (ORC) Power Generators, the Kalina Cycle Power Generators and the Thermoelectric Power Generators. These are described in this appendix in more detail.

Figure 1 shows a comparison of the exergy efficiencies for different kinds of power generation technologies. One should note that the presented efficiencies in Figure 1 are only of illustrative nature, since the data were taken from different sources, which consider different losses when evaluating the efficiencies. The exergy efficiency of a thermoelectric power generator was defined by applying the equations presented in Figure 9 of the BFE report, which is found as reference [1]. The exergy efficiency of the thermoelectric power generator was calculated only on the basis of the ZT factor (more about this factor and the temperature levels of the heat source and the heat sink may be found in Chapter 2.3. Pumping and heat transfer losses were not taken into account. The binary geothermal power plant's efficiency was defined by the application of equations presented in report [2] and it shows real values of operating systems. The exergy efficiency of a magnetic power conversion system was evaluated for two different magnetic flux densities (2 Tesla and 10 Tesla). The evaluation was based on a 30 % volume fraction of a gas/liquid magnetic power generator, for heat sources from 350 °C to 750 °C and liquid/liquid magnetic power generator for heat sources below 350 °C. Additionally, the exergy efficiency for a Thermoacoustic Stirling travelling wave power generator is presented in reference [3]. The “real” and the “optimistic” values in Figure 1, respectively, denote the exergy efficiency when driving a load attached to a resonator and the exergy efficiency, when the resonator dissipation is a small fraction of the total dissipation, what is the case in large scale engines.

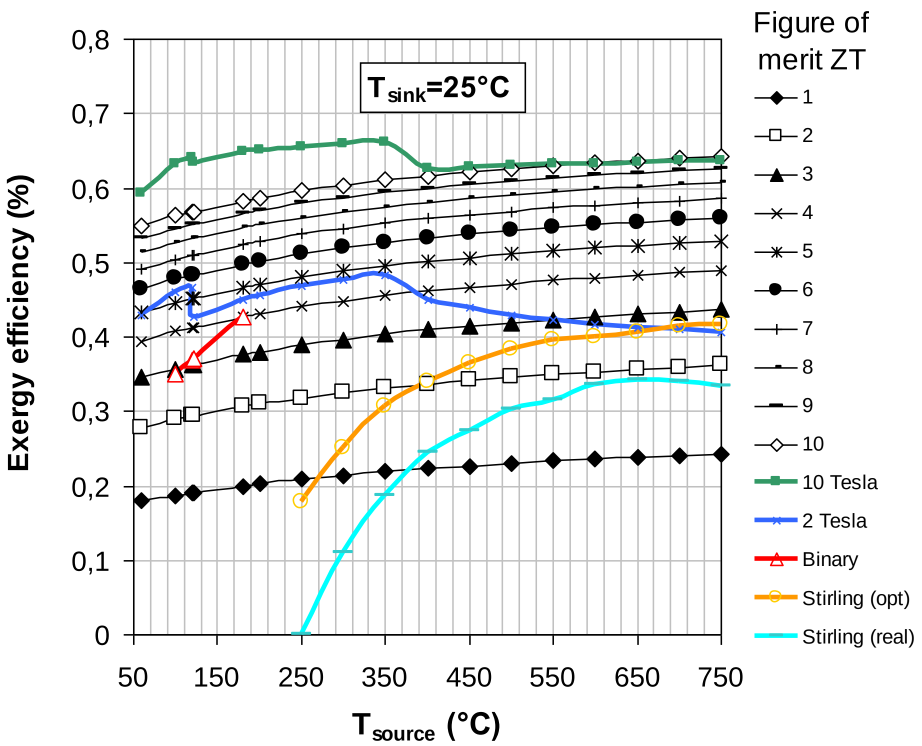


Figure 1: Comparison of different technologies for power production (Thermoelectric power for *ZT*=1 to 10, Magnetic power generation for 30 % vol. fraction at 2 Tesla and 10 Tesla magnetic flux density, Binary ORC power generator and Thermoacoustic Stirling power generator.

2. PRESENTATION OF SOME ALTERNATIVE TECHNOLOGIES

2.1. THE STIRLING POWER GENERATOR

The Stirling power generators are known as external "combustion" engines, where heat is produced outside of the machine. The thermodynamic cycle of these machines consists of two isothermal processes and two isochoric processes. During the isochoric processes, the heat is regenerated between two different pressure levels by the application of a regenerator. This may be performed in different ways. The Stirling thermodynamic cycle is a regenerative cycle. Because the cycle does not perform an evaporation or condensation, such is the case for instance in Rankine cycles, the Stirling cycle may be referred to applications with gases without a phase change. It can be theoretically designed to have the same efficiency as the ideal Carnot cycle engine. Most proposed Stirling applications present small scale 10 to 100 kW engines applied with the parabolic dish concentrators. Rankine devices at this scale have rather low efficiencies. One should note that there are many types of Stirling machines, including magnetic Stirling power generators (theoretically operating between two "heat regenerated" constant magnetizations and two isotherms). However, it is not the goal to present the latter in this section.

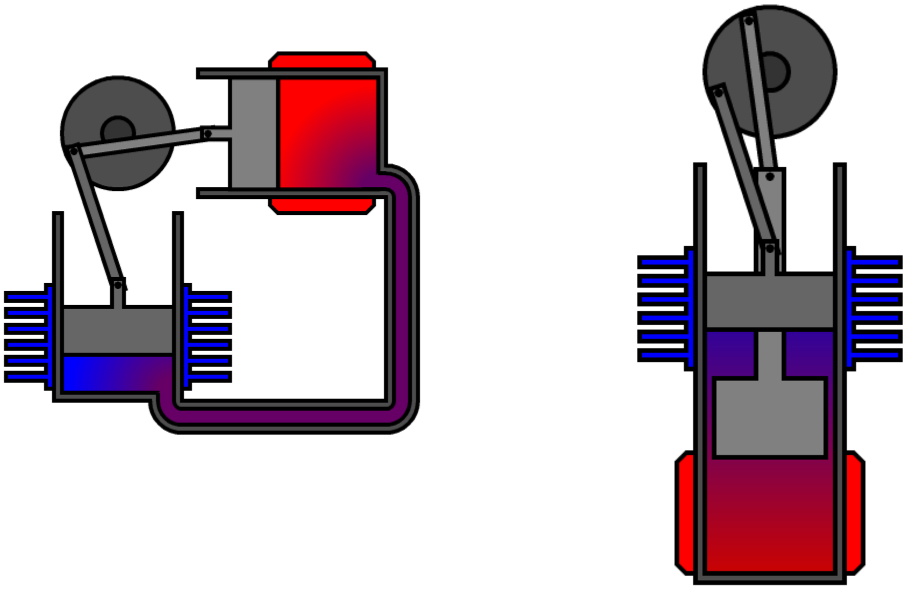


Figure 2: The Alpha and Beta type of a Gas Stirling Machine [5].

The basic gas Stirling engines may be divided into three groups: the Alpha Stirling machine, based on interconnections of the power pistons of multiple cylinders to move the working gas, with the cylinders held at different temperatures; the Beta and Gamma type Stirling engines, applying a displacer piston to move the working gas back and forth between hot and cold heat exchangers in the same cylinder (see Figure 2). The Alpha Stirling machine has two separate pistons in separate cylinders, one "hot" and one "cold" piston, respectively. The "hot" piston cylinder is placed inside the hot heat exchanger and the "cold" piston cylinder inside the cold heat exchanger. This type of engine has a very high power-to-volume ratio. A Beta Stirling has a single power piston placed within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and serves only to shuttle the working gas from the hot heat exchanger to the cold heat exchanger. When the working gas is pushed to the hot end of the cylinder, it expands and moves the power piston. When it is pushed to the cold end of the cylinder, it contracts and the momentum of the machine, usually enhanced by a flywheel, pushes the power piston the other way to compress the gas. While the Alpha type of a Stirling machine usually has problems of sealing due to hot gases, the Beta type avoids the technical problems of hot moving seals. A Gamma Stirling machine is simply a Beta Stirling machine, where the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but it is still connected to the same flywheel. The gas in the two cylinders can flow freely between them and remains a single body. The Gamma Stirling machines have a lower compression ratio, but are mechanically simpler and often used in multi-cylinder Stirling engines [5].

Researches are also made in order to perform a rotary Stirling engine, which may convert power from the Stirling cycle directly into torque, similar as the rotary combustion engine does. However, no practical engine has yet been built, but a number of concepts, models and patents have been produced.

An alternative to the mechanical Stirling device is the Fluidyne engine, which uses hydraulic piston(s) to implement the Stirling cycle. The work produced by a Fluidyne engine provides pumping of the liquid. This engine is a Beta or Gamma type Stirling Engine with one or more liquid pistons. It contains a working gas and either two liquid pistons or one liquid piston and a displacer. In the classic configuration, the work produced by the water pistons is integrated with a water pump. The simple pump is external to the engine and consists of two check valves, one on the intake and one on the outlet. In the engine, the loop of oscillating liquid can be thought of as acting as a displacer piston. The liquid in the single tube extending to the pump acts as the power piston. Traditionally the pump is opened to the atmosphere and the hydraulic head is small, so the absolute engine pressure is close to the atmospheric one [5]. Figure 3 shows a displacer piston and a concentric cylinder based Fluidyne Stirling engine.

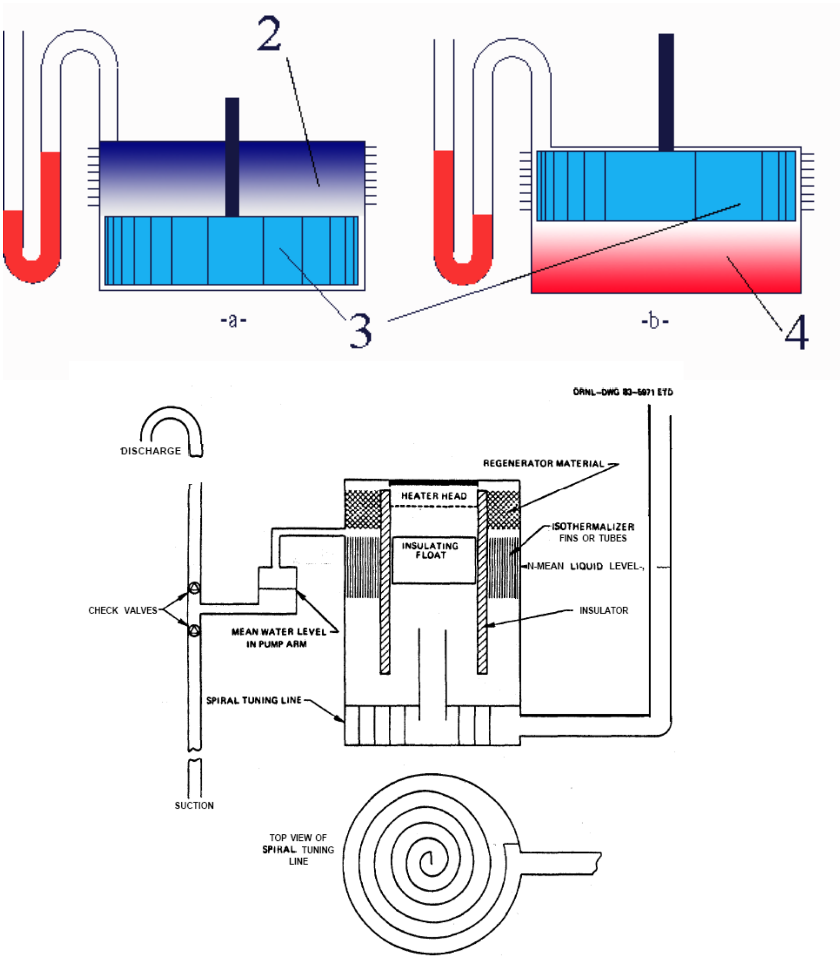


Figure 3: TOP: A Fluidyne Stirling engine with a solid displacer piston (cold compression space (2), piston (3), hot expansion space (4) [5]), BOTTOM: A concentric-cylinder Fluidyne pumping engine [6].

The thermoacoustic power generators may be very different from the usual Stirling devices, despite the working gas molecules with their flow paths follow a real Stirling cycle. High-amplitude acoustic standing waves cause compression and expansion analogous to a Stirling power piston, while out-of-phase acoustic traveling waves cause displacement along a temperature gradient, analogous to a Stirling displacer piston.

There is increased research and development activities in the field of **"**free piston" Stirling cycles engines, including those with liquid pistons and those with diaphragms as pistons. In a "free-piston" device, electrical energy may be added or removed by a linear alternator. This sidesteps the need for a linkage and reduces the number of moving parts, friction and wear.

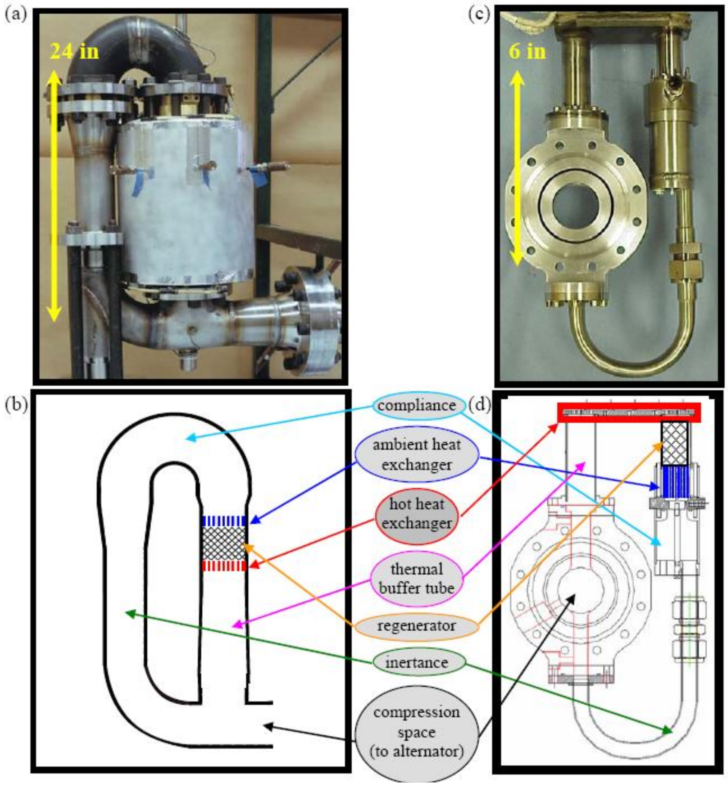


Figure 4: Thermoacoustic-Stirling heat engines [7] (a) LANL 1kW design (b) Northrop Grumman/LANL design (c) and (d) are schematics of the engines' internals with their corresponding parts labeled.

Different working fluids are possible for the Stirling machine. In the case of hydrogen as working fluid, its low viscosity and high thermal conductivity lead to a faster operation than this is the case with other gases. However, particularly at high temperatures, H_2 will leak through the solid metal of the heater. Diffusion through carbon steel is too high, but may be acceptably low for metals such is aluminium or even stainless steel. Certain ceramics also greatly reduce the diffusion. Hermetic pressure vessel seals are therefore necessary to maintain the pressure inside the engine without replacement of the lost gas. Hydrogen can also cause the embrittlement of metals. Hydrogen is a flammable gas, which is a safety concern although the quantity used is very small and it is arguably safer than other commonly used flammable gases.

The working fluid helium is applied in most technically advanced Stirling engines. It enables efficiencies and power density close to that of hydrogen with fewer of the material containment issues.

Other possible working fluid gases may be air, nitrogen, methane, ammonia, etc.

Any temperature difference can power a Stirling engine. It is also the case for magnetic power generation machines, which in some cases may perform a Stirling magnetic cycle. The heat source in Stirling machines may be derived from external fuel combustion. However other sources such as solar, geothermal, waste heat, nuclear or even biological may be used. In cases where a small temperature difference is used to generate a larger amount of power in Stirling machines, large mass flows of heating and cooling fluids must be pumped through the external heat exchangers. As a consequence, parasitic losses reduce the efficiency of the cycle. Figure 5 shows examples of a solar-dish "free piston" Stirling technology.

Figure 5: Two examples of solar dish Stirling generators (see references [8, 9]) .

Some important advantages of the Stirling power generators are presented below:

- It operates with any available heat source: combustion, solar, geothermal, biological, nuclear sources or waste heat from industrial processes (the same characteristics are found for magnetic power conversion).
- The Stirling engines require less lubricant and last longer than the other reciprocating engine types.
- The engine mechanisms are in some ways simpler than the other reciprocating engine types. No valves are needed and the burner system can be relatively simple.
- A Stirling engine uses a single-phase working fluid which maintains an internal pressure close to the design pressure. In this way for a properly designed system the risk of explosion is low. In comparison, a steam engine uses a two-phase gas/liquid working fluid, so a faulty relief valve can cause an explosion. The low operating pressures allow the use of lightweight cylinders.
- The Stirling machines are very flexible. They can be applied as CHP (combined heat and power) in the winter and as coolers in the summer (a special design could also enable this with the magnetic power generation technology).
- The waste heat is relatively easy to harvest (compared to waste heat from an internal combustion engine) making the Stirling engines useful for dual-output heat and power systems.

Some disadvantages of the Stirling engines are the following:

- The Stirling engine designs require pressurized heat exchangers for the heat input and for the heat output (pressure of the working fluid is proportional to the power output). The “hot” heat exchanger is usually at very high temperatures, so the materials must resist the corrosion and the deformation. These requirements substantially increase the cost of the engine. The materials and assembly costs for the “hot” heat exchanger typically accounts for 40 % of the total engine cost.
- The dissipation of waste heat is especially complicated because the coolant’s temperature is kept as low as possible to maximize the thermal efficiency. This increases the size of the radiators, which can make the packaging difficult. Along with the materials cost, this has been one of the factors limiting the adoption of the Stirling engines as automotive prime movers. However, the high power density is not required in stationary microgeneration systems using combined heat and power (CHP).

- The Stirling engines, especially those running on small temperature differences, present large devices since they have a low power density. This is primarily due to the heat transfer coefficient of gaseous convection which limits the heat flux that can be attained in a cold heat exchanger and in a hot heat exchanger. Compared to the internal combustion engines, the heat transfer is one of the most important issues for the Stirling machine. The power density may be increased by a temperature difference and/or pressure. In analogy, a magnetic power generator requires a high temperature difference and the application of layered magnetocaloric material beds and a high magnetic flux density.

- A Stirling engine needs to "warm up" in order to start its operation. This is a characteristic of all external combustion engines, but the warm up time may be shorter for Stirling's than for others of this type such as steam engines.

- The power output of a Stirling tends to be constant what requires a careful design and additional mechanisms.

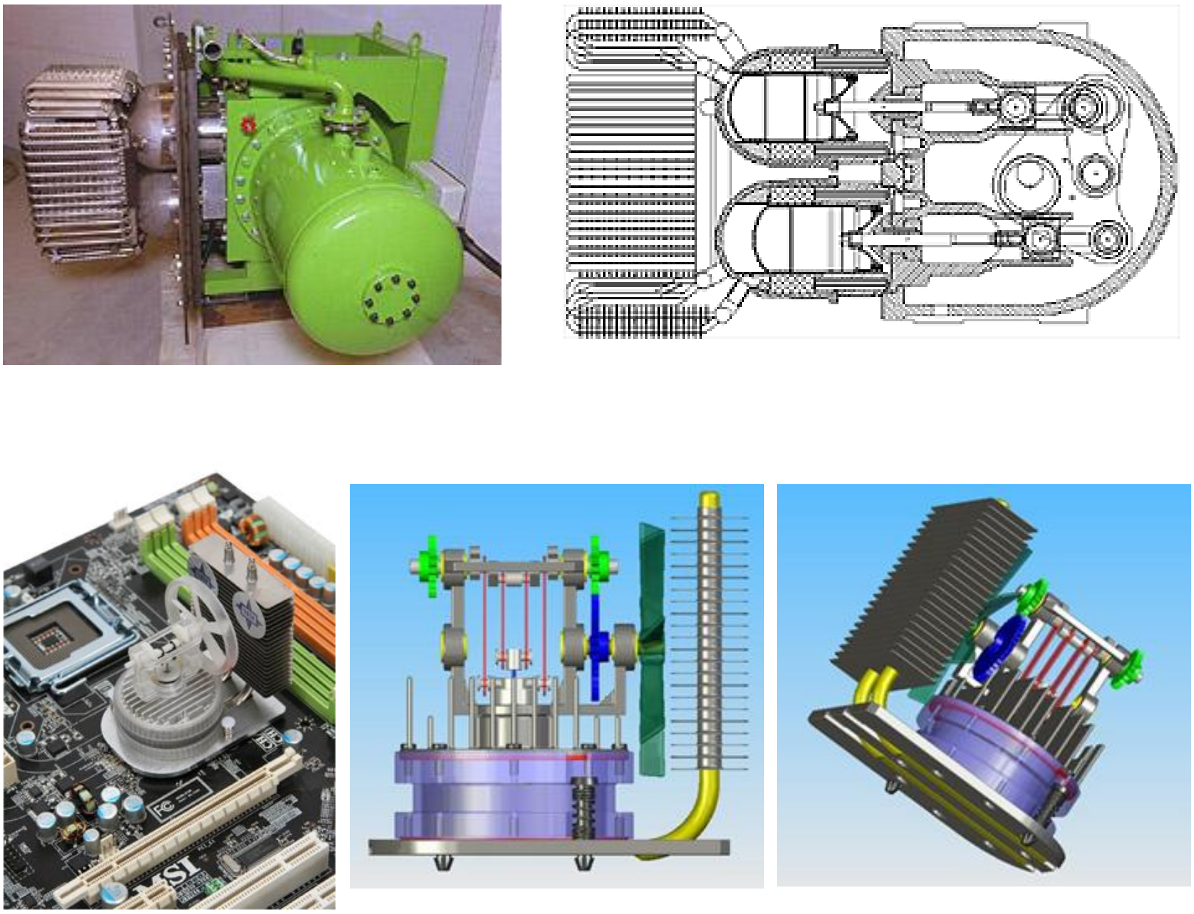


Figure 6: Stirling machines present an increasing market for small CHP power plants (TOP: example for biomass 35 kW power plant Stirling CHP) [10] and also a very interesting domain for certain other niches (BOTTOM: A miniature Stirling based air cooler for the CPU on the motherboard-power by heat from the CPU) [11].

2.2. THE ORC (ORGANIC RANKINE CYCLE) AND KALINA CYCLES

The ORC and Kalina cycles, both are utilizing thermal energy in order to convert it to mechanical power. A Rankine cycle is a closed circuit steam cycle. An "organic" Rankine cycle uses a heated chemical instead of steam as found in the Rankine Cycle. Chemicals used in the Organic Rankine Cycle include freon, butane, propane, ammonia and many other environmentally-friendly refrigerants. On the other hand, the Kalina cycle utilizes a working fluid comprised of at least two different components (typically water and ammonia) and the ratio between those components is varied in different parts of the system to increase the thermodynamic reversibility and therefore increase the overall thermodynamic efficiency. It is actually a kind of inverse absorption cycle for power production. The main advantage of the Kalina cycle is that the boiling of the ammonia-water mixture occurs over a range of temperatures, unlike steam and hence the amount of energy recovered from the gas stream is much higher.

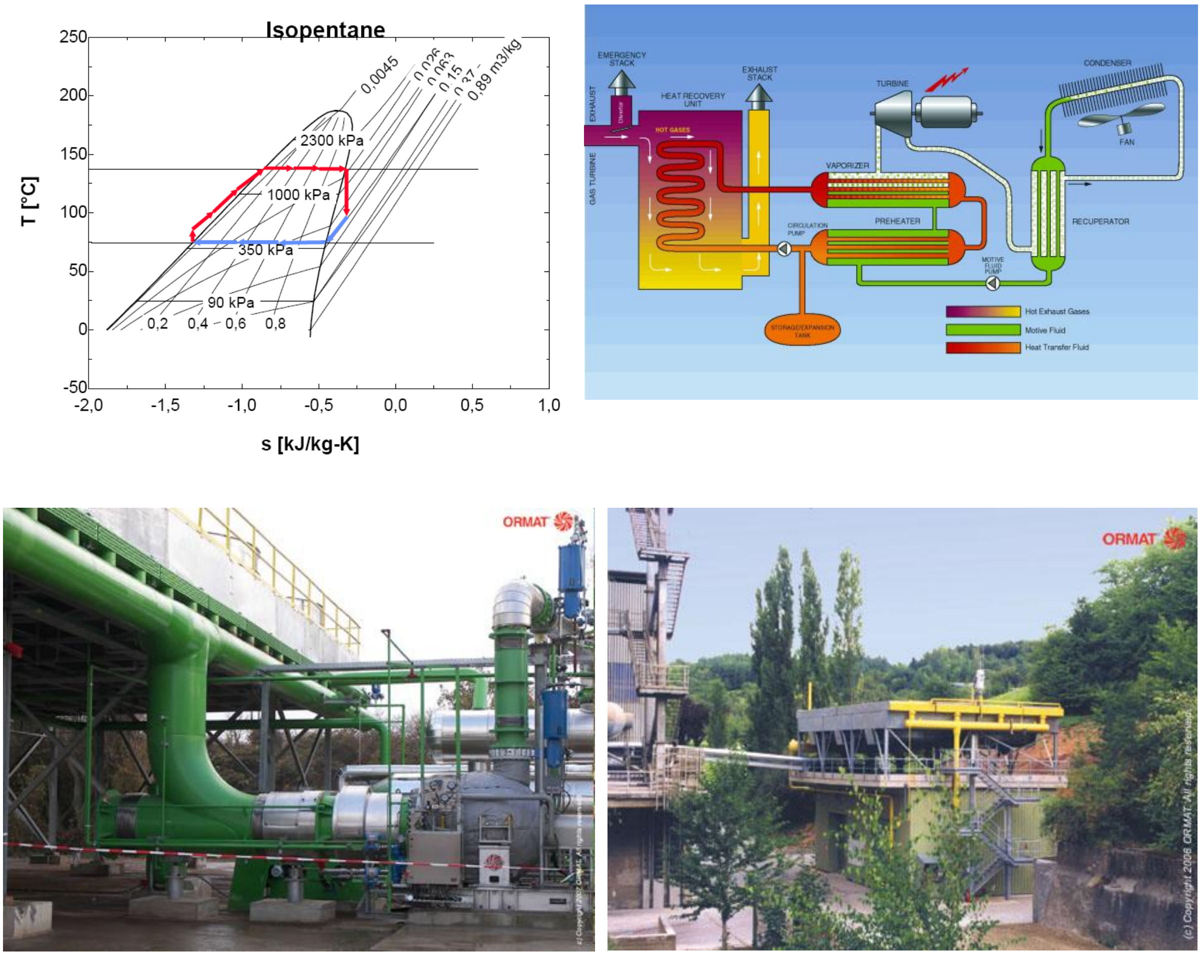


Figure 7: TOP: An example of the ORC cycle in a T-s diagram for the working fluid isopentane [12] and the schematics of the ORC power plant utilizing waste heat from exhaust of a gas turbine [13]; BOTTOM: A 2.9 MW ORC geothermal power plant in Landau in Germany and Industrial ORC heat recovery power plant from Clinker Cooler in Germany [13].

There exist plenty of possible applications for the ORC or Kalina technology, among which the most important domains are waste heat recovery, solar thermal power and geothermal power. Waste heat recovery is the most important development field for the ORC. It can be applied to heat and power plants (for example a small scale cogeneration plant on a domestic water heater) or to industrial and farming processes such as organic products fermentation, hot exhausts from ovens or furnaces, exhaust gases from vehicles, intercooling of a compressor, condenser of a power cycle, etc. The ORC technology may also be used in the solar parabolic trough technology in place of the usual steam Rankine cycle. The ORC allows a lower collector temperature, a better collecting efficiency (reduced ambient losses) and hence the possibility of reducing the size of the solar field. The ORC is perfectly adapted for lower temperatures applications (e.g. < 350 °C). However, it is important to keep in mind that for low-temperature geothermal sources (typically less than 100 °C) the efficiency is very low and strongly depends on the heat sink temperature (defined by the ambient temperature). As one may notice, all these utilizations also fit excellent with magnetic power generation!

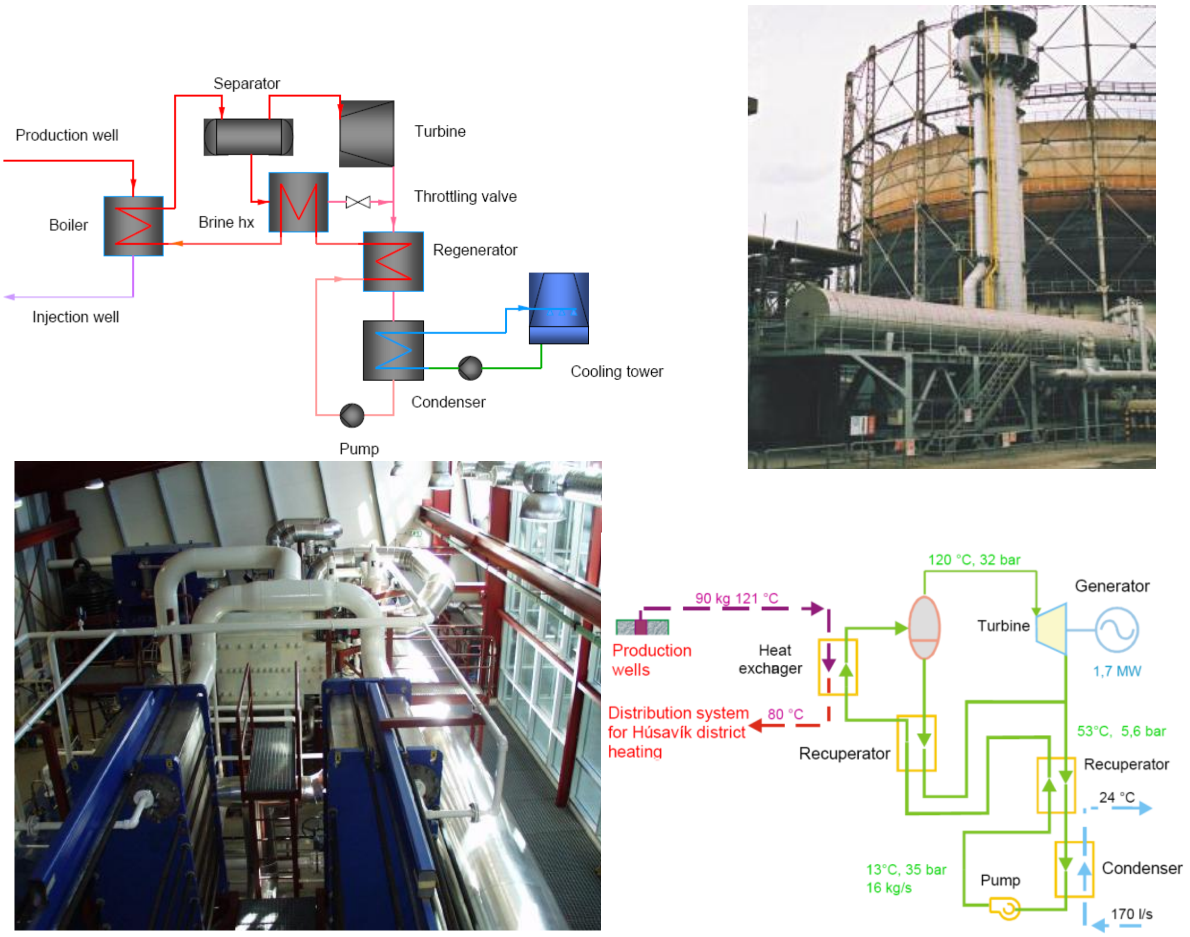


Figure 8: TOP: A schematic example of a process in a Kalina cycle [12] and a photography of a 3.1 MW Power Kalina applying waste heat's recovery from steel plant in Sumitomo, Japan [www.caddet.org]. BOTTOM: Husavik geothermal power plant (1.7 MW, designed for 1.95 MW) [12, 14] with corresponding schematics and operating conditions

The maximum power generated for a given source is greater for the Kalina cycle than for the ORC [12]. A Kalina cycle is well positioned against an ORC for applications with a high utilization time and a base load application. A heat consumer is beneficial for the ORC, as it results in less temperature change of the primary fluid during the boiling process. The Kalina cycle has the boiling or vaporization of the fluid happening over a temperature range up to 100 °C, which is beneficial when the primary fluid's return temperature has to be minimized. As reported in [12], the theoretical efficiency and cost/production ratios are better for Kalina when compared to ORC, while the Kalina cycle is thermodynamically superior or equal to the ORC.

In the Kalina cycle, the mixture of water and ammonia changes its temperatures during boiling and condensation and the geothermal water's temperature falls. The condensation temperature of the mixture can change by varying the ratio of water/ammonia in the mixture. The same applies for other fluid characteristics such as its boiling point and temperature of condensation, and their variations can be used to increase the production efficiency. After the fluid mixture has been heated in a heat exchanger, it enters a separator in which fluid and steam are separated. The steam (e.g. 120 °C, 32 bar in case of Husavik [14]), rich of ammonia, is routed through a turbine and expands as the pressure falls. Connected to the turbine is a generator producing electricity (see Figure 8 on the bottom to the right). The fluid is separated from the steam before the turbine is used for pre-heating a fluid mixture that is being routed to the heat exchanger. After the pre-heater the fluid and the steam from the turbine are mixed together again (e.g. 53 °C, 5.6 bar in case of Husavik [14]). The water/ammonia mixture of both fluid and steam is then sent to a recuperator where it is cooled down. Afterwards it enters a condenser where it returns to a fluid state (13 °C in case of Husavik [14]). The cooling in the condenser is achieved by using cooling water (190 l/s, 5 °C in case of Husavik [14]). The cooling water leaves the condenser at a temperature of 24 °C (depending on production the temperature is between 23 °C and 27 °C in case of Husavik [14]).

Up to present only few Kalina cycles have been realized [1]. According to [1], the disadvantages of the Kalina systems are:

- too few experiences of operation conditions
- working fluid is toxic
- because of the behavior of ammonia, high standards of design in view of materials and sealing are demanded
- more expensive than the ORC system
- requires larger heat exchangers than in the ORC system.

However, certain advantages are also stated for Kalina cycle. These are:

- cheap working fluid (many experiences with ammonia from refrigeration engineering and chemistry)
- adaptation of the working fluid to the given possible temperatures
- theoretically higher efficiencies possible than with ORC

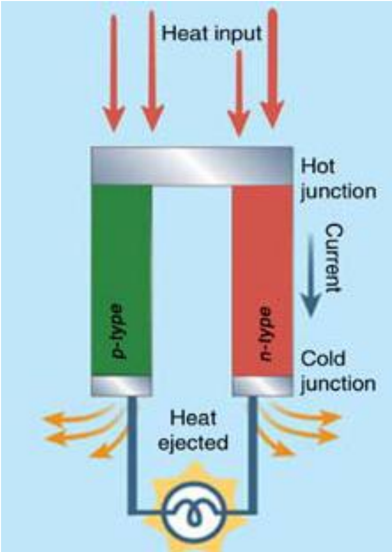
Table 1: Comparison between different geothermal power cycles [1]

	Kalina	**ORC**	**Steam**
Tu - range	70°C - 200°C	70°C - 200°C	from 200°C
investment costs	--	-	0
efficiency at low temperatures	++	+	-
efficiency at high temperatures	0	0	+
operation	-	0	+
experiences with technology	-	+	+

2.3. THE THERMOELECTRIC POWER GENERATORS

A thermoelectric power generator converts heat energy into electrical energy as a heat flux moves from the high to the low temperature spot. The heat source can be of a wide range of temperature, namely from -200 to 2000°C.

In a thermoelectric material there are free electrons (or holes) which carry charge and heat. The electrons and holes in a thermoelectric semiconductor behave like a gas of charged particles [15]. If a normal (uncharged) gas is placed in a box within a temperature gradient, where one side is cold and the other is hot, the gas molecules at the hot end will move faster than those at the cold end. The faster hot molecules will diffuse further than the cold molecules and so there will be a net build up of molecules (higher density) at the cold end. The density gradient will drive the molecules to diffuse back to the hot end. In the steady state, the effect of the density gradient will exactly counteract the effect of the temperature gradient so there is no net flow of molecules. If the molecules are charged, the buildup of charge at the cold end will also produce a repulsive electrostatic force (and therefore an electric potential) to push the charges back to the hot end. The electric potential (voltage) produced by a temperature difference is known as the Seebeck effect and the proportionality constant is called the Seebeck coefficient. If the free charges are positive (the material is of p-type), they will build up on the cold which will have a positive potential. Similarly, negative free charges (n-type of material) will produce a negative potential at the cold end. If the hot ends of the n-type and p-type material are electrically connected and a load connected across the cold ends, the voltage produced by the Seebeck effect will cause the current to flow through the load, generating electrical power. The temperature difference provides the voltage, but it is the heat flow which enables the current to flow.



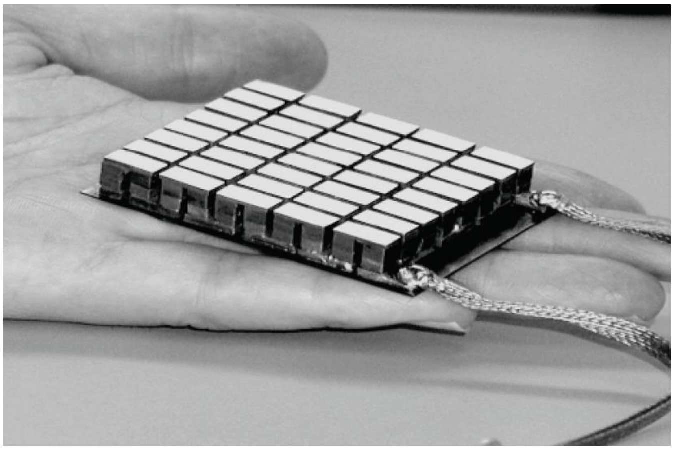


Figure 9: A basic schematics of a thermoelectric power module [16] and a photography of a segmented thermoelectric power module with a power of up to 160 Watt [17].

A thermoelectric generator behaves like an ideal voltage source with an internal resistance due to the resistance of the thermoelectric materials themselves. The voltage at the load is reduced from the open circuit voltage by the Ohm's law voltage drop due to this internal resistance. The maximum efficiency is reached when the load and the internal resistances are nearly equal because this is close to the maximum achievable power. The resistance of the thermoelectric elements depends on the electrical resistivity as well as the length and cross sectional area. Just as the power in a resistor, the power produced in a thermoelectric generator depends on the square of the voltage (Seebeck coefficient and temperature difference) divided by its resistivity. Notice also that the power per area can be arbitrarily adjusted with *l* (length). The efficiency of a generator doesn't just depend on the power produced, but also on how much heat is provided at the hot end. The heat input is needed for the thermoelectric process (Peltier effect) as well as the normal thermal conduction (Fourier's law) and is offset by the Joule heating in the device. Fourier's law of thermal conduction of the thermoelectric materials adds a thermal path from hot to cold that consumes some heat and reduces the efficiency.

The maximum efficiency of a thermoelectric material depends on two terms. The first is the Carnot efficiency. The second is a term that depends on the thermoelectric properties (the Seebeck coefficient, the electrical resistivity and the thermal conductivity). These material properties all appear together and thus form a new material property which is called ZT, the Thermoelectric Figure of Merit.

Figure 10 shows ZT values for different kinds of bulk and also other materials. Many materials have an upper temperature limit of operation above which the material is unstable. Therefore, no single material is the best for all temperature ranges, so different materials should be selected for different applications based on the temperature of operation. This leads to the use of a segmented thermoelectric generator.

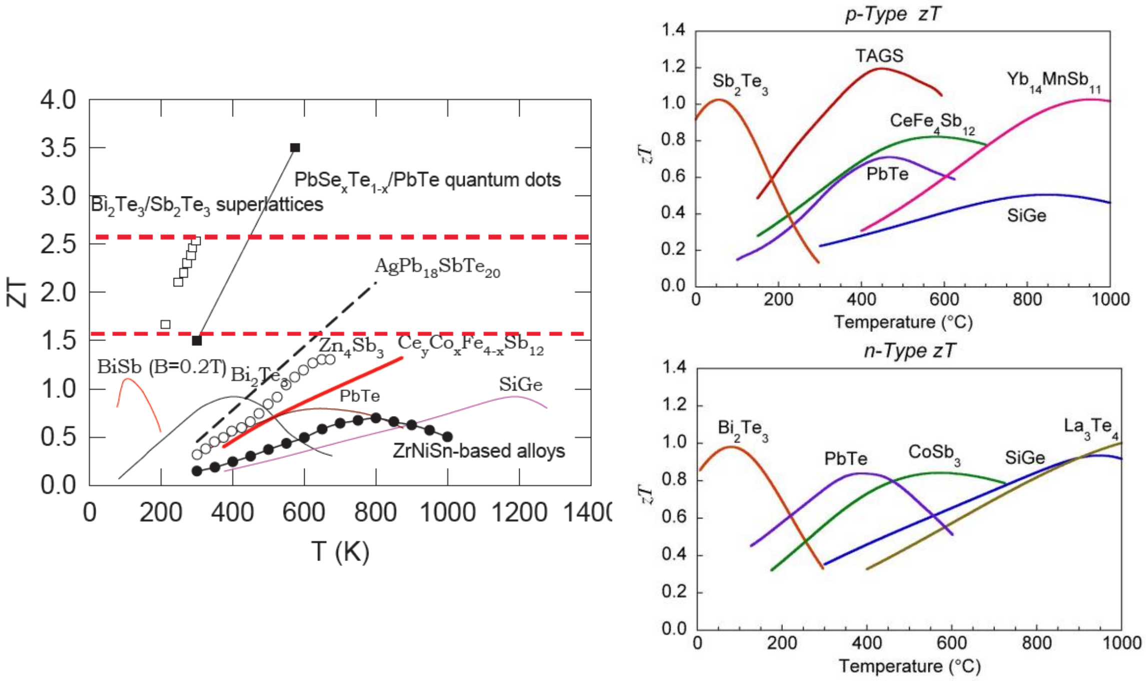


Figure 10: Figures of merits for different types of thermoelectric materials [17] and different temperature levels (from reference [15]).

Until recently, the maximum attainable ZT value was around one. However, significant advances have been made over the last 10 years with new thermoelectric materials being developed (see Figure 11).

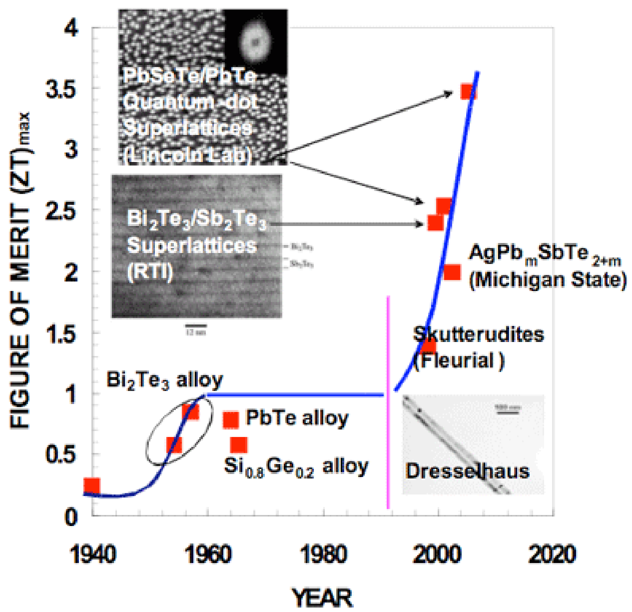


Figure 11: The performance of the thermoelectric power generators is quantified by the figure-of-merit, $ZT=S^2\sigma T/k$, where S is the Seebeck coefficient, σ the electrical conductivity, k the thermal conductivity and T the absolute temperature. The use of nanomaterials aims to increase the thermoelectric efficiency by increasing the ratio of electrical to thermal conductivity, σ/k (see reference[18]).

The thermoelectric power generators have some similar advantages as the other alternative technologies:

- It is a clean and environmentally benign technology which does not depend on fossil fuels or radioactive isotopes and the power is generated simply by a “temperature difference”
- No moving parts, what is also related to durableness
- Small temperature differences are sufficient to generate power
- It may be applied as power generation for almost any heat source
    - Natural (solar heat, ocean heat, geothermal heat, body heat, ambient temperature differences)
    - Artificial (industrial waste heat, transport waste heat, garbage incinerator waste heat, co-generation plants including fuel cells, radioisotopes).

Figure 12 shows some real examples of thermoelectric power generators.

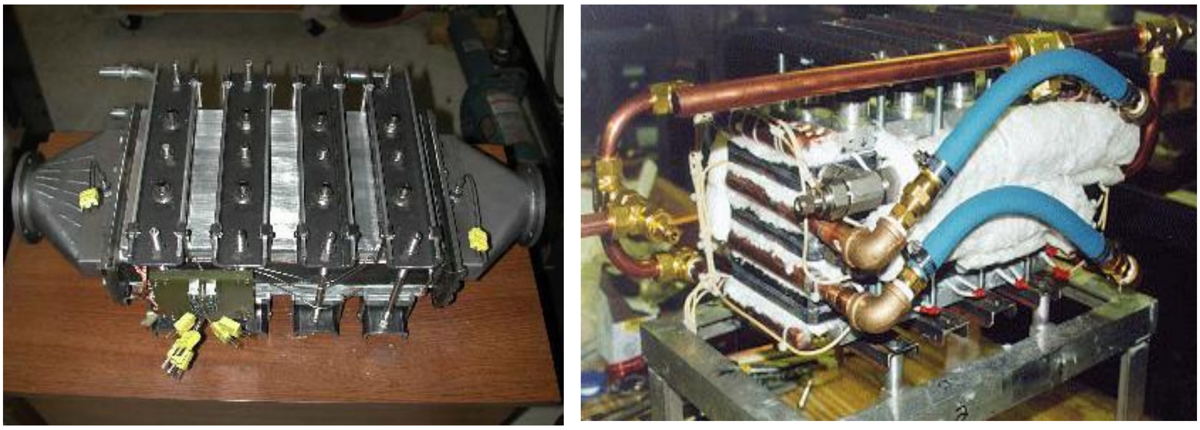


Figure 12: Left: Photo of the 330 W thermo electric power generator for GM 1999 Sierra Pickup Truck equipped with a power management system to charge 12 V and 42 V batteries. Suitable for light trucks and passenger vehicles. Right: Waste heat recovery from burning garbage 500 Watt at 50 V TEG uses hot oil from the garbage burning plant (assembled with 32 modules) (from [19]).

3. CONCLUSION

All the presented power technologies presented in this appendix match the temperature operation levels, as well as the types of heat sources, that would also be applied by the magnetic power generation technology. Figure 1 is an attempt to illustrate different efficiencies of technologies such as Stirling, Organic Rankine, Thermomagnetic and Magnetocaloric. Since the data available on exergy efficiencies are not equally defined for each technology, it is important to emphasize some assumptions. The thermoelectric power generators will reach lower exergy efficiencies for the same ZT factors as presented in Figure 1, because the calculation did not take into account the heat transfer irreversible losses, the heat losses and also the fluid friction losses, which could take some 20 % of the exergy efficiency shown in Figure 1. Furthermore, one should take into account that the thermoelectric materials available on the market do not reach very high ZT factors, so a rather conservative (e.g. ZT<2) approach should be made for the present stage of development of this technology, despite many new research achievements are reported. When considering data on ORC efficiencies, it has to be emphasized that exergy efficiencies correspond to the real plant efficiency, so they probably show most correct results. Unfortunately, the data from some sources available for efficiencies of ORC and Kalina cycle (reported to reach 60 % or higher exergy efficiency in real plants) did not match the exergy efficiency calculations, which we have performed in order to check the correctness of those data, but where much closer to what is presented in Figure 1. One should also note that the real exergy efficiency of ORC or Kalina cycles would follow the red line in the sense of approximately converging to values, which are e.g. presented for thermoelectric power generation with a ZT factor between 4 and

5. However, the BFE report on geothermal power utilization [1] shows temperature utilization limits for the two mentioned cycles approaching the 350 °C, where beyond, more practical would be the implementation of a condensing steam turbine or other types of technologies. For the Stirling thermoacoustic generator, the efficiency marked by "real" (Figure 1) shows more realistic results. It has to be noted that Stirling engines operate also at lower temperatures of heat sources. However, one may generally conclude, that their feasibility compared to the other technologies is much better at higher temperatures of heat sources, what may well define their application according to the temperature source. Unfortunately no data was found for Stirling engine's efficiencies performed for lower or very high temperatures of heat sources.

As a general conclusion one can say that magnetic power generation has especially a high potential in low temperature heat source systems (low exergy), up to some 350 °C. More precisely, the market niches for magnetic power generation seems to be very feasible especially for heat sources below 200 °C. The main reason is the present knowledge and availability of magnetocaloric materials, especially because of the very small activities of research on magnetocaloric materials for high temperature applications. However, based on the results shown in Figure 1, an important conclusion is that special research efforts should also be made in terms of large scale superconducting and high temperature magnetic power generators, because of a predicted superiority over other alternative technologies.

There should be serious investigations also of the potential of hybrid magnetocaloric and other existing technologies.

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