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APPLICATIONS OF MAGNETIC «POWER PRODUCTION» AND ITS ASSESSMENT

OVERVIEW OF AND COMPARISIONS WITH EXISTING TECHNOLOGIES OF POWER CONVERSION

Final report: Appendix 1

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1. INTRODUCTION

This appendix deals with existing technologies, which may be used in power conversion by the utilization of the following heat sources:

- solar
- geothermal
- industrial waste heat
- transport waste heat
- heat from power (CHP) and incineration plants
- special systems and sources.

For these heat sources, different possible applications of the magnetic power conversion exist. Certain applications may have substantial advantages over the others, depending on the operation characteristics. Generally, for a magnetic energy conversion machine with a given magnetic field source and geometry of the magnetocaloric porous structure, this mostly depends on the temperature difference between the heat source and the heat sink, as well as on the working fluid properties.

Most of the above mentioned heat sources do not represent pure exergy and this is as well the case for fossil fuels, nuclear fuels, bio-fuels and similar. However, heat is always a product of these sources, so it presents a possibility for applications of magnetic power conversion.

2. SOLAR POWER

There exist numerous ways for the utilization of solar energy. The most common application is to generate heat from solar radiation on solar collectors, where the heart of a collector is the absorber, usually composed of several narrow metal strips. Such applications serve for the production of heat, e.g. sanitary water or pool heating. Another example is the photovoltaic cells, where electric energy is generated by the photoelectric effect. Some efforts were also made in order to perform hybrid, small scale solar co generators by the combination of the two above mentioned technologies [1, 2]. A small scale solar co generator may also be found as a combination of the photoelectric and thermoelectric effect. Large scale applications, which are generally applied for electric power generation, apply concentrated solar radiation to generate heat, which is then applied in different processes. These processes are mostly based on the Rankine or Stirling cycle, and in some cases also on the Brayton cycle. The last presents a hybrid system, supported by additional fuel burners. There exist also tower systems, which convert solar radiation into a convective air flow in order to run axial turbines.

This chapter does not deal only with conventional solar power generators, but comprises a discussion on all the solar heat sources which may run magnetic power generators. Since these machines require a temperature difference to be operated, similar as Stirling or thermoelectric devices do, almost all the conventional solar heat generation solutions may be applied.

2.1. Solar collectors

Conventional solar collectors are a basic component of a usual solar-heating system. Solar collectors transform sun's radiation into heat, and then transfer heat to water or air or some other heat transfer fluid. The solar thermal energy from solar collectors may be applied for solar pool heaters, solar space-heating systems or in power production. However, low exergy level of the heat source also leads to low thermodynamic efficiency in power production, limited by its maximum defined by the Carnot efficiency. There are several types of solar collectors, but flat-plate collectors and evacuated-tube collectors are the most frequently applied.

Residential and commercial building applications require temperatures below 80 °C and usually apply flat-plate collectors, whereas those requiring temperatures higher than 80 °C use evacuated-tube collectors.

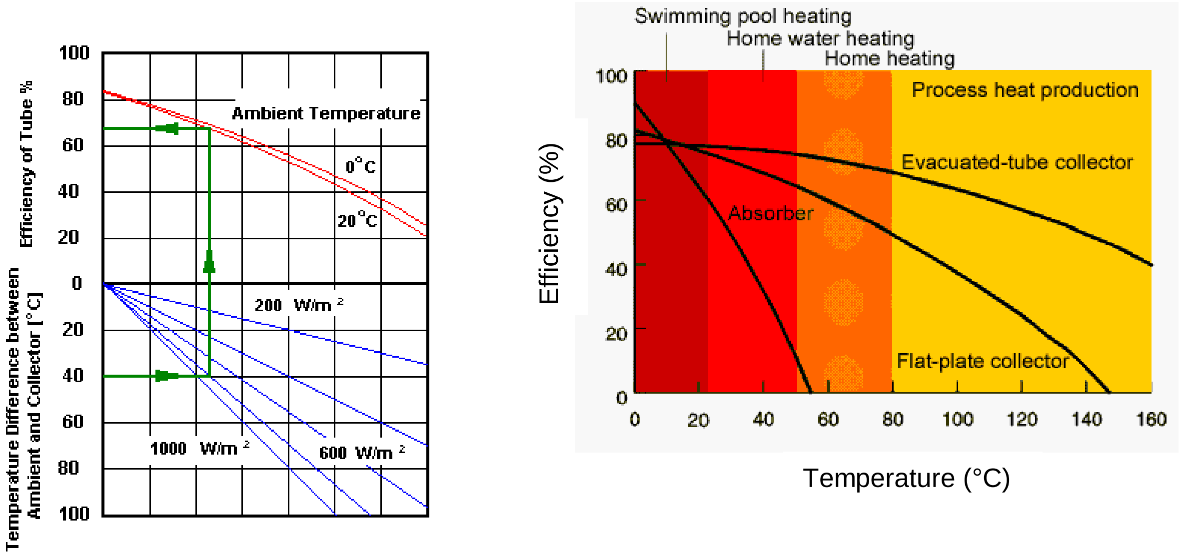


Figure 1: Left: Efficiency graph of an evacuated-tube solar collector for different radiations and different ambient temperatures [3]. The efficiency of a solar collector is defined as the quotient of usable thermal energy versus received solar energy**.** Right: Graph of the efficiency and temperature ranges of various types of collectors (radiation: 1000 W/m²) [4].

2.1.1. Flat-plate collectors

Flat-plate collectors are the most common solar collectors for solar water-heating systems in homes and solar space heating. A flat-plate collector consists of a dark-colored absorber, a transparent cover (glazing), a frame and some insulation. Usually an iron-poor solar safety glass is used as a transparent cover, as it transmits a great amount of the short-wave light's spectrum. These collectors transfer heat to liquid or air at temperatures lower than 80 °C. A small amount of the heat emitted by the absorber escapes through the cover and causes a greenhouse effect. The transparent cover prevents wind and breezes from carrying the collected heat away by convection. Together with the frame, the cover protects the absorber from adverse weather conditions. Typical frame materials include aluminum and galvanized steel; sometimes fiberglass-reinforced plastic is used. The insulation on the back of the absorber and on the side walls reduces the heat losses. Insulation is usually performed by polyurethane foam or mineral wool. Sometimes insulating materials made of mineral fiber like glass wool, rock wool, glass fiber or fiberglass are applied. Flat collectors demonstrate a good price-performance ratio, as well as a broad range of mounting possibilities (on the roof, in the roof itself or unattached).

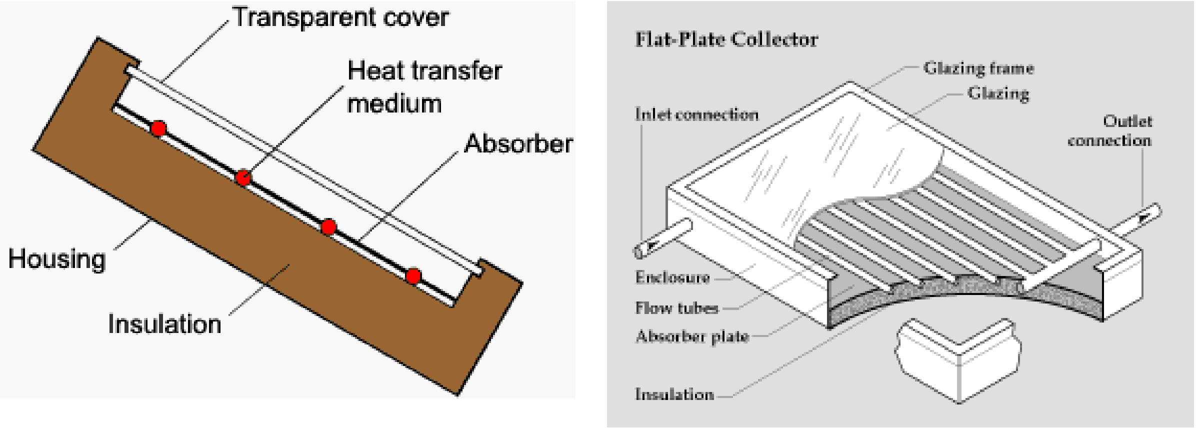


Figure 2: Conventional flat-plate collectors are used for residential water heating and hydronic space-heating installations. [4,5].

Flat-plate collectors with liquid filling

These collectors heat a liquid as it flows through tubes in or attached to the absorber plate. The simplest liquid systems use sanitary water, which is heated as it passes directly through the collector and then flows to the house. Solar pool heating also uses liquid flat-plate collector technology, but the collectors in this case are usually unglazed (see Figure 3).

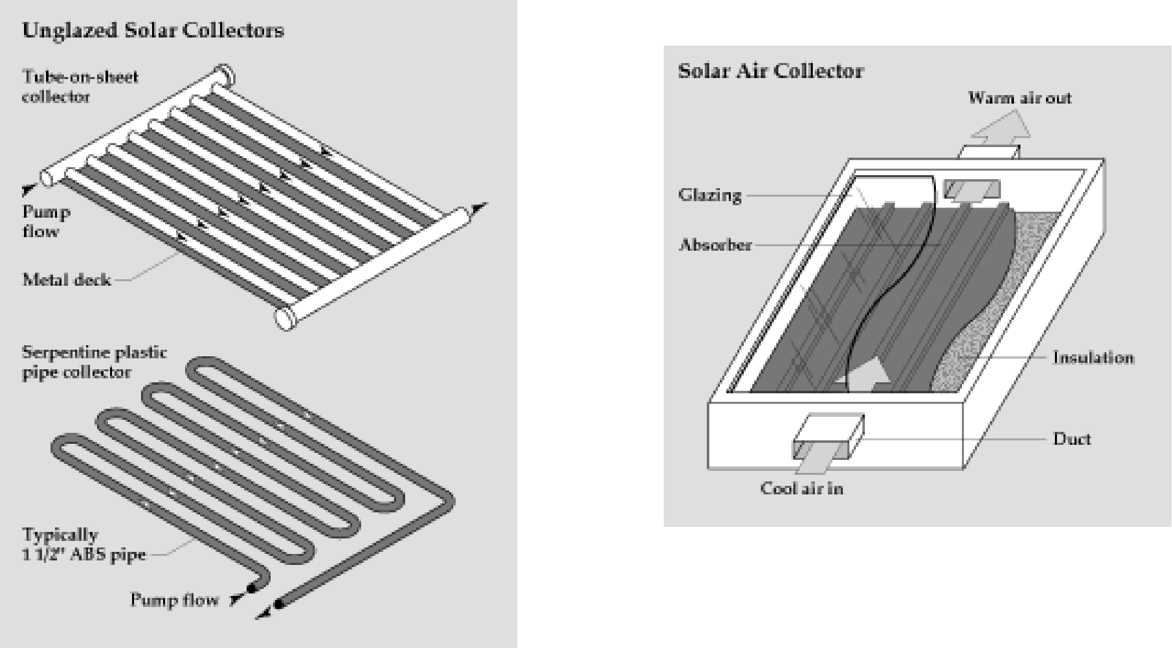


Figure 3: Conventional unglazed solar collectors typically used for swimming pool heating and conventional air flat-plate collectors used for space heating. [5].

Flat-plate collectors with air

Air flat-plate collectors are applied basically for solar space heating. The absorber plates in the air collectors can be metal sheets, layers of screen or non-metallic materials [5]. The air flows by using natural convection or a fan. Because air is not a so good conductor as liquid, less heat is transferred from the air collector's absorber than in the case of a liquid collector's absorber. Air collectors are typically less efficient than liquid collectors.

2.1.2. Evacuated-tube collectors

In order to reduce the heat losses caused by convection, the air can be pumped (evacuated) out of collector tubes. Such collectors are evacuated-tube collectors. They must be re-evacuated once every one to three years. Here, the absorber strip is located in an evacuated and pressure proof glass tube. The heat transfer fluid flows through the absorber directly in a U-tube or in countercurrent, in a tube-in-tube system. Several single tubes serially interconnected or tubes connected to each other via manifold, compose the solar collector [5]. A heat pipe collector comprises a special fluid (e.g. refrigerant) which begins to vaporize even at low temperatures. The steam rises in the individual heat pipes and warms up the carrier fluid in the main pipe by the heat exchanger (Fig. 4). The condensed liquid flows back into the base of the heat pipe. The pipes must be angled at a specific degree above horizontal, so that the process of vaporizing and condensing functions correctly. There exist two types of collector connections to the solar circulation system. In the first the heat exchanger extends directly into the manifold ("wet connection") and in the second it is connected to the manifold by a heat-conducting material ("dry connection"). A "dry connection" allows the replacement of the individual tubes without emptying the entire system [5]. Evacuated tubes operate efficiently with high absorber temperatures and with low radiation. Higher temperatures may also be obtained for applications such as hot water heating, steam production and air conditioning.

Conventional evacuated-tube collectors can achieve very high temperatures (80 °C to 180 °C). However, evacuated-tube collectors are more expensive than flat-plate collectors. Based on the information from reference [4], the evacuated-tube collectors are substantially more expensive (511–1278 Euro/m^2 collector surface) than flat-plate collectors (153 to 613 Euro /m^2) or even plastic absorbers (26 to 102 Euro /m^2).

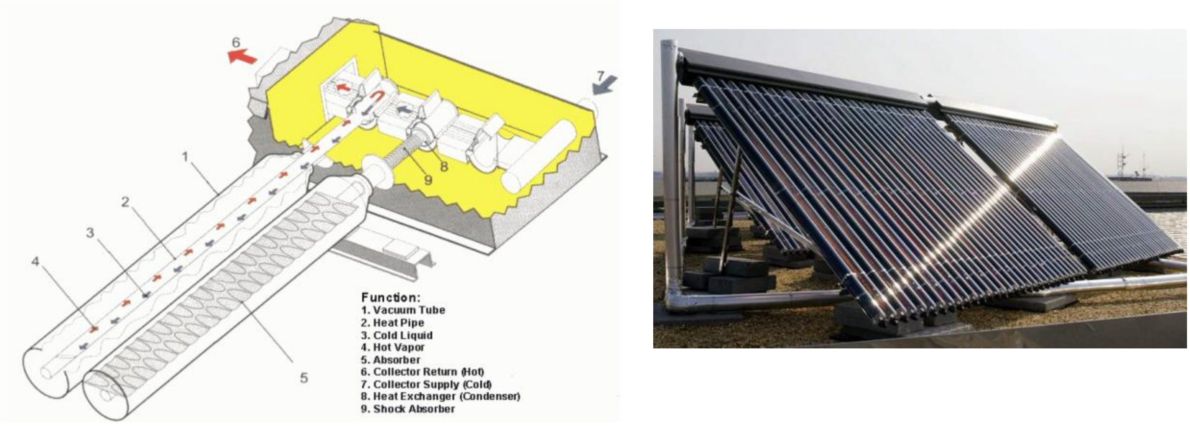


Figure 4: Left: The Titanium Nitride Oxide coated absorber fin transfers heat to the condenser via a heat pipe. The heat pipe is bonded continuously to an absorber fin inside a vacuum-sealed tube. Condensers are inserted into a chamber in the manifold header, where a heat transfer liquid circulates. Right: Example of the 75.6 kW thermal system, see reference [6].

2.1.3. Solar collectors for magnetic power production

A schematic example of the magnetic power generation performed by the application of solar collectors is seen in Figure 14 of the final report [7]. This final report shows different diagrams for the efficiency of liquid/liquid magnetic power generators (see e.g. Fig.'s 5 to 8 of the final report [7]). These results may serve for the evaluation of magnetic power generation by applying solar collector technologies.

As one may immediately notice from the data of the mentioned final report, such systems lead to a low thermodynamic efficiency, due to the low exergy level of the heat source. Based on the data for evacuated tube solar collectors found in reference [4], an analysis was made, in order to estimate the total surface of such collectors required for a magnetic power production of 1 kW of electric power. The analysis was made for different magnetic flux densities as well as different temperatures of the heat source. In the analysis the following parameters were taken into consideration: an ambient temperature of 25 °C, a volume fraction of magnetocaloric material of 30 % and a frequency of operation of 5 Hz. Figure 5 presents the results of the analysis. According to Figure 5, the operation of an evacuated tube collector applied together with magnetic power generation should be kept above 100 °C for the heat source temperature. A magnetic flux density of around 2 T (Tesla) with a solar radiation of 1000 W/m^2 would require approximately 20 m^2 of evacuated tube collectors. Increasing the magnetic flux densities in the range of superconducting magnets (e.g. 10 T) leads to a total required area of collectors for the same radiation of around 9 m^2. For an equivalent photovoltaic system with efficiency 10 %, 10 m^2 of surface would be required. Therefore, an obvious and a very important conclusion is that magnetic power generation based on flat plate glazed or evacuated tube collectors should preferably be performed only as cogeneration (heat and power production). The major reason is the low thermodynamic efficiency (but very high exergy efficiency) of such a system. An advantage of the magnetic power conversion system in this case is that it may present a supplementary heat utilization added to already existing systems. This increases the overall annual utilization and efficiency. Since such solar systems would not present a large scale power production site, permanent magnet based systems should be applied. More information on the efficiency as well as on the mass and the volume of permanent magnet based power generation systems may be found in the final report [7].

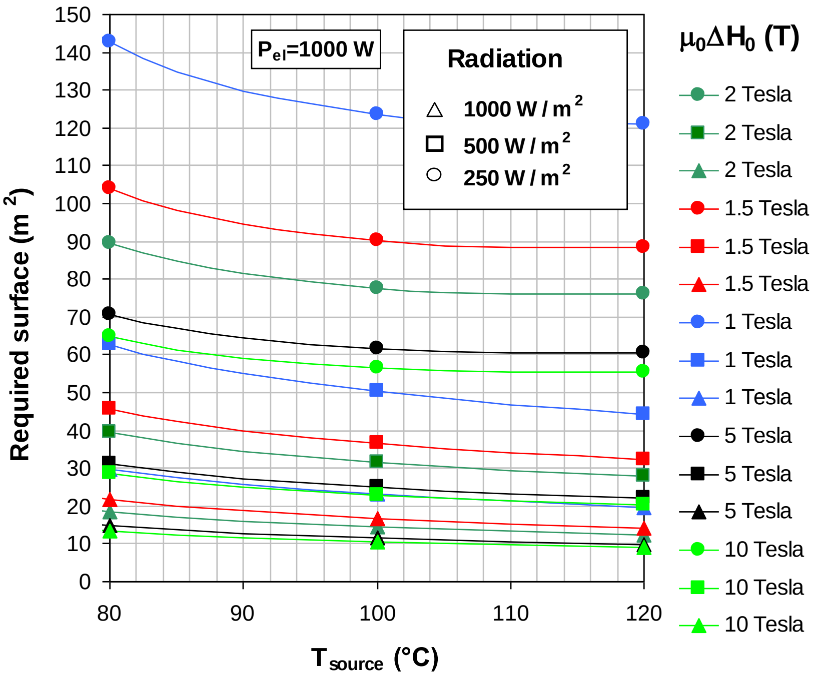


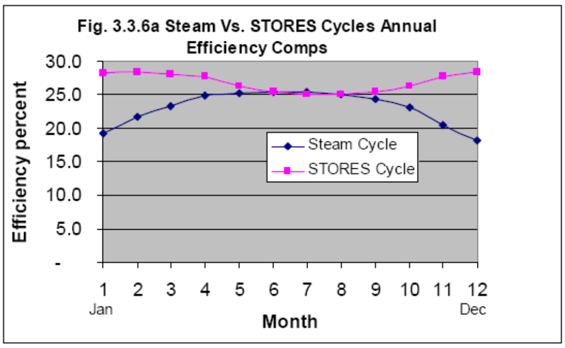
Figure 5: Required surface of the evacuated tube collectors for a magnetic power generation of 1 kW_{el} .

2.2. Concentrated solar energy

The three most common solar thermal power systems applying concentrated solar energy are parabolic troughs, solar towers and dish/engine systems. Because these technologies involve a thermal intermediary, they can be used in a combination with fossil fuels and in some cases adapted to use thermal storage. The basic advantage of performing a hybrid system and/or thermal storage is that these technologies can provide continuous power and operate during periods when solar energy is not available. Hybrid systems and thermal storage can enhance the economic value of the electricity produced and reduce its average cost. In this subchapter, the three technologies are presented and discussed. The photovoltaic concentrated solar power systems are not discussed here, because their operation does not relate to a heat source, despite one may assume that a hybrid concentrated photovoltaic–magnetocaloric power system would be an interesting solution for further investigations.

2.2.1. Parabolic Trough Systems

Parabolic trough technology is currently the most proven solar thermal to electric power conversion technology. These plants range in the size from 10 to 100 MW. Large fields of parabolic trough collectors supply the thermal energy usually applied to produce steam for a Rankine steam cycle. Temperatures of the working fluid vary between 300 to 400 °C, depending on the specific case. The two other options to produce electric power by an application of solar trough systems are ORC (Organic Rankine Cycles) or the Kalina cycle. The Organic Rankine Cycle uses a heated chemical instead of steam, as used in the original Rankine Cycle. Chemicals or refrigerants used in the Organic Rankine Cycle include freon, butane, propane, ammonia and the new "environmentally-friendly" refrigerants. The Kalina cycle is a thermodynamic cycle for converting thermal energy to mechanical power which utilizes a working fluid composed 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. When comparing the ORC with the classical 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 steam cycle cannot increase the output appreciably as a low ambient temperature leads to more condensation problems and thereby limits the performance. This is one of the reasons why in steam power plants, attempts were made to raise the heat transfer fluid temperature as much as possible. The supply of small steam turbines has also declined as the market declined, and small steam power plants are expected to be much more expensive than ORC power plants in the future, when the turbines will continue to be manufactured for pipelines, cryogenic and other markets [8]. Figure 6 shows a comparison between the efficiencies of an optimized Solar Trough Organic Rankine Energy System (STORES) and of steam systems for all twelve months of the year for the Kramer Junction area [8]. Figure 6 presents also the output's increase between the STORES plant and the Steam plant for a Kramer Junction through the year. It may be seen that the output of the STORES plant is significantly higher as the ambient temperature decreases. These differences are considered to be very important for remote areas lacking electrical power.



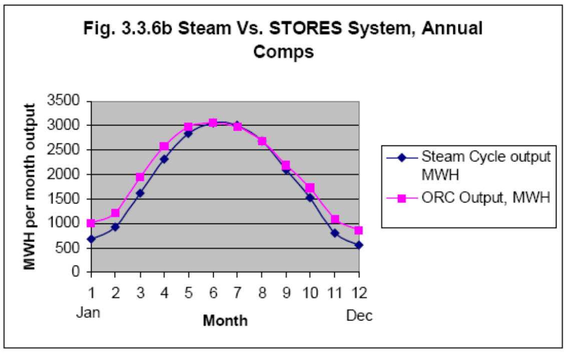


Figure 6: Comparisons STEAM versus STORES systems are presented on the left-hand side. A Kramer Junction area is shown on the photograph on the right-hand side [8, 9].

Generally, the ORC and Kalina cycles are used in geothermal power systems or with waste heat for power utilization. These two systems are more briefly presented in Chapter 2.2. of Appendix 2.

The parabolic trough field consists of a large field of single-axis tracking solar collectors (see Figure 7). It is constructed as a long parabolic mirror (usually coated silver or polished aluminum) with a Dewar tube running on all its length at the focal point. Sunlight is reflected by the mirror and concentrated on the Dewar tube. The solar trough is usually aligned on a north-south axis and rotated to track the sun as it moves across the sky each day. A heat transfer fluid is heated as it circulates through the receiver and returns to a series of heat exchangers in the power block. There, the fluid generates high-pressure superheated steam. The superheated steam is then distributed to a conventional reheat steam turbine/generator to produce electricity. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchangers. Condenser cooling is usually provided by cooling towers. These plants can operate at full rated power using solar energy alone. During the summer season, these plants typically operate for 10 to 12 hours a day at full-rated electric output. However, up to present, all plants have been performed as hybrid solar/fossil plants. They apply a backup fossil-fired system that can be used to supplement the solar output during periods of low solar radiation [5, 10].

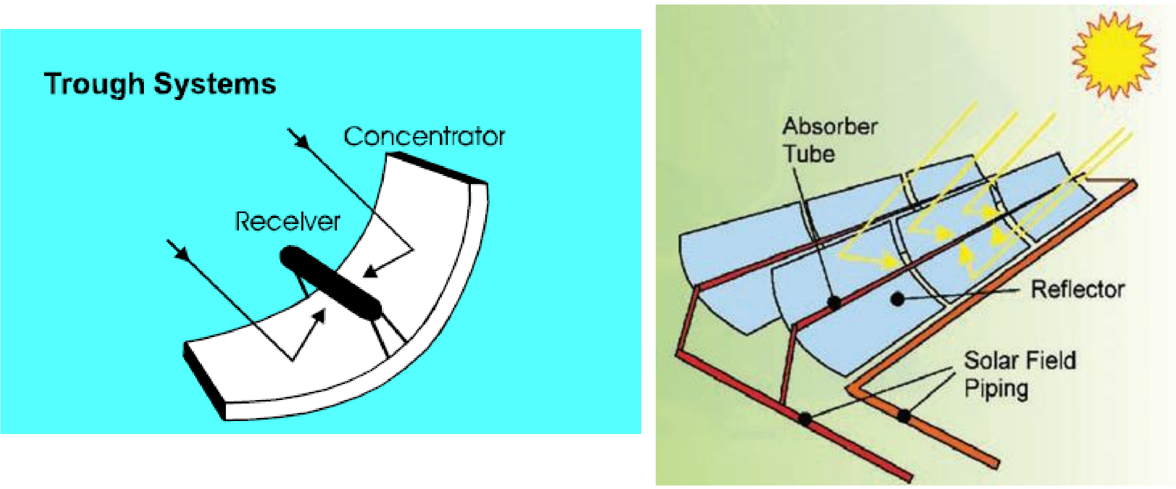


Figure 7: A parabolic trough power system is shown [5, 10].

Figure 8 shows a parabolic trough steam Rankine system, where the optional natural-gas-fired heater is situated in parallel with the solar field. Another case is when the optional gas steam boiler/reheater is located in parallel with the solar heat exchangers. The fossil backup can be used to produce rated electric output during overcast or nighttime periods. Figure 8 also shows the thermal storage as a potential option that can be added to a system.

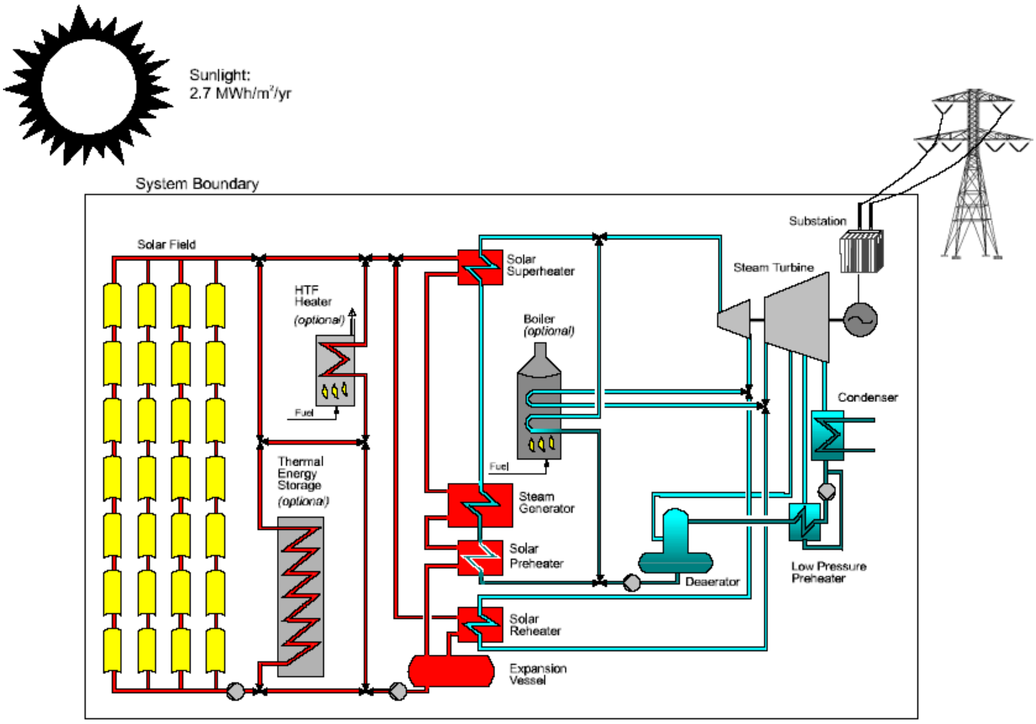


Figure 8: Parabolic trough steam Rankine power system with an optional natural gas heater can be seen above (after reference [5]).

Another solution is an Integrated Solar Combined Cycle System (ISCCS) [5]. This concept integrates a parabolic trough plant with a gas turbine combined-cycle plant. Such a system enables reduced costs and an improvement of the overall efficiency. The ISCCS applies a solar heat as supplement to the waste heat from a gas turbine in order to increase power generation in the steam Rankine cycle. Here solar energy is applied to generate additional steam. The gas turbine's waste heat is used for preheating and steam superheating (see Figure 9).

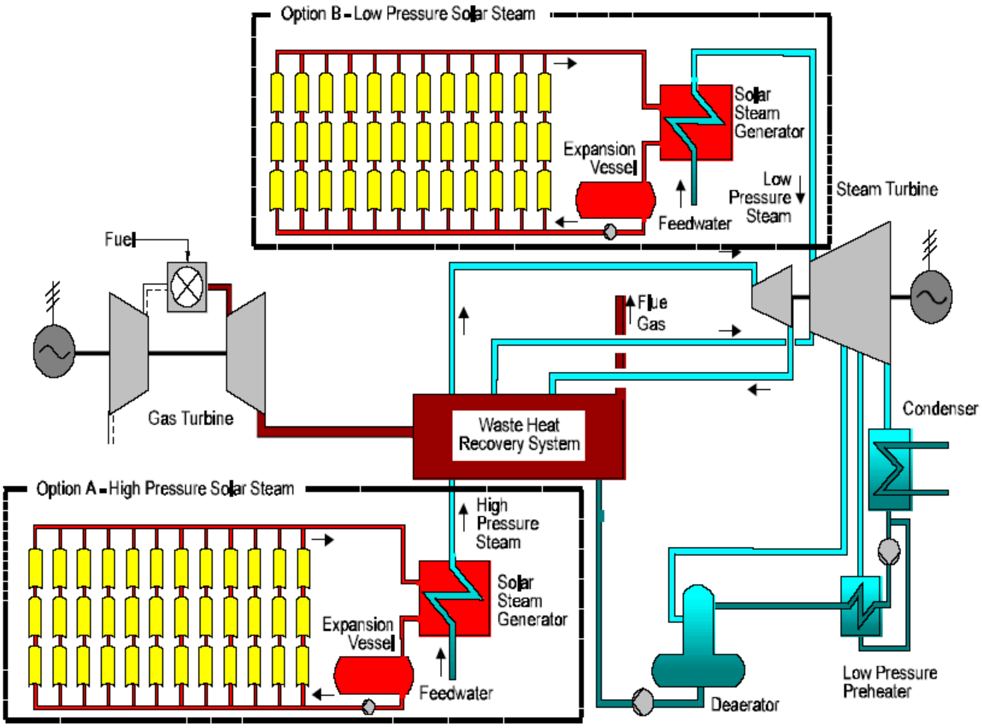


Figure 9: Integrated solar combined cycle system is shown in this drawing (from reference [5]).

2.2.2. Solar trough technology for magnetic power production

An example of a solar trough magnetic power production system is shown in Figure 12 of the final report [7]. Because of the high temperature levels of the heat source, the heat transfer fluid (or working fluid) in magnetic power generators should be carefully selected. Special oils, suitable for high temperatures up to 350 °C, usually present a higher viscosity at lower temperature levels, which substantially decreases with the increase of temperature. Figures 5 to 8 of the cited final report show a discontinuous jump of data at temperature levels of 120 °C. The reason for this jump is based on the assumption that with the heat source temperatures up to 120 °C, a water based system could be performed and that above these levels applications should comprise special heat transfer oils. In order to avoid such a reduction in the efficiency, a more efficient way is the application of a magnetic power generation system, constituted of two sub-systems. The first subsystem would operate at a higher temperature level with a heat sink temperature just below the evaporation of the water (depending on its pressure), e.g. at some 120 °C and with a heat source temperature of the solar trough system. The second subsystem would apply water as working fluid with a heat sink at ambient conditions. Magnetic power conversion, applying solar trough systems (which are rather large scale systems), is especially interesting when using superconducting magnets, especially because of their very high efficiency. More information on the efficiency may be found in the final report [7].

2.2.3. Solar Tower Technology

Solar towers generate electric power from sunlight by focusing concentrated solar radiation on a tower-mounted heat exchanger (receiver). The system uses hundreds to thousands of sun-tracking mirrors (heliostats) to reflect the incident sunlight onto the receiver. These plants are best suited for utility-scale applications in the 30 to 400 MW_{el} range (Figure 10).

In a molten-salt solar power tower, liquid salt is used as the primary fluid in the system. From the “cold” storage tank at some 290 ºC, the fluid is pumped through the receiver, where it is heated to 565 ºC and then distributed to a ‘hot’ tank for storage [5]. When power is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle. From the steam generator, the salt is returned to the cold tank, where it is stored and eventually reheated in the receiver.

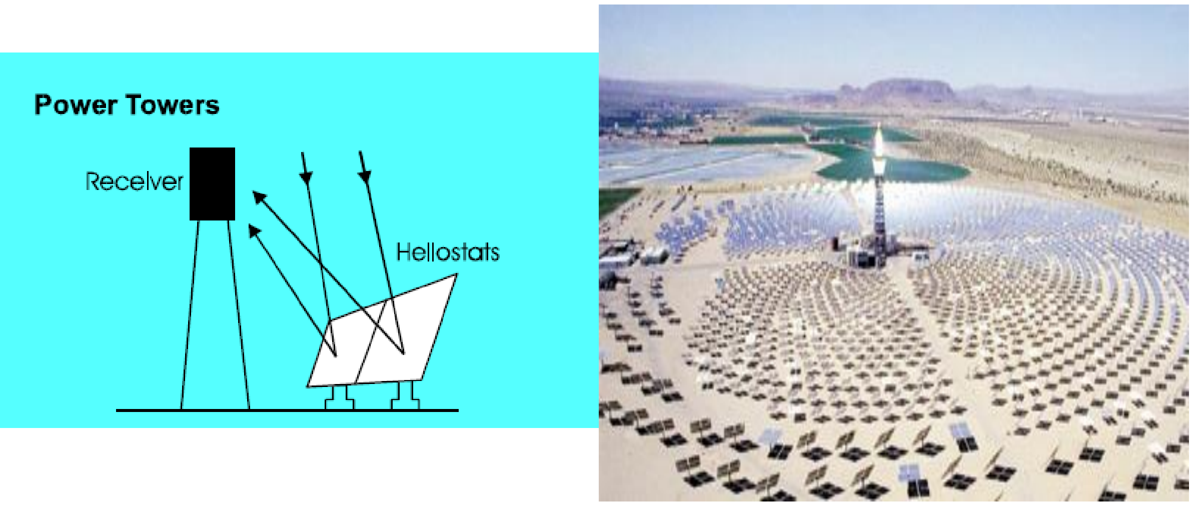


Figure 10: A solar tower system after reference [5].

Figure 11 presents the primary flows' paths in a molten-salt solar power plant. The optimum storage size is an important part of the system design process in order to meet power-dispatch requirements. Storage tanks can be designed with sufficient capacity to power a turbine at full output for up to 13 hours [5].

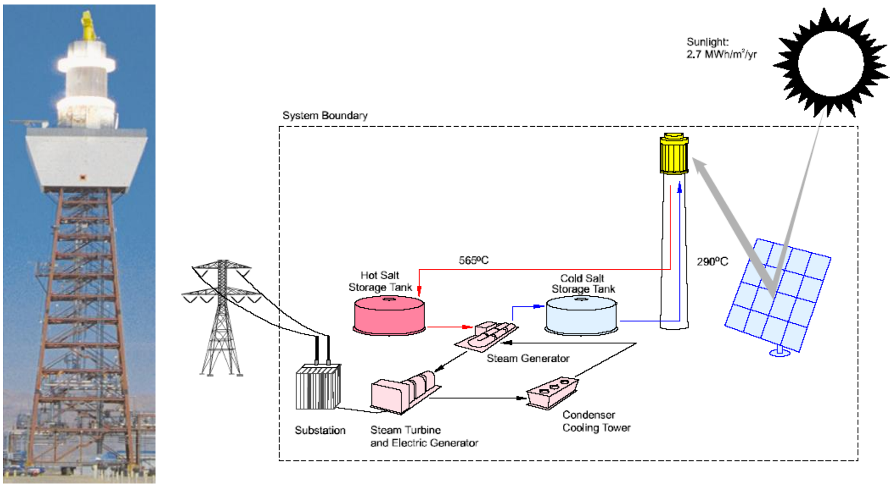


Figure 11: Molten-salt solar power tower system (see reference [5]).

The heliostat field surrounds the tower with the receiver (Figure 11). The field and the receiver are also sized depending on the needs of the utility. Usually the collected solar energy exceeds the maximum which is required for a steam turbine. The thermal storage system can thus be charged at the same time that the plant is producing power at full capacity. The ratio of the thermal power provided by the collector system (the heliostat field and receiver) to the peak thermal power, required by the turbine generator, is called the solar multiple. With a solar multiple of approximately 2.7, a molten-salt power tower located in the California Mojave desert can be designed for an annual capacity factor of about 65 % [5]. Consequently a solar tower could potentially operate for 65 % of the year without the need for a back-up fuel source. Without energy storage, solar technologies are limited to annual capacity factors near 25 %. Because of the storage, the power output from the turbine generator remains constant through fluctuations in solar intensity.

2.2.4. Solar Tower Magnetic Power Generation

The temperature levels of the solar tower technologies exceed the applications' areas of heat transfer oils as the working fluids in a magnetic power generation system. Therefore, one may expect that magnetic power conversion systems could operate as the supplementary machines to steam turbines, where temperature levels of the “cold” storage tank would be sufficient to run such a system. On the other hand, magnetic power generation may be applied as the basic power generation technology. In this case, high temperatures of heat sources call for special fluids such as Bi-Pb or other kind of liquid metal alloys. As in other high-temperature magnetic power generation systems, a solar tower-based magnetic power generation would consist of two or three subsystems, each operating with another working fluid. In such a way, a good overall efficiency could be reached. Because of the large scale system and required special fluids, which are very viscous, superconducting magnets should be applied in order to guarantee a very high efficiency. One should note that at present there are a very small number of magnetocaloric materials (which also have low performance) which would fit such high temperature requirements. A major reason for this is a lack of R&D in this domain of material science. More information is found in the final report [7], especially in Figures 11, 29 and Table 4.

2.2.5. Solar dish-engine systems

Solar dish-engine systems use a mirror array to reflect and concentrate the solar radiation to a receiver in order to achieve the required temperature level. The solar dish tracks the sun on two axes. The concentrated solar radiation is absorbed by the receiver and transferred to an engine.

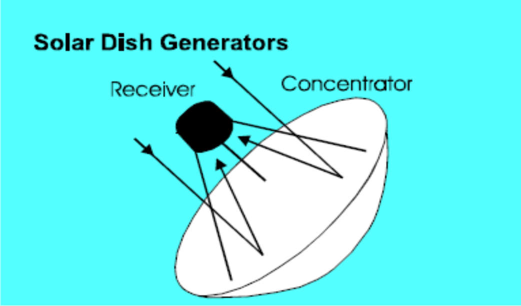


Figure 12: In this picture a solar dish-engine system is sketched [5].

Dish-engine systems apply an array of parabolic mirrors (stretched membrane or flat glass facets) to focus the solar energy onto a receiver located at the focal point [5]. The fluid in the receiver is heated to 750 °C and used to generate electricity in a small engine attached to the receiver. Present engines are mostly based on a Stirling and Brayton cycle technology. Several prototype dish/engine systems, ranging in size from 7 to 25 kW have been applied in practice. High optical efficiency and low startup losses make dish/engine systems the most efficient (29.4 % record solar to electricity conversion) of all solar technologies. The modular design of such systems enables remote power needs in the kilowatt range. When performed as a hybrid (e.g. with fossil fuels), they may serve as end-of-the-line grid-connected applications in the megawatt range [5]. These systems are characterized by high efficiency, modularity, autonomous operation and an inherent hybrid capability (the ability to operate on either solar energy or fossil fuels or both).

Stirling engine receivers transfer concentrated solar energy to a high-pressure oscillating gas, usually helium or hydrogen. In Brayton receivers the flow is steady, but at relatively low pressures. There are two general types of Stirling receivers: direct-illumination receivers (DIR) and indirect receivers, which use an intermediate heat-transfer fluid. Directly-illuminated Stirling receivers adapt the heater tubes of the Stirling engine to absorb the concentrated solar flux. Because of the high heat transfer capability of high-velocity, high-pressure helium or hydrogen, direct-illumination receivers are capable of absorbing high levels of solar flux. To balance the temperatures and heat addition between the cylinders of a multiple cylinder Stirling engine, liquid-metal heat-pipe solar receivers are applied. In the heat-pipe receiver, liquid sodium metal is vaporized on the absorber surface of the receiver and condensed on the Stirling engine’s heater tubes. This results in a uniform temperature on the heater tubes, enabling a higher engine working temperature for a given material and consequently a higher efficiency. The heat-pipe receiver isothermally transfers heat by evaporation of sodium on the receiver/absorber and condenses it on the heater tubes of the engine. The sodium flows to the absorber because of gravity. It is then distributed over the absorber by capillary forces [5]. More information on the Stirling technology is also found in Appendix 2.

2.2.6. Magnetic Power Generation applying solar dish systems

Similar as for the solar tower technology, the magnetic power generation may be applied here as a supplementary technology, based on the lower temperature levels or as a full converter of the whole temperature span. Since solar dish engines are usually not very large-scale systems, such as parabolic troughs and solar tower systems, their application for magnetic power generation should be modified in order to enable large-scale systems with superconducting magnets. This is especially important due to the high efficiencies achieved despite the drawbacks of the applied viscous fluids. It is also very difficult to predict how magnetic power generation systems would operate on a basis of vaporized liquid sodium metals, as this is the case in conventional solar dish engines. Furthermore, the present stage of development of magnetocaloric materials for power production did not enter the field of high temperatures, so it is rather hard to estimate the developments in this direction. Despite that, some valuable information may be found in the final report [7]. In the analysis a fictive magnetocaloric material was tuned to high temperatures with the properties of Gadolinium.

3. GEOTHERMAL POWER

There exist four conventional geothermal power plant technologies to convert hydro-thermal fluids to electricity. These conversion technologies are dry steam, flash, binary and the Kalina cycle. The last two may be grouped together in this particular case. The type of a conversion system depends on the state of the fluid (whether steam or water) and its temperature. Special systems with the supercritical conditions are also studied, especially because of their large exergy potential (see Figure 13).

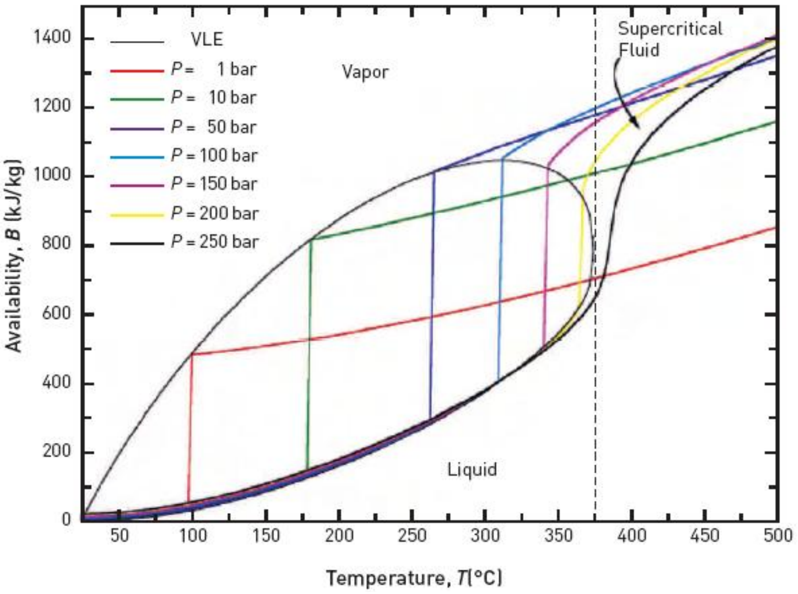


Figure 13: Exergy (availability) diagram for water. The magnitude of the exergy (availability) is a direct measure of the maximum electrical work or power producing potential of aqueous produced geofluid at specific state conditions of temperature and pressure [11].

When compared to fossil fuel power plants, geothermal power plants usually operate at much lower temperature levels; therefore the thermodynamic efficiency is low. Figure 13 shows how the exergy (availability) of the geofluid (taken as pure water) varies as a function of the temperature and pressure. It shows that increasing the pressure or the temperature have a nonlinear effect on the maximum work potential. For example, an aqueous geofluid at supercritical conditions with a temperature of 400 °C and a pressure of 250 bar has more than five times the power potential than a hydrothermal liquid water geofluid at 225 °C. Ultimately, this performance enhancement provides an incentive for developing supercritical condition based geothermal systems.

3.1. Dry Steam Power Plants

These systems present the first generation geothermal power plants. The first such system was built already in 1904 at Lardarello in Italy [5]. Steam from the geothermal reservoir, coming from wells, is distributed directly through turbine/generator units to produce electricity. The steam plants use hydrothermal fluids that are primarily steam. The steam goes directly to a steam turbine, which drives a generator and produces electricity.

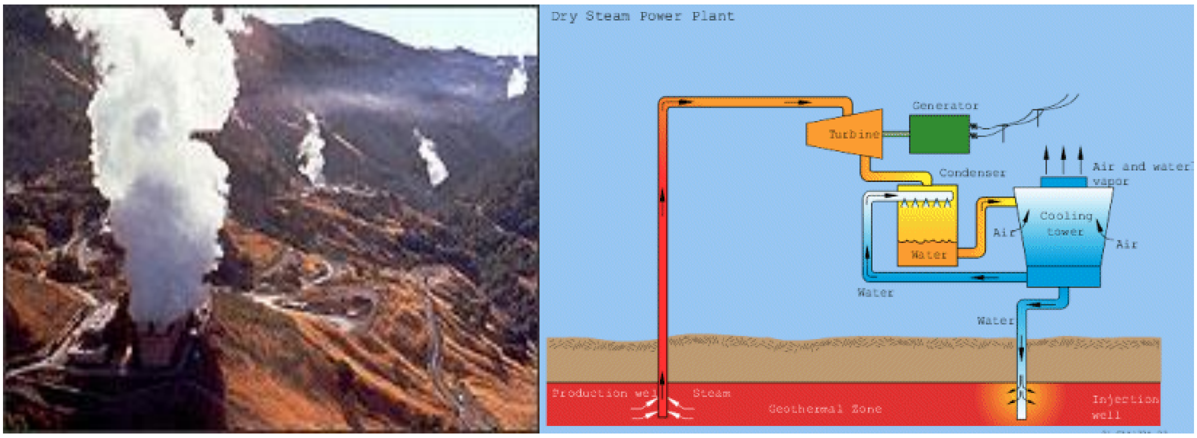


Figure 14: The dry steam power plant process and a photography of the dry steam power plants at The Geysers in California [5].

3.2. Flash Steam Power Plants

Flash steam geothermal power plants are today the most common type of geothermal power generation. They apply water at temperatures above 180 °C. This is pumped under high pressure to the tank, held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize or "flash." The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy.

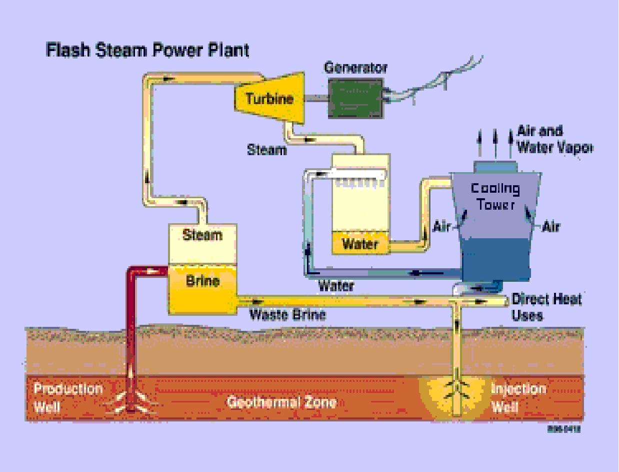


Figure 15: A dry steam power plant is sketched after reference [5].

3.3. Binary Cycle Power Plants

Binary cycle geothermal power generation plants differ from dry steam and flash steam systems in that the water or steam from the geothermal reservoir never comes in contact with the turbine/generator units. Binary cycle plants operate under the ORC (Organic Rankine Cycle) or Kalina cycle. The first applies a heated chemical (freon, butane, propane, ammonia or another refrigerant) instead of steam as found in the conventional Rankine cycle. In the Kalina cycle, the mixture of water and ammonia changes its temperatures during boiling and condensation, unlike the steady temperature for pure substances. It therefore needs to apply a separator similar to a generator in the ammonia–water absorption chillers. Most geothermal areas contain moderate-temperature water (below 200 °C). Energy is utilized from these fluids in the binary-cycle power plants. Hot geothermal fluid and a secondary fluid with a much lower boiling point than water pass through a heat exchanger. Heat from the geothermal fluid causes the secondary fluid to flash to vapor. This vapor then drives the turbines. Because this is a closed-loop system, virtually nothing is emitted to the atmosphere. Moderate-temperature water is by far the more common geothermal resource and most geothermal power plants in the future will be binary-cycle plants [5].

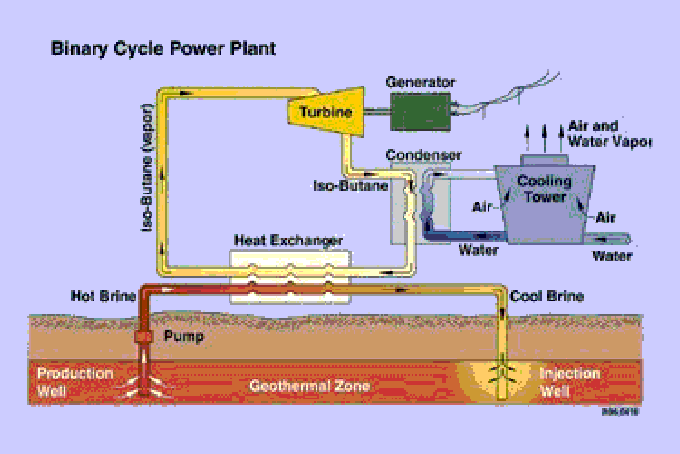


Figure 16: Binary ORC geothermal power (http://www.eere.energy.gov).

More comprehensive information on the ORC and Kalina cycle can be found in Appendix 2.

3.4. Magnetic geothermal power generators

Magnetic geothermal power generators should run similar as the binary cycle system, avoiding a direct contact, which is applied in dry or flash geothermal power plants. When compared to the conventional binary ORC cycle, all the system components on the side of the primary brine, coming from the well remain the same. Magnetic power generators can achieve better exergy efficiency than ORC or Kalina cycle generators. However, a low exergy level of the heat leads to a low thermodynamic efficiency. Since geothermal power systems are very large, there is no doubt that systems with superconducting magnets should be applied. More comprehensive information on the efficiencies may be found in the final report (see also Figure 13 of the final report) [7].

4. COMBINED HEAT AND POWER PLANTS (CHP)

Combined heat and power presents a simultaneous production of electricity and heat energy. Since numerous ways of such generation exist, this chapter deals with groups of different conventional systems, such as:

- Gas turbines (e.g. natural gas)
- Steam turbines (e.g. coal, waste incineration, nuclear power)
- Combined gas–steam processes (any of above listed fuels)
- Reciprocate internal combustion engines (e.g. Otto, Diesel)
- Fuel Cells.

4.1. Gas power plants

Gas turbines may operate with an open or closed Brayton thermodynamic cycle. The last apply working fluids, such as air, CO_2, He, N_2, etc. The closed Brayton cycle can use any kind of heat source which enables normal operation. The main parts of a gas turbine are the compressor, the combustion chamber and the turbine. The air is compressed in the compressor and heated either by directly burning fuel in it or by burning fuel externally in a heat exchanger. The heated (and compressed) air with or without products of combustion expands in a turbine and gives work as output. About two thirds of the work output is used to drive the compressor. The rest (about one third) is available as useful work output [12]. A simple and low-cost cogeneration power plant can be constructed by combining a gas turbine and a heat recovery boiler as shown in Figure 17. Heat is generated by the hot exhaust gases from the gas turbine. Heat can be taken out of the heat recovery boiler either in form of district heat or process steam. The amount of heat that can be recovered depends on the required temperature level of the heat recovery and on the fuel used. Due to sulphur corrosion risk, the exhaust gas temperature must not go below 120 to 170 ^{o}C with oil firing depending on the sulphur content of the oil. When natural gas is used, the temperature can be reduced to 60 to 100 ^{o}C, depending on the returning district heating water temperature [12].

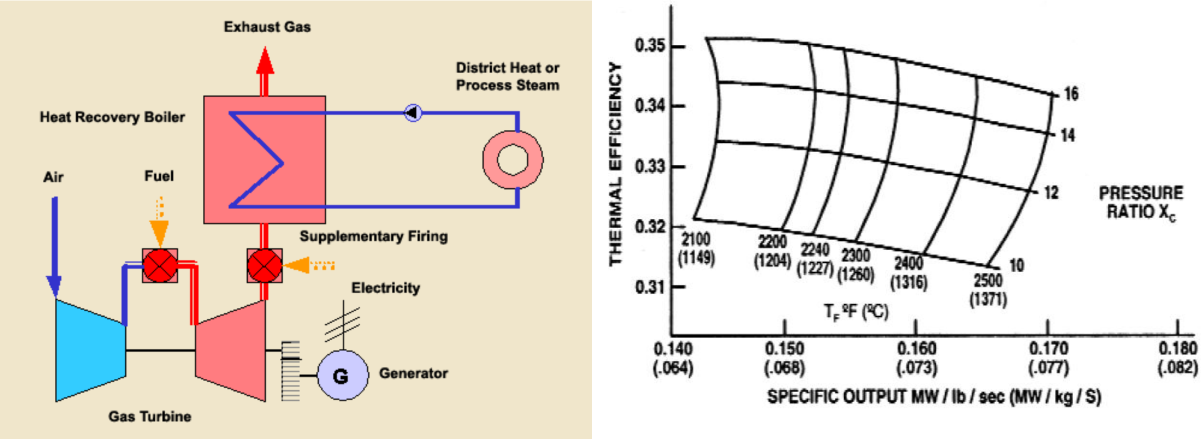


Figure 17: Left: Gas turbine heat recovery boiler power plant [12]. Right: The thermodynamic efficiency of the simple open-cycle gas turbine plant [13].

In some applications the power plant comprises a supplementary burner, which utilizes the exhaust gases of the gas turbine as combustion air, since the gases still contain about 15 % of oxygen. There also exist cases where the power plant contains a by-pass stack past the heat recovery boiler, so that the gas turbine can be operated without the boiler if necessary.

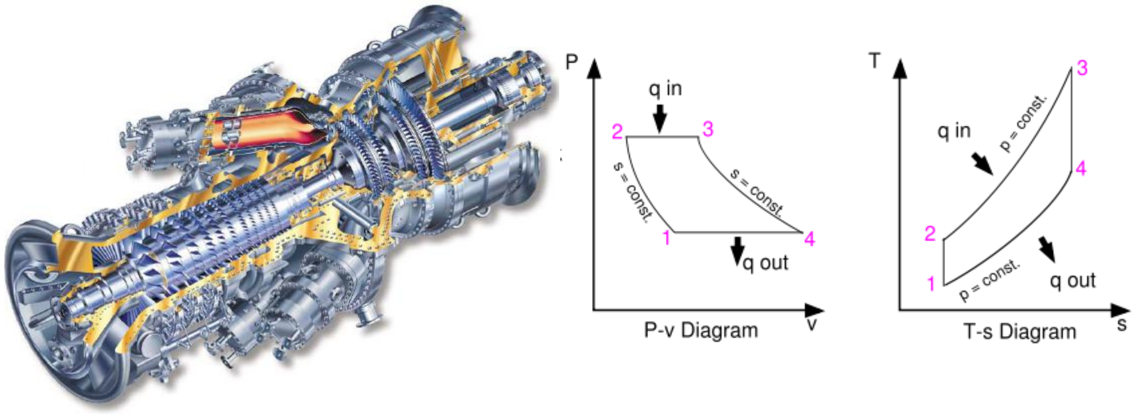
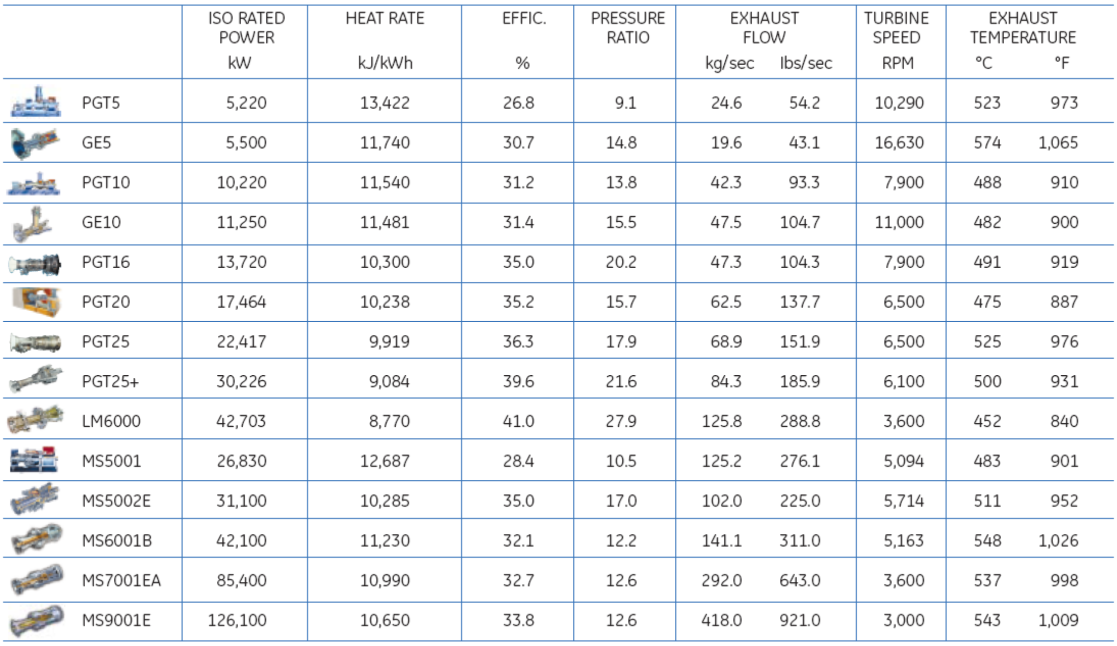


Figure 18: Left: GE MS5002E gas turbine electrical power generation [13]. Right: A Brayton closed thermodynamic cycle for a gas turbine [14].

The pressure ratios in gas turbines are much smaller than in steam turbines. Gas turbines are usually not as efficient as the steam turbines. When used alone, they may be efficiently applied as backup or peak consumption covering units. Gas turbines, compared to steam turbines, require high quality fuels such as natural gas, light diesel oil, etc. Their life cycle is also limited by the high temperature operation. However, some advantages may be obtained by the application of gas turbines instead of steam turbines. These advantages are compactness, low specific price per power, short start up time, small self consumption of energy (if the compressor work is not included) and simple maintenance. Some of the characteristics of gas turbines may be seen in Figure 19 (see reference [13]).



	ISO RATED POWER kW	HEAT RATE kJ/kWh	EFFIC. %	PRESSURE RATIO	EXHAUST FLOW kg/sec	EXHAUST FLOW lbs/sec	TURBINE SPEED RPM	EXHAUST TEMPERATURE °C	EXHAUST TEMPERATURE °F
PGT5	5,220	13,422	26.8	9.1	24.6	54.2	10,290	523	973
GE5	5,500	11,740	30.7	14.8	19.6	43.1	16,630	574	1,065
PGT10	10,220	11,540	31.2	13.8	42.3	93.3	7,900	488	910
GE10	11,250	11,481	31.4	15.5	47.5	104.7	11,000	482	900
PGT16	13,720	10,300	35.0	20.2	47.3	104.3	7,900	491	919
PGT20	17,464	10,238	35.2	15.7	62.5	137.7	6,500	475	887
PGT25	22,417	9,919	36.3	17.9	68.9	151.9	6,500	525	976
PGT25+	30,226	9,084	39.6	21.6	84.3	185.9	6,100	500	931
LM6000	42,703	8,770	41.0	27.9	125.8	288.8	3,600	452	840
MS5001	26,830	12,687	28.4	10.5	125.2	276.1	5,094	483	901
MS5002E	31,100	10,285	35.0	17.0	102.0	225.0	5,714	511	952
MS6001B	42,100	11,230	32.1	12.2	141.1	311.0	5,163	548	1,026
MS7001EA	85,400	10,990	32.7	12.6	292.0	643.0	3,600	537	998
MS9001E	126,100	10,650	33.8	12.6	418.0	921.0	3,000	543	1,009

Figure 19: Gas turbines and their characteristics, given by manufacturers (see reference [13]).

The highest temperature of heat supply may be around 1500 °C (see also exhaust temperature example and pressure ratios in Figure 19) and the maximum pressure around 30 bar. Improvements of the gas turbine efficiency may be obtained by heat regeneration between two isobars (in order to preheat the air coming to the compressor by extracting heat from exhaust gases) or by reheating processes. In the last case, compression and expansion are performed in several stages, where each stage comprises a burner. In the limit case of an infinite number of stages, the Brayton thermodynamic cycle approaches the Carnot cycle.

4.2. Steam power plants

Steam turbines are classified in two main groups: the backpressure steam turbines and the condensing steam turbines. A turbine may have different stages, a high pressure, a medium pressure and a low pressure stage, where especially the last may be designed by different number of casings, usually made as tandems. Steam power plants are operating with a Rankine steam cycle, where reheating, regeneration or supercritical operation may be applied. The maximum pressures in steam turbines are around 300 bar with a minimum pressure of 0.05 bar, while maximum temperature ranges approximately to 540 …630 °C. The specifications of a steam turbine also depend on the primary fuel source. Therefore, one must distinguish between steam turbines designed for the steam boiler or those related to the nuclear reactor. Steam turbines can be distinguished as impulse and reaction steam turbines. The first are based on fixed spraying nozzles and serve as high pressure turbines. The second are usually applied as low pressure turbines, where the turbine blades are performed in order to form convergent nozzles (see Figure 21). The overall electric efficiency of the conventional steam power plant (including self use of energy) is between 30-42 %. Since the fossil fuel, such as coal, gas or another fuel, presents pure exergy, this may also be considered as the overall exergy efficiency of the steam power plant. One should note that the efficiency of a nuclear power plant is generally lower than that of a conventional one. The reasons are the lower parameters of the steam, which is available (produced) in the reactor.

4.2.1. Backpressure power plants

In a backpressure turbine the steam is taken out of the turbine at a higher pressure than this is the case in a condensing power plant. The main objective is that steam is applied also for heating purposes as shown in Figure 20. Backpressure steam can be used directly as process steam in industrial applications such as paper machines or the steam can be condensed in heat exchangers, whereby the heat is transferred to the heating media such as district heating water.

The backpressure power plants may be divided in two main groups:

- Industrial backpressure power plants
- District heating power plants

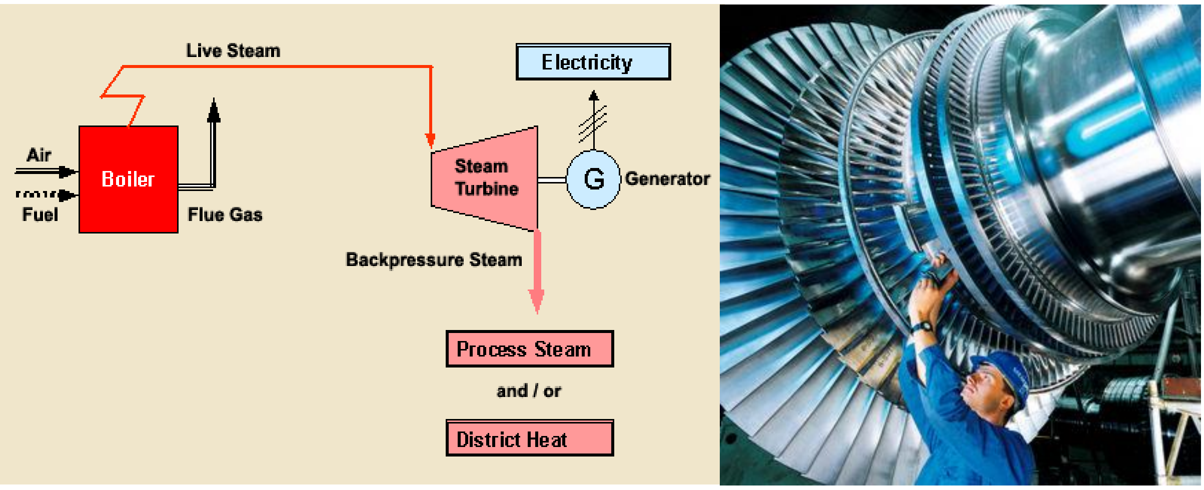


Figure 20: Left: Backpressure power plant [12]. Right: A rotor of a modern steam turbine [14].

The level of backpressure depends on the required heating temperature and is generally higher in industrial applications than in district heating power plants.

4.2.2. Condensing power plants

Despite heat is generally not meant to be a by-product of these plants, many of them are built to produce heat at a certain temperature level. This may be done by the extraction of a part of the steam from the turbine, before it reaches the last turbine stages and the condenser. District heat can be generated with the extracted steam in the same way as in district heating power plants or the steam can be supplied to industrial purposes.

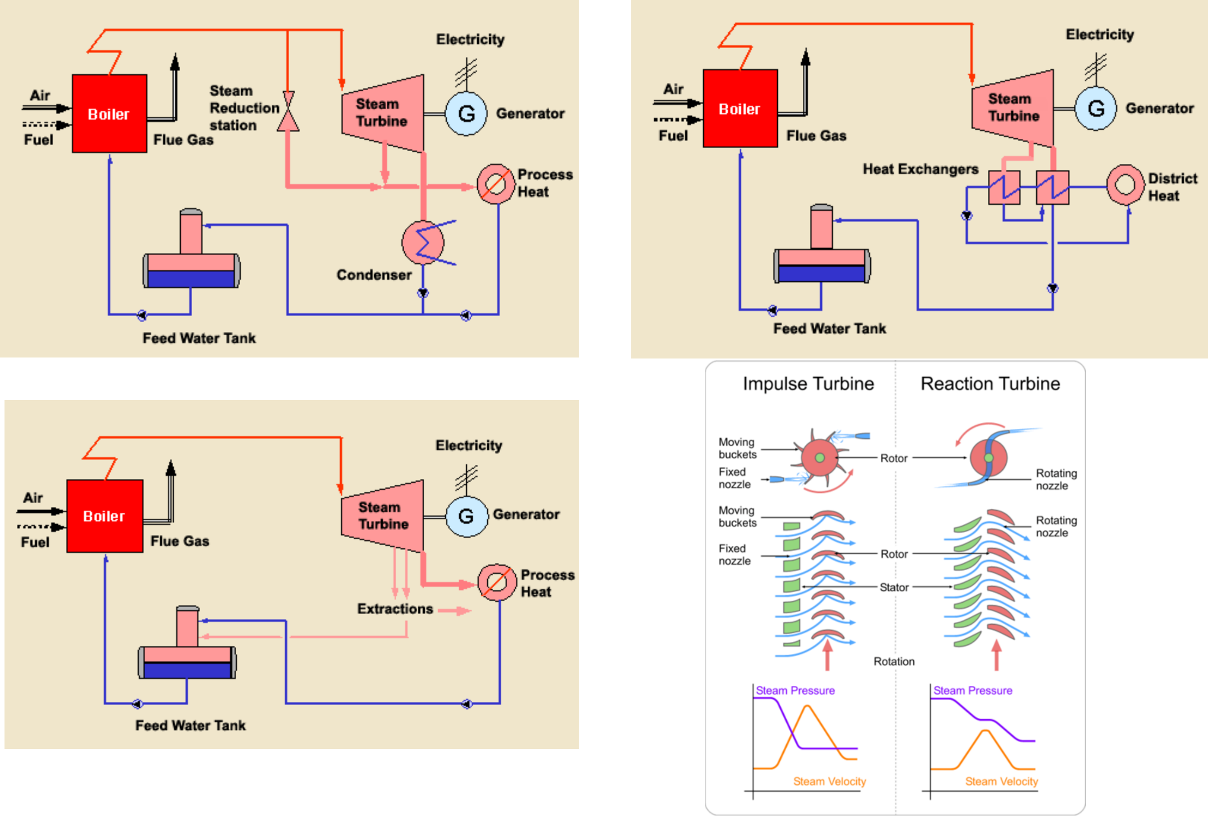


Figure 21: Extraction/condensing power plant configurations and two different types of turbines [12, 14].

Figure 21 shows a steam reduction station, which can be used when the steam turbine is not available. This is important in order to secure the process heat to the factory or district heating system. The steam turbine and the steam reduction station may run simultaneously. In this case, a distinction has to be made concerning the part of steam going through the turbine and the part of steam going through the reduction station. It is a common practice to construct steam reduction stations in all cogeneration power plants, where steam is used for CHP heat supply [12].

4.3. Combined cycle power plant

A combined cycle power plant usually comprises one or more gas and steam turbines, which are connected in one single power plant process. These systems apply heat recovery boiler in order to produce steam for the steam turbine, heated by the exhaust gases of the gas turbine. In some cases the heat recovery boiler can apply supplementary firing by using the gas turbine exhaust gases as the combustion air. The fuel used in the burners of the supplementary firing system may differ from the gas turbine fuel. In a combined cycle condensing power plant the total exergy efficiency is generally in the range of around 50 %, despite some systems achieve even 60 % [13].

Based on the steam turbine type, the power plant can be either a condensing or a cogeneration power plant. Figure 22 shows a cogeneration combined cycle power plant generating both electricity and district heat. The power of this example is provided by two gas turbines, two heat recovery boilers and one steam turbine.

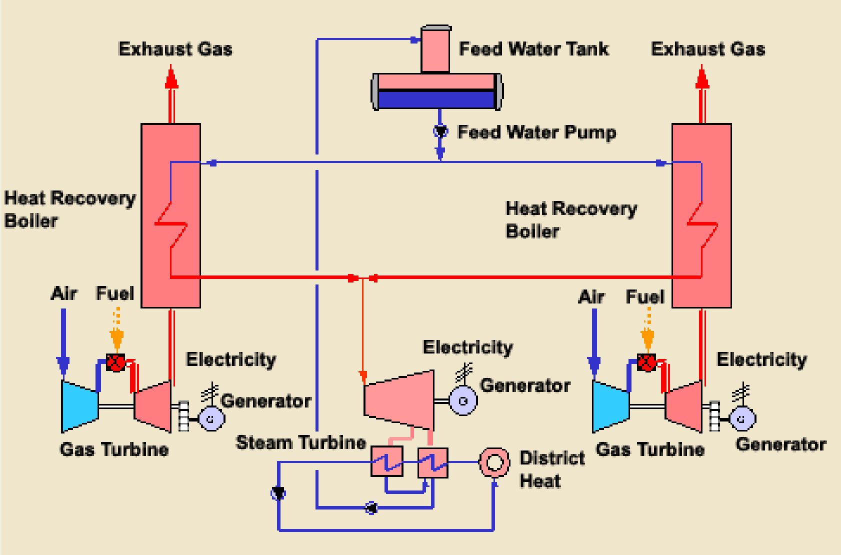


Figure 22: A combined cycle cogeneration power plant (after reference [12]) is shown.

Exhaust gases may also be applied as combustion air in a normal power boiler, which may use coal or some other solid fuel as main fuel. Another application of exhaust gases may be found by replacing existing high pressure feed water heaters with heat exchangers, where gas turbine flue gases are used as heating medium. However, in such cases, the power plant would not present a complete combined cycle power plant [12].

4.4. Reciprocating engine power plant

In a reciprocating engine power plant heat can be recovered from the lubrication oil and engine cooling water as well as from exhaust gases (Figure 23). The electric efficiency (exergy efficiency) of reciprocating engines varies from 35 to 42 %. In cases where low nitrogen oxide (NO_x) emissions are required by legal standards, the efficiencies that can be reached are about one percentage lower [12]. A reciprocating engine plant may be designed in order to provide sufficient temperature levels at the coolant side for district heating or even cold production by the application of sorption chillers (see chapter on Polygeneration).

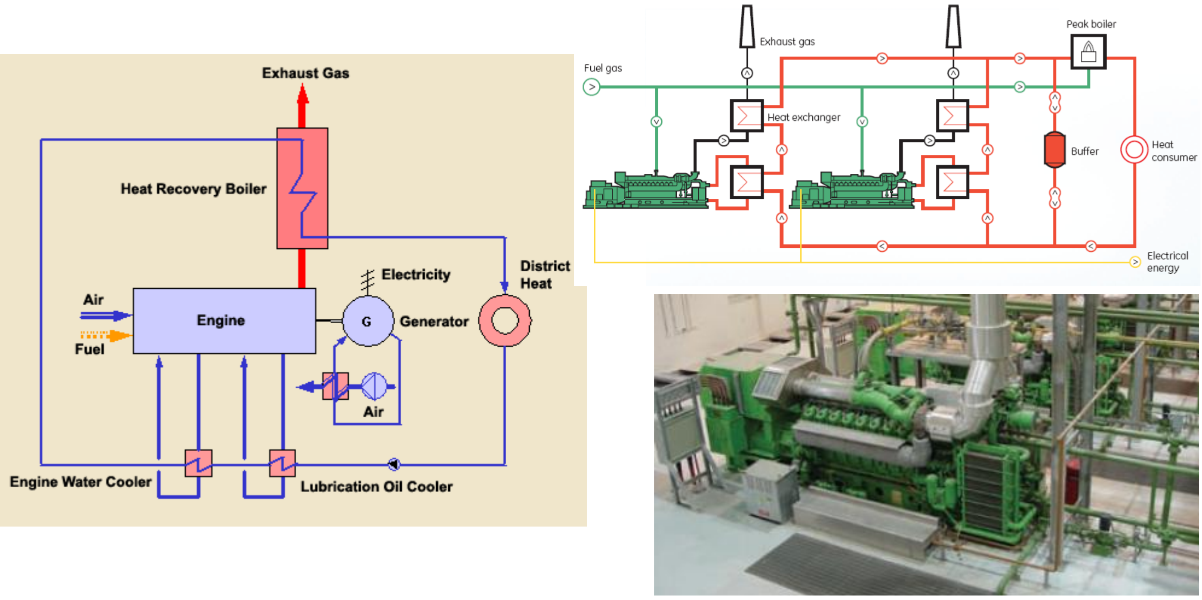


Figure 23: Left: Reciprocating engine power plant [12]. Right: Sketch of a gas reciprocate CHP plant (top) and a photography of it (bottom) (see reference [15]).

The modern reciprocating engines have rather cool exhaust gases (approximately 400 ^{o}C). Therefore, only a part of the heat can be recovered in form of steam. For example a diesel engine generating 4.2 MW of electricity can generate about 1.5 MW of steam and about 3.1 MW of warm and hot water. Since the fuel consumption is about 10.0 MW, the total efficiency of the plant in this example is 88 % (note this is not the exergy efficiency, but a sum of electric power output and heat in the form of steam and low exergy hot water). When using supplementary firing, about 9.5 MW of steam or district heat can additionally be generated with the remaining oxygen in flue gases [12].

4.5. Polygeneration power plant

The polygeneration power plants are very important when the total amount of operation hours is required to be as high as possible. Compared to cogeneration plants these plants increase the annual efficiency. In opposite to polygeneration, cogeneration plants may face certain problems during the summer season, because of the small consumption in district heating networks. In such cases it operates at lower power and also at lower efficiencies (internal efficiency of steam turbine strongly depends on its load). If the full load operation of the turbines is required, cogeneration plants need to reject heat to the ambient via e.g. cooling towers, which is an additional energy consumption.

The polygeneration power plants enable three kinds of energy products:

- electric energy (backpressure steam turbines, extraction condensing steam turbines, gas turbines, combined cycles, reciprocating engines or fuel cells)
- heat (heat from backpressure turbine, heat from the exhaust gases, heat from extraction condensing steam turbine, engine water or oil coolants)
- cold (use of hot water, steam or gas driven sorption chillers, optionally use of electric energy to drive compressor chillers in a combination with sorption ones).

Figure 24 shows an example of a polygeneration (“trigeneration”) power plant with the application of gas reciprocate engines. This kind of plant is used for rather low electric power units, usually used to supply industries, bigger commercials or other similar centers.

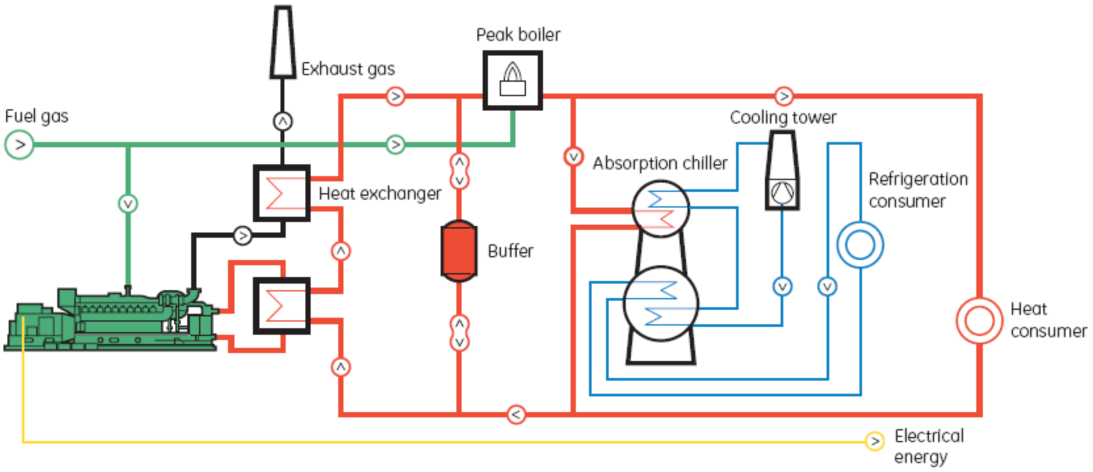


Figure 24: An example of a polygeneration power plant, using a reciprocating gas generator, is shown [15].

4.6. Fuel cells

Fuel cells have been developed in the mid 19th century and the US space program has used them since the early 1960's. A fuel cell operates like a battery: it converts oxygen and hydrogen into electricity in the presence of an electrically conductive material called an electrolyte. A fuel cell is made of three basic components: a fuel reformer or processor, a power section and a power conditioner. The reformer or process extracts pure hydrogen (H_2) from hydrocarbon fuels such as natural gas. The power section is where the hydrogen and oxygen are combined to generate electricity and "waste" heat. If alternating power is required, then a power conditioner converts direct current power to AC power. A variety of fuels can be used to power a fuel cell with the most common being natural gas (methane). However ethanol, methanol, landfill gas and liquefied petroleum gas can all be used as hydrogen feedstocks. The general design of most fuel cells is similar except for the electrolyte. The five main types of fuel cells are defined by their electrolyte. They are alkaline fuel cells, proton exchange membrane fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, direct methanol fuel cells and solid oxide fuel cells (see Figure 25). Alkaline and solid polymer fuel cells operate at lower temperatures and are mainly designed for use in transportation applications, while the other three operate at higher temperatures and are being developed for applications where waste heat can be used (cogeneration) or in large central power plants. Fuel cells have a variety of potential applications. They can provide energy for systems as large as power plants and as small as a laptop computer. They have several benefits over conventional combustion-based technologies currently used in many power plants and passenger vehicles. They produce much smaller quantities of greenhouse gases and none of the air pollutants that create smog and cause health problems. If pure hydrogen is used as fuel, the fuel cells emit only heat and water as a byproduct.

A single fuel cell consists of an electrolyte and two catalyst-coated electrodes (a porous anode and cathode). While there are different fuel cell types, they all work on the same principle [16]:

- Hydrogen or a hydrogen-rich fuel is fed to the anode where a catalyst separates the hydrogen's negatively charged electrons from the positively charged ions (protons).
- At the cathode, oxygen combines with electrons and in some cases, with species such as protons or water, resulting in water or hydroxide ions, respectively.
- For polymer electrolyte membrane and phosphoric acid fuel cells, the protons move through the electrolyte to the cathode to combine with oxygen and electrons. This produces water and heat.
- For alkaline, molten carbonate and solid oxide fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons.
- The electrons from the anode side of the cell cannot pass through the electrolyte to the positively charged cathode. They must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current.

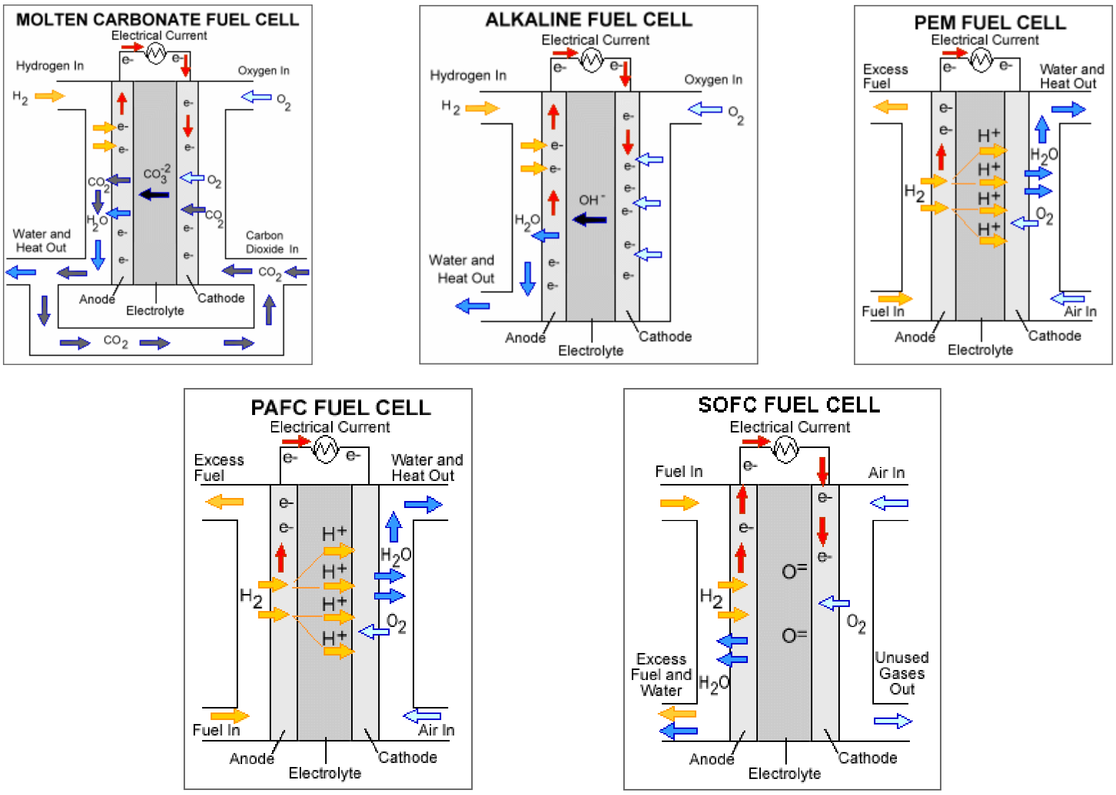


Figure 25: Some designs showing the operation of different types of fuel cells (after reference [16]).

The polymer electrolyte membrane (PEM) fuel cells are also called proton exchange membrane fuel cells. They comprise a solid polymer as electrolyte and porous carbon electrodes containing a platinum catalyst. They apply hydrogen, oxygen from the air and water to operate. They do not require corrosive fluids like some fuel cells and are typically fueled with pure hydrogen supplied from storage tanks or onboard reformers. They are used primarily for transportation applications and some stationary applications. Due to their fast startup time, low sensitivity to orientation and favorable power-to-weight ratio they are particularly suitable for use in passenger vehicles, such as cars and buses.

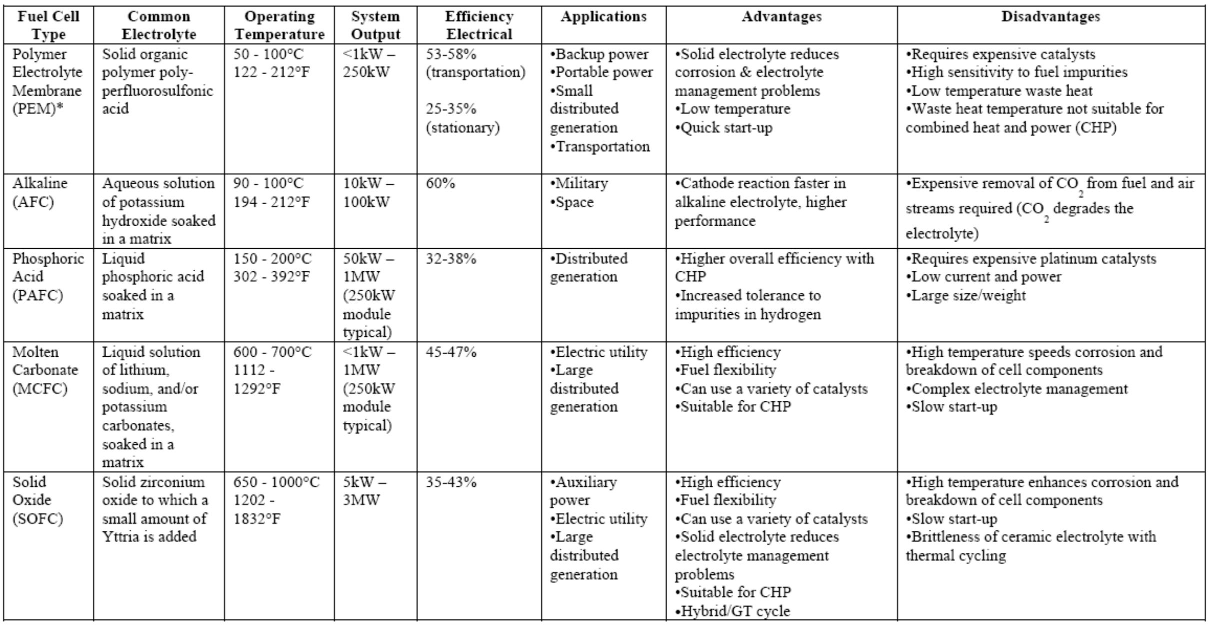
The direct methanol fuel cells (DMFCs), in contrary to the other fuel cell technologies applying hydrogen, use pure methanol, which is mixed with steam and fed directly to the fuel cell anode. These fuel cells lack many of the fuel storage problems typical of some fuel cells since methanol has a higher energy density than hydrogen. Methanol is also easier to transport and supply since it is a liquid.

The alkaline fuel cells (AFCs**)** were one of the first fuel cell technologies developed. These fuel cells apply a solution of potassium hydroxide in water as electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. High-temperature AFCs operate at temperatures between 100 °C and 250 °C. However it is reported in reference [16] that the newest AFC designs operate at lower temperatures (23 °C to 70 °C).

The phosphoric acid fuel cells use liquid phosphoric acid as electrolyte. The phosphoric acid is contained in a Teflon-bonded silicon carbide matrix. The porous carbon electrodes contain a platinum catalyst. These fuel cells are considered as the "first generation" of modern fuel cells [16]. This type of fuel cell is one of the most mature cell types. It is typically used for stationary power generation, but some of units were applied in larger vehicles such as city buses.

The molten carbonate fuel cells (MCFCs) are used in applications with natural gas and coal-based power plants for electrical utility, industrial and military applications. This high-temperature fuel cells use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix. Since they operate at very high temperatures of 650 °C and above, non-precious metals can be used as catalysts at the anode and cathode, what reduces the costs. Unlike alkaline, phosphoric acid and polymer electrolyte membrane fuel cells, MCFCs do not need an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which MCFCs operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces the cost.

The solid oxide fuel cells (SOFCs) comprise a hard, non-porous ceramic compound as electrolyte. Since the electrolyte is a solid, the cells do not need to be constructed in the plate-like configuration typical of the other fuel cell types. Solid oxide fuel cells operate at very high temperatures (around 1000°C). That removes the need for precious-metal catalyst and thus reduces the cost. It also allows SOFCs to reform fuels internally. This leads to the possibility to apply a variety of fuels and reduces the cost associated with adding a reformer to the system.



Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Efficiency Electrical	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)*	Solid organic polymer poly-perfluorosulfonic acid	50 - 100°C 122 - 212°F	<1kW – 250kW	53-58% (transportation) 25-35% (stationary)	•Backup power •Portable power •Small distributed generation •Transportation	•Solid electrolyte reduces corrosion & electrolyte management problems •Low temperature •Quick start-up	•Requires expensive catalysts •High sensitivity to fuel impurities •Low temperature waste heat •Waste heat temperature not suitable for combined heat and power (CHP)
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 - 100°C 194 - 212°F	10kW – 100kW	60%	•Military •Space	•Cathode reaction faster in alkaline electrolyte, higher performance	•Expensive removal of CO_2 from fuel and air streams required (CO_2 degrades the electrolyte)
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 - 200°C 302 - 392°F	50kW – 1MW (250kW module typical)	32-38%	•Distributed generation	•Higher overall efficiency with CHP •Increased tolerance to impurities in hydrogen	•Requires expensive platinum catalysts •Low current and power •Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C 1112 - 1292°F	<1kW – 1MW (250kW module typical)	45-47%	•Electric utility •Large distributed generation	•High efficiency •Fuel flexibility •Can use a variety of catalysts •Suitable for CHP	•High temperature speeds corrosion and breakdown of cell components •Complex electrolyte management •Slow start-up
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of Yttria is added	650 - 1000°C 1202 - 1832°F	5kW – 3MW	35-43%	•Auxiliary power •Electric utility •Large distributed generation	•High efficiency •Fuel flexibility •Can use a variety of catalysts •Solid electrolyte reduces electrolyte management problems •Suitable for CHP •Hybrid/GT cycle	•High temperature enhances corrosion and breakdown of cell components •Slow start-up •Brittleness of ceramic electrolyte with thermal cycling

Figure 26: Comparison of different types of fuel cells [16]

4.7. Magnetic power generation and CHP plants

A variety of different applications are possible with the magnetic power generation in a combination with the CHP plants. Since up to present R&D on magnetocaloric materials was not focused on high-temperature applications, the lack of materials in the high-temperature regions disable their present use as primary application in CHP plants. Therefore, at the present stage of development of magnetocaloric materials, the magnetic power generation seems not to be alternative to gas or steam turbines, when considering temperature levels above 350 °C to occur. However, the results presented in the final report show that when having good magnetocaloric materials with high Curie temperatures (e.g. performances as Gd has), then magnetocaloric power generation may also be a good alternative to other conventional power generation units. Therefore, large efforts should be made in finding such materials.

The magnetocaloric power generation as a CHP plant or its supplementary component may generally be divided into two groups. The first is presented by large-scale applications, for which there is no doubt that superconducting magnet systems should be applied. Such systems could use their cryostat cooling system not only for cooling the coils producing the magnetic field in magnetocaloric machines, but also for the superconducting power generation (as a supplementary unit or comprised as a part of a magnetocaloric machine). The analysis [7] has shown that such systems could beat the existing technologies because of their very high exergy efficiencies. Small scale units, such as some fuel cells, as well as reciprocate engines, could have a supplementary power generation system, based on permanent magnets. Much more information on their efficiencies and possible applications are given in the final report [7].

5. POWER GENERATION IN TRANSPORT

In transport vehicles, such as cars, trucks, buses and even ships, there exists an enormous potential to improve the energy efficiency. Most of the losses in these vehicles occur as heat losses that may be converted into electricity. Heat losses may be due to the following causes: waste heat from the internal combustion engine or fuel cell coolants and waste heat from exhaust gases.

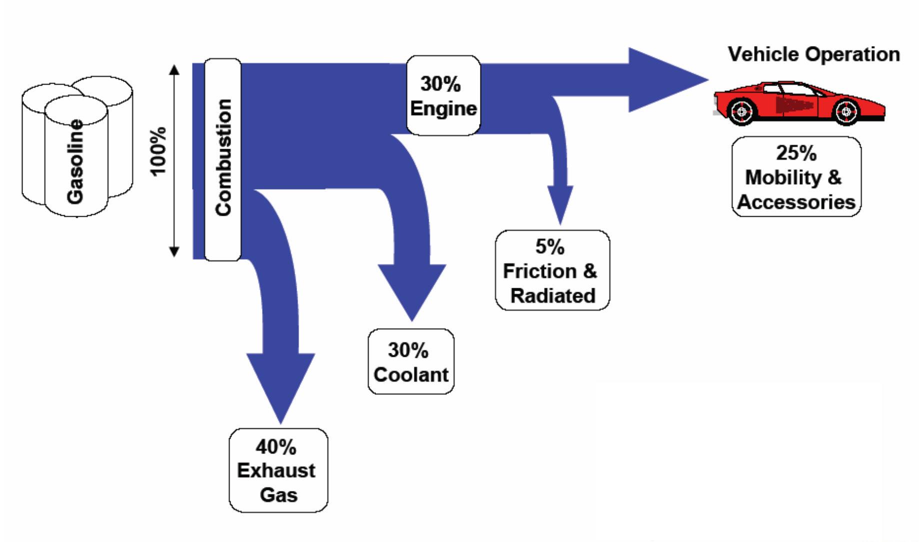


Figure 27: An energy flux diagram showing energy losses in vehicles (see reference [17]).

5.1. Waste heat from exhaust gases

Temperatures of the exhaust gases strongly vary (200 to 800 °C) depending on the position in the car (exhaust pipe behind engine, catalyst, center muffler, rear muffler). Present research to exploit this kind of heat source is primarily focused on thermoelectric generators. However, their very low efficiency and high costs at the present stage of development present a large drawback (see also Appendix 2). Exhaust losses present approximately 40 % of all the energy input into a vehicle motor. Therefore strong efforts should be made in order to find a good way to have efficient heat utilization, especially because the exhaust heat presents a high exergy source.

5.2. Waste heat from engine coolant

Heat from the engine cooling water presents approximately 30 % of the primary energy used in a car. The temperature of the cooling fluid of the engine usually varies up to 110 °C. In fuels cells this would depend on their specific type. Similar as in the case of the heat utilization of exhaust gases, some efforts were made in the domain of thermoelectric and much more in the domain of sorption cooling (air-conditioning).

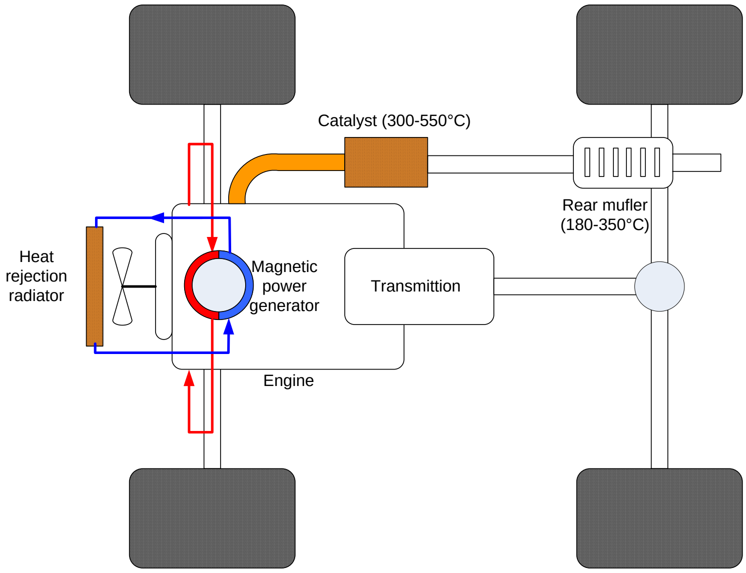


Figure 28: An example of utilizing the heat of the engine coolant for magnetic power generation.

5.3. Magnetic power generation in transport

In small scale vehicles (cars, trucks and buses) and in sea transport (boats and small yachts) magnetic power generation is not feasible at the present stage of development. A major reason is not the efficiency but the large mass systems applying permanent magnets. Namely, superconducting magnet systems may be applied only in large scale vehicles, such as the ones in sea transport, e.g. in Navy ships, tourist/passenger cruisers and in transport carriers. For these, a system applying superconducting magnets could efficiently utilize waste gases as well as heat from coolants of engines. More information on efficiencies may be found in the final report [7].

6. POWER GENERATION FROM WASTE HEAT SOURCES

A large amount of waste heat is produced in industrial processes such as:

- (petro)chemical industry
- refineries
- metal industry (e.g. foundries)
- incineration
- pulp and paper
- food industry
- pharmaceutics.

Many of these sources present lower exergy levels of heat. While some systems with higher temperature levels apply steam turbines, other technologies, such as ORC or Kalina cycle processes are successfully applied in order to convert low exergy heat into useful electric power (for more information on the two technologies see Appendix 2). Combined with such industrial waste heat, a large number of sorptive cooling units may also be found as a way of heat utilization in order to produce cold. However, none of the existing technologies is able to successfully convert heat of 100 °C or below into power. At such temperature levels, the thermodynamic efficiency cannot be high (around 8 % with the Binary ORC cycle). Many industrial processes deliver large amounts of heat, which may also be centralized. Especially in such cases, large scale superconducting magnetic power generation would present a very good alternative for power conversion, especially at lower temperatures of the heat sources, where there is no real competitor to the magnetic power conversion technology. When applying permanent magnets a magnetic flux density of around 1.5 T should be provided in order to operate with efficiencies beyond those of ORC or Kalina cycles. Because of the variety of different processes, the information on the efficiencies given in the final report is a helpful tool in order to evaluate the potential of waste heat utilization. Figure 29 shows a comparison of the costs for different power generation technologies.

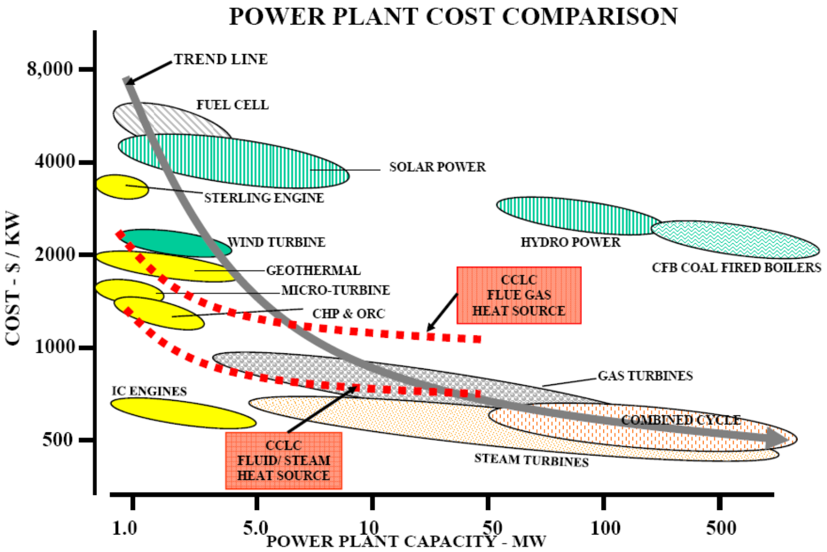


Figure 29: Cost comparison between different types of power plants are presented in this diagram [18].

Unfortunately, these cannot be shown yet for magnetic power generation. Industrial waste heat presents a large power generation potential as it may clearly be seen in Figure 30. Petrochemical industry and refining industries present 50 % of this potential.

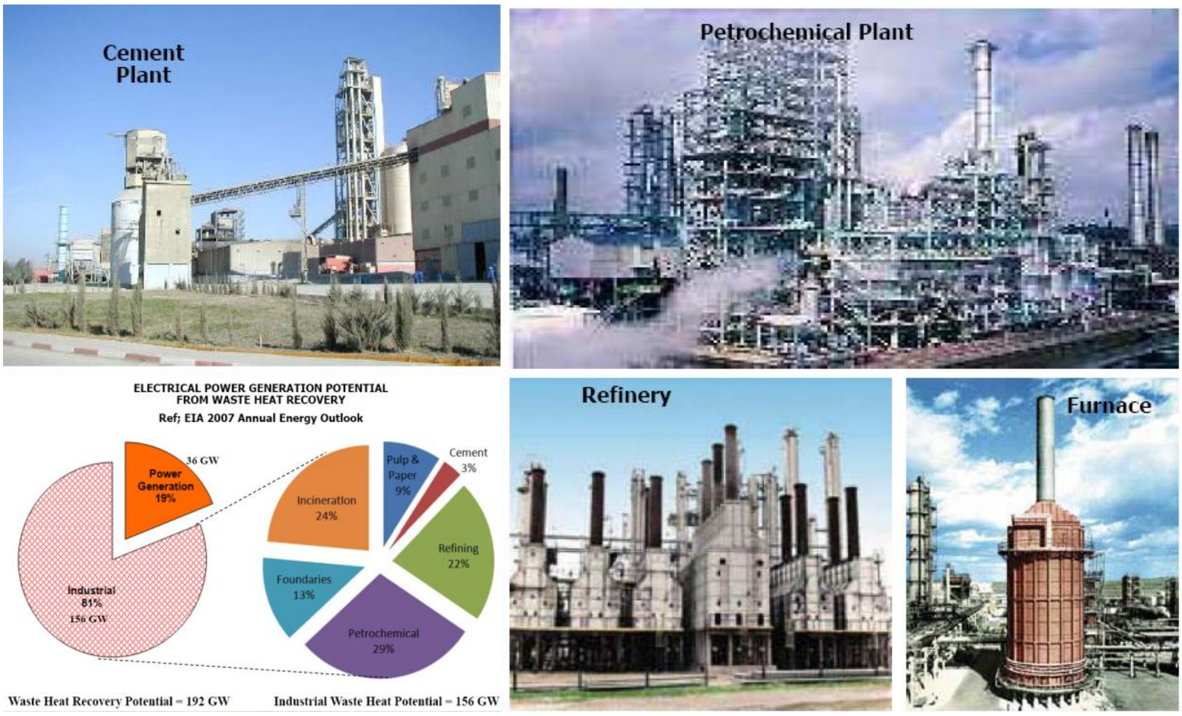


Figure 30: Industrial waste heat presents a large potential to be utilized more consequently in the future [18].

7. SPECIAL HEAT TO POWER CONVERSION SYSTEMS

Special systems in this appendix present systems which require a temperature difference between the temperature of a heat source and that of a heat sink, where the height of the temperature levels is unimportant. Such examples exist also in nature, as the following list proves:

- Power conversion based on a sea (or a lake) temperature difference
- Power conversion based on the temperature fluctuations of the ambient air
- Power conversion based on the temperature difference between ambient air and soil
- Power conversion based on the temperature fluctuations or the fluctuations in the soil (does not mean geothermal).
- Hybrid power conversion using solar or other of the above mentioned examples.

For instance in a desert, large day/night fluctuations occur in the temperature of the ambient air, as well as at the soil's surface. The above mentioned examples are probably only a few of the dozens possible. In order to exploit renewable energy sources, this kind of systems should not be neglected as unimportant. Only one domain where such systems are applied in practice is known to us. This is described in more detail in the next subchapter.

7.1. Ocean thermal energy conversion (OTEC)

Ocean thermal energy conversion (OTEC) is a method for generating electricity which applies a temperature difference which exists between deep and shallow waters to run a heat engine. This temperature difference generally increases with decreasing latitude, e.g. near the equator, in the tropics (see Figure 31). However, evaporation prevents the surface temperature from exceeding 27 °C. Also the subsurface water rarely falls below 5 °C. The main problem of OTEC systems is to efficiently generate significant amounts of power from such small temperature differences. On the other hand, this energy is an unlimited and renewable energy source. The total potential energy available from systems of this technology is one or two orders of magnitude larger than the other ocean energy options such as wave power systems. However, the small temperature difference makes the energy extraction difficult and expensive due to the low thermodynamic efficiency. Earlier OTEC systems had an overall efficiency of only 1 to 3 % (the theoretical maximum Carnot efficiency lies between 6 and 7 %). With good technical solutions, this technology could approach higher efficiencies (limited by the ideal Carnot). The energy source (seawater) is free, but it has an access cost associated with the pumping material and energy cost. Although an OTEC plant operates at a low overall efficiency, it can be configured to operate continuously as a base load power generation system.

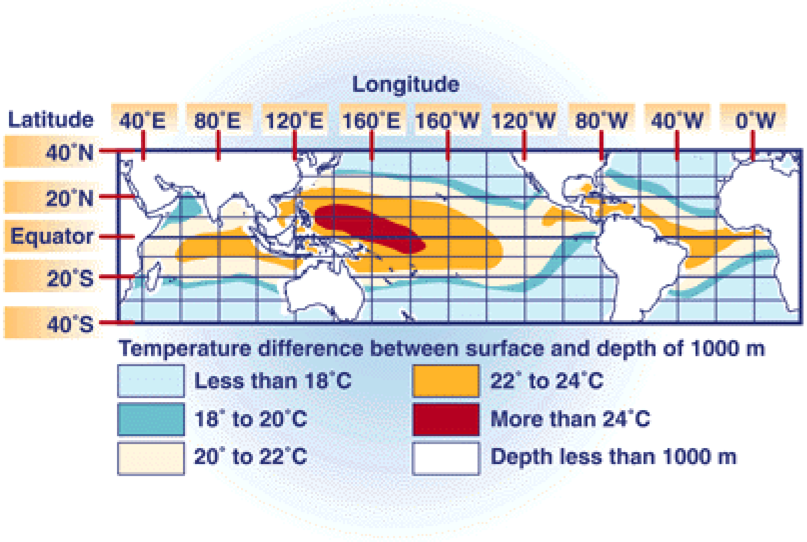


Figure 31: Temperature difference between the water at sea level and in a depth of 1000 meters [10].

Up to date the only heat cycle suitable for OTEC was the Rankine cycle, using a low-pressure turbine. The systems may operate with either closed-cycle or open-cycle. The closed-cycle engines apply working fluids that are typically used as refrigerants such as for instance ammonia. The open-cycle engines use the water heat source as working fluid (see Figure 32).

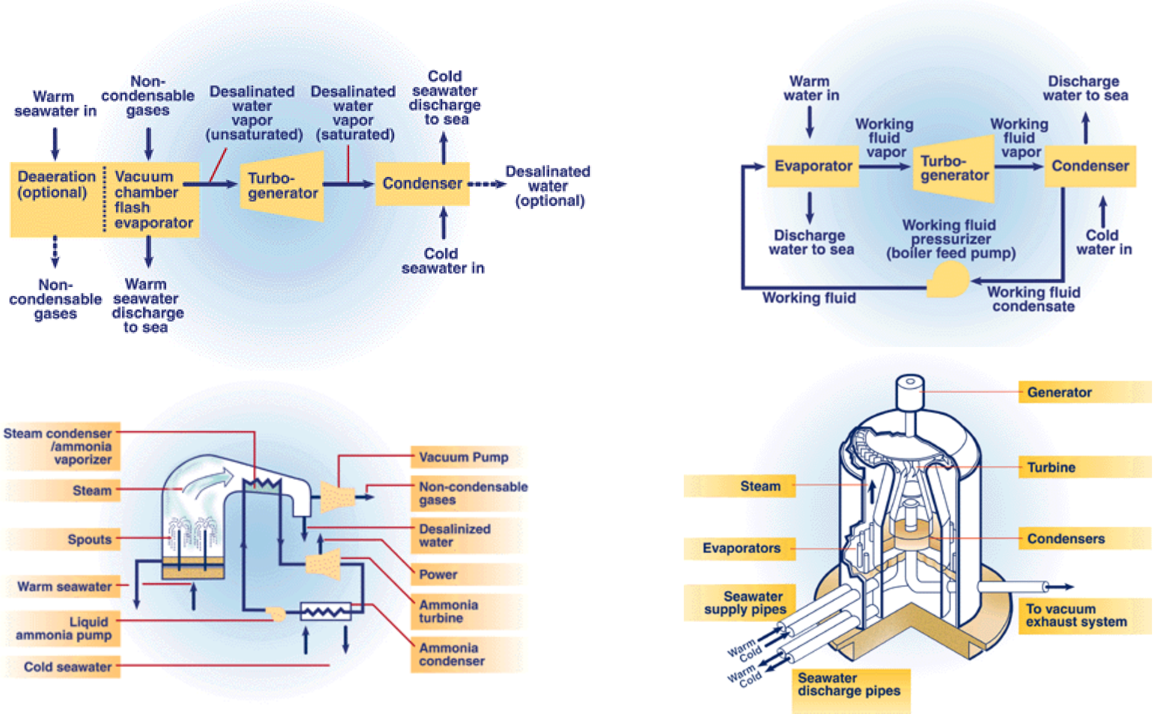


Figure 32: Top left: An open OTEC process. Top right: A closed OTEC process. Bottom left: A hybrid open-closed OTEC process. Bottom right: An example of the closed OTEC energy converter [10].

Based on the reports, found in references [19-21], an example of a hybrid (open-closed), regenerative magnetic power generation with supplementary desalination process was made (Figure 33). In order to increase the temperature span between the deep sea cold water and the surface warm sea water, an option would be to additionally heat the surface sea water by the application of concentrated solar energy. By the regulation of the mass flow of sea water, the temperatures at the exit of the concentrated solar system (e.g. solar trough) would not operate at so high temperature levels that may be found in conventional applications, but rather low temperatures with e.g. a maximum up to the evaporation temperature of water at normal ambient conditions (e.g. 100 °C). Since the deep sea water has a temperature of around 5°C, the maximum temperature span between the heat source and the heat sink would be some 95 K. The example in Figure 33 shows a closed magnetic power conversion system with its own working fluid. An analysis was made for a heat sink temperature of 5 °C, taking into account 30 % of volume fraction, water as working fluid at a frequency of operation of 5 Hz. An analysis was performed for different temperature levels of heated sea water and different magnetic flux densities. For this special case it was also considered that hot and cold heat exchangers (CHEX and HHEX respectively) could be designed in order to have minimum irreversible heat transfer losses (e.g. 0.5 K each). The same was considered for the internal heat transfer in the magnetocaloric porous structure (with a temperature loss of 0.5 K for each heat transfer process inside of it). Figure 34 shows the results of the analysis.

According to the Figure 34, the magnetic power conversion OTEC system supported by the solar heating could present a very good alternative to the conventional OTEC systems, which achieve around 1-3% efficiency at operation temperatures of 5 °C/ 27 °C. A very high exergy efficiency may be achieved especially with magnetocaloric systems operated by superconducting magnets. Furthermore, most of the present magnetocaloric materials suitable for power conversion above or close to the ambient temperature exist in the range of the case presented in Figures 33-34.

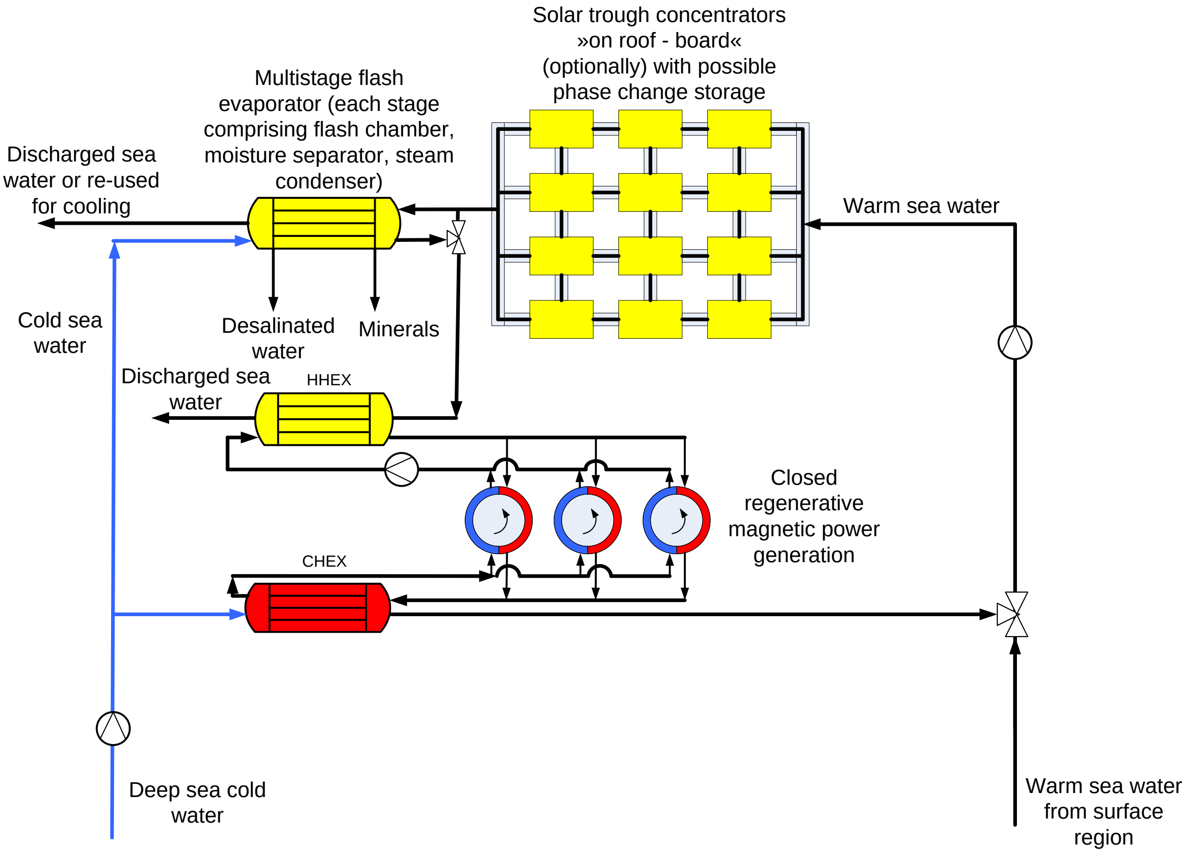


Figure 33: An example of magnetic power generator for the OTEC technology with desalination and optional use of solar pre-heaters.

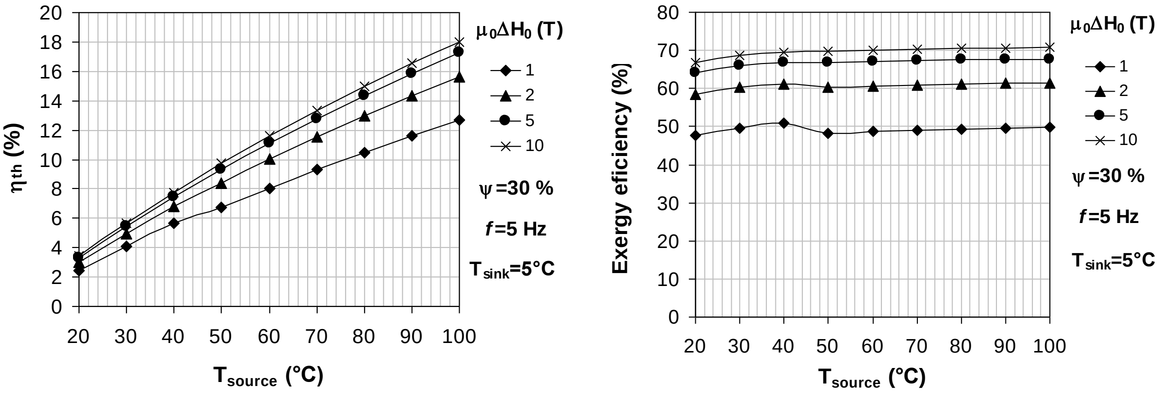


Figure 34: An example of a magnetic power generator for the OTEC technology with desalination and optional use of solar pre-heaters.

OTEC systems may be performed on the coast or as floating platforms (ships) on the sea. The two real examples of such systems are shown in Figure 35.

As reported in reference [10], the OTEC's benefits are the following:

- It helps produce fuels such as hydrogen, ammonia and methanol
- It produces base-load electrical energy
- It produces desalinated water for industrial, agricultural and residential uses
- It is a resource for on-shore and near-shore mariculture operations
- It provides air-conditioning for buildings (by applying deep sea water in e.g. district cooling system)
- It provides moderate-temperature refrigeration (by applying deep sea water in e.g. district cooling system)
- It has a significant potential to provide clean, cost-effective electricity for the future
- It enhances the energy independence and the energy security.
- It has a potential to mitigate greenhouse gas emissions resulting from burning fossil fuels.

Figure 35: Left: View of a land based OTEC facility at Keahole Point on the Kona coast of Hawaii. Right: Floating OTEC plant constructed in India in 2000 [14].

8. CONCLUSION

This Appendix presents most of the existing conventional technologies for power conversion. It does not deal with the efficiency of magnetic power conversion systems, since the comprehensive data on the efficiencies may be found in the final report [7]. It gives an insight, where the magnetic power conversion could present an alternative to existing technologies. Generally, at the present stage of development of magnetocaloric materials these would be limited to rather low temperatures of heat sources what becomes especially interesting in utilizing solar, geothermal and waste heat energy, as well as the supplementary technology to existing CHP plants. Furthermore, special power conversion systems, such as based on a temperature difference between the heat source and the heat sink and not their temperature level, should also be seriously taken into consideration. Most of the presented technologies would lead to rather large scale systems, where also superconducting magnet based power generation seems to be feasible. The feasibility of applying superconducting magnets, followed by the economic evaluation should be made in future. More efforts should also be made in research and development of new “high temperature T_C (Curie)” magnetocaloric materials. The permanent magnet based systems become important when the magnetic flux density is rather high, (above 1.5 Tesla). Such systems, as well as the superconducting based ones, should be prototyped in order to make the first steps of development of this green technology, especially because it shows a high potential to convert low exergy heat sources into valuable pure exergy, in the form of mechanical or electric energy.

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