Binary Cycle Geothermal Power Systems

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Summary

Energy consumption of the world is predicted to increase considerably in the coming years.

With more environmental concerns and less dependency on fossil fuels, demand for sophisticated power supply options has greatly increased. Environmental concerns are in form of global warming, acid rains, air, water and soil pollution, ozone depletion, forest devastation and landscape preservation.

Most geothermal power plants today are located in high-temperature (T>180°C) areas and the geothermal vapor is used directly in steam turbines to produce electricity. This method has been called Flash technology and 93% of geothermal power plants in the world make use of it.

Utilizing medium temperature, geothermal heat along with attempts to derive energy out of similar renewable low grade thermal heat sources, have motivated the use of ORC.

ORC or Organic Rankine cycle basically resembles the steam cycle according to working principles. In ORC, water is replaced with a high molecular mass fluid with lower degree of boiling temperature in comparison with water. Fluid characteristics make ORC favorable for applications of low temperature geothermal heat recovery, normally less than 180°C.

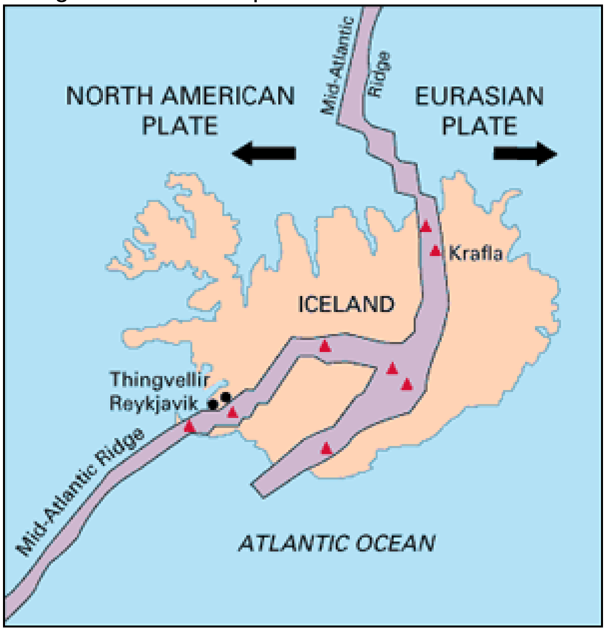
In geothermal ORC the heat in geothermal water from the earth is used to heat up another liquid, with a low evaporation temperature, which then in turn is used to power steam turbines. The working liquid is enclosed in a cycle not unlike a refrigerator system. This method has also been called the Binary Cycle Technology. Only about 7% of geothermal power plants in the world today utilize this technology.

This report discusses why Binary Power Plants should be taken more into consideration and become in fact an ever increasing and important factor in the future harnessing of geothermal energy.

Introduction

Geothermal energy is the heat that can be extracted from the interior of the earth for generation of electricity or for direct use such as residential heating, swimming pools etc. The heat from deep down in the earth, extracted and made use of for benefit of mankind, is usually considered renewable because earth's heat is practically inexhaustible source of energy. The terrestrial energy current therefore corresponds well with the concept of renewable energy.

Figure 1. Tectonic plate boundaries in Iceland



The flow of energy to the surface of the earth is either by conduction or convection. Convection works satisfactory with permeable stratum, occasional magma intrusion and abundance of groundwater flow. On the other hand the long recovery time required to restore lost heat energy in impermeable rocks due to low conductivity could make it look like finite energy resources.

The terrestrial energy current flowing from the mantle to the surface of the Earth is more intensive at the tectonic plate boundaries than within the plates. See figure 1. Therefore it has been considered more attractive to utilize the high-temperature areas in the beginning by taking advantage of the less costly flash power plants. Exploitation of regions with lower temperatures, where the more costly binary power plants would be considered, has hitherto been ranked as of secondary importance.

High temperature areas are located at plate boundaries and usually away from the more urban areas. Therefore substantial cost is normally associated with transmission lines leading to considerable increase in energy cost for electrical power production. Recently the striking beauties of high temperature geothermal areas with geysers, fumaroles and colorful stones and landscape has fascinated people and increased in importance from environmental point of view. Therefore any interruption of the natural groundwater with deep-drilling and construction of large man-made structures in these areas are becoming more and more controversial. Recent development of high temperature geothermal power plants seems to be in direction of smaller unit size and to make use of decentralized structures and coordinated system operation. Smaller unit size lends itself more to make the power plant structures less visible in the delicate landscape.

Medium temperature areas, suitable for geothermal binary power plants, can be found farther away from plates boundaries, even in vicinity of urban areas. Several countries, which are interested in geothermal utilization for power production, only have access to medium temperature areas. In that respect one could mention India with no volcanic activity required for high geothermal opportunities. Friction heat of continental drift towards the Himalayas and associated earthquakes has created medium temperature geothermal opportunities all over the country.

Binary turbines are less susceptible to chemical composition of the geothermal brine and could be made to operate more environmentally friendly than in the case of flash turbines. Recent examples from Iceland have revealed excessive Hydrogen Sulfide H_2S emission of geothermal area in vicinity of Reykjavik town. Emission from binary turbines could be made relatively much lower than for flash turbines as the steam expansion in the turbines is conducted by a separate working fluid in a closed circuit and could be more easily controlled. Binary turbines with Organic Rankine Cycles have a proven record of success over the past decades. They could be made more feasible by mass production of the small sized (i.e. < 3 MW) units.

In the paper we are considering the question if medium temperature geothermal development using binary turbines has been lagging behind in the recent geothermal power production development all over the world?

This could be an important window of opportunity for a binary power plant manufacturers.

Geothermal Power Production

In geothermal power plants steam rotates a turbine that activates a generator, which produces electricity. The power plants use steam produced from reservoirs of hot water found a couple of km or more below the Earth's surface.

There are three basic types of geothermal power plants, as illustrated in figures 1, 2 and 3:

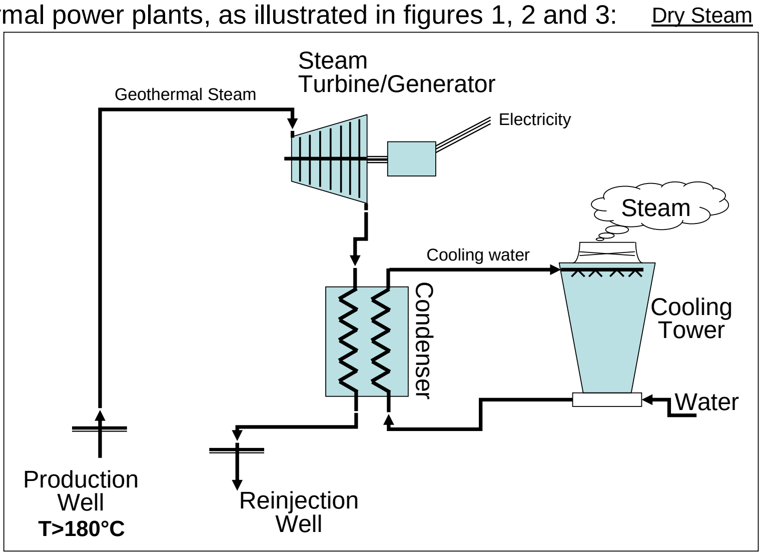


Figure 1. **Dry steam power plants** draw from underground resources of steam. The steam is piped directly from underground wells at temperature of 180°C or greater to the power plant, where it is directed into a turbine/generator unit. Dry steam plants are the simplest and the oldest design of geothermal power plants.

Figure 2. **Flash steam power plants** are the most common type. They use geothermal reservoirs of water with temperatures greater than 180°C. This very hot and compressed water flows up through wells in the ground. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and used to power an on-surface turbine/generator.

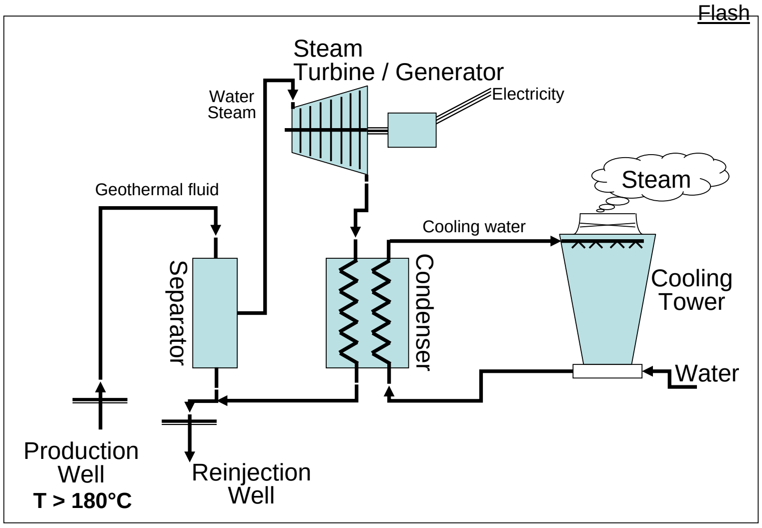
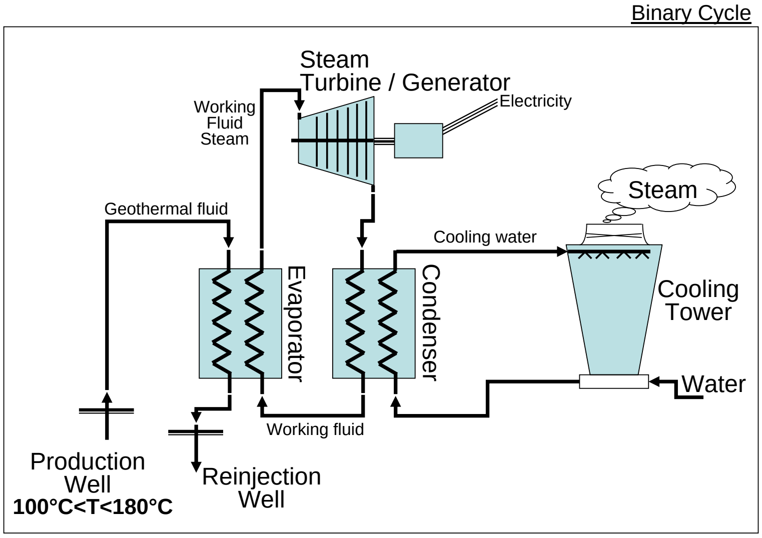


Figure 3. **Binary cycle power plants** operate with geothermal water at lower temperature of about 130-180°C. Temperature of 80-130°C is also possible but generally not considered feasible. The power plants use heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. The working fluid is vaporized in a heat exchanger and used to rotate a turbine. The water is then reinjected into the ground where it is reheated and contributes to maintain the pressure in the reservoir. The geothermal water and the working fluid are kept separated during the whole process so there is little negligible air emission.

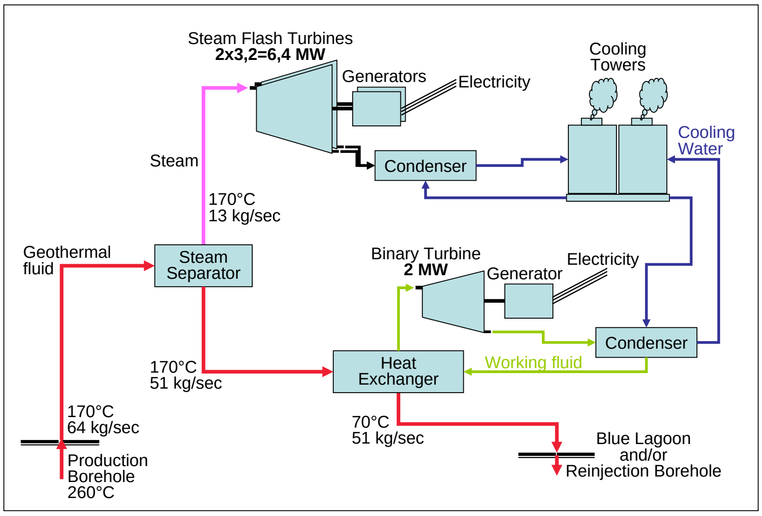


Binary cycle power plants are the most recent development in geothermal technology, and can already accept fluid temperatures as low as 80°C although a temperature of at least 130°C is needed for a feasible power production. Binary Power Plants could gradually become the most common type of geothermal electricity plants being constructed in the near future. The Organic Rankine Cycle concept could even make use of different technologies, based on brine temperature. Steam generation within the binary cycle can take place either in a single pressure level unit, or double pressure level unit. The single pressure level cycle is most commonly used, whereas the double pressure unit promises higher electricity output at same boundary conditions but more equipment increases installation costs. Additionally the so called supercritical cycles become more and more attractive especially at low resource temperatures. In the supercritical cycle the working fluid is evaporated above the critical pressure of the working fluid before directed to the turbine. The technology is similar to single level but higher evaporation pressure level within the cycle consequences higher operation costs due to more needed pumping power.

Therefore, all advantages and disadvantages of available technologies have to be evaluated carefully before selecting a certain type of technology and apply in a geothermal power plant.

The three basic types of geothermal power plants illustrated in figures 1-3 can also be combined in many different ways as the following example demonstrates:

Figure 4. **Combined Flash and Binary Cycle power plants.** In this setup geothermal water from the separator is recycled through a heat exchanger of a binary plant to increase substantially overall power production. Importance of the Binary cycle power plant addition is obvious.



Any leftover water and condensed steam is preferably reinjected into the reservoir, for the purpose of making it a more sustainable resource. Sometimes, as in Iceland, the separated water is used for heating purposes, greenhouses, Blue Lagoons etc, before being reinjected.

Small-scale geothermal power plants (< 5 MW) have the potential for widespread application in rural areas, possibly even as distributed energy resources. Distributed energy resources refer to a variety of small, modular power-generating technologies that can be combined to improve the operation of an electricity power system.

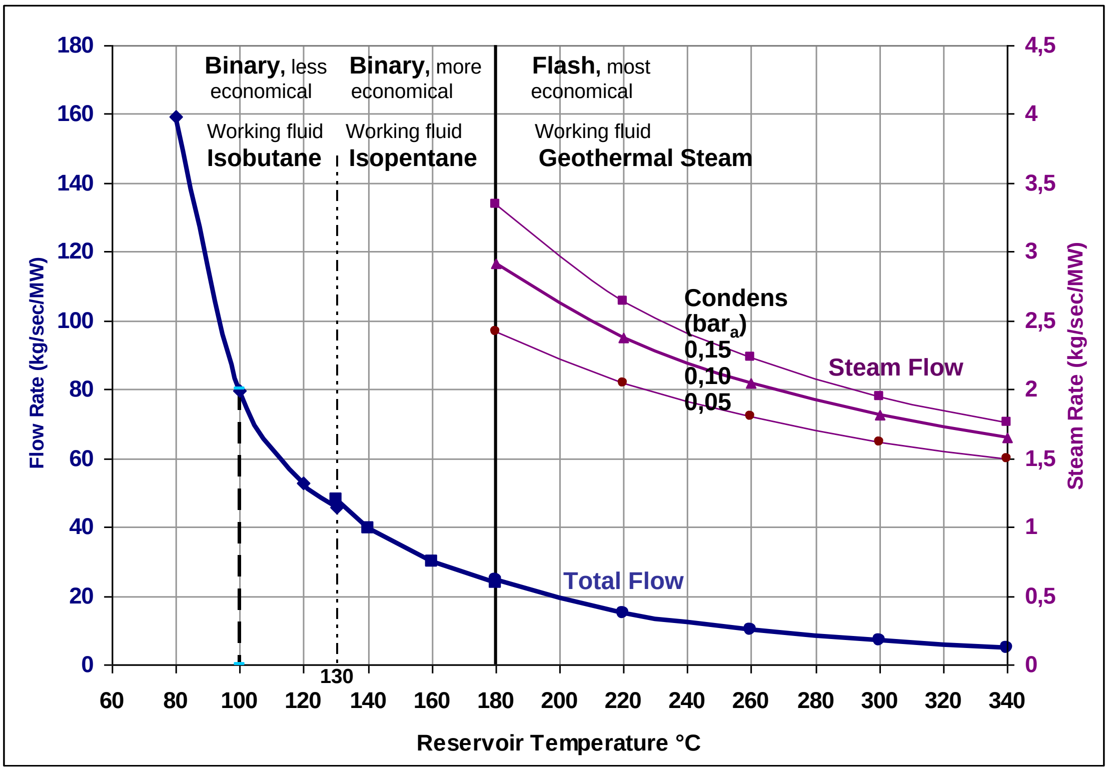
Characteristics of geothermal utilization

Figure 5 shows geothermal flow needed for generation of 1 MW of electrical power.

For binary plants (T<180°C) the total flow is directed through a heat exchanger.

For flash type of plants (T>180°C) the total flow is directed through a steam separator. The separated steam is then directed through the turbine and the exhaust to a condenser which must be cooled down with water from cooling towers, by using water from a nearby stream or more rarely ocean water.

Figure 5. Geothermal flow rate (Source: Valdimar K Jonsson professor emeritus)



Geothermal Energy distribution

The energy per mass unit of a geothermal resource increases with temperature. The amount of energy within a given temperature class is the number of geothermal resources within that temperature class multiplied by the specified energy valid for the resource within that temperature class. Then it is possible to construct a shape of a curve describing magnitude of geothermal energy as a function of temperature of the resource [03].

Figure 6 illustrates an attempt to describe distribution of the magnitude of geothermal energy in the world as a function of resource temperature.

Figure 6. Geothermal energy as a function of resource temperature.

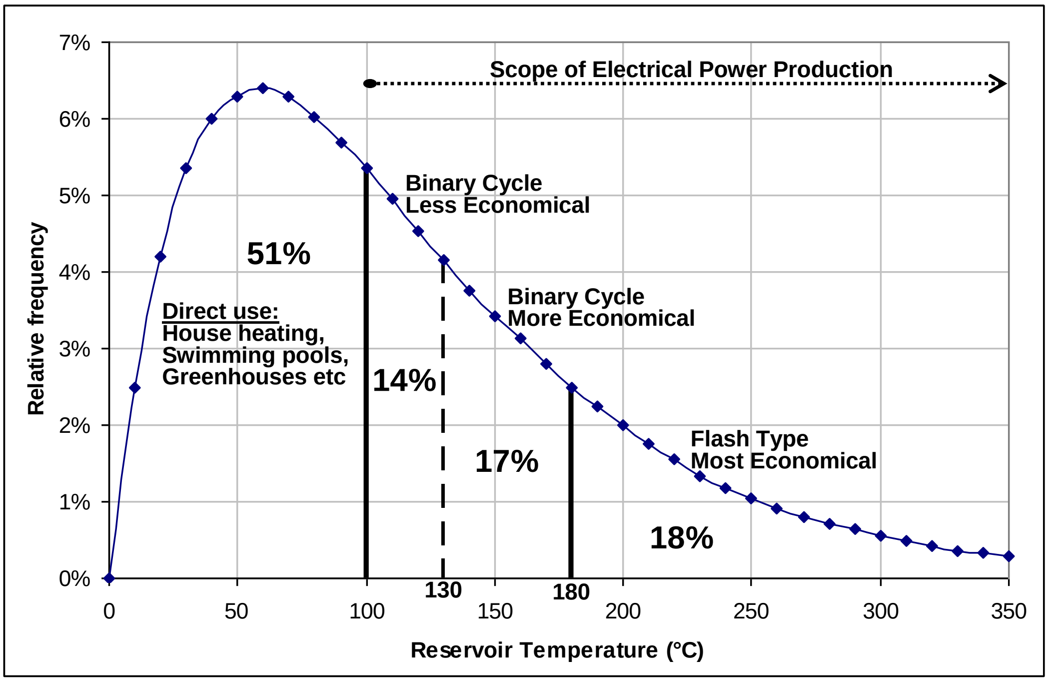
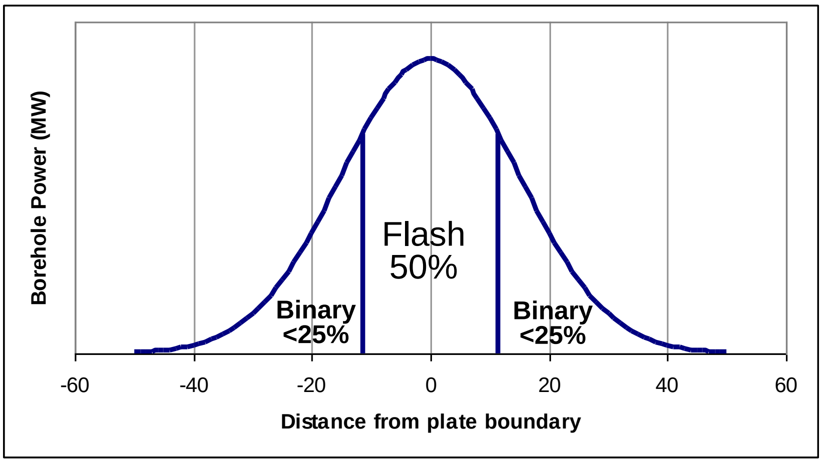


Figure 6 reveals that energy potential of the lower temperature Binary Cycle type is of the same size of magnitude or even a little bit higher than for the high temperature Flash type.

The results are that 18/(14+17+18)=37% of the total geothermal electricity potential could be generated by conventional (flash) technique and that additionally (14+17)/(14+17+18)=63% should be available from geothermal resources if binary turbines are also considered.

Figure 7. Geothermal activity and tectonic plate boundaries



In geothermal areas, first the high-temperature zones (T>180°C) near plate boundaries are utilized. When borehole opportunities in these areas are getting exhausted, be it either by environmental consideration or exhaustion of geothermal reservoirs, drilling farther away from the plate boundaries are required. This could result in less powered boreholes, fit for utilization by the binary technology. Unsuccessful boreholes intended for flash power plants are sometimes fully eligible for Binary Cycle Power Plants.

This is explained schematically in figure 7.

Geothermal Power Production Capability

In reference [02] it is estimated, based on distribution of active volcanoes, that the world geothermal potential for electrical power generation with high resource temperature (T>130°C) is 210.000 MW_e.

Half of it or 105.000 MW_e is for temperature T>180°C and the other half or 105.000 MW_e for temperature 130°C>T>180°C.

Lower temperature resources T<130°C including residual energy from electricity production, suitable for direct use is estimated 4.400.000 MW_{th}.

For comparison installed geothermal power capacity in the world is currently ca 11.000 MW_e (5,2% utilization) and thereof 575 MW_e is installed in Iceland.

Table 1 illustrates geothermal power plants of the world in the year of 2011 [04]:

Table 1. Categories of Geothermal power plants of the world. Sept 2011

		Capacity	**Number of**	**Ave.Size**	**Share**
	Type	**MW_e**	**Units**	**MW_e**	**(%)**
1	**Dry Steam**	2.862	63	45,4	**27,0%**
2	**Single Flash**	4.717	150	31,4	**44,5%**
3	**Double Flash**	2.187	64	34,2	**20,6%**
4	**Back Pressure**	147	26	5,7	**1,4%**
5	**Binary Cycle**[1]	688	154	4,5	**6,5%**
6	**Hybrid**[2]	6	2	3,0	**0,1%**
	Total	**10.607**	**459**	**23,1**	**100,0%**

Source: IGA

The first four categories are high temperature (T>180°C) and the two lowest categories are medium temperature (T<180°C).

In view hereof we conclude that 93% of the current world geothermal machinery is installed in high temperature areas where underground reservoir temperature is T>180°C. Only 7% of the geothermal machinery is of the binary cycle type.

The reason for this is that borehole success factor, in terms of yield of the borehole measured in temperature, flow rate and chemical composition, is larger in high temperature areas and therefore drilling is less costly than for lower temperature areas. On-surface power plants of the binary type are also more spacious and costly than for the flash type. For practical purposes the upper bound for installed capacity of binary power plants is therefore considerably lower than for flash power plants and therefore has been less attractive for power producers.

In general, high temperature areas are located at tectonic plate boundaries and usually away from the more densely populated areas. Therefore considerable cost would be associated with transmission lines with considerable increase in energy cost for electrical power utilities.

Lower temperature areas, suitable for geothermal binary power plants, could be found farther away from the plates boundaries, even in vicinity of urban areas. In some countries building of geothermal capacity for power production is subsidized by the local government to increase electrical power production from renewable resources. One form of such a support is the (sometimes very high) feed in tariff for electricity generated from geothermal resources in many European countries (Germany). Newly introduced Contract for Differences (CfD) in UK serves similar purpose.

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[1] Back Pressure refers to a two stage process where i.e. a flash plant delivers steam from its turbine to a binary turbine for further power production. Another type of Back Pressure is when a steam turbine releases steam directly into the air in absence of a low pressurized condenser.

[2] The Hybrid type is associated with high underground water pressure. The first stage in the power plant would be a hydro turbine receiving high pressure water and delivering the water with lower pressure to a binary turbine.

Cost of energy

In table 2 costs of a Geothermal Flash type and a Binary Cycle type Power plant are compared. The numbers are somewhat hypothetical but should be "ballpark values".

Table 2. Costs of Flash and Binary type Geothermal Power Plants. Prices 2011

Item	**(Unit)**	**Flash**	**Binary**	**Binary**
Cost of Drilling		100%	100%	33%
Civil Works and infrastructure	(M$/MW)	0,200	0,100	0,100
Production Boreholes	(M$/MW)	0,600	1,200	0,400
Reinjection Boreholes	(M$/MW)	0,400	0,800	0,266
On-surface Power Plant	(M$/MW)	1,500	1,800	1,800
Electric Works and Installation	(M$/MW)	0,200	0,200	0,200
Total Installation Costs	**(M$/MW)**	**2,900**	**4,100**	**2,766**
Annuity (interest 7%, lifetime 25 year)	(%)	8,58%	8,58%	8,58%
Annuity Costs	(M$/MW)	0,249	0,352	0,237
Operation (% of Inst Costs)	(%)	2,50%	3,00%	3,00%
Cost of operation	(M$/MW)	0,073	0,123	0,083
Total Levelised Costs	(M$/MW)	0,346	0,505	0,350
Utilization	(h/year)	8000	8000	8000
Energy Costs	**($/MWh)**	**43,29**	**63,10**	**43,79**
Cost of Binary compared to Flash	(%)		+46%	+1%

The last column in the table explains the cost structure of a Binary Cycle Power Plant in the case of an abandoned borehole originally intended for Flash type Power Plant, but overtaken for the Binary Cycle Power Plant at a cost of 33% of actual drilling cost.

Conclusion

According to table 1, utilization of the geothermal areas has until now been much faster for high temperature than for medium temperature geothermal areas based on more attractive drilling opportunities and lower overall production costs.

Proximity to markets, favorable high feed-in tariff for geothermal, standardizing and mass production of small binary geothermal plants etc. could change this picture and make harnessing of medium temperature areas more feasible.

By state of the art technology including proper and optimized ORC turbine would make the binary turbine system more compact and simple. This could, for higher capacities (>10 MW?), even eliminate the need for gear box and lubrication system then the pump, turbine and generator would be on a single shaft. The advantages will include higher availability, lower operation and maintenance requirements and more quiet operation.

References

[01] Valgardur Stefansson, Orkustofnun, Iceland: "Estimate of the World Geothermal Potential". Geothermal Training Programme. 20th Anniversary Workshop. Oct 1998.

[02] Valgardur Stefansson, Orkustofnun, Iceland: "World Geothermal Assessment". Proceedings World Geothermal Congress 2005, Antalya Turkey 23-27 July 2005.

[03] http://www.renewableenergyworld.com/rea/tech/geoelectricity

[04] The International Geothermal Association (IGA) Database, last updated Sept 2011. http://www.geothermal-energy.org/