Geothermal Heat and Power

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS –** The global capacity of geothermal power plants is approximately 9 GW$_e$, with an annual electricity generation of about 60 TWh$_e$, which is equivalent to less than 1% of the global electricity demand. Geothermal heating plants have a global capacity of approximately 18,000 MW$_{th}$ and produce about 63 TWh$_{th}$ per year. By and large, technologies for the exploitation of what is called 'conventional and shallow' geothermal energy resources are commercially available. These technologies include: ■ **Dry steam plants**; ■ **Flash plants**; ■ **Binary plants**; ■ **Combined-cycle or hybrid plants**; ■ **Combined Heat and Power based on geothermal energy**; ■ **Heating based on geothermal energy**. However, these resources are rather limited. The current challenge is the development of **Enhanced Geothermal Systems** (EGS) – also known as 'Hot Dry Rocks' - to exploit *deep geothermal resources,* which could expand the potential of geothermal energy considerably. An overview of temperature levels, applications and the variety of exploitation technologies of geothermal resources, is shown in Figure 1.
- **COSTS –** The investment cost of **geothermal power plants** depends considerably on the site, depth and characteristics of the geothermal resources. A value of \$4000/kW$_e$ (US\$ 2008) may represent an average indicative cost, with considerable variations. Assuming an average annual operation and maintenance (O&M) cost of 3.5% of the investment cost (approximately \$140/kW$_e$ per year), the resulting generation cost is approximately \$90/MWh. For **geothermal-based combined heat and power plants**, the investment cost is higher (typically, \$10,000/kW$_e$), the O&M costs are around \$250/kW$_e$ per year, and the generation cost may reach approximately \$200/MWh. For **geothermal heating systems,** an average investment cost is estimated at \$1800/kW$_{th}$, with the O&M costs at \$35/kW$_{th.}$ The heat generation cost is approximately \$45/MWh$_{th}$.
- **POTENTIAL AND BARRIERS –** Large-scale geothermal power development is currently limited to tectonically active regions such as areas near plate boundaries, rift zones, and mantle plumes or hot spots. These active, high heat-flow areas include countries around the 'Ring of Fire' (Indonesia, The Philippines, Japan, New Zealand, Central America, and the West Coast of the United States) and rift zones such as Iceland and East Africa. These areas are the most promising for geothermal development in the next decade, with a potential increase of geothermal power capacity from 13 GW$_e$ in 2010 to 30 GW$_e$ in 2030. If technological breakthroughs made new geothermal power technologies available (EGS), then geothermal power might expand to other regions and commercial geothermal capacity could increase beyond 30 GW$_e$.

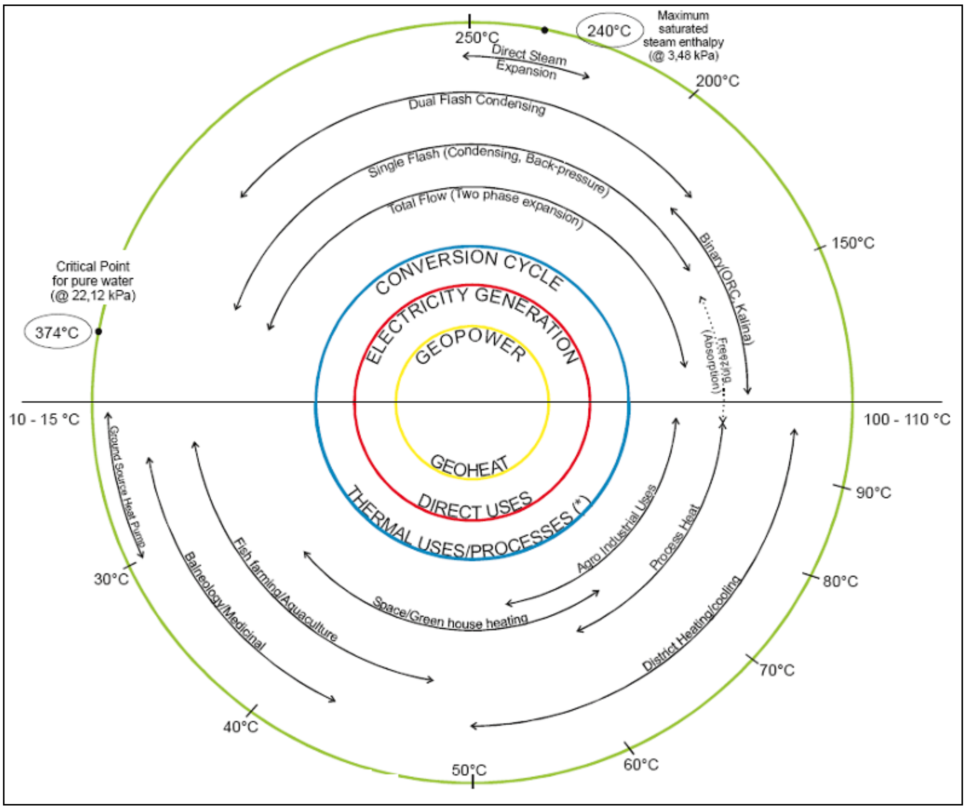

Fig. 1 - Geothermal resource utilisation potential (Antics and Ungemach, 2009)

PROCESS AND TECHNOLOGY STATUS – Geothermal resources include basically **low-enthalpy fields**, which have long been used **for direct heating** applications (e.g. district heating, industrial processing, domestic hot water, space heating, etc.) and high-quality **high-enthalpy fields** (e.g. high-temperature natural steam at less than 2-km depth), which are used for **power generation**. On a global scale, geothermal-based heat and power amount to 2 EJ/year (IEA, 2008). In 2008, with a global capacity in operation of approximately 9000 MW$_e$ (out of a total installed capacity of about 10,000 MW$_e$), geothermal power plants generated approximately 60 TWh, which is about 0.25% of the global electricity generation. Geothermal heating plants produced some 63 TWh of heat, with an installed capacity of approximately 18,000 MW$_{th}$.

Geothermal power generation - Fields of pure natural steam are rather rare. Most geothermal projects are based on a mixture of steam and hot water requiring *single- or double-flash systems* to separate the hot water. In general, high-enthalpy geothermal fields are only available in areas with volcanic activity, whereas the rest of the fields are low- or medium-enthalpy resources. Geothermal power generation is currently based on four technology options (Long et al, 2003) that are briefly illustrated as follows. **■ Dry steam plants -** Only the Italian geothermal fields of Larderello and the Geysers in the United States provide *vapour-dominated fluids* (Renner, 2002, Figure 2). In this case, the conversion devices consist of geothermal steam turbines that are designed to make effective use of the comparatively low-pressure and high-volume fluid produced in such conditions. Dry steam plants commonly use condensing turbines. The condensate is re-injected (closed cycle) or evaporated in wet cooling towers. A typical geothermal plant's capacity is 50-60 MW$_e$, but more recently 110-MW$_e$ plants have been commissioned and are currently in operation (EGEC, 2009). **■ Flash plants -** Similar to dry steam plants, geothermal flash plants are used to extract energy from high-enthalpy geothermal resources, in which, however, the steam is obtained from a separation process (flashing). The steam is then directed to the turbines and the resulting condensate is sent to re-injection or further flashing at lower-pressure. The fluid fraction exiting the separators, as well as the steam condensate (except for condensate evaporated in a wet cooling system), are usually re-injected (Figure 3). The typical size of flash plants is between 2 and 45 MW$_e$ (DiPippo, 1999). **■ Binary plants -** Binary plants are usually applied to low- or medium-enthalpy geothermal fields where the resource fluid is used, via heat exchangers, to heat a process fluid in a closed loop. The process fluid (e.g. ammonia/water mixtures used in kalina cycles or hydrocarbons in organic Rankine cycles, ORC) has physical properties (i.e. boiling and condensation points) that match the geothermal resource temperature better (Köhler and Saadat, 2003). In the binary plants, the exhaust resource fluids are often re-injected in the field along with all the original constituents. Therefore, these plants are true zero-discharge technologies (Figure 4).

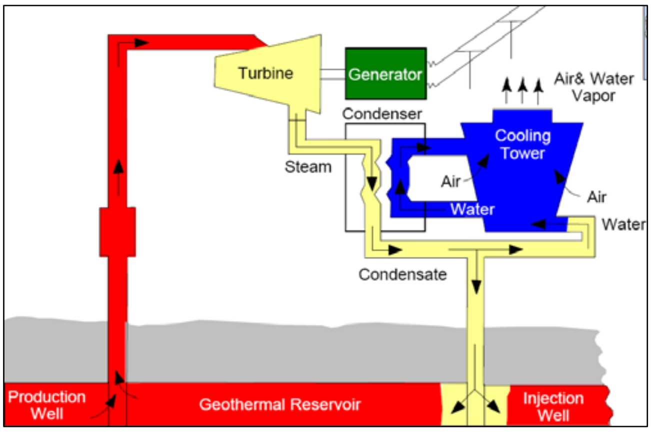

Fig. 2 - Direct steam geothermal power plant (Sanner, 2007)

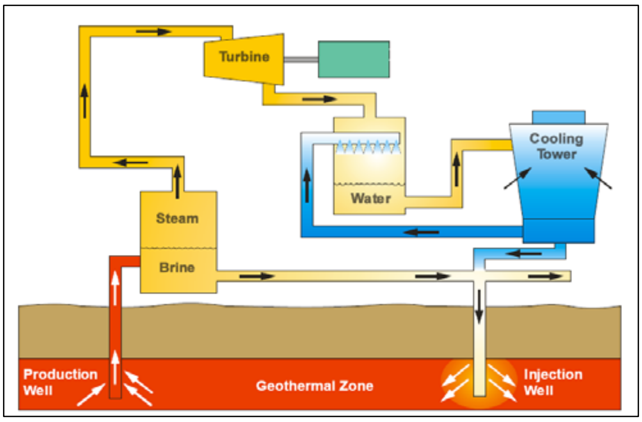

Fig. 3 - Flash geothermal power plant (Kutscher, 2004)

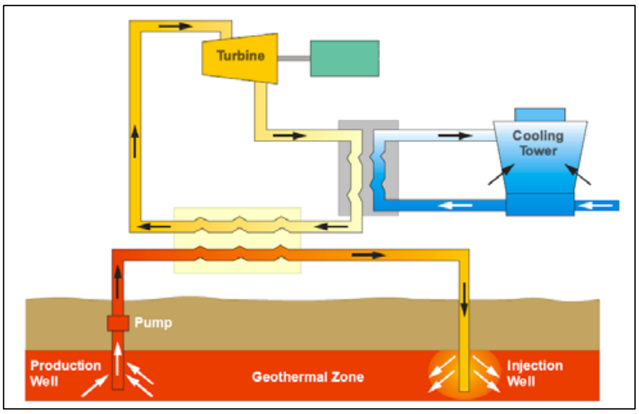

Fig. 4 - Binary cycle geothermal power plant (Kutscher, 2004)

The typical size of binary plants is < 5 MW$_e$ (DiPippo, 1999). **■ Combined-cycle or hybrid plants -** Newer geothermal plants in New Zealand and Hawaii use a traditional Rankine cycle on the top end and a binary cycle on the bottom end (Figure 5). Using two cycles in series provides relatively high electric efficiency (DiPippo, 1999; Thain, 2009). The typical size of combined-cycle plants ranges from a few MW up to 10 MW$_e$ (Lund, 1999; DiPippo, 1999).

■ **Geothermal combined heat & power (CHP) - Geothermal CHP** from medium-enthalpy sources using organic Rankine cycles and a low-temperature boiling process fluid would be cost effective if there is sufficient demand for heat production (e.g. district heating). In general, CHP plants are economically viable and largely used in (Northern) Europe where space heating demand is significant and constant over the year (Internet Source 1; Lund, 2005, Figure 6). Therefore, in these areas, combined heat and power is used more than power generation alone. The typical size of combined heat and power plants ranges from a few MW$_e$ up to 45 MW$_e$ (EGEC, 2009). ■ **Heating based on geothermal energy -** Both high- and low-enthalpy geothermal resources can be directly used in a number of heating applications, such as space heating and cooling, industry, greenhouses, fish farming, health spas, etc. From an economic point of view, however, direct heat applications are site-sensitive as steam and hot water are hardly transported over long distances (Fridleifsson et al, 2008). The most common application of geothermal heat is for district heating schemes[1]. It is estimated that in 2008 geothermal heating plants produced some 63 TWh, with a global capacity of approximately 18,000 MW$_{th}$. If the geothermal heat source is of insufficient quality (temperature too low), then geothermal heat pumps can be used as an alternative technology option.

Table 1 - Costs of Conventional Geothermal Binary-Cycle Power Plants in the US (Internet S. 2–7)

Project	Capacity [MW$_e$]	O&M cost [M\$]	Invest. cost [\$/kW$_e$]	Generation cost [a] [\$/MWh$_e$]
Thermo (Utah)	10.5	33	3143	78
Faulkner 1 (NV)	40.1	180	4489	94
Hatch (Utah)	40.0	150	3750	N/A
Buena Vista CO	10.0	40	4000	N/A
Aggregate	100.6	403	~4000	~90

a - Generation costs are based on data of supply contracts

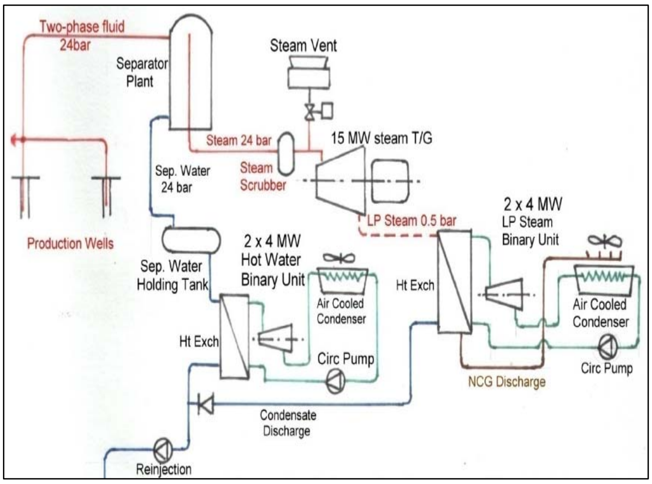

Fig. 5 - Hybrid geothermal power plant (Thain, 2009)

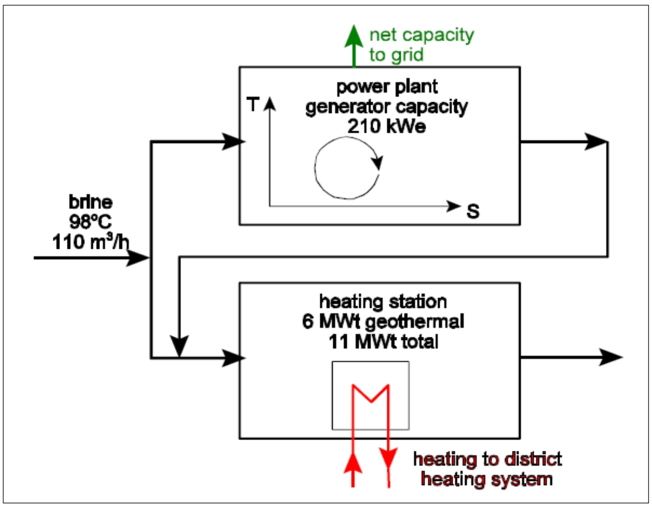

Fig. 6 - CHP plant Neustadt-Glewe (Lund, 2005)

COSTS – In relative terms, new technologies are helping to reduce the cost of conventional geothermal resources and exploit resources that would have been uneconomic years ago from both a power generation and field development point of view (Hance, 2005). The investment cost of **conventional geothermal power** is currently estimated to range from \$3400/kW$_e$ to \$4500/kW$_e$ (EERE, 2009a). These are indicative, average costs that are considerably higher than costs recorded years ago because of the higher prices of materials (steel), engineering, etc. However, geothermal energy investment costs are very site-sensitive. There are sites with very favourable conditions (e.g. Italy, Iceland) where the investment costs are significantly lower. In the United States, the electricity generation cost (levelised cost) based on geothermal power is estimated to range between \$68/MWh and \$118/MWh with an average of \$89/MWh (Sener et al, 2009). For Italy and Iceland, the cost can be at least 20% to 30% lower due to more favourable geological conditions. Table 1 presents cost data for four **conventional geothermal** power plants in operation or to be built in the US (Internet Sources 2–7), with an average investment cost of \$4000/kW$_e$. Assuming that annual O&M costs are 3.5% of the investment cost (\$140/kW$_e$ per year), then the generation cost is approximately \$90/MWh. For **geothermal CHP**, the investment cost is approximately \$10,000/kW$_e$, which is more expensive than the 'power only' option mentioned above but offers the possibility to increase overall efficiency and generate additional income from heat supply. In this case, the O&M cost is \$250/kW$_e$ per year, and the generation cost may reach approximately \$200/MWh. For **geothermal heating**, the average investment cost is \$1800/kW$_{th}$, the O&M cost is roughly \$35/kW$_{th}$ per year and the production cost is \$45/MWh. Cost projections and estimates based on technology learning and economy of scale suggest that the investment cost of **conventional geothermal power** could come down modestly to \$3150/kW$_e$ in 2030, with similar reductions in the O&M cost. The reduction in the **geothermal CHP** investment cost is assumed to be more

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[1] In some cases, geothermal heat can also be exploited on small scale for e.g. office building heating and cooling.

pronounced, dropping to $6400/kW$_e$ in 2030, with corresponding percentage reduction in the O&M cost. The investment costs of **geothermal heating** plants are also estimated to decline to $1500/kW$_{th}$ by 2020.

POTENTIAL AND BARRIERS – Large-scale geothermal power development is currently limited to tectonically active regions such as areas near plate boundaries, rift zones, and mantle plumes or hot spots. These active, high heat-flow areas include countries around the 'Ring of Fire' (Indonesia, The Philippines, Japan, New Zealand, Central America, and the West Coast of the United States) and rift zones (Iceland and East Africa). These areas are the most promising for geothermal developments in the next decade (IEA, 2008).

Table 2 presents the indicative potential of geothermal power generation (in GW$_e$) and geothermal heat (in GW$_{th}$) based on current and future technology (Stefansson, 2005). A wide difference exists between the lower and upper limit of the technical potential, both for geothermal power generation and geothermal heat. This is due to the potential of new technologies, notably the **Enhanced Geothermal Systems (EGS),** which could substantially increase the potential of geothermal energy as they could expand geothermal applications in regions other than those that are currently being exploited. Table 3 shows how the EGS development is part of the geothermal power potential. Technical potential of geothermal heat and power has been analysed by Bertani (2009) and by Stefansson (2009). Starting from a correlation between the existing geothermal high-temperature resources and the number of volcanoes, the estimated potential is 200 GW$_e$, (Table 2, Stefansson, 2009). EGS based on deep geothermal resources could add hundreds of GW$_e$[2]. Global *economic* potential is estimated at 140 GW$_e$ in 2050.

Figure 7 provides a projection of the global geothermal capacity. In 2007, the *operative* capacity was 8.6 GW$_e$, and the projection for 2010 was from 10.7 GW$_e$ to 13.5 GW$_e$ (Internet Source 8). In 2008, the US capacity was about 3 GW$_e$ (EERE, 2009a), with projections for rapid expansion by 4 to 7 GW$_e$ (Internet Source 9). With 4 GW$_e$ added in the US (operational capacity) and a world growth roughly consistent with projections (Bertani, 2007), the global 2010 capacity could be somewhere in the order of 13.3 GW$_e$. According to Global Data (2009), further 7.5 GW$_e$ could be added between 2010 and 2015. Other sources (Internet Source 10) estimate that a capacity addition of 2 GW$_e$ per year may be feasible in about five years. The geothermal capacity is therefore expected to grow by 16.5 GW$_e$ between 2010 and 2020 (Figure 7). More detailed projections by country are provided in Table 4.

Table 2 - Estimated technical potential (GW) of world's geothermal resources (Stefansson, 2005)

	Lower limit technical potential	Potential for identified resources	Upper limit technical potential
Power Generation Resources	50	200	1000-2000
Direct Heating Use Resources suitable for	1000	4400	22,000-44,000

Table 3 - Geothermal technology development, barriers and opportunities (EERE, 2009b)

Tech.	State-of-the-art	Barriers	Innovation	Applied to
Drilling	Rotary table rigs; Trone roller and PDC bits; Telescoping casing; wireline downhole.	Costs & Temp. Limits; designed for oil, gas	Continuous drilling; monobore casting; casing while drilling; high-temp. tools	Hydro-th. fields, EGS
Reservoir Stimulation	Demo projects, 25 kg/s flow rates,1 km^3 reservoir volume	Immature tech., 40-80 kg/s flow rates needed	High-temp. packers, novel well interval isolation techniques, 'first-to-commercial'	Marginal hydro-th. fields, EGS
Downhole Pumps	Line-Shaft Pumps to 600 m, Electric Submersible to 175°C	Temp. and Depth Limits	High-temp. electrical submersible pumps	EGS, hydro-th. fields 175–225C (too hot to pump, too cool to flash)
Energy Conversion Systems Power Plants	Binary cycle (isobutane): 100–200+C, Cooling Towers, Air-Cooled Condensers	Efficiency limits, low power output at high room temp.	Supercritical Rankine cycle, novel binary fluids, adv. cooling	Medium-low temp. hydro-thermal, EGS
Exploration and Resource Tests	Surface evidence; ground heat- flow tests; well exploration; stress field analysis (EGS)	Costly well expl. & drilling; time (yrs) to prove a field	GIS mapping geoth.indic. to assess resources novel techs for field test temp, stress, fluid, depth, airborne identification	Hydro-thermal, EGS

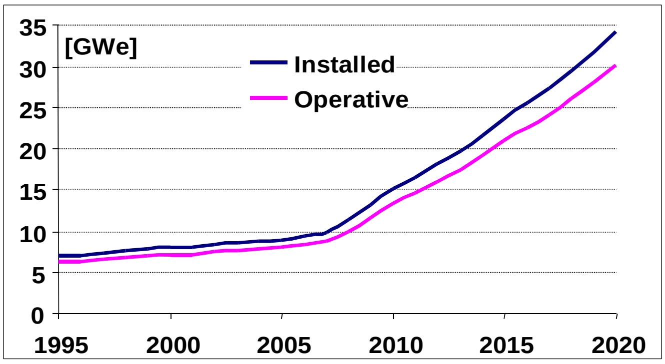

Fig. 7 - Global geothermal power projections 1995-2020 (Bertani, 2009; Global Data, 2009; Internet S. 7–8)

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[2] EGS in the US could provide more than 100 GW$_e$, (Thorsteinsson, 2008).

Table 4 - Projected operative geothermal capacity [MW_e]

Country	2005	2010	2015	2020	Country	2005	2010	2015	2020
Australia	0.1	0.2	200	314	Japan	530.2	530	600	675
Argentina	0.7		50	100	Kenya	128.8	145	300	471
Austria	1.1	1.1	20	30	Mexico	953	1040	1300	1550
China	18.9	25	100	250	New Zealand	403	521	818	1284
Costa Rica	162.5	174	273	429	Nicaragua	38	126	198	311
El Salvador	119	180	283	444	Papua New Guinea	6	49	78	122
Ethiopia	7.3	7.3	11	18	Philippines	1838	1856	2000	2200
Guadeloupe	14.7	31	49	76	Azores(Pt)	13	31	49	76
Germany	0.2	7	100	250	Russia	79	163	256	402
Guadeloupe (F)	29	47	73	115	Thailand	0.3	0.3	50	79
Iceland	202	450	650	850	Turkey	18	73	115	181
Indonesia	838	1052	1200	1350	United States	1,935	5,970	11,159	17,520
Italy	699	803	900	1000	**Total**	**8,035**	**13,282**	**20,831**	**30,096**

Table 5 – Summary Table: Key Data and Figures for Geothermal Heat and Power Technologies

Technical Performance	**Typical current international values and ranges**		
Energy input	Geothermal energy		
Output	Electricity		
Technologies	Binary cycle **BIN**	Comb. Heat & Power **CHP**	Heat plant **HP**
Efficiency, %	8 – 15	Not applicable	Not applicable
Construction time, months	Minimum 12; Typical 24; Maximum 36		
Technical lifetime, yr	30–50+		
Load (capacity) factor, %	80	80	55
Max. (plant) availability, %	95	95	95
Typical (capacity) size, MW_e	25	0.5	100
Installed (existing) capacity, GW_e (GW_{th})	9–10 (all types)	<<1	18 (estimate)
Average capacity aging	Differs from country to country		
Environmental Impact			
CO_2 and other GHG emissions, kg/MWh	Negligible	Negligible	Negligible
SO_2, g/MWh	Negligible	Negligible	Negligible
Costs (US$ 2008)			
Investment cost, incl. interest during construction, $/kW	3400 – 4500	6000 – 15,000	1000 – 3000
O&M cost (fixed and variable), $/kW/a	120	250	20 – 60
Fuel cost, $/MWh	N/A	N/A	N/A
Economic lifetime, yr	20		
Interest rate, %	10		
Total production cost, $/MWh	80 – 110	120 – 300	25 – 75
Market share	0.25	Negligible	N/A

Data Projections	**2010**			**2020**			**2030**	
Technology	**BIN**	**CHP**	**HP**	**BIN**	**CHP**	**HP**	**BIN**	**CHP**
Investment cost, incl. interest during construction, $/kW (BIN/CHP/HP)	4,000	10,000	1,800	3,500	8,000	1,500	3,100	6,400
Total production cost, $/MWh	90	200	45	79	160	37.5	70	130
Market share, % of global electricity output	~¼	<<1		~½	<<1		1–2	<1

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