CLIMATE CHANGE REFERENCE BOOK

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Prepared for the Office of Renewable Energy by Meridian Corporation

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ENERGY SYSTEM EMISSIONS AND MATERIEL REQUIREMENTS

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Executive Summary

The purpose of this analysis is to construct comparable measures of emissions and materiel requirements for power production technologies. The goal is to develop a consistent framework for making comparisons between technologies at each stage of the energy production process, as well as comparisons of the overall impacts of each generating technology taken in its entirety. The intended outcome is a cumulative view of emissions that focuses on quantities of emissions as a function of energy supplied. Five technologies are included in this analysis:

- a conventional coal plant with a scrubber (500 MW)
- an Atmospheric Fluidized Bed Combustion (AFBC) plant (500 MW)
- an Integrated Gasification Combined Cycle (IGCC) plant (1000 MW)
- a boiling water nuclear reactor (1000 MW)
- a central station photovoltaic plant (100 MW)

This study attempts to view all environmental impacts associated with a technology as part of one system designed to produce energy over the useful life of a technology. By relating environmental impacts at all stages of energy production to a technology's total useful output of energy, the usual segregated, single-aspect view of energy production is overcome and a basis is established for comparing technologies that have very different capital, fuel, and operating characteristics.

To accomplish these purposes the analysis is conducted within a framework that delineates three basic aspects of energy production;

- Energy production stages -- fuel extraction, construction, operation, and decommissioning
- Environmental impacts -- air, water, solid wastes, and materiel requirements
- Power production technologies -- coal, nuclear, and photovoltaics

These three aspects form a matrix of data that allows comparisons of environmental impacts across technologies at each stage of their energy production cycle. In order to maximize comparability, emissions and materiel demands are normalized over the entire operating life of each technology and related to a common measure of each technology's performance, gigawatt-hours (GWh) of electricity production.

Because this analysis attempts to take a unique, comprehensive view of emissions from power production technologies, only a limited amount of data were reasonably available. A limited number of studies that attempted a comprehensive view of specific power production technologies provided the basis for updating information and estimating the effects of newer technologies. For the most part, however, the literature on emissions from power production technologies tends to focus either on environmental effects or on power production, without relating the two. The information also tends to be very specialized. Some sources investigate only certain emissions from a technology and do not relate them to other emissions. Most ignore the effects of fuel extraction and plant construction. The task of generating original scientific data would require a major effort in examining and comparing the actual designs and operating information on equipment and procedures used in mining, construction, materiels fabrication, operation, and decommissioning, and then translating the information into emissions and energy production data for use in the analysis. This analysis is limited to examining major issues using data from available sources. As a result, gaps appear in the data and simplifying assumptions had to be used to produce comparable data. Further discussion of the sources and the treatment of the data used in the analysis is provided in the body of the report.

Despite the limitations of the data and the analysis, the effort does provide insights into the environmental and materiel impacts of different energy technologies. In examining air emissions the results clearly portray the significant contribution of coal plant operation to CO_2, NO_x, and SO_x production. If also shows the relatively narrow range of improvements that can be expected from clean coal technologies such as AFBC and IGCC in reducing CO_2 emissions. The IGCC investigation highlights IGCC's advantages in terms of sharply reducing SO_x, NO_x, and particulate emissions, but also shows limited impacts in terms of reducing CO_2 emissions.

Comparing nuclear and photovoltaics to the coal technologies demonstrates the well-accepted notion that these two technologies are preferable from the standpoint of major air emissions. The results also clearly show that their contribution is not zero when all the elements of their fuel cycle are considered, and that they have emissions which are different but also potentially significant, especially if their role in energy production is expanded. No technology is completely environmentally benign.

Water emissions data, though limited, are useful for pointing out the key point of impact in the coal extraction stage -- an impact that is often overlooked because of the separation between mining and energy conversion. By taking a "total" view of energy production this type of analysis helps quantify the problem in real terms as a direct side-effect of energy production and consumption.

Solid waste emission data clearly demonstrate the link between fuel-intensity and solid waste generation, as well as the broad range of solid wastes from coal preparation to radioactive by-products of uranium fission. All solid wastes present disposal problems and all represent a growing mass of materiel that will not dissipate rapidly, unlike many air emissions which become dilute or degrade into less harmful by-products over a relatively short time-frame. Not included are major by-products such as elemental sulfur from IGCC plants, because they have a value and are not emissions in the sense of being wastes.

In addition to direct emissions, materiel requirements of power production technologies are examined, since they can have direct or indirect environmental effects. In the case of land requirements, impacts occur at entirely different stages of energy production. For fuel-intensive technologies, land use is concentrated in the fuel extraction stage. For a materiels-intensive technology like photovoltaics, the major land impacts occur at the plant site. Coal facilities show a low demand for construction materiels relative to output, but have high demands for water and significant land requirements during operation and fuel extraction, respectively. Nuclear shows comparatively lower demand for concrete, steel and land, but substantial water requirements.

Photovoltaics, recognized as a highly materiels-intensive technology, does have greater materiel requirements than the conventional technologies per output, but the difference is not as great when all the aspects of energy production are considered and the investigation is expanded beyond PV's one-time construction impacts. PV land requirements, as an example, are comparable to coal strip mining. However, because of its limitations the analysis does not address the duration or quality of these impacts, which is especially important in examining materiel requirements. The land used in coal and uranium mining can be reclaimed for other uses fairly quickly. The land which PV, coal, and nuclear require for the plant site is closed to alternative uses until the plant is decommissioned and removed. At the other extreme, nuclear waste storage areas, which were not examined for lack of representative data, will require isolation for thousands of years, representing a basically permanent removal of land from other uses.

Similarly, the implications of water demand are more complex than this limited analysis implies. In the water-scarce American West, water rights and use are very important, but are less so in the Eastern U.S. Thus a conventional coal or nuclear plant's high water demand could be a major issue in one region of the country, but less so in another.

This analysis does not provide a basis for recommending one technology over another. Rather, it provides a useful comparison of the environmental aspects of these technologies, which is only one aspect that should be considered in their deployment. Without information on costs, the suitability of a technology to particular sites and energy demand situations, and localized environmental impacts associated with particular projects, it is impossible to say one technology is preferable to another. Instead the analysis points out the wide variety and extent of impacts that should be considered and their relation to energy production; it shows just how broad the implications of energy use are, and demonstrates the favorable environmental tradeoffs that might be made by pursuing a mix of generating technologies, each chosen to maximize benefits while limiting negative side effects.

Study Approach and Organization

By investigating the impact of each stage of the energy production process, the analysis attempts to normalize differences between representative materiel- and fuel-intensive technologies in order to provide a fair basis for comparison. When emissions and materiel demands are normalized in terms of each facility's useful power output, the association between electricity production, emissions and materiel demands for each technology becomes clearer.

The analysis constructs a comparative structure for assessing different power production technologies by examining each technology within a common framework. The first aspect of the framework is a delineation of all the environmental points of interest associated with power production systems, from extraction of fuel, to raw materiel production for plant manufacture, to plant operation, to decommissioning. Within each of these stages of energy production the analysis attempts to catalog impacts on air, water, solid wastes, and materiel requirements, noting the type and magnitude of emissions or materiel demand affecting each category of environmental impact at each stage of the energy production process. This matrix of energy production stages and emission/materiel data is produced for each technology, so that each power production technology can be compared at each stage of energy production and in terms of each type of emission or materiel demand.

Emissions are usually expressed in terms of quantities over time, which in turn relate to levels of concentration in the atmosphere. This approach is an offshoot of health-based standards, such as the National Ambient Air Quality Standards (NAAQS), which establish the parameters of a healthy environment and are then used to derive emission standards which will maintain that status. This approach is well-suited to the goals of environmental protection, but it is less useful for cross-comparing the negative and positive impacts of technologies. Pounds per hour or pounds per million Btu of input only indirectly show the impact of the product society actually consumes -- watt-hours of electricity. This analysis attempts to make the tradeoffs between emissions and energy output clearer by construing emissions as a function of useful power output, and placing the information side by side for each technology.

Similarly, this study assesses materiel requirements in terms of the raw materiels used to fuel, build, and operate a technology as a function of useful power output rather than the usual capital cost approach. In this way the energy we use as a society can be valued in terms of the demand for raw materiels different energy technologies require, and in terms of the associated environmental impacts of using these materiels.

This study also breaks with more traditional environmental analyses in that it attempts to view all environmental impacts associated with a technology as part of one system designed to produce energy over the useful life of a technology. Consequently, the emissions and resource impacts of coal mining, coal transportation, and coal plant construction are included with the usual measurements of the environmental impacts of coal plant operations. Thus photovoltaics, which has practically no emissions during operation, but requires large one-time inputs of raw materiels, can be compared with a coal plant, which requires constant inputs of fuel and chemicals, and produces its most significant emissions during operation.

Technologies

The particular power production technologies chosen for comparison were selected on the basis of providing highly contrasting impacts and operating characteristics to illustrate the range of technological considerations involved. The conventional coal plant provides a baseline for comparison; it is an established technology with well-known pros and cons that provide a benchmark for alternatives.

The Atmospheric Fluidized Bed Combustion (AFBC) plant represents an innovative alternative to conventional coal combustion and scrubbers.[1] The Integrated Gasification Combined Cycle (IGCC) plant represents an emerging advanced technology which offers significant improvements in coal combustion.[2]

Nuclear reactors are a large-scale alternative to fossil fuels and present an opportunity to illustrate the very different nature of emissions from nuclear versus fossil fuel plants. Photovoltaics represents an emerging technology that provides a fundamentally different approach to the production of electricity using a renewable fuel source and exhibiting limited emission impacts during operation.

The first section of the report focuses on the power production technologies. It describes the processes and equipment involved for each technology during fuel extraction (fuel mining, transportation, preparation, etc.), construction, and operation. An examination of decommissioning was not attempted for lack of data, although it should be considered as part of the consequences of energy production.

The next section addresses the major emissions and materiel inputs used during each stage of the energy production process for each technology: 1) air emissions, 2) water emissions, 3) solid wastes, and 4) materiel requirements. Each major emission and resource is described in terms of its ecological significance. Within each category of impacts, the emission/resource profile of the various technologies are presented together with comparisons and discussions of each technology's characteristics.

By necessity the comparisons presented are generalizations. Each energy facility is to some extent unique. For example, the amount of steel and concrete used in a PV facility will vary with site conditions and the type of equipment used. Coal mining impacts depend on the extent and depth of deposits, site conditions, and mining methods. Combustion emissions from coal are impacted by both generating equipment and by coal chemistry, which varies from mine to mine. Some issues, such as the impact of iron ore mining associated with the steel used in plant construction, were simply not addressed for lack of resources.

Fuel Extraction

Coal Fuel Extraction -- Emissions associated with fuel extraction and transportation for the coal technologies were scaled to the fuel demands of each coal technology by dividing the annual fuel demand of the power plant by the capacity of the assumed fuel extraction, processing and transportation facilities. This demand/output ratio was multiplied by the emissions from each fuel supply facility to derive the share of emissions from the facility attributable to the final generating plant. It was assumed that the coal supplied to each technology was mined and transported under the same conditions, so variations in emissions from fuel extraction are mainly a function of each plant's relative efficiency in burning coal. However, the emissions data for the AFBC and IGCC plant for SO_x and NO_x were based on Illinois number 4 coal, which is the design basis for these technologies and has a somewhat higher sulfur content.

The fuel extraction stage for coal includes the impacts of mining, processing and transporting fuel to the site where it will be converted to energy. It is assumed that the coal will be mined at an eastern bituminous coal surface mine which produces 2.5 million tons of coal annually from a 6-foot seam. The coal is assumed to be 52% fixed carbon, 34% volatile matter, 9% ash, 3% moisture, and 2% sulfur.[3] About 365 acres of land are affected by the mining operation each year. The coal is transported by a unit train comprised of 105 cars with a capacity of 100 tons each. Four 3000-hp diesel locomotives haul the train on a 1400-mile round trip 90 times per year.[4] A mine-mouth plant at an underground coal mine would have different magnitudes and types of impacts, but this example is more useful as an illustration of the range of possible impacts.

Nuclear Fuel Extraction -- The nuclear calculations were made in the same general manner as the coal calculations, with fuel demand at the power plant traced back through fuel fabrication, enrichment, processing, and mining in order to allocate the emissions from each stage of fuel manufacture in proportion to each stage's contribution to final power production. An additional increment to emissions was added to the source values based on each fuel processing facility's electricity demand.

The impacts of electricity and fuel use were examined in order to capture some of the significant impacts of secondary energy use involved in power production, especially in the nuclear fuel cycle. A coefficient for CO_2 emissions as a function of electricity production in the entire U.S. was calculated and then applied to the electricity demand of the nuclear plant. In this way electricity is treated as a generic commodity for all the technologies and the issue of allocating hydropower or other sources of power with low emissions is avoided.[5,6,7] The approach used produces a national average of CO_2 emissions associated with the electricity used in the energy production cycle for the technologies examined. Fuel CO_2 coefficients for gas, coal and oil were also applied to the fossil fuels used at the plant and in the resource extraction stage. The other technologies were assessed in a similar fashion, where energy use data were available, but the increment to emissions was negligible.

The fuel extraction stage for the nuclear plant includes uranium mining, conversion, enrichment, and fabrication. The mine supplies 1060 tons of "yellow cake" (75% U_3O_8) per year from roughly 530,000 tons of raw ore (0.2% U_3O_8).[8]

The yellow cake is then converted to uranium hexafluoride at a conversion facility. The plant produces roughly 5500 tons of uranium hexafluoride annually from 7340 tons of yellow cake using either the dry hydrofluor or wet solvent exchange process, with appropriate environmental controls. The plant uses approximately 46,000 MWh of electricity for processing.[9]

Once the yellow cake is converted to uranium hexafluoride it is enriched to 4% U_{235} for use as reactor fuel. Using the gaseous diffusion process, the plant produces approximately 12,000 tons of enriched uranium per year. The process is very energy intensive, requiring 26,000 MWh of electricity.[10]

Finally the fuel is fabricated into fuel pellets, assemblies, and rods at a fuel fabrication plant. The fuel fabrication plant produces roughly 980 tons of fuel per year.[11]

Photovoltaics Fuel Extraction -- Photovoltaics has no direct fuel extraction impacts.

Construction

The construction phase includes the indirect impacts of the technologies in terms of their demand for raw materiels and the emissions associated with manufacturing the raw materiel inputs. Steel and concrete are the major materiel inputs examined and the major sources of secondary emissions.

The construction stage accounts for the greatest differences between materiels- versus fuel-intensive technologies, with the former producing the highest environmental impacts at this stage. The estimates in this analysis focus exclusively on emissions from final manufacture of major materiels used in construction. Highly variable impacts such as fugitive dust emissions or exhaust from construction equipment were not evaluated for lack of typical data.

Emissions and materiel inputs used or produced in the course of construction were taken from source documents for the conventional coal, nuclear and photovoltaics plants. This does not represent a comprehensive review of all emissions. There are secondary impacts associated with the mining of raw materiels like iron ore, bauxite, etc., which are used to make the steel and other inputs to construction, but these types of impacts were not calculated for any of the technologies for lack of valid and comparable data. Emissions associated with materiels manufacture were derived by multiplying coefficients of emissions per pound of materiel times the gross quantity of materiel used by each technology.[12]

Both the materiel inputs and their associated emissions were divided by the annual output of the technology times the operational life of the technology to derive materiel inputs and emissions per unit of output over plant life.

Raw materiel requirements for all the technologies vary widely depending on site requirements and design specifications. The photovoltaic and nuclear raw materiel requirements were both based on specific designs.[13,14] The photovoltaic plant is a conceptual design of a theoretical central station using photovoltaic materiels with efficiencies and operating characteristics that have not yet been proven. Both the nuclear and photovoltaic designs are taken as representative plants, but there has been no thorough investigation as to whether the materiels used in their designs is typical. The estimates of resource use in a coal plant are generalized estimates of what a typical plant would require.[15]

Analyses of power plant capital requirements generally focus on dollar values rather than tonnages of raw physical inputs, and where materiels are reported they are generally given in terms of the items purchased, such as linear feet of cable or cubic yards of concrete. However, coefficients for emissions for these materiels are generally reported as a function of tons of output. Thus there are inconsistencies in the basic measurements of the materiels, which required that the concrete estimates be converted from cubic yards by assuming all concrete used had a mass density of 127 pounds per cubic foot.[16] Cables were assumed to be aluminum, with a weight of 1 pound per linear foot. Other materiels were provided in tons as cited in the source materials.

In the case of the IGCC plant and the AFBC plant, direct estimates of materiel requirements were unavailable. Therefore the values were derived by adjusting the materiels used in a conventional plant by the proportionate capacity associated with the AFBC and IGCC plant.[17] It is acknowledged that this simple assumption ignores the significant technology differences and the effects of differing economies of scale between technologies.

Emissions factors for aluminum, glass, steel and concrete were available in the source documents, and so only these materiels were used to calculate the incremental addition to emissions caused by the manufacture of raw materiels used in plant construction.[18] These are the predominant raw materiels used in plant construction, so a majority of the secondary emissions are captured in the analysis. The CO_2 emission factor for these four materiels was not available, but a factor was derived for steel by examining fuel demand as a function of industry output, and then multiplying the resultant estimate of fuel use per ton of output times a CO_2 emission coefficient to derive an estimate of CO_2 per ton of output. This estimate was then used to calculate the CO_2 emissions associated with steel demands. Electricity as an energy input to steel was converted to CO_2 inputs by calculating the fuel mix for electricity in 1987, multiplying the quantities by their respective coefficients, and then allocating the gross CO_2 emissions over the total number of gigawatt-hours produced in 1987.[19, 20, 21]

The CO_2 coefficient for steel is based on reliable data from a recent, comprehensive data base.[22] The coefficient for concrete is based on a study that examined concrete's role in worldwide CO_2 emissions.[23] The CO_2 coefficients for the various fuels are based on estimates produced for global studies of CO_2 emissions.[24]

Emissions from PV cell manufacture were not examined in detail, nor were data included in the main data matrices simply because there is little overlap between the significant emissions from the manufacture of PV materiels and the other technologies, so there is no basis for comparison. However, a table showing some of the annual emissions from a PV manufacturing plant are included in separate tables at the end of the data appendix.[25]

Operation

In the case of the conventional coal plant and the nuclear plant, the values for emissions and materiel inputs associated with operations were taken from the source documents. The annual value was then divided by the annual GWh of output for each technology to derive emissions per unit of output. The values for the IGCC and AFBC plants were assumed to be similar, in terms of the rate of emissions, to the conventional plant and thus were only adjusted for the increased efficiency and power output per ton of coal input gained from each technology (if any). The only values that were examined independently were SO_x, NO_x, particulates, scrubber sludge, ash, and water demand. These factors were adjusted so that they agree with comparative assessments provided in the source documents. The impacts of maintenance and repair activities were not assessed for any of the technologies.

For photovoltaics, the major impact during operation is water used in array cleaning.[26] This value was included because it was built into the design used to represent photovoltaics. However, recent photovoltaic designs either eliminate or drastically reduce array washing requirements, simply because it has been found to be unnecessary and/or uneconomic. Therefore this estimate of water requirements should be taken as a value at the high end of the range of estimates.

Coal--Impacts at the operation stage are measured in terms of emissions produced while the plants are actively generating energy. The conventional coal plant in the assessment is assumed to be a 500 MW facility producing 3500 GWh of electricity annually. It represents a new plant built to meet or exceed existing environmental standards, and to maximize performance. The plant lifetime is assumed to be 30 years. About 1.9 million tons of eastern bituminous coal is consumed annually. The coal is processed to remove unusable portions of the coal and prepare it for feed to the boiler, which results in significant coal wastes, which are included in plant operations. Particulates are controlled by an electrostatic precipitator. A wet lime/limestone scrubber is used to control SO_x emissions.[27]

The AFBC plant controls sulfur in the combustion chamber, and thus the flue gases only have to be treated to remove particulates. In addition, the fluid motion of the solids in the combustion bed improves combustion efficiency and allows combustion to take place at lower temperatures, which reduces the formation of NO_x. The AFBC plant examined is rated at 500 MW with annual energy production of 3500 GWh. Its useful life is 30 years. Nearly 2 million tons of Illinois coal is required to fuel the plant annually. Particulates are controlled by either an electrostatic precipitator or a baghouse.[28]

Major advantages of IGCC technology include eliminating the need for flue gas cleanup, the production of solid wastes which are environmentally benign and actually have by-product value, less demanding requirements for coal quality, and enhanced SO_x and NO_x removal. The space required for an IGCC plant is comparable to the land requirements for a conventional plant with scrubber, so the IGCC system has little relative impact on land requirements. IGCC technology also promises to reduce power plant water demand by 40-50%.[29] The IGCC plant is rated at 945 MW and produces roughly 6700 GWh annually. The assumed heat rate for the plant is 8,920 Btu/kWh. Its useful life is 30 years. The plant consumes roughly 3 million tons of coal annually.[30]

Nuclear--The nuclear plant is a boiling water reactor design rated at 1000 MW, producing 6130 GWh annually. It utilizes natural draft cooling towers, which are the main source of make-up water requirements. The plant requires 34 tons of uranium fuel annually. Its useful life is 30 years.[31] The advantages of nuclear include very small fuel requirements and very limited fossil fuel emissions, although nuclear plants do produce a range of other emissions that have significant environmental implications.

Photovoltaics--The PV plant is assumed to be a 100 MW facility located at Barstow, California. Photovoltaics' main advantage is its freedom from fuel and related emissions, and the option of deploying the technology in modular increments closely matched to utility demand requirements. The representative plant consists of ground-mounted arrays of flat-plate thin-film silicon modules with an assumed 15% efficiency, based on research expectations. These are specifications for a conceptual commercial photovoltaic plant, once competitive cells and modules are developed. Total energy production is 209 GWh annually over a 30-year life span.[32] It would provide peaking power to the utility system, compared to the baseload generation available from the other technologies.

Emissions

Air Emissions Summary

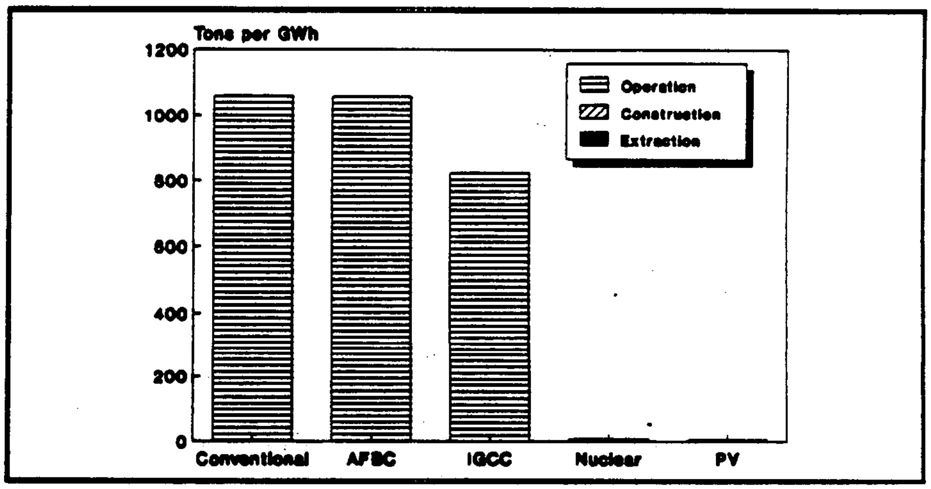
The major air emissions examined are carbon dioxide (Figure 1), nitrogen oxides (Figure 2), sulfur oxides (Figure 3), and particulates (Figure 4).

Coal--For the coal technologies, most air emissions occur during operations, barring significant particulate emissions at the fuel extraction stage. CO_2 emissions per ton of coal combusted are assumed to be basically similar for each technology, but the gross emissions are spread over a higher GWh output per ton of coal for the IGCC plant. This is an important point because efficiency in generation can be as effective at reducing emissions as efficiency in end-use, especially for pollutants such as CO_2 which are less amenable to technological control measures.

Among the various coal technologies, the conventional plant discharges the highest emissions, followed closely by the AFBC plant, which does offer significant advantages in reducing NO_x. AFBC plants use varying ratios of lime within the bed of the boiler which acts as a sorbent for sulfur. NO_x production within an AFBC boiler is minimized by using lower operating temperatures.[33] An IGCC plant minimizes SO_x emissions by converting the coal to gas and scrubbing the gas before it is combusted. The IGCC process also significantly reduces NO_x emissions.[34]

To an extent, these types of emission reductions are driven by cost. The technology exists to remove or avoid the production of very high proportions of particulates, SO_x, and NO_x emissions in both conventional and advanced plants, but cost is a constraining factor. The technology for removing CO_2 from coal plant emissions is less feasible, technologically and economically.

Nuclear--Air emissions from the nuclear reactor should be viewed as a range, since a portion of the emissions are associated with fossil fuel combustion required to produce electrical and other inputs to uranium processing operations and the occasional use of fossil fuel boilers and generators during operation. There is also an input of fossil fuel to operate backup and auxiliary steam and electricity generators at the plant site during normal refueling and operations.[35] The effect of these systems varies depending on plant design, the occurrence and extent of planned and unplanned outages, and normal maintenance requirements. Note that the CO_2 emissions were calculated using standard fuel coefficients and a national average coefficient for electricity, as explained in the discussion of fuel extraction for the nuclear plant. Because most emissions from nuclear plants are not comparable to photovoltaics



	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
CO_2					
Extraction	NA	NA	NA	1.642	NA
Construction	1.048	1.048	1.048	1.088	5.890
Operation	1057.143	1055.143	822.945	5.861	NA
Total	1058.191	1057.090	823.993	8.590	5..890

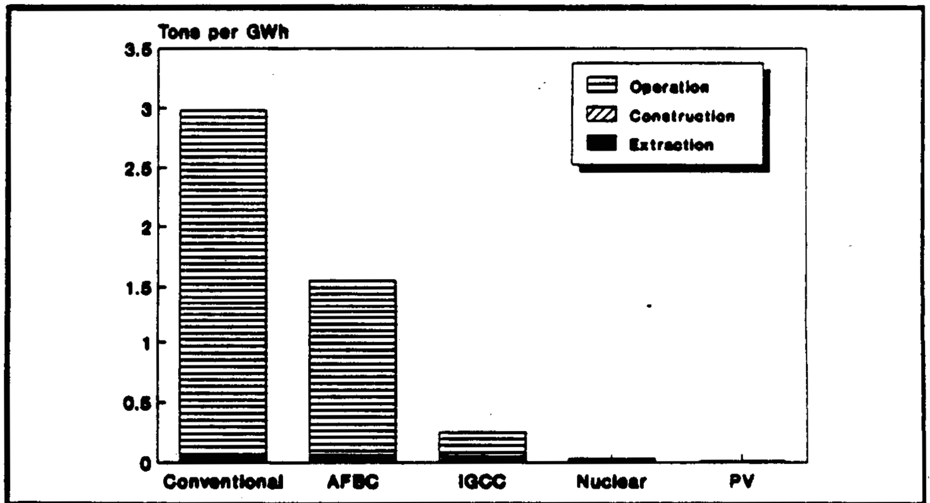
Figure 1: Carbon Dioxide Emissions

or coal, they are not included in the summary tables, but they are noted in the more detailed data provided in the appendix.

Photovoltaics--Air emissions from the photovoltaic plant are exclusively related to the construction of the plant and the emissions from the steel, concrete, and aluminum plants that manufacture the raw materiels.[36] Air emissions related to PV construction are higher than the emissions related to construction for the other technologies because of the materiels-intensity of photovoltaic technology. But overall photovoltaic emissions are a very small fraction of the emissions from coal technologies and are for the most part less than or comparable to nuclear. Like nuclear, PV has emissions (associated with cell manufacture) that are unique and have no counterparts in other technologies' emissions. Possible emissions are presented in the table which follows the data appendix.

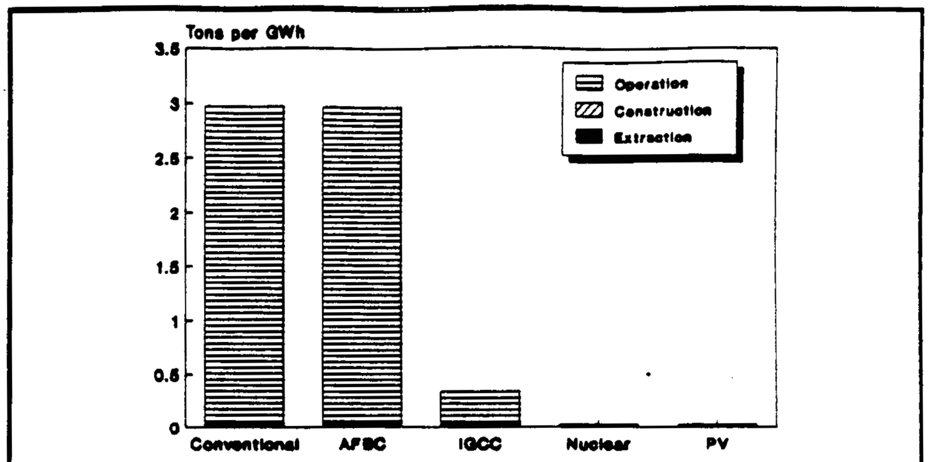
Air Emission Characteristics

Carbon dioxide (CO_2) is a nonregulated emission with no significant biological impacts, but is the most significant factor in



	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
NO_x					
Extraction	0.066	0.066	0.052	0.022	NA
Construction	0.001	0.001	0.001	0.001	0.008
Operation	2.914	1.484	0.198	0.011	NA
Total	2.986	1.551	0.251	0.034	0.008

Figure 2: Nitrogen Oxide Emissions



	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
SO_x					
Extraction	0.055	0.055	0.043	0.024	NA
Construction	0.002	0.002	0.002	0.001	0.023
Operation	2.914	2.911	0.291	0.003	NA
Total	2.971	2.968	0.336	0.029	0.023

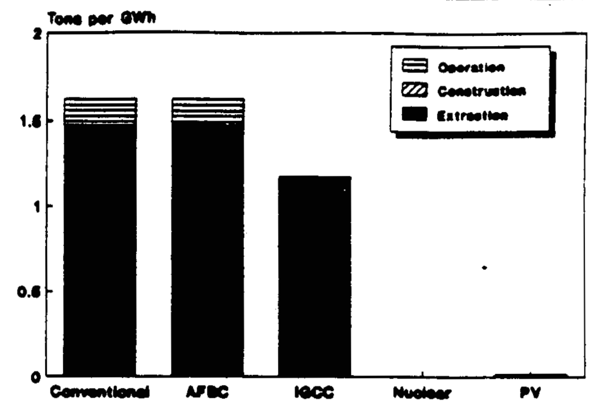
Figure 3: Sulfur Oxide Emissions

the greenhouse/global warming effect. CO_2 from fossil fuel combustion is considered by some scientists as a major environmental concern, because the gas is suspected of trapping solar heat in the lower atmosphere, resulting in a general global warming trend. In turn, this warming could adversely impact rainfall patterns, sea levels, and agriculture through its impacts on the global climate system.[37]

Nitrogen oxides (NO_x) can produce respiratory illness and lung damage. They are also a key element in the photochemical effect which produces ozone. Ozone causes respiratory tract problems, eye irritation, nasal congestion, reduced resistance to infection, and possible premature aging of lung tissue.[38] NO_x is also a factor in acid rain.

Sulfur oxides (SO_x) produce respiratory tract problems and also harm lung tissues. SO_x is also a precursor to acid rain, which damages aquatic habitats, forests, crops, and buildings.[39]

Particulates are a concern because they can cause eye and throat irritation, bronchitis, lung damage, and impaired visibility. They



	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Particulates					
Extraction	1.482	1.480	1.173	0.002	NA
Construction	0.001	0.001	0.002	0.001	0.017
Operation	0.143	0.143	0.001	neg	NA
Total	1.626	1.624	1.176	0.003	0.017

Figure 4: Particulate Emissions

are also a transport mechanism for trace metals emitted during combustion, such as lead, cadmium, zinc, and arsenic.[40] Trace metals have a variety of toxic effects on humans and animals.[41] More information on trace metal emissions is contained in the appendix.

In addition to the major air emissions summarized here, a range of other emissions were also investigated. The results are shown in the data appendix. Aldehyde emissions for coal were derived from published estimates for coal fuel extraction, from the exhaust from heavy equipment and train transport. Estimates for aldehyde emissions from coal plant operation were not available. This estimate also fails to capture aldehyde emissions from heavy equipment used in PV and coal plant construction, but the missing portions of the data are probably insignificant compared to fuel extraction, which involves the continuous use of heavy equipment to move tons of materiels. Aldehyde emission data for uranium extraction are unavailable.

Trace metals emissions are a product of coal chemistry and the ability of control equipment to reduce particulate emissions, which are the main transport mechanism for trace metals. Estimates of trace metals emissions from AFBC and IGCC plants were not available and were not estimated because of the difficulty in evaluating different combustion characteristics and particulate control technologies to derive an adequate estimate from the available data.

Radioactive air emissions from nuclear plants have no counterpart emissions for coal or PV plants, with the exception of minor amounts of uranium and associated radon that are bound up as trace elements of some coals. Different types of emissions occur at different stages of the uranium fuel cycle, so even different steps in the nuclear cycle are difficult to compare. All figures are derived from the data sources.

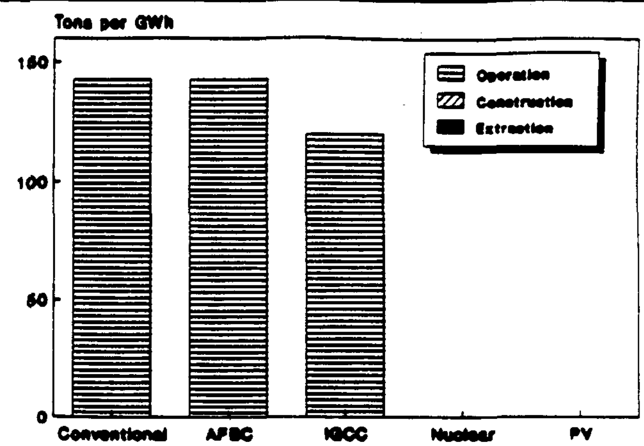
Water Emissions

The major water impacts associated with energy production are dissolved and suspended solid emissions. They are complementary measures of amounts of foreign materiel in the water.

Water emissions data are generally from the source materiels. Information on discharges for coal technologies concentrate on fuel extraction, transportation, and plant manufacture. It is impossible to estimate emissions from plant operations because surface runoff varies widely from site to site.[42] Effects of runoff during plant construction are also not estimated for lack of data, and because of wide variability from site to site. Nuclear plants have a much wider variety of both radioactive and chemical emissions because of extensive emissions from extraction and processing of uranium.

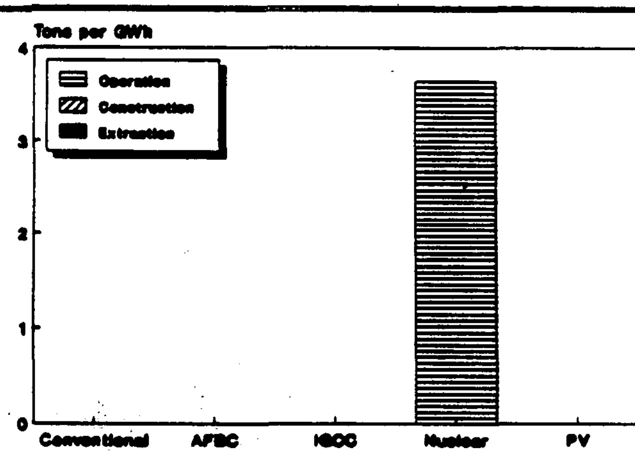
Solid Waste Emissions

Solid waste emissions are shown on a gross basis because some of the technology information lacks a breakdown of solid wastes by type, hindering comparison. Data on two major categories of solid waste from coal and nuclear technologies are shown in Figures 5 and 6, respectively. A measure of mining overburden was not available. Solid waste emissions are based on available data for conventional coal, nuclear, and PV technologies. Iron oxide, slag, pickle liquor, and part of the dust/sludge data are variable with steel manufacturing processes, depending on methods used to recycle waste products.[43] Data were not available to estimate solid waste emissions from other materiels manufacturing processes besides steel. The ash figure for IGCC is based on the percentage



	Conventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Coal Waste					
Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	142.857	142.694	120.110	NA	NA
Total	142.857	142.694	120.110	NA	NA

Figure 5: Coal Wastes



	Conventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Low Level Radwaste					
Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	3.638	NA
Total	NA	NA	NA	3.638	NA

Figure 6: Low-Level Radioactive Waste

of ash in the coal times the amount of coal used, minus the small amount emitted as particulates.

Coal--Typical waste for coal technologies would include scrubber sludge (for a conventional plant using a flue gas desulfurization system), depleted sorbent materiel from AFBC plants, fly ash, bottom ash, and waste materiel from coal preparation. IGCC plants also produce significant quantities of elemental sulfur, but it is sold as a by-product, and is not reported here.[44] The ash and other materiels from coal plants carry varying concentrations of heavy metals and other elements found in the coal and pollution control equipment.[45] In general, coal ash is not classified as hazardous, so its main environmental impact is felt in terms of demand for limited landfill space. Scrubber sludges are treated and contained onsite, and would not normally be released to the environment.[46] Data were not available on overburden from coal mining, partly because it varies widely from deposit to deposit.

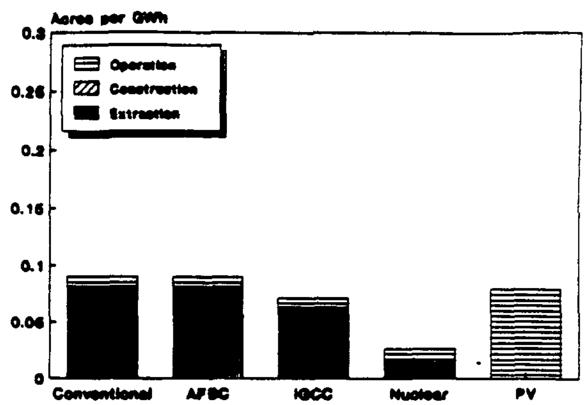
Nuclear--Low-level radioactive waste is an important quantity because of the difficulty in isolating and disposing of the materiels in an environmentally safe manner. Because of their high carcinogenic and teratogenic impact, and long lifetimes, radioactive wastes are fundamentally different from coal or other wastes. Overburden from uranium mining is significant both for the quantities involved and the radioactivity left in the tailings, but estimates were not included in the summary data for lack of corresponding values for coal.

Photovoltaics--Photovoltaics' only solid waste emissions are the product of raw materiel manufacturing in the construction stage.

Materiel Requirements

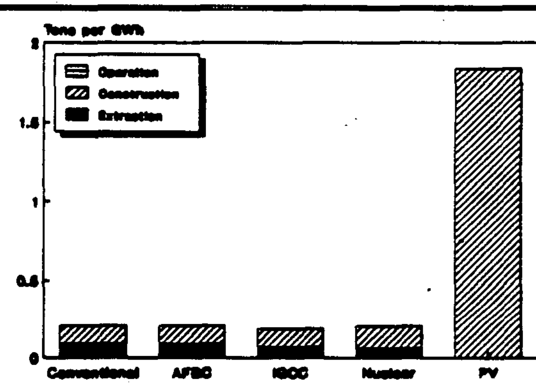
Materiel demands are mainly of concern because of the environmental impacts associated with making the materiels. There is also the potential problem of demand for scarce or critical materiels.

Materiel information in this analysis is limited to major inputs to the technologies: land, steel, and water. Data on each are presented in Figures 7, 8, and 9, respectively. This information provides an indication of the relative size of the secondary impacts associated with each technology in terms of indirect environmental impacts caused by demand for materiels.



	Conventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Land (acres)					
Extraction	0.082	0.082	0.064	0.015	NA
Construction	NA	NA	NA	NA	NA
Operation	0.008	0.008	0.008	0.012	0.080
Total	0.090	0.090	0.072	0.027†	0.080

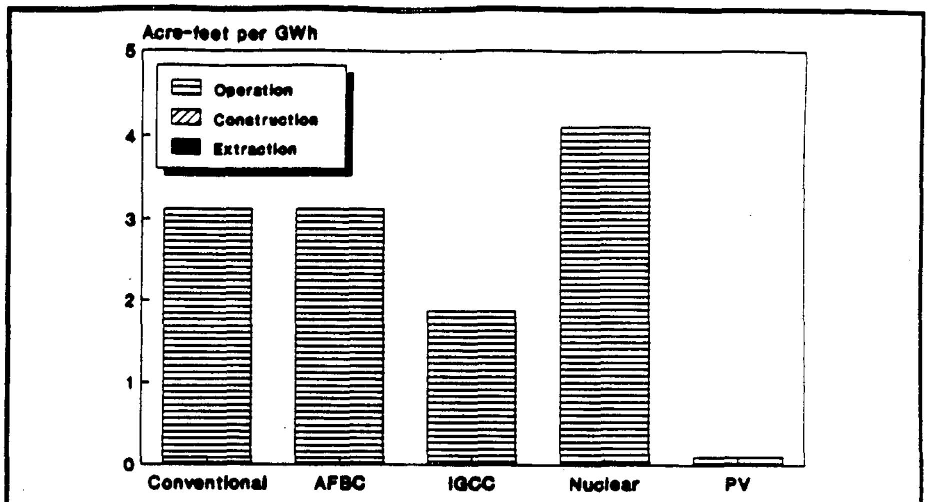
Figure 7: Land Utilization



	Conventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Steel					
Extraction	0.089	0.089	0.069	0.060	NA
Construction	0.133	0.133	0.113	0.139	1.838
Operation	neg.	neg.	neg.	neg.	neg.
Total	0.222	0.222	0.222	0.200	1.838

Figure 8: Steel Utilization

† Total includes mining activity at a surface uranium mine, as well as the acreage of the conversion and fuel fabrication facilities and the plant site. Land use for the enrichment facility, waste reprocessing, permanent waste storage, and plant decommissioning are not included.



	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Water (acre-ft.)					
Extraction	0.023	0.023	0.018	0.046	NA
Construction	neg.	neg.	neg.	neg.	neg.
Operation	3.097	3.097	1.856	4.078	0.102
Total	3.120	3.120	1.874	4.124	0.102

Figure 9: Water Utilization

Coal-- Coal is very materiels-intensive in terms of water demand for plant operations and land use in coal mining. The alternative coal plants are somewhat comparable in construction materiels intensity, although the IGCC technology is somewhat less reliant on water than the conventional plant. Unlike emissions, materiels are not closely correlated with capacity and output because of economies of scale in building. As an example, an 800 MW power plant will not require twice the steel and concrete of a 400 MW power plant.[47] Materiels intensity can also vary widely with design considerations and the demands of different sites.[48]

Nuclear --Nuclear requires large inputs of water, especially in the operations stage, but it is only moderately materiels-intensive in the construction phases. There are significant land impacts from uranium mining, but they appear to affect a smaller area than coal strip mining.

Photovoltaics--Photovoltaics is a materiels-intensive technology in the construction phases, especially for structural materiels. However, in terms of land it is comparable with coal when strip mining is considered. It compares very favorably with coal and nuclear for water use.

Summary

When compared on the basis of emissions and materiel inputs used versus power output over the life of an energy facility, the environmental advantages of a materiels-intensive technology like photovoltaics versus a fuel-intensive system such as a coal plant become clear. The emissions from a photovoltaic plant originate in the production of materiels--concrete, steel, glass, etc.,--that go into constructing the plant.

A photovoltaic plant's environmental impacts are proportionately larger than a coal plant's at the construction stage. However, once it is installed a photovoltaic plant's ongoing impacts are small. In comparison, a coal plant generates continual increments to emissions and places continual demands on fuel resources for every unit of output, on top of the one-time environmental impact associated with materiels used in construction of the plant. To a lesser extent, nuclear fuel requirements create the same ongoing emission problem, although a nuclear plant's emission profile is radically different from coal or PV. These fuel-related emissions far exceed the one-time impacts of construction-related impacts in overall magnitude and in terms of emissions as a function of power output.

Data Appendix

AIR EMISSIONS: ELECTRIC GENERATION SYSTEMS
(Tons per GWh)

	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
CO_2					
Fuel Extraction	-	-	-*	1.642	NA†
Construction	1.048	1.048	1.048	1.088	5.890
Operation	1057.143	1055.942	822.945	5.861	NA
Total	1058.191	1057.090	823.993	8.590	5.890
NO_x					
Fuel Extraction	0.066	0.066	0.052	0.022	NA
Construction	0.001	0.001	0.001	0.001	0.008
Operation	2.914	1.484	0.198	0.011	NA
Total	2.986	1.551	0.251	0.034	0.008
SO_x					
Fuel Extraction	0.055	0.055	0.043	0.024	NA
Construction	0.002	0.002	0.002	0.001	0.023
Operation	2.914	2.911	0.291	0.003	NA
Total	2.971	2.968	0.336	0.029	0.023
Particulates					
Fuel Extraction	1.482	1.480	1.173	0.002	NA
Construction	0.001	0.001	0.002	0.001	0.017
Operation	0.143	0.143	0.001	neg	NA
Total	1.626	1.624	1.176	0.003	0.017
CO					
Fuel Extraction	0.061	0.061	0.048	0.002	NA
Construction	0.001	0.001	0.001	0.001	0.003
Operation	0.206	0.205	-	0.016	NA
Total	0.267	0.267	-	0.018	0.003
HC					
Fuel Extraction	0.039	0.039	0.030	0.001	NA
Construction	-	-	-	-	0.002
Operation	0.063	0.063	-	-	NA
Total	0.102	0.102	-	0.001	0.002
Aldehydes					
Fuel Extraction	0.008	0.008	0.006	-	NA
Construction	-	-	-	-	-
Operation	neg‡	neg	neg	neg	NA
Total	0.008	0.008	0.006	neg	-

* (-) symbolizes unavailable or incomplete data in an area where this impact would be expected to occur.
† (NA) stands for not applicable for this technology or stage of production.
‡ (neg) stands for negligible.

AIR EMISSIONS: ELECTRIC GENERATION SYSTEMS (Cont'd)
(Tons per GWh)

	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Trace Metals					
Arsenic					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	0.064	-	-	NA	NA
Total	0.064	-	-	NA	NA
Cadmium					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	0.001	-	-	NA	NA
Total	0.001	-	-	NA	NA
Manganese					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	0.043	-	-	NA	NA
Total	0.043	-	-	NA	NA
Lead					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	-	-	-	-	-
Operation	0.030	-	-	NA	NA
Total	0.030	-	-	-	-
Selenium					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	0.016	-	-	NA	NA
Total	0.016	-	-	NA	NA
Noble Gases					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	1.843	NA
Total	NA	NA	NA	1.843	NA
Tritium					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	0.018	NA
Total	NA	NA	NA	0.018	NA
C14					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	0.001	NA
Total	NA	NA	NA	0.001	NA
Radon					
Fuel Extraction	NA	NA	NA	0.092	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	NA	NA
Total	NA	NA	NA	0.092	NA

WATER EMISSIONS: ELECTRIC GENERATION SYSTEMS
(Tons per GWh)

	Conventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Dissolved Solids					
Fuel Extraction	0.278	0.277	0.216	-	NA
Construction	-	-	-	-	-
Operation	-	-	-	-	-
Total	0.278	0.277	0.216	-	-
Suspended Solids					
Fuel Extraction	0.005	0.005	0.004	-	NA
Construction	-	-	-	-	-
Operation	-	-	-	-	-
Total	0.005	0.005	0.004	-	-
Oil/Grease					
Fuel Extraction	neg	neg	neg	neg	NA
Construction	neg	neg	neg	neg	0.002
Operation	neg	neg	neg	neg	neg
Total	neg	neg	neg	neg	0.002
Ammonia					
Fuel Extraction	neg	neg	neg	0.002	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	NA	NA
Total	neg	neg	neg	0.002	NA
Sulfate					
Fuel Extraction	0.192	0.191	0.149	0.001	NA
Construction	neg	neg	neg	neg	neg
Operation	neg	neg	neg	0.004	neg
Total	0.192	0.191	0.149	0.005	neg
Fluorine					
Fuel Extraction	NA	NA	NA	0.005	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	NA	NA
Total	NA	NA	NA	0.005	NA
Nitrate					
Fuel Extraction	NA	NA	NA	0.004	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	NA	NA
Total	NA	NA	NA	0.004	NA
Sodium					
Fuel Extraction	NA	NA	NA	0.001	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	0.002	NA
Total	NA	NA	NA	0.003	NA
Tritium					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	0.002	NA
Total	NA	NA	NA	0.002	NA

SOLID WASTE EMISSIONS: ELECTRIC GENERATION SYSTEMS (Tons per GWh)

	Con-ventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Dust/Sludge					
Fuel Extraction	neg	neg	neg	0.001	NA
Construction	0.003	0.003	0.003	0.034	0.015
Operation	55.143	-	-	neg	neg
Total	55.146	-	-	0.035	0.015
Fly/Bottom Ash					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	neg	neg	neg	neg	neg
Operation	35.714	35.674	41.416	NA	NA
Total	35.714	35.674	41.416	neg	neg
Coal Waste					
Fuel Extraction	-	-	-	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	142.857	142.694	120.110	NA	NA
Total	142.857	142.694	120.110	NA	NA
Iron Oxides					
Fuel Extraction	neg	neg	neg	0.001	NA
Construction	0.003	0.003	0.003	0.064	0.012
Operation	NA	NA	NA	NA	NA
Total	0.003	0.003	0.003	0.065	0.012
"Pickle Liquors"					
Fuel Extraction	neg	neg	neg	neg	NA
Construction	neg	neg	neg	neg	neg
Operation	NA	NA	NA	NA	NA
Total	neg	neg	neg	neg	neg
Calcium Fluoride					
Fuel Extraction	NA	NA	NA	0.004	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	NA	NA
Total	NA	NA	NA	0.004	NA
Mining Overburden					
Fuel Extraction	-	-	-	437.339	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	NA	NA
Total	-	-	-	437.339	NA
Low Level Radwaste					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	3.638	NA
Total	NA	NA	NA	3.638	NA
Radioactive Filter Waste					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	NA
Operation	NA	NA	NA	0.003	NA
Total	NA	NA	NA	0.003	NA

MATERIEL REQUIREMENTS: ELECTRIC GENERATION SYSTEMS
(Tons per GWh)

	Conventional Plant	AFBC Plant	IGCC Electric Plant	Boiling Water Reactor	PV Central Station
Steel					
Fuel Extraction	0.089	0.089	0.069	0.060	NA
Construction	0.113	0.113	0.113	0.139	1.838
Operation	NA	NA	NA	NA	NA
Total	0.222	0.222	0.222	0.200	1.838
Concrete					
Fuel Extraction	-	-	-	0.114	NA
Construction	0.876	0.876	0.875	1.702	1.384
Operation	NA	NA	NA	NA	NA
Total	0.876	0.876	0.875	1.816	1.384
Aluminum					
Fuel Extraction	0.001	0.001	0.001	0.001	NA
Construction	0.038	0.038	0.037	-	0.019
Operation	NA	NA	NA	NA	NA
Total	0.039	0.039	0.038	-	0.019
Land (acres)					
Fuel Extraction	0.082	0.082	0.064	0.015	NA
Construction	NA	NA	NA	NA	NA
Operation	0.008	0.008	0.008	0.012	0.080
Total	0.090	0.090	0.072	0.027††	0.080
Water(acre-ft)					
Fuel Extraction	0.023	0.023	0.018	0.046	NA
Construction	neg	neg	neg	neg	neg
Operation	3.097	3.097	1.856	4.078	0.102
Total	3.120	3.120	1.874	4.124	0.102
Silicon					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	NA	NA	NA	NA	0.084
Operation	NA	NA	NA	NA	NA
Total	NA	NA	NA	NA	0.084
Glass					
Fuel Extraction	NA	NA	NA	NA	NA
Construction	-	-	-	-	1.650
Operation	NA	NA	NA	NA	NA
Total	NA	NA	NA	NA	1.650

†† Total includes mining activity at a surface uranium mine, as well as the acreage of the conversion and fuel fabrication facilities and the plant site. Land use for the enrichment facility, waste reprocessing, permanent waste storage, and plant decommissioning are not included.

Atmospheric Emissions from PV Manufacturing Facilities (kg/yr)*

Compound	Source	Emission Rate (with controls)
Diborane	a-Si glow discharge a-Si reactive sputtering a-Si CVD	0
Methane	Zn_3P_2-MOCVD	-
Phosphine	Zn_3P_2-MOCVD	80
Silane	a-Si glow discharge a-Si CVD	73
Silicon tetra-fluoride	a-Si glow discharge	25

Solid Waste Emissions from PV Manufacturing Facilities (kg/yr)

Silicon Compounds	205

* Emission rates for a 10 MW_p per year manufacturing facility.

** (-) stands for an insignificant emission.

Source: Organisation for Economic Co-Operation and Development. *Environmental Impacts of Renewable Energy*. OECD Compass Project. 1988, p. 37.

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ENVIRONMENTAL EMISSIONS FROM ENERGY TECHNOLOGY SYSTEMS: THE TOTAL FUEL CYCLE

- Abstract
- Introduction
- Analysis Concept
- Emission Analysis and Comparison by Energy Production Stage
- CO_2 Emissions Summary
- Renewable Energy CO_2 Displacement Projections
- Conclusion

Abstract

To accurately quantify and compare environmental emissions from energy technologies, each phase of the fuel cycle, including resource extraction, facility construction and facility operation, must be evaluated. Meaningful comparisons among the various technologies should also be based on a common measure of each technology's useful output. This analysis establishes a framework for conducting a comparative evaluation of the total fuel cycle of different energy technologies. Environmental considerations for each technology and each phase of the fuel cycle, categorized by major types such as air emissions, water emissions, solid waste emissions and materiel requirements, are evaluated individually for different environmentally significant substances.

The result is a comparative analysis of 14 electric generating technologies using the total energy cycle framework and metric tons per gigawatt hour (GWh) as a consistent unit of measurement for comparison.

Introduction

The analysis presented in this paper examines environmental factors by building on a previous study conducted for the U.S. Department of Energy's Office of Renewable Energy, *Energy System Emissions and Materiel Requirements,*[1] which developed an overall methodology for direct comparison of electric power technologies. That assessment viewed all environmental impacts associated with a technology as part of a total system designed to extract and produce energy over a specified operating life. By relating environmental emissions from the resource extraction, facility construction, and facility operation phases, a basis was established for comparing electric technologies that have different capital, fuel, and operating characteristics. The five electric power technologies evaluated were:

- a conventional pulverized coal plant
- an Atmospheric Fluidized Bed Combustion (AFBC) plant
- an Integrated Gasification Combined Cycle (IGCC) plant
- a boiling water nuclear reactor
- a central station photovoltaic plant

The earlier work evaluated more than 30 environmental factors including atmospheric emissions such as carbon dioxide (CO_2) and nitrogen oxide (NO_x); water emissions such as dissolved solids; solid waste; and land and water requirements; all reported on the basis of quantities per unit of electric output (e.g. tons/GWh).

This paper builds upon the earlier report by expanding the number of energy technologies compared. Fossil fuel technologies included in this analysis are:

- a conventional pulverized coal plant
- an Atmospheric Fluidized Bed Combustion (AFBC) plant
- an Integrated Gasification Combined Cycle (IGCC) plant
- an oil-fired steam electric plant
- a gas-fired steam electric plant

The non-fossil energy technologies examined include:

- a boiling water nuclear reactor
- a wood-fired steam electric generating station
- an open-cycle Ocean Thermal Energy Conversion (OTEC) plant
- a dry-steam hydrothermal geothermal power station
- a large hydropower plant
- a small hydropower plant
- a wind energy conversion system

- a central station photovoltaic plant
- a distributed receiver solar thermal electric plant

Among the types of emissions analyzed, carbon dioxide represented one of the most significant quantities of emissions on a per gigawatt-hour basis. Therefore, to illustrate how comparative analyses can be conducted using a total energy cycle methodology, data for CO_2 emissions from each of the above technologies will be the focus of this presentation. Also, some studies suggest carbon dioxide, from a combination of fossil fuel combustion and deforestation, accounts for nearly 50% of the "enhanced" greenhouse effect resulting from increasing concentrations of greenhouse gases.[2]

Analysis Concept

Because this analysis attempts to take a detailed, directly comparative view of emissions from power production technologies, only limited data were readily available. For the most part the literature on emissions of electric technologies tends to focus on power production. Emissions associated with extraction and transportation of fuel, or associated with plant construction, have been less fully documented and the available literature is limited with respect to the relationship to point-of-use characterizations. The National Acid Precipitation Assessment Program (NAPAP) has made important progress in addressing integrated fuel cycles and identifying data gaps. Most do not address the effects of fuel extraction and facility construction. As a result of these limitations this analysis is restricted to examining major issues using data from available sources.

This analysis does not seek to recommend one technology over another. Rather, it is intended to provide a useful comparison of each technology's emissions profiles, which is only one factor that should be considered in their deployment. Without information on costs, the suitability of a technology to particular sites and energy demand situations, and other environmental impacts associated with particular projects, it is impossible to say one technology is preferable to another.

Study Approach

The analysis used in this paper is based on two fundamental considerations. First, the environmental effects of energy production at all stages of the energy production cycle must be viewed as a direct function of generating the final energy product. Only by analyzing the complete energy cycle can these effects be fully and consistently evaluated. The second consideration requires that a common measure of the environmental factors be established such that the total energy cycle for different technologies can be cross-compared within specific categories of emissions, while controlling for variation in energy output, materiel requirements, fuel demand, etc.

By investigating the impact of each stage of the energy production process, the analysis attempts to normalize differences between materiel- and fuel-intensive technologies in order to provide a fair basis for comparison. When emissions are normalized in terms of each facility's useful power output, the association between electricity production and emissions for each technology becomes clearer.

CO_2 emissions are rarely expressed in terms of quantities as a function of useful power output, largely because CO_2 has never been regulated or measured as an air pollutant. Raw tonnages of CO_2 only indirectly show the impact of the product society actually consumes -- watt-hours of electricity.

This study estimates CO_2 emissions associated with each stage of energy production for each technology as part of one system designed to produce energy, from fuel extraction through construction, operation, and decommissioning. The goal of this approach is to make the impact of a technology like photovoltaics, which has practically no emissions during operation, but requires significant one-time inputs of raw materiel, comparable to emissions from a technology like a coal plant, which produces its most significant emissions during operation.

By necessity the comparisons presented are generalizations. Each energy facility is to some extent unique. For example, the amount of steel and concrete used in a PV facility will vary with site conditions and the type of equipment used. Coal mining impacts depend on the extent and depth of deposits, site conditions, and mining methods. Combustion emissions from coal are impacted by both generating equipment and coal chemistry, which varies from mine to mine. Some issues, such as the impact of iron ore mining associated with the steel used in plant construction, were not addressed. The following section discusses and compares the impact of resource extraction, facility construction and plant operation for the fossil fuel, nuclear, and renewable energy technologies examined.

Emission Analysis and Comparison by Energy Production Stage

Comparing nuclear and renewable energy to the coal technologies confirms the generally accepted belief that non-fossil technologies represent an advantage from the standpoint of CO_2 emissions. The results also clearly show, however, that their contribution is not zero when all the elements of their fuel cycle are considered. No technology is completely environmentally benign. The CO_2 emissions from the power production technologies examined are shown in Table 1.

Fuel Extraction

Fossil Fuel Extraction -- The fuel extraction stage for fossil fuel includes the impacts of mining, processing, and transporting fuel to the site where it will be converted to energy. Emissions associated with fuel extraction and transportation for the fossil fuel technologies were scaled to the fuel demands of each fossil fuel technology by dividing the annual fuel demand of the power plant by the capacity of the fuel extraction, processing, and transportation facilities. This demand/output ratio was multiplied by the emissions from each fuel supply facility to derive the share of emissions from the facility attributable to the final generating plant. For coal it was assumed that the fuel supplied to each technology was mined and transported under the same conditions, so variations in emissions from fuel extraction are mainly a function of each plant's relative efficiency in generating electricity.[3] Oil and gas fuel extraction data were not complete so the impact of fuel extraction activity could not be assessed.

Renewable Energy Fuel Extraction -- Most of the renewable energy technologies, including photovoltaics, solar thermal, wind, hydropower, and ocean thermal energy conversion (OTEC) have no direct fuel extraction impacts. Geothermal field development and well drilling activities emit minor amounts of CO_2 as a result of gas released from wells.

Biomass energy can produce net reductions in CO_2 over the life of the facility assuming that fuel is extracted from a sustainable, managed source of biomass such as a short-rotation,

Table 1. Carbon Dioxide Emissions: Electric Technologies

Technologies	Emissions by Energy Production Stage (Metric Tons per GWh) Fuel Extraction	Construction	Operation	Total
Conventional Coal Plant	1.0	1.0	962.0	964.0
AFBC Plant	1.0	1.0	960.9	962.9
IGCC Electric Plant	1.0	1.0	748.9	750.9
Oil Fired Plant	-	-	726.2	726.2
Gas Fired Plant	-	-	484.0	484.0
Ocean Thermal Energy Conversion	NA	3.7	300.3	304.0
Geothermal Steam	0.3	1.0	55.5	56.8
Small Hydropower*	NA	10.0	NA	10.0
Boiling Water Reactor	1.5	1.0	5.3	7.8
Wind Energy	NA	7.4	NA	7.4
Photovoltaics	NA	5.4	NA	5.4
Solar Thermal	NA	3.6	NA	3.6
Large Hydropower	NA	3.1	NA	3.1
Wood (sustainable harvest)	-1509.1	2.9	1346.3	-159.9

(-) Missing or inadequate data for analysis, estimated to contribute ≤1%.

(NA) Not Applicable

*This analysis considered construction of new dams. According to a recent Federal Energy Regulatory Commission report there is 8,000 MW of small hydropower under construction or projected, much of it involving refurbishing or refitting existing dams, which would substantially reduce small hydropower's CO2 impact.

intensive-culture wood plantation, which is examined here. Sustainable biomass energy production will fix CO_2 equal to the amount of CO_2 released through combustion over the life of the plant. Sources of CO_2 emissions external to this cycle, notably from inputs of fertilizers and pesticides and the use of fossil fuels in cultivating, harvesting, and transporting the fuel, were evaluated and included in the analysis as net contributors to CO_2 emissions. However, these emissions, are offset by the carbon storage capacity of the roots and other unharvested portions of the biomass that remain in place (and growing in the case of coppiced species). Over the life of a generating plant this harvest/regrowth cycle can yield a net *reduction* in CO_2 emissions over all stages of biomass-fired electricity production.

A Scenario of Biomass Fuel Regrowth

A managed, short-rotation forest fixes or sequesters 45 metric tons of carbon per hectare per year (165 metric tons CO_2 per hectare per year) during its growth period. If trunks and branches from the short-rotation forest are harvested and used in a power plant, 82.5 metric tons of CO_2 per hectare remain in the forest, stored in the root system and soil. Therefore, even with harvesting and energy production, substantial carbon remains fixed after the first harvest. Subsequent harvests and wood utilization would be balanced from a CO_2 standpoint in that growth of new trunks and branches would offset CO_2 released back to the atmosphere during combustion.

In 1986, U.S. fossil-fired electricity production emitted 1.62 billion metric tons of CO_2. Thus, it would require 9.88 million hectares (approximately the size of the state of Virginia) of newly planted forest to offset all 1.62 billion metric tons of CO_2. Each tree offsets approximately 338 kilograms (0.34 metric tons) of CO_2 per year during its annual growth cycle. At that recapture rate, 4.8 billion new short- rotation trees would need to be planted to absorb the 1.62 billion metric tons of CO_2 in 1986. With a population in the U.S. of 240 million, each person would have to plant approximately 20 trees to achieve this offset. (At CO_2 offset rates for natural forests, 26 million hectares would be required to uptake 1.62 billion metric tons of CO_2 or each person would plant over 50 trees.)

Nuclear Fuel Extraction -- The nuclear calculations were made in the same general manner as the coal calculations, with fuel demand at the power plant traced back through fuel fabrication, enrichment, processing, and mining in order to allocate the emissions from each stage of fuel manufacture in proportion to each stage's contribution to final power production.[4] An additional increment to emissions was added to the source values based on each fuel processing facility's electricity demand. A coefficient for CO_2 emissions as a function of the electric generating fuel mix in the U.S. was calculated and then applied to the electricity demand of the nuclear plant.

Construction

The construction phase includes the indirect impacts of the technologies in terms of CO_2 emissions associated with manufacturing the raw materiel inputs. Steel and concrete are the major materiel inputs examined and the major sources of CO_2 emissions.

The construction stage accounts for the greatest differences between materiel- versus fuel-intensive technologies, with the former producing the highest environmental impacts at this stage. The estimates in this analysis focus exclusively on emissions from final manufacture of major materiel used in construction; it does not represent a comprehensive estimate of all emissions. There are secondary emissions associated with the mining of raw materiel (such as iron ore, bauxite, etc.) and actual in situ assembly of materiel and components, but these types of impacts were not addressed.

The emissions associated with materiel manufacture were divided by the annual output of the technology times the operational life of the technology to derive CO_2 emissions per unit of output over plant life. The CO_2 emission factor for steel was derived by examining fuel demand as a function of industry output, and then multiplying the resultant estimate of fuel use per ton of output times a CO_2 emission coefficient to derive an estimate of CO_2 per ton of output. This estimate was then used to calculate the CO_2 emissions associated with steel demands. Electricity as an energy input to steel was converted to CO_2 inputs by calculating the fuel mix for electricity in 1987, multiplying the quantities by their respective coefficients, and then allocating the gross CO_2 emissions over the total number of gigawatt-hours produced in 1987.[5, 6, 7] The CO_2 coefficients for steel, concrete, and for the various fuels considered are based on data from industry data bases or global climate investigations, respectively.[8, 9, 10]

Fossil Fuel Construction -- In the case of the IGCC plant and the AFBC plant, direct estimates of materiel requirements were unavailable. Therefore the values were derived by adjusting the materiel used in a conventional plant by the proportionate capacity associated with the AFBC and IGCC plant.[11] It is acknowledged that this assumption ignores the significant technology differences and the effects of differing economies of scale between technologies. Data were unavailable for the oil and natural gas plants, and no estimates of their impacts were made. In general, emissions from fossil fuel plant construction are small relative to the output over the operating life of the plant.

Renewable Energy Construction -- Like conventional technologies, the materiel requirements for renewable energy plants can vary widely depending on specific site conditions and technical requirements. The different technologies vary widely in their materiel intensity and CO_2 emissions per GWh. For each renewable energy technology, the Department of Energy Renewable Energy Program has estimated materiel requirements per MW of capacity, given an "average" or typical facility.

The steel and concrete estimates of a PV plant are for a conceptual utility-scale design developed by the Electric Power Research Institute. The PV plant is assumed to employ flat-plate, thin-film arrays with 15% efficiency located in Barstow, California. Plant size was 100 MW, with 209 GWh of annual energy output.[12] Geothermal plant construction requirements are basically equivalent to a conventional fossil fuel plant with comparable materiel requirements. The wood combustion generating plant also has construction materiel requirements similar to a comparable fossil plant.

Nuclear Construction -- Construction-related CO_2 emissions from nuclear energy are quite low when considered over the life of the plant. Although they require a considerable amount of materiel initially, nuclear plant impacts are spread over a high lifetime power output.[13]

Operation

The values for emissions and materiel inputs associated with operating the technologies were taken from source documents and Renewable Energy Program inputs. The annual value for emissions was then divided by the annual GWh of output for each technology to derive emissions per unit of output. Values for the IGCC and AFBC plants were assumed to be similar to the conventional plant in terms of the rate of emissions, and thus were only adjusted for the increased efficiency and power output per ton of coal input gained from each technology (if any).

Fossil Fuel Plant Operation -- Impacts at the operation stage are measured in terms of emissions produced while the plants are actively generating energy. The conventional coal plant in the assessment is assumed to be a 500 MW facility producing 3500 GWh of electricity annually. It represents a new plant built to meet or exceed existing environmental standards, and to maximize performance. The plant lifetime is assumed to be 30 years, prior to major refurbishment, repowering or retirement.

The AFBC plant examined is rated at 500 MW with annual energy production of 3500 GWh. Its useful life is 30 years. Nearly 2 million tons of Illinois coal is required to fuel the plant annually. The IGCC plant is rated at 945 MW and produces roughly 6700 GWh annually. The assumed heat rate for the plant is 9,410 kJ/kWh. Its useful life is 30 years. The plant consumes roughly 3 million tons of coal annually.[14]

The oil-fired plant is rated at 800 MW and produces 3850 GWh annually using 954 million liters of #6 residual fuel oil. The gas-fired plant is rated at 800 MW and produces 3850 GWh annually using 1.05 billion cubic meters of natural gas annually. Both are conventional steam turbine plants. A combined cycle gas plant would be much more efficient and thus produce lower emissions per useful unit of energy production, but data for an assessment of a combined cycle plant were not available. In general the fossil-fired emissions of CO_2 during operation are 962 metric tons per GWh for conventional coal, over 740 metric tons per GWh for IGCC, 725 metric tons per GWh for oil, and 484 metric tons per GWh for natural gas.

Renewable Energy Plant Operation -- Hydropower, wind, photovoltaic, and solar thermal technology emissions during plant operation are essentially zero. The wood-fired generating facility has the highest CO_2 emissions of any technology during operation but it is important to note that this is offset by fuel regrowth, so that net CO_2 emissions are zero, or slightly negative. Among the renewable energy technologies, the OTEC plant has the next highest emissions during operation and the highest overall emissions at 304 tons per GWh. This represents only one OTEC technology option. A closed-cycle system would dramatically reduce the release of entrained gas in the seawater as it is flashed, thus bringing OTEC CO_2 emissions in line with the other renewable energy technologies. Similarly, the geothermal dry-steam system is also an open-cycle, which allows venting of CO_2 trapped in the hydrothermal steam that powers the turbine generator. This open-cycle hydrothermal system produces 56 tons of CO_2 per GWh. Closed-cycle flash steam systems and binary-cycle plants would eliminate the majority of these emissions. Binary technology is especially suited to the most abundant moderate temperature resources, and so is likely to play a larger role in future development of geothermal energy.

Nuclear Plant Operation -- The nuclear plant is a boiling water reactor design rated at 1000 MW, producing 6130 GWh annually over a useful life of 30 years.[15] The CO_2 emissions during nuclear plant operation should be viewed as the high end of a possible range of emissions, since they are based on the assumed operation of fossil fuel backup generators and boilers during normal operation. Under actual operating conditions a nuclear plant can be expected to operate with less reliance on fossil-fired auxiliary systems. It is estimated that a Pressurized Water Reactor (PWR) will have a similar (±5%) CO_2 profile. Although the PWR requires somewhat less fuel per gigawatt hour, it uses a more highly enriched fuel concentration.

Carbon Dioxide Emissions Summary

Summary by Technology

The total CO_2 emission profile of each of the technologies is shown graphically in Figure 1.

Fossil Fuels -- Conventional coal provides a baseline for comparison of CO_2 emissions from electric generating technologies; it is an established technology with well-known characteristics that provide a benchmark for alternatives. The Atmospheric Fluidized Bed Combustion (AFBC) plant represents an innovative alternative to conventional coal combustion and scrubbers.[16] The Integrated Gasification Combined Cycle (IGCC) plant represents an emerging advanced technology which offers significant improvements in coal combustion.[17] Oil and particularly gas are attractive for their lower CO_2 emissions profile, and gas is an increasingly important component of the U.S. electric generating system.

For fossil-fired generating technologies, most CO_2 emissions occur during operations. CO_2 emissions per ton of coal combusted are assumed to be basically similar for each technology, but the gross emissions are spread over a higher GWh output per ton of coal for the IGCC plant, which accounts for its improved emissions profile. Oil and gas have much lower CO_2 emissions per unit of energy output, but still have significantly higher emissions than renewable energy technologies.

Renewable Energy -- CO_2 emissions from the hydropower, wind, photovoltaic and solar thermal plant are primarily related to the

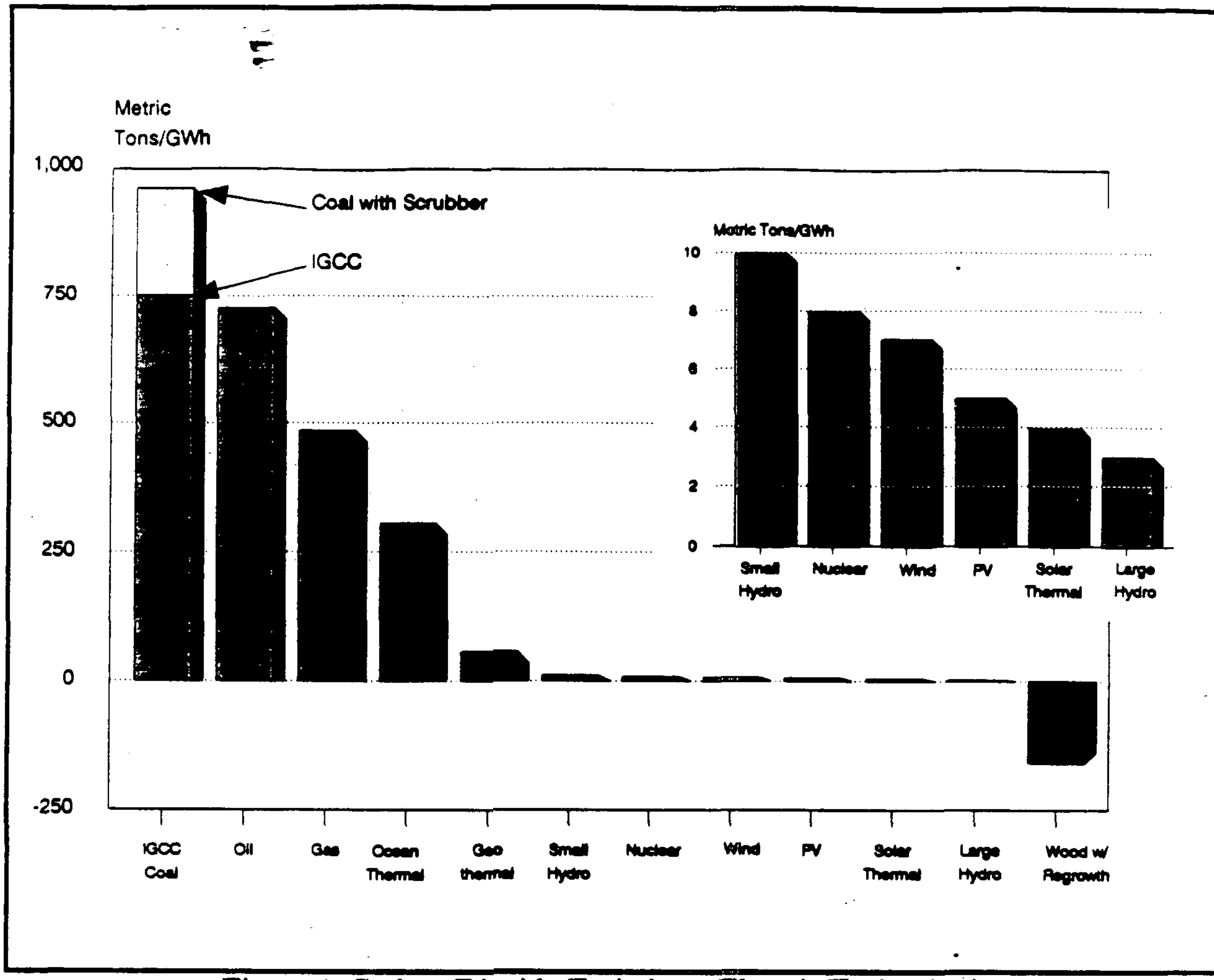

Figure 1. Carbon Dioxide Emissions: Electric Technologies

construction of the generating station and the emissions from the steel and concrete plants. For these technologies, air emissions related to construction are higher than the emissions related to construction for the other technologies because of the materiel-intensive nature of the technology. But overall their emissions are a very small fraction of the emissions from coal technologies and are for the most part less than or comparable to nuclear. Biomass, OTEC, and geothermal have relatively higher emissions during operation. Biomass in particular has higher emissions than a coal plant during operation, but when a managed biomass fuel cycle is considered, which includes regrowth of the feedstock, utilization of wood to produce power can minimize or eliminate net CO_2 emissions.

An open-cycle OTEC plant has CO_2 emissions comparable to a gas-fired plant during operation, although these emission levels are not inherent in the technology since a closed-cycle could substantially reduce CO_2 emissions. Geothermal's emissions during operation are large in comparison to the solar, wind and hydropower technologies, but far less than gas-fired generation. Like OTEC, geothermal CO_2 emissions are not inherent in the technology, and could be substantially eliminated through the use of closed-cycle systems.

Nuclear -- CO_2 emissions from the nuclear reactor should be viewed as a range, since a portion of the emissions are associated with fossil fuel combustion required to produce electrical and other inputs to uranium processing operations and the occasional use of fossil fuel boilers and generators during operation. There is also an input of fossil fuel to operate backup and auxiliary steam and electricity generators at the plant site during normal refueling and operations.[18] The effect of these systems varies depending on plant design, the occurrence and extent of planned and unplanned outages, and normal maintenance requirements.

Renewable Energy CO_2 Displacement Projections (A Sample Case)

Introduction

While the environmental advantages of renewable energy are evident on a micro level, the following analysis is presented as an illustration of the potential macro impacts of renewable energy technology deployment. The following analysis is based on a DOE projection of energy supply and demand to 2010 and the renewable energy CO_2 emission measurements developed in the previous sections of this report. The contribution of renewable energy technologies in power generation is examined to determine the extent to which they will displace both conventional baseload and peaking power generation technologies. The analysis is developed from data contained in the Department of Energy's *Long-Range Energy Projections to 2010 (LEP)*.[19]

Figure 2 shows projections of future electricity contributions based on three LEP scenarios ("High," "Reference," and "Low") along with projections from the Gas Research Institute (GRI) and the North American Electric Reliability Council (NERC). Overall, the "reference" case represents the middle range of LEP projections and shows general agreement with utility industry projections, thus it was selected as a reasonable estimate for projected electricity use through the year 2010.

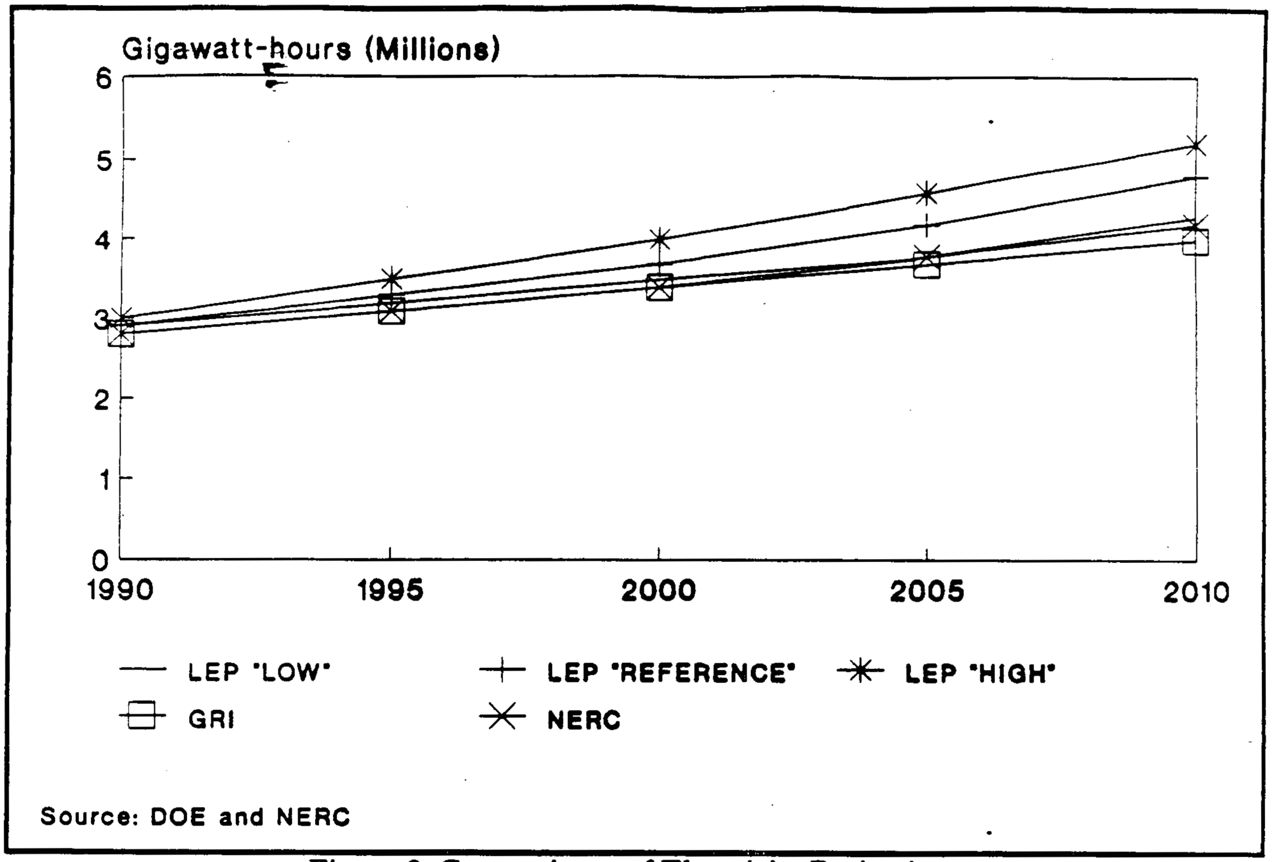

Figure 2. Comparisons of Electricity Projections

LEP Assumptions

Electricity consumption is projected to grow in every sector, averaging just over 3% per year between now and 1990 and between 2.4% and 2.7% per year thereafter. The projected growth in electricity consumption is due to a number of factors, including its inherent flexibility, the continuing increases in the efficiency of its end uses and, perhaps most important, the increasing relative prices of oil and natural gas. LEP assumed oil prices in the range of $18 and $22 per barrel ($1986) by 1990. Beyond 1990, price projections are much more uncertain, but are projected to be between $29 and $37 by 2000 and between $44 and $61 by 2010.

The electricity consumption projections imply that significant new capital expansion will be required starting in the early 1990s. By 2000, according to LEP projections, at least 50 gigawatts (GW) of new generating capacity in addition to the approximately 70 GW currently under construction or announced will be needed. In the LEP "reference" projection, over the near term the bulk of new capacity coming into operation will be coal and nuclear, as plants currently under construction are completed. Much of the new and as yet unplanned generating capacity, anticipated in LEP, is for low-emission coal-fired technologies, with newer "clean coal" technologies such as coal combined cycle and fluidized bed combustion making a growing contribution. Oil use in the electric utility sector is projected to rise, but existing excess oil capacity may negate the need for significant quantities of new conventional oil capacity. Natural gas consumption is also expected to rise, with small amounts of new gas turbine and gas combined-cycle capacity expected. However, by the late 1990s, oil use is expected to decline due to rising fuel costs, while nuclear expansion is assumed to diminish due to the lack of new plant orders over the past fifteen years. Small hydro, geothermal, wind, and photovoltaic renewable energy facilities are projected to produce moderate but growing amounts of electricity.

In order to determine the potential contribution of renewable energy technologies in displacing future fossil-fired CO_2 emissions, fossil-fired electric generating systems were compared with renewable energy systems with similar operating characteristics. It was assumed that gigawatt-hours from hydropower, geothermal, biomass, and ocean thermal production would displace a mix of baseload fossil- and nuclear-generated electricity. Gigawatt-hours generated by wind, photovoltaics, and solar thermal technologies were assumed to displace a mix of intermediate/peaking oil- and gas-fired electricity.

Net CO_2 Displaced by Renewable Energy Technologies

By the year 2010 renewable energy technologies taken collectively are projected to displace over 8.5 billion metric tons of CO_2, on a 24-year cumulative basis, as shown in Table 2 and Figure 3, and would continue to expand substantially beyond 2010. The scenario considered here is based on conservative estimates of future energy use and renewable energy contribution. As the authors of the LEP point out, their scenario(s) should be interpreted simply as points of departure for understanding possible future energy development. The same is true for this analysis of CO_2 displacement potential.

Scenarios for renewable energy's contribution in the U.S. could significantly exceed the projections by the LEP, depending on the future price of conventional energy, the overall competitiveness of renewable energy technologies in the future, and the nature and

Table 2. Net CO_2 Displaced by Technology

	(Millions of Metric Tons)					
Baseload Renewables	**1986**	**1990**	**1995**	**2000**	**2005**	**2010**
Hydropower	215.2	215.0	244.2	278.3	292.4	296.5
Geothermal	14.7	21.7	36.2	46.1	66.2	80.5
Biomass	0.9	0.8	1.7	4.4	6.4	7.3
Ocean Thermal	0.0	0.0	0.0	0.4	1.4	2.8
Peaking Renewables						
Solar Thermal	0.0	0.0	0.6	2.4	4.2	6.6
Photovoltaics	0.0	0.0	0.0	2.4	11.4	43.2
Wind	0.0	0.6	6.5	22.0	39.4	70.0
Total	230.9	238.1	289.2	356.0	421.4	506.8
Cumulative Total	230.9	1172.4	2516.4	4162.8	6138.9	8502.2

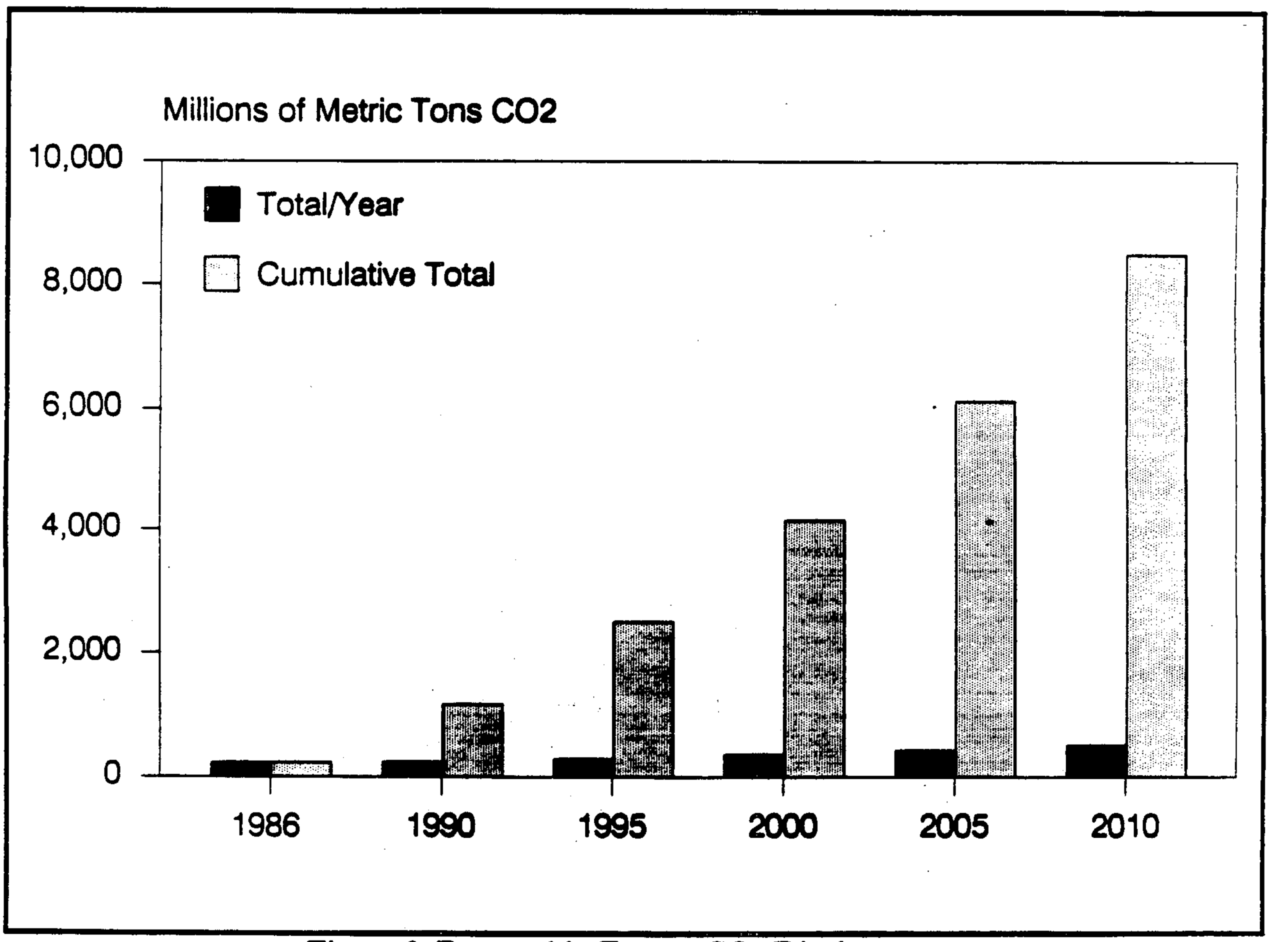

Figure 3. Renewable Energy CO_2 Displacement

aggressiveness of U.S. and international policy initiatives for addressing global climate change. Advances in renewable energy technology research could greatly accelerate their overall contribution to mitigating CO_2 emissions from conventional electric generation technologies.

Conclusion

In order to compare measures of emissions and materiel requirements for power production technologies, they must be examined in their entirety, taking into account each stage of the energy production process. This comprehensive approach provides a cumulative view of emissions that focuses on quantities of emissions as a function of energy supplied; a measurement convention that facilitates comparisons between different technologies.

From a historical perspective, the mix of fossil-fired electric power generation in the U.S. in 1986 produced an average of 874 metric tons of CO_2/GWh, while renewable energy technologies produced an average of approximately 18 metric tons of CO_2/GWh. Thus each GWh from renewable energy displaced approximately 856 metric tons of CO_2, or a 98% reduction. From a future perspective, projections to 2010 indicate that renewable energy electric technologies could reduce CO_2 emissions by 519 million metric tons per year in the U.S., or an 18% displacement of CO_2 related to an equivalent electrical output from fossil-fired power facilities.

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GEOTHERMAL
DETAILS

Geothermal Technologies

Technology Description

Energy from geothermal systems is provided by steam or hot water produced from underground reservoirs located in volcanic regions. Since the geothermal fluids are produced in volcanic settings, and at times are contained in carbonate reservoirs, they all contain carbon dioxide gas. However, not all geothermal technologies provide pathways for CO_2 to reach the atmosphere. These technologies and their limited contribution to ambient levels of this gas are discussed below.

Electric Power Generation

All commercial geothermal power is generated today with hydrothermal fluids. The technologies employed vary with the form in which hydrothermal energy occurs -- vapor.dominated or liquid-dominated -- and/or its temperature. Dry steam, a relatively rare occurrence, is fed to the generating system just as it comes from the earth; conventional turbine-generator equipment is employed. In plants designed to use liquid-dominated, or hot water, reservoirs, the liquid is allowed to flash to steam as it reaches the surface under reduced pressure; the steam and remaining liquid are separated; and the steam then enters the turbine. This is known as flash steam technology. Most flash plants in operation or under design today optimize energy extraction from the hot fluid by utilizing a dual flash design -- i.e., steam is produced at two pressure levels (high/low) from the incoming brine.

Generally, flash steam technology is not economic at temperatures below 200°C. The state-of-the-art technology for generating power with brines in the 150-200°C range is binary cycle technology. Some very small binary units operate successfully at even lower temperatures. In this type system, the heat from the geothermal fluid is used to vaporize a high-pressure fluid such as a hydrocarbon. The vaporized working fluid is expanded through a turbine, condensed, and repressurized in a closed loop.

Prior to construction of geothermal power plants, drilling of geothermal wells occurs at several stages of development -- exploration, reservoir confirmation, reservoir engineering, and production to serve the plant. Injection wells are also drilled in which to dispose of the spent fluids. The size of the well field may range from one production well and one injection well for small wellhead binary units to multiple wells for large plants. New production and injection wells may be needed during the life of the plant. The size and complexity of fluid gathering lines will also vary with plant capacity.

Direct Use

Hydrothermal fluids are also used in a number of direct heat applications. These include district heating systems, space heating and cooling, commercial greenhouses and fish farms, and industrial processing. The technology for such uses is for the most part drawn from conventional hot water and steam handling equipment employed in these applications using heat from sources other than geothermal. For example, a geothermal district heating system will generally have the same components as a conventional system. The geothermal production field, which includes wells, pumps, and collecting mains, replaces the boiler in a conventional system. All other components, such as piping, valves, controls, and metering would be the same. The most common space heating equipment -- forced air, convection, and hydronic radiant floor or ceiling panels -- are all adaptable to geothermal energy. In Klamath Falls, Oregon, where over 400 wells are used to provide space heat to individual homes and businesses, the principal heat extraction system is a closed-loop downhole heat exchanger utilizing city water in the loop. In fish farming, heating can be accomplished using hot water bearing pipes in the growth ponds or by direct addition of suitable quality hot water in order to maintain optimum pond temperatures. Other technologies for geothermal direct applications are similarly akin to conventional technology.

The major difference is that some accommodation may have to be made to the fluid chemistry to avoid corrosion and scaling. Most of these problems are surmounted by materials selection and proper engineering. For others, heat exchangers may be needed to limit geothermal contact to a small portion of the overall system. Typically, low-temperature fluids are utilized for many direct uses which minimize corrosion and scaling problems. Frequently, sufficient heat for the intended use can be found at depths shallow enough to be reached with standard water well drilling equipment.

Current Use

U.S. Use

As of October 1988, 38 liquid-dominated, or hot water, geothermal power plants are on-line or under construction. The total capacity of these plants is about 575 MWe. Twenty-eight dry steam plants are on-line or under construction at The Geysers with a total capacity of nearly 2,000 MWe.[1] Thus, total U.S. geothermal power plants account for nearly 2,575 MWe, or enough electricity to serve over two million power customers. This use accounts for an annual savings of over 23 million barrels of oil per year.

The total installed geothermal direct use capacity in the U.S. is 5.7 billion Btu/hour, or 1,700 MWt with an annual energy use of nearly 17,000 billion Btu/year or 4.5 million barrels of oil equivalent.[2]

Worldwide Use

Geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.3

At the end of 1984, the latest year for which worldwide figures are available, the installed thermal power of all geothermal direct use projects was about 7,072 MWt. The thermal energy used was nearly 24,000 GWh, replacing an estimated 21 million barrels of oil per year.4

Projected Use

U.S. Use

The following projections on U.S. geothermal power development were made by the Electric Power Research Institute in 1987.5 The survey is based on the responses of 26 electric utilities which provided data on installed geothermal capacity at the end of 1986, firm expectations of capacity to be on-line by the end of 1987, and estimates of future geothermal power plant capacity for the periods to 1990, 1995, and 2005 at the three levels of confidence shown in the table.

Table 1: Geothermal Capacity, Megawatts

	1986 Actual	1987 Firm	1990 Est.	1995 Est.	2000 Est.	2005 Est.
Announced						
NoWest	0	0	0	0	0	0
SoWest	42	93	93	213	249	269
Cal-Ha	2070	2111	2628	2845	2876	2876
Gulf	0	0	0	0	0	0
Total	**2112**	**2204**	**2721**	**3058**	**3125**	**3145**
Probable						
NoWest			0	10	30	65
SoWest			113	258	344	464
Cal-Ha			2710	3154	3869	4419
Gulf			1	1	1	5
Total			**2824**	**3423**	**4244**	**4953**
Possible						
NoWest			0	15	65	140
SoWest			113	258	377	596
Cal-Ha			2960	3536	4864	5979
Gulf			1	5	10	20
Total			**3074**	**3814**	**5316**	**6735**

It is possible that the results of EPRI's 1988 survey will be known before this document is finalized, and projections to 2010 will be available.

All earlier projections on geothermal direct use in the U.S. are now outdated by the results of a 1988 survey of direct use projects conducted by the Geo-Heat Center at Oregon Institute of Technology.2 The survey found that the use of groundwater and earth-coupled heat pumps has grown beyond expectations -- and was expected to increase by another 50 percent in 1988 over 1987

-- and that use of geothermal energy for aquaculture operations and swimming pools and spas is much larger than previously reported. Thus, new projections are now needed to provide a basis for realistic expectations.

Worldwide Use

The most recent and authoritative projections on worldwide use of geothermal power were made in April 1987.6 They are as follows:

Year	MWe
1986 -	4,733
1990 -	6,166
1995 -	7,870
2000 -	9,123

So far as is known, no projections on increases in worldwide geothermal direct use projects exist. These uses are diverse, many times small, and are not represented by major trade interests or international agencies.

Resource Acquisition

Acquisition of the geothermal resource involves several phases of field development. Exploratory activities such as surface geophysical surveys, numerical modeling, and geologic mapping produce no CO_2 emissions. There is also little likelihood that measurable emissions would result from drilling of temperature gradient holes. However, flow testing of "wildcat" wells and stepout wells used to identify and confirm the resource provides opportunity for some of the entrained CO_2 to break out of solution and escape to the atmosphere. For a 50 MWe plant, about six wells might be drilled during the exploration and confirmation phases. The ambient concentrations of CO_2 would vary from reservoir to reservoir and from one site to another at the same reservoir due to the variable nature of the chemical composition of geothermal fluids. The mode emission level of CO_2 resulting from resource acquisition (exploration and confirmation) for geothermal power plants is estimated in Table 1. Direct use applications are limited in extent by cost and do not involve these phases.

CO_2 Contribution of Geothermal Power Plants* (lbs CO_2/MWhr)

	Steam	Flash	Binary
Resource Acquisition	0.6	0.42	10
Facility Construction**	1.2	0.84	20
Facility Operation	122.0	100	0
Fuel Utilization	0.0	0.0	0
Total	124	101	30

CO_2 Contribution of Geothermal Direct Heat Applications (lbs CO_2/MWt)

Resource Acquisition	0.0
Facility Construction	0.1
Facility Operation	0.1
Fuel Utilization	0.0
Total	0.2

Facility Construction And Equipment Manufacture

During the power plant construction phase, the geothermal field is developed with about 12 production wells for a 50 MWe plant and one or more injection wells. Fluid gathering lines are installed, and roads are completed. Major CO_2 sources in the field include the fuel used to drill wells and fluid emissions during well testing. Construction of the power plant involves a turbine/generator and, depending on the technology to be used, flash tanks or heat exchangers. Information on the energy used in the manufacture and installation of this equipment and the resulting CO_2 emissions

* Based on a 50MWe plant, 30-year life.

** Does not include CO# contribution to building the turbo-generator systems. Contribution would be the same as that for fossil and nuclear power plants.

is not readily available. The estimated CO_2 contribution from development of the field is shown in Table 1.

The construction phase for direct applications consists of one or two shallow wells with nominal plumbing for distribution and injection of spent fluid. The estimated CO_2 contribution is shown in Table 2.[7]

Facility Operation

Power Generation

The levels of CO_2 emissions generated by geothermal power plants not only range with the chemistry of the resource, but with the technology used as well. Although the dry steam plants at The Geysers are all equipped with systems to control emissions of another noncondensible gas, hydrogen sulfide, this equipment does not treat or contain CO_2 emissions, and it is estimated that all of the gas present enters the atmosphere.7 However, the percent by weight of constituent CO_2 averages less than one percent in Geysers wells,8 and available data indicate that the emission rates range from two to four percent of those of an equivalent western coal plant.

By its very nature, flash plant technology generates CO_2 emissions because the gas is liberated during the pressure reduction that permits flashing.[8]

Since there are to date no air pollution control standards limiting CO_2 emissions, the gas present is typically removed from the condenser by air ejectors and vented to the atmosphere. It is reported that resource conditions in one new flash plant permit# the noncondensible gas to remain entrained in the spent brine which is injected back to the subsurface. In this case, no CO_2 is emitted to the atmosphere. The mode emission rate for typical flash plants is estimated in Table 1.

No emissions of CO_2 or any other gases occur during the operation of geothermal binary plants since they are closed systems. In addition, the use of well pumps prevents flashing in the wells, keeping the fluid in the liquid state.

Direct Use

There is little potential for CO_2 emissions from direct heat applications of geothermal resources for several reasons. First, in most direct heat applications, the fluid is brought to the surface in the liquid phase with no flashing and no gaseous emissions. Direct heat projects are small, requiring fewer wells per development than power generation, at shallow depths and lower temperatures. Fluids of this character are usually much more benign in chemical composition than high temperature resources found at great depths under massive rock structures. However, should gaseous constituents be present, problems can be virtually eliminated for direct heat applications by using closed loop systems that prevent emissions. For the estimated mode CO_2 emission rate, see Table 2.

Fuel Utilization

This topic is not applicable to geothermal operations since the hydrothermal brines are the fuels.[9]

References

1. *Geothermal Progress Monitor*, Issue No. 11, Department of Energy, In Publication.

2. *Geothermal Direct Use Developments in the United States,* Geo-Heat Center, Oregon Institute of Technology, Aug. 1988.

3. DiPippo, R., "Worldwide Geothermal Power Development," Proceedings: Ninth Annual Geothermal and Second IIE-EPRI Geothermal Conference and Workshop, Vol. 2, Aug. 1987.

4. Gudmundsson, J.S., "Direct Uses of Geothermal Energy in 1984," 1985 Symposium on Geothermal Energy, International Volume, *Geothermal Resources Council Transactions*, 1985.

5. Kruger, P., "1987 EPRI Survey of Geothermal Electric Utilities," Proceedings: Tenth Annual Geothermal Conference and Workshop, Feb. 1987.

6. DiPippo, R., "Geothermal Electric Power: Where Are We Headed?" *Geothermal Report,* April 1, 1987.

7. Personal Communication, Vasel Roberts, Electric Power Research Institute, Oct. 12, 1988.

8. Kestin, J., Ed., *Sourcebook on the Production of Electricity from Geothermal Energy*. Department of Energy, March 1980.

Hydrothermal Power Generation

Technology Description

Energy from hydrothermal geothermal systems is provided by steam or hot water produced from underground reservoirs located in volcanic regions. Since the geothermal fluids are produced in volcanic settings, and at times are contained in carbonate reservoirs, they all contain carbon dioxide gas. However, not all geothermal technologies in commercial use provide pathways for CO_2 to reach the atmosphere. These technologies and their limited contribution to ambient levels of this gas are discussed below.

Other forms of geothermal energy include geopressured brines containing dissolved methane; hot dry rock from which heat can be extracted with a man-made reservoir for circulating fluids; and magma, or molten rock. The technologies for exploiting these forms of the resource are under development. By technical definition, the systems for extracting heat from hot dry rock and magma are closed systems, providing no avenue for escape of CO_2 emissions to the atmosphere.

Electric Power Generation

The technologies employed for generating power with hydrothermal fluids vary with the form in which the resource occurs -- vapor-dominated or liquid-dominated -- and/or its temperature. Dry steam, a relatively rare occurrence, is fed to the generating system just as it comes from the earth; conventional turbine-generator equipment is employed. In plants designed to use liquid-dominated, or hot water, reservoirs, the liquid is allowed to flash to steam as it reaches the surface under reduced pressure; the steam and remaining liquid are separated; and the steam then enters the turbine. This is known as flash steam technology. Most flash plants in operation or under design today optimize energy extraction from the hot fluid by utilizing a dual flash design -- i.e., steam is produced at two pressure levels (high/low) from the incoming brine.

Generally, flash steam technology is not economic at temperatures below 200°C. The state-of-the-art technology for generating power with brines in the 150-200°C range is binary cycle technology. Some very small binary units operate successfully at even lower temperatures. In this type system, the heat from the geothermal fluid is used to vaporize a high-pressure fluid such as a hydrocarbon. The vaporized working fluid is expanded through a turbine, condensed, and repressurized in a closed loop.

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Worldwide Use

Geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.[2]

Projected Use

U.S. Use

The following projections on U.S. geothermal power development were made by the Electric Power Research Institute in 1987.[3] The survey is based on the responses of 26 electric utilities which provided data on installed geothermal capacity at the end of 1986, firm expectations of capacity to be on-line by the end of 1987, and estimates of future geothermal power plant capacity for the

Table 2: Geothermal Capacity, Megawatts

	1986 Actual	1987 Firm	1990 Est.	1995 Est.	2000 Est.	2005 Est.
Announced						
NoWest	0	0	0	0	0	0
SoWest	42	93	93	213	249	269
Cal-Ha	2070	2111	2628	2845	2876	2876
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Total			**3074**	**3814**	**5316**	**6735**

periods to 1990, 1995, and 2005 at the three levels of confidence shown in the table.

It is possible that the results of EPRI's 1988 survey will be known before this document is finalized, and projections to 2010 will be available.

Worldwide Use

The most recent and authoritative projections on worldwide use of geothermal power were made in April 1987.[4] They are as follows:

Year	MWe
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Resource Acquisition

Acquisition of the geothermal resource involves several phases of field development. Exploratory activities such as surface geophysical surveys, numerical modeling, and geologic mapping produce no CO_2 emissions. There is also little likelihood that measurable emissions would result from drilling of temperature gradient holes. However, flow testing of "wildcat" wells and step-out wells used to identify and confirm the resource provides opportunity for some of the entrained CO_2 to break out of solution and escape to the atmosphere. For a 50 MWe plant, about six wells might be drilled during the exploration and confirmation phases. The ambient concentrations of CO_2 would vary from reservoir to reservoir and from one site to another at the same reservoir due to the variable nature of the chemical composition of geothermal fluids. The modal emission level of CO_2 resulting from resource acquisition (exploration and confirmation) for geothermal power plants is estimated in Table 1.

Facility Construction And Equipment Manufacture

During the power plant construction phase, the geothermal field is developed with about 12 production wells for a 50 MWe plant and one or more injection wells. Fluid gathering lines are installed, and roads are completed. Major CO_2 sources in the field include the fuel used to drill wells and emissions during well testing. Construction of the power plant involves a turbine/generator and, depending on the technology to be used, flash tanks or heat exchangers. Estimates of the CO_2 contribution of equipment manufacture are in preparation. The estimated CO_2 contribution from development of the field is shown in Table 1.

Facility Operation

Power Generation

The levels of CO_2 emissions generated by geothermal power plants not only range with the chemistry of the resource, but with the technology used as well. Although the dry steam plants at The Geysers are all equipped with systems to control emissions of another noncondensible gas, hydrogen sulfide, this

equipment does not treat or contain CO_2 emissions, and it is estimated that all of the gas present enters the atmosphere.[5] However, the percentage by weight of constituent CO_2 averages less than one percent in Geysers wells,[6] and available data indicate that the emission rates range from 2 to 4 percent of those of an equivalent western coal plant.

By its very nature, flash plant technology generates CO_2 emissions because the gas is liberated during the pressure reduction that permits flashing. Since there are to date no air pollution control standards limiting CO_2 emissions, the gas present is typically removed from the condenser by air ejectors and vented to the atmosphere. It is reported that one new flash plant injects the noncondensible gases back to the subsurface. In this case, no CO_2 is emitted to the atmosphere. The modal emission rate for typical flash plants is estimated in Table 1.

No emissions of CO_2 or any other gases occur during the operation of geothermal binary plants since they are closed systems. In addition, the use of well pumps prevents flashing in the wells, keeping the fluid in the liquid state.

Fuel Utilization

This phase is not applicable to geothermal operations since the hydrothermal brines are the fuels.

Other Impacts

<u>Compatibility with Existing Infrastructure</u>

With California taking the lead, strict environmental regulations have been placed on the geothermal industry, but not such rigid ones as to stifle development. The industry works with the cognizant authorities from the early stages of each development, and a good relationship appears to exist in each of the major areas of development. If the federal government or the states move to restrict CO_2 emissions from all sources, the geothermal industry appears to be in a favorable position, both technically and in its relationship with the regulating agencies, to be in the forefront of compliance.

National Security

Geothermal energy provides a baseload alternative to fossil-fired power plants along with hydropower and nuclear. In areas where geothermal resources are abundant, new hydropower sites have become limited. And in some of the same areas, nuclear plants have encountered opposition on various grounds. Thus, if a national consensus develops that CO_2 emissions must be reduced drastically, geothermal power plants using an indigeneous fuel will be the prime candidate for ensuring continued energy security in some very heavily populated areas.

Primary References

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2. DiPippo, R., "Worldwide Geothermal Power Development," Proceedings: Ninth Annual Geothermal and Second IIE-EPRI Geothermal Conference and Workshop, Vol. 2, Aug. 1987.

3. Kruger, P., "1987 EPRI Survey of Geothermal Electric Utilities," Proceedings: Tenth Annual Geothermal Conference and Workshop, Feb. 1987.

4. DiPippo, R., "Geothermal Electric Power: Where Are We Headed?" Geothermal Report, April 1, 1987.

5. Personal Communication, Vasel Roberts, Electric Power Research Institute, Oct. 12, 1988.

6. Kestin, J., Ed., *Sourcebook on the Production of Electricity from Geothermal Energy*, Department of Energy, March 1980.

Carbon Dioxide Displacement: Hydrothermal Power Generation, Steam

Technology Description:
Hydrothermal steam systems use a conventional turbine, which is powered directly by the steam as it comes from the earth. Field Development and well drilling occurs at every stage of project development.

Current Use:
U.S. capacity is nearly 2,575 MWe, or enough electricity to serve over two million power customers with an annual savings in oil of over 23 million barrels. Worldwide, geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.

Projected Use*:
Domestic and worldwide use at present and in future years are:

	1986 Domestic	1986 World	2010 Domestic	2010 World
MWe	2,575	5,000	4,953-6,735	9,123

Total CO_2 Contribution = 62.35 tons/GWh

Resource Extraction

Fuel	Steam
CO_2 Contributors:	
Well Drilling	.3 tons/GWh
CO_2/GWh	0.3

Facility Construction (Tons)

Concrete†	308.61
Steel‡	28
CO_2/GWh	1.05

Facility Operation

Capacity	1 MW
Annual Energy (GWh)	7.008
CO_2/GWh	61

* Source: Electric Power Research Institute
† Concrete CO_2 coefficient is .50313 tons per ton of concrete, based on process emissions alone.
‡ Steel CO_2 coefficient is 2.314, based on energy input to steel. CO_2 coefficients for other materials not available..

Carbon Dioxide Displacement: Hydrothermal Power Generation, Flash-Steam

Technology Description:
In flash steam systems the Liquid resource is allowed to flash to steam as it comes to the surface under reduced pressure: the steam separated from the remaining liquid is fed to the turbine, usually used with fluid temperatures of over 200°C. Closed-cycle flash systems are being developed which would basically eliminate emissions during operation. Field Development and well drilling occurs at every stage of project development.

Current Use:
U.S. capacity is nearly 2,575 MWe, or enough electricity to serve over two million power customers with an annual savings in oil of over 23 million barrels. Worldwide, geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.

Projected Use*:
Domestic and worldwide use at present and in future years are:

	1986 Domestic	1986 World	2010 Domestic	2010 World
MWe	2,575	5,000	4,953-6,735	9,123

Total CO_2 Contribution = 51.26 tons/GWh

Resource Extraction	
Fuel	Steam
CO_2 Contributors:	
Well Drilling	.2 tons/GWh
CO_2/GWh	0.2

Facility Construction (Tons)	
Concrete†	308.61
Steel‡	28
CO_2/GWh	1.05

Facility Operation	
Capacity	1 MW
Annual Energy (GWh)	7.008
CO_2/GWh	50

* Source: Electric Power Research Institute
† Concrete CO_2 coefficient is .50313 tons per ton of concrete, based on process emissions alone.
‡ Steel CO_2 coefficient is 2.314, based on energy input to steel. CO_2 coefficients for other materials not available..

Carbon Dioxide Displacement: Hydrothermal Power Generation, Binary

Technology Description:
Binary technology uses Geothermal heat to vaporize a secondary fluid which operates the turbine; it represents the state-of-the-art for use of moderate- temperature fluids. Field Development and well drilling occurs at every stage of project development.

Current Use:
U.S. capacity is nearly 2,575 MWe, or enough electricity to serve over two million power customers with an annual savings in oil of over 23 million barrels. Worldwide, geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.

Projected Use*:
Domestic and worldwide use at present and in future years are:

	1986 Domestic	1986 World	2010 Domestic	2010 World
MWe	2,575	5,000	4,953-6,735	9,123

Total CO_2 Contribution = 1.25 tons/GWh

Resource Extraction	
Fuel	Steam
CO_2 Contributors:	
Well Drilling	.2 tons/GWh
CO_2/GWh	0.2

Facility Construction (Tons)	
Concrete†	308.61
Steel‡	28
CO_2/GWh	1.05

Facility Operation	
Capacity	1 MW
Annual Energy (GWh)	7.008
CO_2/GWh	0

* Source: Electric Power Research Institute

† Concrete CO_2 coefficient is .50313 tons per ton of concrete, based on process emissions alone.

‡ Steel CO_2 coefficient is 2.314, based on energy input to steel. CO_2 coefficients for other materials not available..

Carbon Dioxide Displacement: Geopressured Power Generation

Technology Description:
Geopressured brines contain three forms of energy: thermal, chemical (methane), and mechanical. The energy is extracted through the use of modified high pressure oil and gas rotary drilling equipment and gas-liquid separators to extract the methane from the brines. A power generation experiment is planned that will utilize both the heat and methane in a hybrid binary plant.

Current Use:
There is no current commercial use of geopressured brines.

Projected Use:
Industry cannot evaluate the economics of geopressured geothermal utilization until more accurate means to predict reservoir behavior and longevity are available.

Total CO_2 Contribution = 207.45 tons/Gwh

Resource Extraction

Fuels: Steam, Methane

CO_2 Contributors:
Well Drilling 0.5 tons/GWh

CO_2/GWh 0.5

Facility Construction (Tons)

Concrete†	308.61
Steel‡	28
CO_2/GWh	1.05

Facility Operation*

Capacity	1 MW
Annual Energy (GWh)	7.008
CO_2/GWh	206.35

* The CO2 balance for flash steam plants was derived from a 12 production well concept developed in Ref. 1. (See attached narrative.) The declining flows and energy production for the 19-year projected life of a reservoir were averaged over the 19 years. The estimated amount of CO2 and methane released to the atmosphere during flashing is based on general literature on solubilities. There would be no emissions during operation of a binary system. The produced methane was assumed to be burned for power generation.

† Concrete CO2 coefficient is .50313 tons per ton of concrete, based on process emissions alone.

‡ Steel CO2 coefficient is 2.314, based on energy input to steel. CO2 coefficients for other materials not available.

Carbon Dioxide Displacement: Hot Dry Rock Power Generation

Technology Description:
To obtain energy from hot dry rock, a hydraulically fractured reservoir is created. Water is injected into the reservoir through one well, absorbing heat while flowing through the fractures, and bringing the heat to the surface in a production well. The heat may be used to generate power using either flash or binary technology. Where economic, the heat may also be used in direct applications.

Current Use:
There is no current commercial use of hot dry rock.

Projected Use:
Industry is beginning to evaluate the economic feasibility of commercial hot dry rock development.

Total CO_2 Contribution = 9.1 tons/GWh

Resource Extraction		Facility Construction* (Tons)		Facility Operation	
CO_2 Contributors:		Concrete†	308.61	Capacity	1 MW
Well		Steel‡	7.008	Annual	
Drilling .05 tons/GWh				Energy (GWh)	7.008
CO_2/GWh	0.05	CO_2/GWh	1.05	CO_2/GWh	8.0

* Estimates of the CO_2 contribution of the manufacture of power plant equipment were based on the assumption that the geothermal plant would use the same amount of materials as a similar size coal plant.

† Concrete CO_2 coefficient is .50313 tons per ton of concrete, based on process emissions alone.

‡ Steel CO_2 coefficient is 2.314, based on energy input to steel. CO_2 coefficients for other materials not available..

GEOTHERMAL
SOURCE
ESTIMATES

GLOBAL WARMING

CARBON DIOXIDE DISPLACEMENT

GEOTHERMAL TECHNOLOGY

TECHNOLOGY DESCRIPTION

Energy from geothermal systems is provided by steam or hot water produced from underground reservoirs located in volcanic regions. Since the geothermal fluids are produced in volcanic settings, and at times are contained in carbonate reservoirs, they all contain carbon dioxide gas. However, not all geothermal technologies provide pathways for CO_2 to reach the atmosphere. These technologies and their limited contribution to ambient levels of this gas are discussed below.

Electric Power Generation

All commercial geothermal power is generated today with hydrothermal fluids. The technologies employed vary with the form in which hydrothermal energy occurs -- vapor-dominated or liquid-dominated -- and/or its temperature. Dry steam, a relatively rare occurrence, is fed to the generating system just as it comes from the earth; conventional turbine-generator equipment is employed. In plants designed to use liquid-dominated, or hot water, reservoirs, the liquid is allowed to flash to steam as it reaches the surface under reduced pressure; the steam and remaining liquid are separated; and the steam then enters the turbine. This is known as flash steam technology. Most flash plants in operation or under design today optimize energy extraction from the hot fluid by utilizing a dual flash design -- i.e., steam is produced at two pressure levels (high/low) from the incoming brine.

Generally, flash steam technology is not economic at temperatures below 200°C. The state-of-the-art technology for generating power with brines in the 150-200°C range is binary cycle technology. Some very small binary units operate successfully at even lower temperatures. In this type system, the heat from the geothermal fluid is used to vaporize a high-pressure fluid such as a hydrocarbon. The vaporized working fluid is expanded through a turbine, condensed, and repressurized in a closed loop.

Prior to construction of geothermal power plants, drilling of geothermal wells occurs at several stages of development -- exploration, reservoir confirmation, reservoir engineering, and production to serve the plant. Injection wells are also drilled in which to dispose of the spent fluids. The size of the well field may range from one production well and one injection well for small wellhead binary units to multiple wells for large plants. New production and injection wells may be needed during the life of the plant. The size and complexity of fluid gathering lines will also vary with plant capacity.

Direct Use

Hydrothermal fluids are also used in a number of direct heat applications. These include district heating systems, space heating and cooling, commercial greenhouses and fish farms, and industrial processing. The technology for such uses is for the most part drawn from conventional hot water and steam handling equipment employed in these applications using heat from sources other than geothermal. For example, a geothermal district heating system will generally have the same components as a conventional system. The geothermal production field, which includes wells, pumps, and collecting mains, replaces the boiler in a conventional system. All other components, such as piping, valves, controls, and metering would be the same. The most common space heating equipment -- forced air, convection, and hydronic radiant floor or ceiling panels -- are all adaptable to geothermal energy. In Klamath Falls, Oregon, where over 400 wells are used to provide space heat to individual homes and businesses, the principal heat extraction system is a closed-loop downhole heat exchanger utilizing city water in the loop. In fish farming, heating can be accomplished using hot water bearing pipes in the growth ponds or by direct addition of suitable quality hot water in order to maintain optimum pond temperatures. Other technologies for geothermal direct applications are similarly akin to conventional technology.

The major difference is that some accommodation may have to be made to the fluid chemistry to avoid corrosion and scaling. Most of these problems are surmounted by materials selection and proper engineering. For others, heat exchangers may be needed to limit geothermal contact to a small portion of the overall system. Typically, low-temperature fluids are utilized for many direct uses which minimize corrosion and scaling problems. Frequently, sufficient heat for the intended use can be found at depths shallow enough to be reached with standard water well drilling equipment.

CURRENT USE

U.S. Use

As of October 1988, 38 liquid-dominated, or hot water, geothermal power plants are on-line or under construction. The total capacity of these plants is about 575 MWe. Twenty-eight dry steam plants are on-line or under construction at The Geysers with a total capacity of nearly 2,000 MWe.[1] Thus, total U.S. geothermal power plants account for nearly 2,575 MWe, or enough electricity to serve over two million power customers. This use accounts for an annual savings of over 23 million barrels of oil per year.

The total installed geothermal direct use capacity in the U.S. is 5.7 billion Btu/hour, or 1,700 MW_t, with an annual energy use of nearly 17,000 billion Btu/year or 4.5 million barrels of oil equivalent.[2]

Worldwide Use

Geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.[3]

At the end of 1984, the latest year for which worldwide figures are available, the installed thermal power of all geothermal direct use projects was about 7,072 MW_t. The thermal energy used was nearly 24,000 GWh, replacing an estimated 21 million barrels of oil per year.[4]

PROJECTED USE

U.S. Use

The following projections on U.S. geothermal power development were made by the Electric Power Research Institute in 1987.[5] The survey is based on the responses of 26 electric utilities which provided data on installed geothermal capacity at the end of 1986, firm expectations of capacity to be on-line by the end of 1987, and estimates of future geothermal power plant capacity for the periods to 1990, 1995, and 2005 at the three levels of confidence shown in the table.

	Capacity (MWe) by Year					
	1986 Actual	1987 Firm	1990 Est.	1995 Est.	2000 Est.	2005 Est.
Announced						
NoWest	0	0	0	0	0	0
SoWest	42	93	93	213	249	269
Cal-Ha	2070	2111	2628	2845	2876	2876
Gulf	0	0	0	0	0	0
Total	2112	2204	2721	3058	3125	3145
Probable						
NoWest			0	10	30	65
SoWest			113	258	344	464
Cal-Ha			2710	3154	3869	4419
Gulf			1	1	1	5
Total			2824	3423	4244	4953
Possible						
NoWest			0	15	65	140
SoWest			113	258	377	596
Cal-Ha			2960	3536	4864	5979
Gulf			1	5	10	20
Total			3074	3814	5316	6735

It is possible that the results of EPRI's 1988 survey will be known before this document is finalized, and projections to 2010 will be available.

All earlier projections on geothermal direct use in the U.S. are now outdated by the results of a 1988 survey of direct use projects conducted by the Geo-Heat Center at Oregon Institute of Technology.[2] The survey found that the use of groundwater and earth-coupled heat pumps has grown beyond expectations -- and was expected to increase by another 50 percent in 1988 over 1987 -- and that use of geothermal energy for aquaculture operations and swimming pools and spas is much larger than previously reported. Thus, new projections are now needed to provide a basis for realistic expectations.

Worldwide Use

The most recent and authoritative projections on worldwide use of geothermal power were made in April 1987.[6] They are as follows:

	MWe
1986 -	4,733
1990 -	6,166
1995 -	7,870
2000 -	9,123

So far as is known, no projections on increases in worldwide geothermal direct use projects exist. These uses are diverse, many times small, and are not represented by major trade interests or international agencies.

RESOURCE ACQUISITION

Acquisition of the geothermal resource involves several phases of field development. Exploratory activities such as surface geophysical surveys, numerical modeling, and geologic mapping produce no CO_2 emissions. There is also little likelihood that measurable emissions would result from drilling of temperature gradient holes. However, flow testing of "wildcat" wells and step-out wells used to identify and confirm the resource provides opportunity for some of the entrained CO_2 to break out of solution and escape to the atmosphere. For a 50 MWe plant, about six wells might be drilled during the exploration and confirmation phases. The ambient concentrations of CO_2 would vary from reservoir to reservoir and from one site to another at the same reservoir due to the variable nature of the chemical composition of geothermal fluids. The mode emission level of CO_2 resulting from resource acquisition (exploration and confirmation) for geothermal power plants is estimated in Table 1. Direct use applications are limited in extent by cost and do not involve these phases.

TABLE 1

CO_2 Contribution of Geothermal Power Plants[1]
(lbs $CO_2/MW_e hr$)

	Steam	Flash	Binary
Resource Acquisition	0.6	0.42	10
Facility Construction[2]	1.2	0.84	20
Facility Operation	122.0	100	0
Fuel Utilization	0.0	0.0	0
Total	124	101	30

(1) Based on a $50MW_e$ plant, 30-year life.
(2) Does not include CO_2 contribution to building the turbo-generator systems. Contribution would be the same as that for fossil and nuclear power plants.

TABLE 2

CO_2 Contribution of Geothermal
Direct Heat Applications
(lbs CO_2/MW_t)

Resource Acquisition	0.0
Facility Construction	0.1
Facility Operation	0.1
Fuel Utilization	0.0
Total	0.2

FACILITY CONSTRUCTION AND EQUIPMENT MANUFACTURE

During the power plant construction phase, the geothermal field is developed with about 12 production wells for a 50 MWe plant and one or more injection wells. Fluid gathering lines are installed, and roads are completed. Major CO_2 sources in the field include the fuel used to drill wells and fluid emissions during well testing. Construction of the power plant involves a turbine/generator and, depending on the technology to be used, flash tanks or heat exchangers. Information on the energy used in the manufacture and installation of this equipment and the resulting CO_2 emissions is not readily available. The estimated CO_2 contribution from development of the field is shown in Table 1.

The construction phase for direct applications consists of one or two shallow wells with nominal plumbing for distribution and injection of spent fluid. The estimated CO_2 contribution is shown in Table 2.

FACILITY OPERATION

Power Generation

The levels of CO_2 emissions generated by geothermal power plants not only range with the chemistry of the resource, but with the technology used as well. Although the dry steam plants at The Geysers are all equipped with systems to control emissions of another noncondensible gas, hydrogen sulfide, this equipment does not treat or contain CO_2 emissions, and it is estimated that all of the gas present enters the atmosphere.[7] However, the percent by weight of constituent CO_2 averages less than one percent in Geysers wells,[8] and available data indicate that the emission rates range from two to four percent of those of an equivalent western coal plant.

By its very nature, flash plant technology generates CO_2 emissions because the gas is liberated during the pressure reduction that permits flashing.

Since there are to date no air pollution control standards limiting CO_2 emissions, the gas present is typically removed from the condenser by air ejectors and vented to the atmosphere. It is reported that resource conditions in one new flash plant permits the noncondensible gas to remain entrained in the spent brine which is injected back to the subsurface. In this case, no CO_2 is emitted to the atmosphere. The mode emission rate for typical flash plants is estimated in Table 1.

No emissions of CO_2 or any other gases occur during the operation of geothermal binary plants since they are closed systems. In addition, the use of well pumps prevents flashing in the wells, keeping the fluid in the liquid state.

Direct Use

There is little potential for CO_2 emissions from direct heat applications of geothermal resources for several reasons. First, in most direct heat applications, the fluid is brought to the surface in the liquid phase with no flashing and no gaseous emissions. Direct heat projects are small, requiring fewer wells per development than power generation, at shallow depths and lower temperatures. Fluids of this character are usually much more benign in chemical composition than high temperature resources found at great depths under massive rock structures. However, should gaseous constituents be present, problems can be virtually eliminated for direct heat applications by using closed loop systems that prevent emissions. For the estimated mode CO_2 emission rate, see Table 2.

FUEL UTILIZATION

This topic is not applicable to geothermal operations since the hydrothermal brines are the fuels.

REFERENCES

1. Geothermal Progress Monitor, Issue No. 11, Department of Energy, In Publication.

2. Geothermal Direct Use Developments in the United States, Geo-Heat Center, Oregon Institute of Technology, Aug. 1988.

3. DiPippo, R., "Worldwide Geothermal Power Development," Proceedings: Ninth Annual Geothermal and Second IIE-EPRI Geothermal Conference and Workshop, Vol. 2, Aug. 1987.

4. Gudmundsson, J.S., "Direct Uses of Geothermal Energy in 1984," 1985 Symposium on Geothermal Energy, International Volume, Geothermal Resources Council Transactions, 1985.

5. Kruger, P., "1987 EPRI Survey of Geothermal Electric Utilities," Proceedings: Tenth Annual Geothermal Conference and Workshop, Feb. 1987.

6. DiPippo, R., "Geothermal Electric Power: Where Are We Headed?" Geothermal Report, April 1, 1987.

7. Personal Communication, Vasel Roberts, Electric Power Research Institute, Oct. 12, 1988.

8. Kestin, J., Ed., Sourcebook on the Production of Electricity from Geothermal Energy, Department of Energy, March 1980.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Hydrothermal Power Generation

Technology Description:

Dry Steam - Steam is used in a conventional turbine as it comes from the earth. Flash Steam - Liquid resource is allowed to flash to steam as it comes to the surface under reduced pressure; steam separated from remaining liquid is fed to turbine; usually used with fluid temperatures of over 200°C. Binary - Geothermal heat vaporizes a secondary fluid which operates turbine; state-of-the-art for moderate-temperature fluids. Field Development - Well drilling occurs at every stage of project development.

Current Use:

U.S. capacity is nearly 2,575 MWe, or enough electricity to serve over two million power customers with an annual savings in oil of over 23 million barrels. Worldwide, geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.

Projected Use:

U.S. Growth Projections (Electric Power Research Institute)

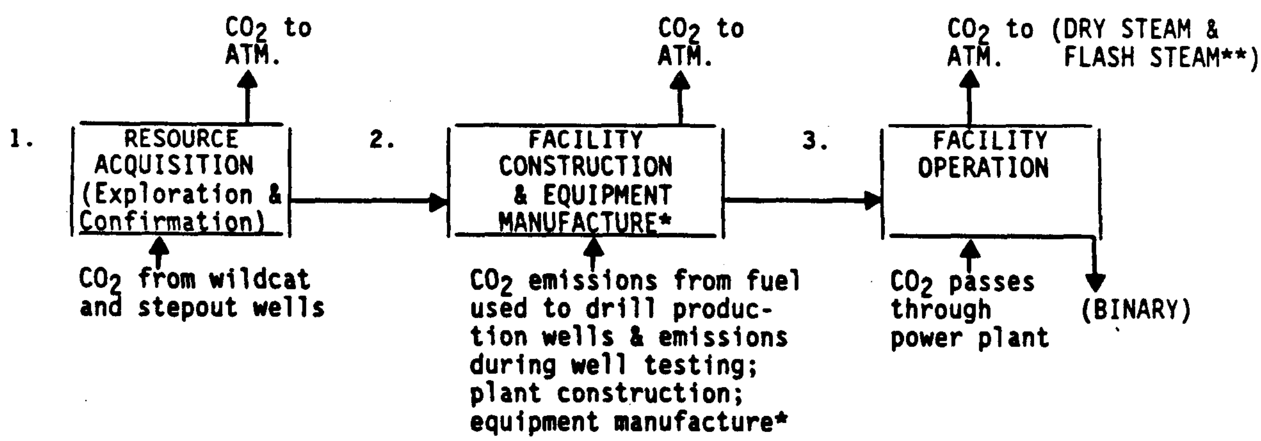
Probable 4,953 MWe
(Based on successful demonstration of technology for economic utilization of moderate-temperature hydrothermal resources.)

Possible 6,735 MWe
(Based additionally on anticipated growth of electric power demand and a favorable regulatory climate.)

Worldwide Growth Projections (DiPippo, April 1987)

1986 - 4,733 MWe 1990 - 6,166 MWe 1995 - 7,780 2005 - 9,123

HYDROTHERMAL POWER GENERATION



CO_2 BALANCE***
(lbs CO_2/MWeh)

Dry Steam

	INPUTS	OUTPUTS
1.	0	0.6
2.	0	1.2
3.	0	122.0

Flash Steam

	INPUTS	OUTPUTS
1.	0	0.42
2.	0	0.84
3.	0	100.0

Binary

	INPUTS	OUTPUTS
1.	0	10
2.	0	20
3.	0	0

* Estimates of the CO_2 contribution of the manufacture of power plant equipment are in preparation.

** If flash steam plants reinject noncondensible gases, there will be no atmospheric emissions of CO_2.

***Based on a 50 MWe plant, 30 year life.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Hydrothermal Direct Use

Technology Description:

The direct uses of hydrothermal fluids include district heating systems, space heating and cooling, commercial greenhouses and fish farms, and industrial processing. The technology for such uses is for the most part drawn from conventional hot water and steam handling equipment employed in these applications using heat from sources other than geothermal.

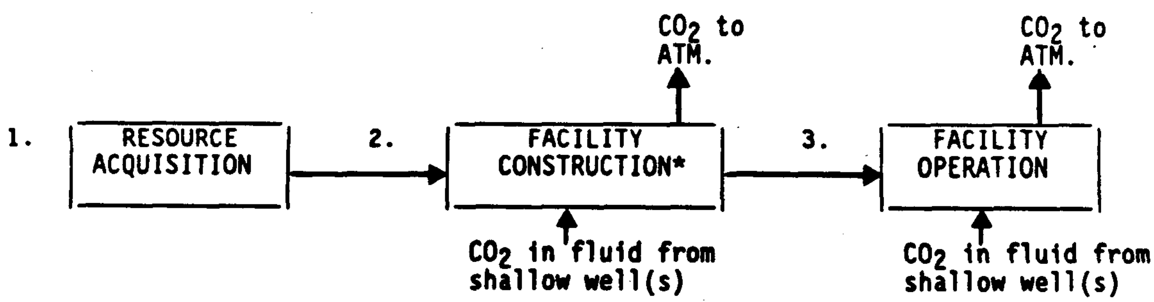
Current Use:

The total installed geothermal direct use capacity in the U.S. is 5.7 billion Btu/hour, or 1,700 MW_t, with an annual energy use of nearly 17,000 billion Btu/year or 4.5 million barrels of oil equivalent. At the end of 1984, the latest year for which worldwide figures are available, the installed thermal power of all geothermal direct use projects was about 7,072 MW_t. The thermal energy used was nearly 24,000 GWh, replacing an estimated 21 million barrels of oil per year.

Projected Use:

A new 1988 survey of direct use projects in the U.S. conducted by the Geo-Heat Center at Oregon Institute of Technology has rendered all existing projections on growth in this industry obsolete. The survey found that the use of groundwater and earth-coupled heat pumps has grown beyond expectations -- and was expected to increase by another 50 percent in 1988 over 1987 -- and that use of geothermal energy for aquaculture operations and swimming pools and spas is much larger than previously reported. Thus, new projections are needed to provide a basis for realistic expectations. So far as is known, no projections on increases in worldwide geothermal direct use projects exist. These uses are diverse, commonly small, and are not represented by major trade interests or international agencies.

HYDROTHERMAL DIRECT USE



CO_2 BALANCE
(POUNDS CO_2/MW_t)

	INPUTS	OUTPUTS
1.	0	0
2.	0	0.1
3.	0	0.1

* Direct uses of geothermal energy involve equipment of many types, sizes, and materials, ranging from a small heat exchanger for residential use to district heating systems serving multiple public/private buildings to large industrial process use. It is not possible to derive an average CO_2 contribution of the manufacture of such widely varying equipment. It would be the same, however, as for similar equipment used in non-geothermal projects.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Hot Dry Rock Power Generation

Technology Description:

To obtain energy from hot dry rock, a hydraulically fractured reservoir is created. Water is injected into the reservoir through one well, it absorbs heat while flowing through the fractures, and brings the heat to the surface in a production well. The heat may be used to generate power using either flash or binary technology. Where economic, the heat may also be used in direct applications.

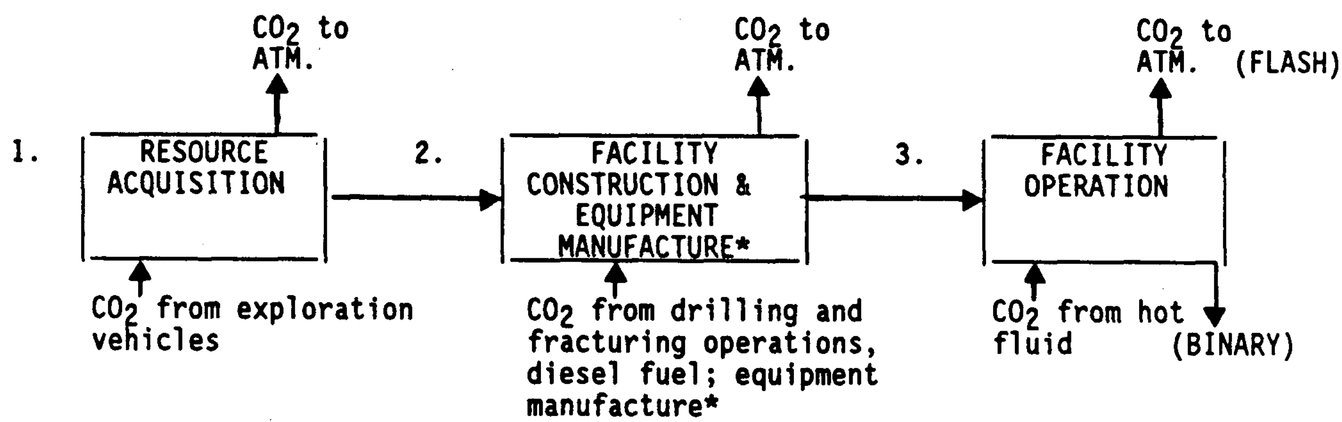
Current Use:

There is no current commercial use of hot dry rock.

Projected Use:

Industry is beginning to evaluate the economic feasibility of commercial hot dry rock development.

HOT DRY ROCK POWER GENERATION



CO_2 BALANCE
(lbs CO_2/MWeh)

Flash Steam

	INPUTS	OUTPUTS
1.	0	0.1
2.	0	1.0
3.	0	16.0**

Binary

	INPUTS	OUTPUTS
1.	0	0.1
2.	0	1.0
3.	0	0

* Estimates of the CO_2 contribution of the manufacture of power plant equipment are in preparation.
** Based on hypothetical 50 MWe dual flash plant.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Magma Power Generation

Technology Description:

It is currently envisioned that magma bodies can be reached with experimental drilling systems which will chill, solidify, and fracture magma. A working fluid will be circulated through the fractures for direct contact heat transfer. A heat transfer fluid will be circulated through a closed loop from the high-temperature magma exchanger to a surface exchanger and back down the well. The use of binary technology is planned for the first experimental use of magma for power generation.

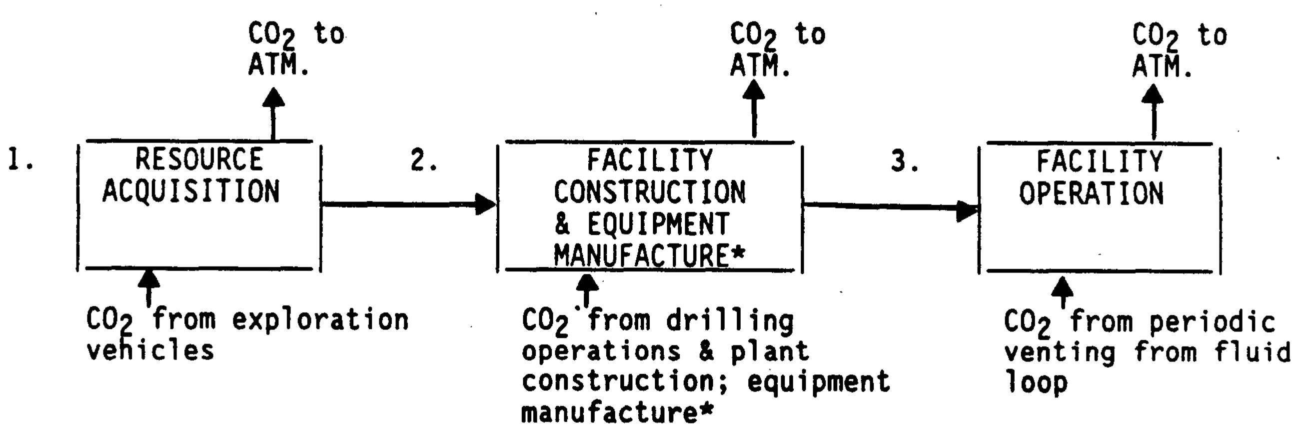
Current Use:

There is no current commercial use of magma energy.

Projected Use:

The technology for extracting energy from magma is in its infancy. The current effort is to evaluate the feasibility of the technology, and power systems are not yet in design.

MAGMA POWER GENERATION



CO_2 BALANCE
(lbs CO_2/MWeh)

	INPUTS	OUTPUTS
1.	0	<0.1
2.	0	5.0
3.	0	17.0

* Estimates of the CO_2 contribution of the manufacture of power plant equipment are in preparation.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Geopressured Power Generation

Technology Description:

Geopressured brines contain three forms of energy -- thermal, chemical (methane), and mechanical. The energy is extracted through the use of modified high pressure oil and gas rotary drilling equipment and gas-liquid separators to extract the methane from the brines. A power generation experiment is planned that will utilize both the heat and methane in a hybrid binary plant.

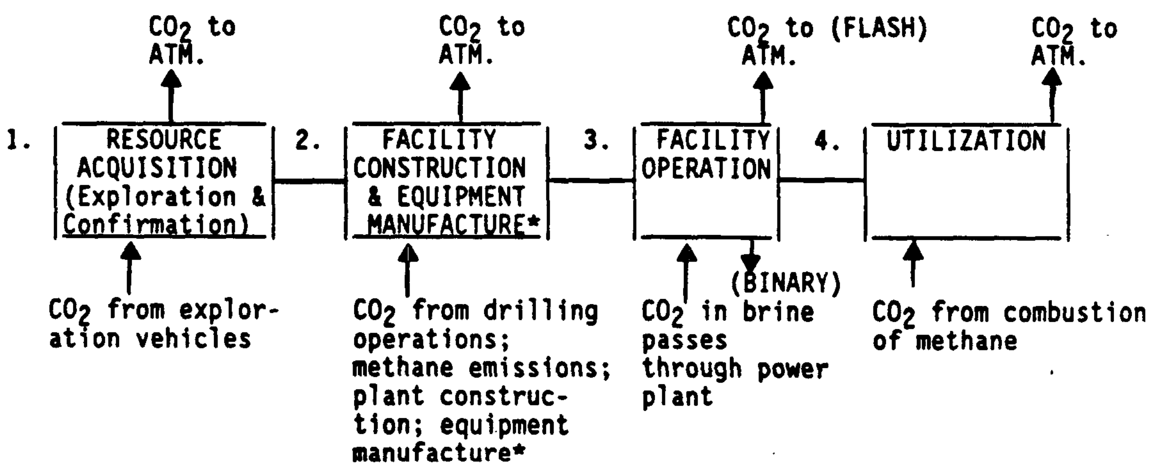
Current Use:

There is no current commercial use of geopressured brines.

Projected Use:

Industry cannot evaluate the economics of geopressured geothermal utilization until more accurate means to predict reservoir behavior and longevity are available.

GEOPRESSURED POWER GENERATION



CO_2 BALANCE***
(lbs CO_2/MWeh)

Flash Steam**

	INPUTS	OUTPUTS
1.	0	<0.1
2.	0	16.0
3.	0	0.7

Binary**

	INPUTS	OUTPUTS
1.	0	<0.1
2.	0	16.0
3.	0	0

Gas Combustion**

	INPUTS	OUTPUTS
4.	0	410

* Estimates of the CO_2 contribution of the manufacture of power plant equipment are in preparation.

** The CO_2 balance for flash steam plants was derived from a 12 production well concept developed in Ref. 1. (See attached narrative.) The declining flows and energy production for the 19-year projected life of a reservoir were averaged over the 19 years. The estimated amount of CO_2 and methane released to the atmosphere during flashing is based on general literature on solubilities. There would be no emissions during operation of a binary system. The produced methane was assumed to be burned for power generation.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Hydrothermal Power Generation

TECHNOLOGY DESCRIPTION

Energy from hydrothermal geothermal systems is provided by steam or hot water produced from underground reservoirs located in volcanic regions. Since the geothermal fluids are produced in volcanic settings, and at times are contained in carbonate reservoirs, they all contain carbon dioxide gas. However, not all geothermal technologies in commercial use provide pathways for CO_2 to reach the atmosphere. These technologies and their limited contribution to ambient levels of this gas are discussed below.

Other forms of geothermal energy include geopressured brines containing dissolved methane; hot dry rock from which heat can be extracted with a man-made reservoir for circulating fluids; and magma, or molten rock. The technologies for exploiting these forms of the resource are under development. By technical definition, the systems for extracting heat from hot dry rock and magma are closed systems, providing no avenue for escape of CO_2 emissions to the atmosphere.

Electric Power Generation

The technologies employed for generating power with hydrothermal fluids vary with the form in which the resource occurs -- vapor-dominated or liquid-dominated -- and/or its temperature. Dry steam, a relatively rare occurrence, is fed to the generating system just as it comes from the earth; conventional turbine-generator equipment is employed. In plants designed to use liquid-dominated, or hot water, reservoirs, the liquid is allowed to flash to steam as it reaches the surface under reduced pressure; the steam and remaining liquid are separated; and the steam then enters the turbine. This is known as flash steam technology. Most flash plants in operation or under design today optimize energy extraction from the hot fluid by utilizing a dual flash design -- i.e., steam is produced at two pressure levels (high/low) from the incoming brine.

Generally, flash steam technology is not economic at temperatures below 200°C. The state-of-the-art technology for generating power with brines in the 150-200°C range is binary cycle technology. Some very small binary units operate successfully at even lower temperatures. In this type system, the heat from the geothermal fluid is used to vaporize a high-pressure fluid such as a hydrocarbon. The vaporized working fluid is expanded through a turbine, condensed, and repressurized in a closed loop.

Prior to construction of geothermal power plants, drilling of geothermal wells occurs at several stages of development -- exploration, reservoir confirmation, reservoir engineering, and production to serve the plant. Injection wells are also drilled in which to dispose of the spent fluids. The size of the well field may range from one production well and one injection well for small wellhead binary units to multiple wells for large plants. New production and injection wells may be needed during the life of the plant. The size and complexity of the fluid gathering system will also vary with plant capacity.

CURRENT USE

U.S. Use

As of October 1988, 38 liquid-dominated, or hot water, geothermal power plants are on-line or under construction. The total capacity of these plants is about 575 MWe. Twenty-eight dry steam plants are on-line or under construction at The Geysers with a total capacity of nearly 2,000 MWe.[1] Thus, total U.S. geothermal power plants account for nearly 2,575 MWe, or enough electricity to serve over two million power customers. This use accounts for an annual savings of over 23 million barrels of oil per year.

Worldwide Use

Geothermal power plants are in operation in 18 countries with a total capacity of about 5,000 MWe.[2]

PROJECTED USE

U.S. Use

The following projections on U.S. geothermal power development were made by the Electric Power Research Institute in 1987.[3] The survey is based on the responses of 26 electric utilities which provided data on installed geothermal capacity at the end of 1986, firm expectations of capacity to be on-line by the end of 1987, and estimates of future geothermal power plant capacity for the periods to 1990, 1995, and 2005 at the three levels of confidence shown in the table.

	Capacity (MWe) by Year					
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Worldwide Use

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	MWe
1986 -	4,733
1990 -	6,166
1995 -	7,870
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CO_2 CONTRIBUTION

1. Resource Acquisition

Acquisition of the geothermal resource involves several phases of field development. Exploratory activities such as surface geophysical surveys, numerical modeling, and geologic mapping produce no CO_2 emissions. There is also little likelihood that measurable emissions would result from drilling of temperature gradient holes. However, flow testing of "wildcat" wells and step-out wells used to identify and confirm the resource provides opportunity for some of the entrained CO_2 to break out of solution and escape to the atmosphere. For a 50 MWe plant, about six wells might be drilled during the exploration and confirmation phases. The ambient concentrations of CO_2 would vary from reservoir to reservoir and from one site to another at the same reservoir due to the variable nature of the chemical composition of geothermal fluids. The modal emission level of CO_2 resulting from resource acquisition (exploration and confirmation) for geothermal power plants is estimated in Table 1.

2. <u>Facility Construction and Equipment Manufacture</u>

During the power plant construction phase, the geothermal field is developed with about 12 production wells for a 50 MWe plant and one or more injection wells. Fluid gathering lines are installed, and roads are completed. Major CO_2 sources in the field include the fuel used to drill wells and emissions during well testing. Construction of the power plant involves a turbine/generator and, depending on the technology to be used, flash tanks or heat exchangers. Estimates of the CO_2 contribution of equipment manufacture are in preparation. The estimated CO_2 contribution from development of the field is shown in Table 1.

TABLE 1

CO_2 Contribution of Geothermal Power Plants[1]
(lbs $CO2/MW_e/h$)

	Steam	Flash	Binary
Resource Acquisition	0.6	0.42	10
Facility Construction[2]	1.2	0.84	20
Facility Operation	122.0	100	0
Fuel Utilization	0.0	0.0	0
Total	124	101	30

(1) Based on a 50MWe plant, 30-year life.
(2) Does not include CO_2 contribution to building the turbo-generator systems. Contribution would be the same as that for fossil and nuclear power plants.

3. Facility Operation

Power Generation

The levels of CO_2 emissions generated by geothermal power plants not only range with the chemistry of the resource, but with the technology used as well. Although the dry steam plants at The Geysers are all equipped with systems to control emissions of another noncondensible gas, hydrogen sulfide, this equipment does not treat or contain CO_2 emissions, and it is estimated that all of the gas present enters the atmosphere.[5] However, the percent by weight of constituent CO_2 averages less than one percent in Geysers wells,[6] and available data indicate that the emission rates range from two to four percent of those of an equivalent western coal plant.

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No emissions of CO_2 or any other gases occur during the operation of geothermal binary plants since they are closed systems. In addition, the use of well pumps prevents flashing in the wells, keeping the fluid in the liquid state.

4. Fuel Utilization

This topic is not applicable to geothermal operations since the hydrothermal brines are the fuels.

OTHER IMPACTS

Compatibility with Existing Infrastructure

With California taking the lead, strict environmental regulations have been placed on the geothermal industry, but not such rigid ones as to stifle development. The industry works with the cognizant authorities from the early stages of each development, and a good relationship appears to exist in each of the major areas of development. If the federal government or the states move to restrict CO_2 emissions from all sources, the geothermal industry appears to be in a favorable position, both technically and in its relationship with the regulating agencies, to be in the forefront of compliance.

National Security

Geothermal energy provides a baseload alternative to fossil-fired power plants along with hydropower and nuclear. In areas where geothermal resources are abundant, new hydropower sites have become limited. And in some of the same areas, nuclear plants have encountered opposition on various grounds. Thus, if a national consensus develops that CO_2 emissions must be reduced drastically, geothermal power plants using an indigeneous fuel will be the prime candidate for ensuring continued energy security in some very heavily populated areas.

<u>PRIMARY REFERENCES</u>

1. Geothermal Progress Monitor, Issue No. 11, Department of Energy, In Publication.

2. DiPippo, R., "Worldwide Geothermal Power Development," Proceedings: Ninth Annual Geothermal and Second IIE-EPRI Geothermal Conference and Workshop, Vol. 2, Aug. 1987.

3. Kruger, P., "1987 EPRI Survey of Geothermal Electric Utilities," Proceedings: Tenth Annual Geothermal Conference and Workshop, Feb. 1987.

4. DiPippo, R., "Geothermal Electric Power: Where Are We Headed?" Geothermal Report, April 1, 1987.

5. Personal Communication, Vasel Roberts, Electric Power Research Institute, Oct. 12, 1988.

6. Kestin, J., Ed., <u>Sourcebook on the Production of Electricity from Geothermal Energy</u>, Department of Energy, March 1980.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Hydrothermal Direct Use

TECHNOLOGY DESCRIPTION

All direct uses of geothermal heat today employ hydrothermal fluids. The technology for recovering energy for this purpose from geopressured brines, hot dry rock, or magma is not yet economically available.

Energy from hydrothermal geothermal systems is provided by steam or hot water produced from underground reservoirs. Since the fluids are produced in volcanic settings, and at times are contained in carbonate reservoirs, they all contain carbon dioxide gas. However, not all geothermal technologies in commercial use provide pathways for CO_2 to reach the atmosphere. This is particularly true of direct applications of geothermal heat for several reasons as discussed below.

The direct use of hydrothermal fluids include district heating systems, space heating and cooling, commercial greenhouses and fish farms, and industrial processing. The technology for such uses is for the most part drawn from conventional hot water and steam handling equipment employed in these applications using heat from sources other than geothermal. For example, a geothermal district heating system will generally have the same components as a conventional system. The geothermal production field, which includes wells, pumps, and collecting mains, replaces the boiler in a conventional system. All other components, such as piping, valves, controls, and metering would be the same. The most common space heating equipment -- forced air, convection, and hydronic radiant floor or ceiling panels -- are all adaptable to geothermal energy. In fish farming, heating can be accomplished using hot water bearing pipes in the growth ponds or by direct addition of suitable quality hot water in order to maintain optimum pond temperatures. Other technologies for geothermal direct applications are similarly akin to conventional technology.

The major difference is that some accommodation may have to be made to the fluid chemistry to avoid corrosion and scaling. Most of these problems are surmounted by materials selection and proper engineering. For others, heat exchangers may be needed to limit geothermal contact to a small portion of the overall system. Typically, the low-temperature fluids utilized for many direct uses are chemically benign and minimize corrosion and scaling problems. Frequently, sufficient heat for the intended use can be found at depths shallow enough to be reached with standard water well drilling equipment.

CURRENT USE

U.S. Use

The total installed geothermal direct use capacity in the U.S. is 5.7 billion Btu/hour, or 1,700 MW_t, with an annual energy use of nearly 17,000 billion Btu/year or 4.5 million barrels of oil equivalent.[1]

Worldwide Use

At the end of 1984, the latest year for which worldwide figures are available, the installed thermal power of all geothermal direct use projects was about 7,072 MW_t. The thermal energy used was nearly 24,000 GWh, replacing an estimated 21 million barrels of oil per year.[2]

PROJECTED USE

U.S. Use

All earlier projections on geothermal direct use in the U.S. are now outdated by the results of a 1988 survey of direct use projects conducted by the Geo-Heat Center at Oregon Institute of Technology.[1] The survey found that the use of groundwater and earth-coupled heat pumps has grown beyond expectations -- and was expected to increase by another 50 percent in 1988 over 1987 -- and that use of geothermal energy for aquaculture operations and swimming pools and spas is much larger than previously reported. Thus, new projections are now needed to provide a basis for realistic expectations.

Worldwide Use

So far as is known, no projections on increases in worldwide geothermal direct use projects exist. These uses are diverse, many times small, and are not represented by major trade interests or international agencies.

CO_2 CONTRIBUTION

1. Resource Acquisition

Extensive exploration and confirmation are typically not necessary to develop the low temperature resources used in direct use applications, and the cost of these phases would severely curtail such uses. Thus, no CO_2 contribution is anticipated at these stages of development.

2. Facility Construction and Equipment Manufacture

The construction phase for direct applications consists of one or two shallow wells with nominal plumbing for distribution and injection of spent fluid. The estimated CO_2 contribution is shown in Table 1. The CO_2 contribution of the manufacture of the wide range of equipment used the various direct heat applications is not included; the contribution would be the same as for equipment for similar non-geothermal uses.

TABLE 1

CO_2 Contribution of Geothermal
Direct Heat Applications
(lbs CO_2/MW_t)

Resource Acquisition	0.0
Facility Construction	0.1
Facility Operation	0.1
Fuel Utilization	0.0
Total	0.2

3. Facility Operation

Direct Use

There is little potential for CO_2 emissions from direct heat applications of geothermal resources for several reasons. First, in most direct heat applications, the fluid is brought to the surface in the liquid phase with no flashing and no gaseous emissions. Direct heat projects are small, requiring fewer wells per development than power generation, at shallow depths and lower temperatures. Fluids of this character are usually much more benign in chemical composition than high temperature resources found at great depths under massive rock structures. However, should gaseous constituents be present, problems can be virtually eliminated for direct heat applications by using closed loop systems that prevent emissions. For the estimated modal CO_2 emission rate, see Table 1.

4. Fuel Utilization

This topic is not applicable to geothermal operation since the hydrothermal brines are the fuels.

OTHER IMPACTS

Compatibility with Existing Infrastructure

California has taken the lead in fostering geothermal direct use projects in the state through grants and low-cost loans. Thus, it is evident that such applications meet the environmental goals of a highly environmentally-conscious state. If the state or federal government should embark upon a broad-scale CO_2 reduction program, geothermal direct use applications would provide the needed substitute for those fuel uses that contribute much more heavily to the nation's ambient CO_2 concentrations. Many of other states could also take advantage of this alternative because the temperature of their geothermal resources is adequate for direct applications, but not power generation in all cases.

National Security

If a national consensus develops that CO_2 must be reduced drastically, geothermal energy provides an indigenous resource with which to replace fossil-burning heating systems throughout much of the U.S. This substitution would reduce the CO_2 emissions from this type source to nearly zero.

REFERENCES

1. Geothermal Direct Use Developments in the United States, Geo-Heat Center, Oregon Institute of Technology, Aug. 1988.

2. Gudmundsson, J.S., "Direct Uses of Geothermal Energy in 1984," 1985 Symposium on Geothermal Energy, International Volume, Geothermal Resources Council Transactions, 1985.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Geopressured Power Generation

TECHNOLOGY DESCRIPTION

Geopressured geothermal resources consist of water containing dissolved methane, at moderately high temperatures and at pressures higher than normal hydrostatic pressure. Geopressured resources along the Texas and Louisiana Gulf Coast are estimated to be quite large. The wells are typically 10,000 to 16,000 feet deep. Similar formations may exist elsewhere in the U.S.

The major problems in the technologies for producing geopressured brines, brine handling, and disposal of large volumes of spent brine have been resolved through the DOE R&D program. The modifications made by the program in oil and gas drilling and well completion techniques to accommodate the physical characteristics of the brines are available to industry. However, it may be that the earliest commercial use of geopressured brines may not involve a drilling phase. Wells drilled and abandoned by the oil and gas industry as unproductive of their products, but which would provide ample supplies of geopressured energy, may provide a more economic substitute.

In utilization, geopressured brines offer a unique opportunity to employ more than one form of energy in producing electricity. In an upcoming power production experiment, both the geothermal heat and the methane will be used in a hybrid binary system. The methane, separated at the wellhead, will fuel a gas turbine, and exhaust heat from the engine will be used with the brine to vaporize isobutane to drive the turbine. This type system can produce up to 15 to 20 percent more electricity over the same amount of fuel and geothermal fluid processed separately.

CURRENT USE

There is no current commercial use of geopressured energy.

PROJECTED USE

Before valid projections of industry interest can be made, more reliable methods for predicting reservoir behavior and longevity must be developed.

CO_2 CONTRIBUTION

1. Reservoir Acquisition

In the case of geopressured development, the resource acquisition phase will be concurrent with the construction phase since the resource is acquired through drilling the wells. However, some vehicular use of fossil fuel will be involved in surface exploration. It is estimated that this fuel use will contribute less than 0.1 pound CO_2 per MWe hour, gross.

2. Facility Construction and Equipment Manufacture

The geopressured field will be developed during the power plant construction phase. The estimated CO_2 contribution for this phase of development is based on 12 wells, per the scenario developed in Ref. 1. (As noted above, it is possible that well drilling will be eliminated or reduced by the use of existing oil and gas wells. No CO_2 estimates can be made at this time for such a scenario.) Power plant construction will involve site preparation, construction of structural requirements, and installation of the turbo-generator, condenser, and cooling tower, and, depending on technology to be used, heat exchangers or flash system. On the basis of a 12-well field, it is estimated that this phase will contribute about 16 pounds CO_2 per MWeh, gross. Estimates of the CO_2 contribution of equipment manufacture are in preparation.

3. Facility Operation

In binary plant operations using only the heat and mechanical energy of geopressured brines, there will be no opportunity for CO_2 emissions. The fluid will be used in heat exchange with the working fluid and go through closed pipes to disposal wells. On the basis of current knowledge, the amount of CO_2 and methane released to the atmosphere by flashing geopressured brines must be estimated based on general literature on solubilities. This estimate is about 0.7 pounds of CO_2 per MWeh, gross.

4. Utilization

Geopressured energy is the only form of geothermal energy that today produces a byproduct for separate utilization. It is assumed here that the methane produced with the brine in the 12-well scenario will be burned for power generation and will emit about 410 pounds of CO_2 per MWeh, gross. This estimate also assumes efficient scrubbing of CO_2 from the gas stream.

OTHER IMPACTS

Compatibility with Environment Requirements

It has been determined that very large quantities of spent geopressured brines can be safely injected back to the subsurface without adverse environmental effects. In addition, continuous monitoring for subsidence, seismicity, and surface water quality have detected no problems of these types in the sensitive coastal areas.

National Security

While the current costs of geopressured technology are not competitive with conventional fuels, improvements are anticipated by the 1990's. In the event of a national energy emergency, these brines could be developed to provide an indigenous source of energy. In addition, each barrel of brine produced could provide 25-40 standard cubic feet of methane (natural gas) suitable for use in any application amenable to this fuel.

PRIMARY REFERENCES

1. Southwest Research Institute, Geopressured Energy Availability, Prepared for Electric Power Research Institute, EPRI AP-1457, July 1980.

2. Taylor, R.J., Memo to Ray Fortuna, "Analysis of Geopressured Fluids," Aug. 1988.

3. Traeger, R.K., Private Communication, Sandia National Laboratories, Nov. 1988.

GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Hot Dry Rock Power Generation

TECHNOLOGY DESCRIPTION

Hot dry rock resources consist of relatively water-free hot rock at accessible depths. To obtain heat from this source, two wells are drilled with modified conventional equipment capable of high directional accuracy and connected by hydraulically created fractures. Water pumped down one well is heated as it circulates through the fractures, and is brought to the surface through the second well. The recovered heat can be used for power generation or direct applications, although cost reductions will be needed before the latter is economically feasible in many locations.

If binary technology is employed to produce power, the hot water in the production well will be kept under sufficient pressure to prevent it from boiling, its heat removed in heat exchangers, and the water returned to recirculate and recover more heat in a closed loop. A working fluid vaporized by heat exchange with the hot fluid will be used to drive the turbo-generator.

In flash steam plants, some of the circulating water will be flashed to steam and transported to the plant for use in the turbine. For this technology to be employed, an ample and economic supply of water will be needed. Some water is lost in the flashing process and make-up will be required to replenish the flow in the loop. It can be expected that if flash steam technology is used at hot dry rock reservoirs, dual flash systems will be employed since this technology requires 20 to 30 percent less water than single flash plants to produce the same amount of electricity.

In the dual flash system, steam is admitted to the turbine at two different pressures with the combined stream exhausting to a surface condenser. Excess condensate not evaporated in the cooling tower is returned to the well-field injection water storage tank for reservoir injection. The electrical system, turbine building, and auxiliary systems of the power plant are similar to those for an equal capacity power plant for other geothermal resources.

CURRENT USE

There is no current commercial use of the heat of hot dry rock in the U.S. or abroad.

PROJECTED USE

Experiments with the extraction and use of hot dry rock energy have been on-going in this country and England for a number of years. Industry is only beginning to be attracted to the technology; thus, projections as to future use are not possible at this time.

CO_2 CONTRIBUTION

1. Resource Acquisition

In the case of the hot dry rock technology, the resource acquisition phase is concurrent with the construction phase since the resource is acquired through constructing the wells and fracturing the reservoir. However, some vehicular use of fossil fuel will be involved in surface exploration and geophysical measurements. It is estimated that this fuel use will contribute 0.1 pound of CO_2 per MWeh, gross.

2. <u>Facility Construction and Equipment Manufacture</u>

Construction of a hot dry rock reservoir will involve drilling injection and production wells as well as water supply wells and construction of surface facilities such as injection, gathering, and flash systems. Power plant construction involves site preparation, construction of structural requirements, and installation of the turbo-generator, condenser, and cooling tower, and, in the case of binary technology, heat exchangers. It is estimated that this phase will contribute about 1 pound of CO_2 per MWeh, gross. As noted above, the plant components will be similar to those of other types of geothermal power plants which in turn are similar to conventional plant equipment. Estimates of CO_2 contribution of equipment manufacture are in preparation.

3. <u>Facility Operation</u>

In the case of hot dry rock binary plant operations, there will be no opportunity for CO_2 emissions. The hot water (supplied from fresh water sources) is continuously circulated -- down the injection well, through the rock, up the production well, through the plant, and down the injection well again. The water is used over and over again, and is not released to the atmosphere.

Although some CO_2 emissions will result from hot dry rock flash plant operations, the CO_2 concentration in the flashed steam is likely to be low since the alteration in the reservoir rock is expected to be weak. The estimated contribution from this source is 16 pounds of CO_2 per MWeh, gross.

4. Fuel Utilization

This topic is not applicable to hot dry rock operations since the heat of the circulated fluid is the fuel.

OTHER IMPACTS

Compatibility with Environmental Requirements

Hot dry rock installations should meet and exceed any current or anticipated environmental regulations. Estimated CO_2 emissions are only a fraction of the values expected from western coal-fired power plants. No odorous gaseous emissions would result since such operations would not tap an existing pool of underground water, potentially bringing its constituents to the surface. Fresh water of good quality would be circulated, and were it necessary to discharge any amount of water under abnormal conditions, it would meet state water quality standards.

National Security

While the current costs of hot dry rock technology are not competitive with conventional fuels, further cost reductions are anticipated by the 1990's in some high quality areas. In the event of a national energy emergency, these identified sites could be developed to provide an indigenous source of base load electricity.

PRIMARY REFERENCES

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2. Murphy, H., Private Communication, Los Alamos National Laboratory, Nov. 1988.

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GLOBAL WARMING
Carbon Dioxide Displacement

Geothermal Energy
Magma Power Generation

TECHNOLOGY DESCRIPTION

Magma resources consist of heat contained in molten or partially molten rock at accessible depths in the earth's crust. The accessible depths are currently believed to be between 10,000 and 30,000 feet. Temperatures are on the order of 1000 to 1200°C (1800 to 2000°F). Magma resources are generally limited to areas of recent volcanism, in the contiguous western states, Alaska, and Hawaii.

The technology for tapping this resource is only in its infancy. Currently, R&D focuses on evaluating the feasibility of the technology rather than design of power systems. Thus, this discussion of magma energy extraction technology is as yet theoretical.

The technology for extracting the heat of magma would vary with the type of magma to be penetrated, but experimental work centers today on silicic magma bodies since they are most representative of the bodies expected at most western U.S. sites. The basic drilling technology is available, but special drilling and completion techniques will have to be employed because of the effects of high temperatures and chemical-laden environment. Special engineering materials that can survive several years downhole will also be required. Research on these aspects is ongoing.

Current research on energy extraction from the molten rock centers on a "solidifying while drilling" technique -- i.e., as the drill bit advances, water is injected into the hole to chill and solidify the molten materials in front of and around the drill bit. Laboratory experiments have shown that the resulting mass will be extensively fractured by thermally-induced stresses, thereby creating a heat transfer area. A working fluid will be circulated through the fractures absorbing the heat through direct contact. The heat will be sent to the surface through its transfer to fluid circulating in a closed loop. This fluid will in turn transfer the heat to the working fluid in a binary cycle power plant and then return back down the well to continue the heat extraction cycle. The vaporized working fluid in the plant loop will operate the turbo-generator.

CURRENT USE

There is no current commercial use of the heat of magma resources.

PROJECTED USE

While the scientific feasibility of capturing and utilizing the heat of magma has been demonstrated, the engineering feasibility and economics of doing so have yet to be proven. However, the high temperature of the resource and the estimated high temperatures of the heat transfer working fluid appear to lead easily to efficient conventional techniques for generating electricity.

CO_2 CONTRIBUTION

1. Resource Acquisition

In magma energy extraction technology, the resource acquisition phase is essentially concurrent with the construction phase since the resource is acquired through well drilling and installation of the heat exchange system. However, some vehicular use of fossil fuel will be involved in preliminary surface exploration and geophysical surveys, and, in some cases, exploratory geophysical drilling. The CO_2 contribution from these activities is estimated at <0.1 pound CO_2 per MWe hour, gross. However, once the existence of a magma body is verified with power production, very little further exploration will be needed at a given site.

2. Construction

Current estimates for magma energy extraction/power production are about 25 to 50 MWe per well with maximum well depth of about 32,000 feet. Therefore, one 110 MWe turbine would be supplied by about five wells. The drilling operation to complete the wells and power plant construction are the major activities contributing to CO_2 emissions during this phase. CO_2 emission rates are estimated at 5 pounds CO_2 per MWe hour, gross.

3. Operation

A binary system will be used to extract energy from magma, in the manner described above. With this system, no magmatic gases will be emitted during normal operation. However, there will be significant CO_2 in the magma fluid loop and periodic venting to prevent vapor locks or to control chemistry will probably be required. Potential CO_2 emissions are estimated at 17 pounds CO_2 per MWe hour, gross.

4. Fuel Utilization

It is possible that fuels other than heat can be derived from magma. Their nature or application are unknown at this time.

MAJOR REFERENCES

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3. Dunn, J.C., Private Communication, Nov. 1988.