Environ. Sci. Technol. **2002**, *36,* 3194−3200

Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin

SERGIO PACCA[†] AND ARPAD HORVATH*,[‡]
Energy and Resources Group, University of California, 310 Barrows Hall, Berkeley, California 94720, and Department of Civil and Environmental Engineering, 215 McLaughlin Hall, University of California, Berkeley, California 94720-1712

As demand for electricity increases, investments into new generation capacity from renewable and nonrenewable sources should include assessment of global (climate) change consequences not just of the operational phase of the power plants but construction effects as well. In this paper, the global warming effect (GWE) associated with construction and operation of comparable hydroelectric, wind, solar, coal, and natural gas power plants is estimated for four time periods after construction. The assessment includes greenhouse gas emissions from construction, burning of fuels, flooded biomass decay in the reservoir, loss of net ecosystem production, and land use. The results indicate that a wind farm and a hydroelectric plant in an arid zone (such as the Glen Canyon in the Upper Colorado River Basin) appear to have lower GWE than other power plants. For the Glen Canyon hydroelectric plant, the upgrade 20 yr after the beginning of operation increased power capacity by 39% but resulted in a mere 1% of the CO_2 emissions from the initial construction and came with no additional emissions from the reservoir, which accounts for the majority of the GWE.

Introduction

In 2001, California and the rest of the West Coast of the United States started to experience severe shortages of electricity. Investments in both renewable and nonrenewable sources of electricity have been planned. Nationwide, the demand for renewable or "green" energy is increasing. For example, New York State Governor Pataki issued an executive order in 2001 requiring agencies to purchase at least 10% of their power from renewable sources by 2005 (*1*). To address the West Coast's crisis and the demand for renewable power, the National Hydropower Association (NHA) has urged Congress and the Administration to pass hydropower licensing reform legislation and create incentives for new hydroelectric capacity through efficiency upgrades or by adding turbines to existing dams (*2*). The NHA estimated that another 8800 MW of new capacity (equivalent to about 14 average-sized coal-fired power plants) could be developed nationwide, 2500 MW in California alone, through upgrades of existing dams. As much as 10 400 MW could be gained from installing turbines on dams that currently have none.

* Corresponding author telephone: (510)642-7300; fax: (510)643-8919; e-mail: horvath@ce.berkeley.edu.
[†] Energy and Resources Group.
[‡] Department of Civil and Environmental Engineering.

The debate about the environmental impacts of different electricity generation technologies is also intensifying. A study by the World Commission on Dams in 2000 (*3*) summarized many of the concerns associated with hydroelectric plants such as air emissions from reservoirs, loss of habitat, relocation of population, problems with sediment, etc. While hydroelectric, solar, and wind power plants do not need fuel inputs for operation, fossil-fueled power plants contribute to air pollution significantly through sustained annual emissions. In the United States, 40.5% of anthropogenic CO_2 emissions (*4*), 38% of toxic air emissions (*5*), and 15% of total toxic releases (*5*) were attributed to the combustion of fossil fuels for electricity generation in 1998.

As all environmental systems analyses, the comparison of the environmental performance of various electricity generation technologies requires a life cycle perspective. This paper compares greenhouse gas (GHG) emissions from three renewable (hydro, solar, and wind) and two nonrenewable sources (coal and natural gas), including not only the operations phase of electricity generation (where the fossil-fueled plants have a distinct disadvantage as a result of fuel burning) but also the construction of the facilities as well as the emissions from the hydroelectric plant's reservoir. (The end-of-life phase of the facilities was not assessed due to data unavailability.) The hypothetical power plants were located in the same geographical area (since local conditions affect the design and operation of hydro, solar, and wind plants) and scaled to have the same output.

Framework for Comparative Assessment of Global Warming Effects

To assess the greenhouse effects of constructing and operating various power plants, the amounts of the major material and energy inputs were obtained, and life cycle assessment (LCA) was used. LCA is a method that attempts to systematically quantify the environmental effects of the various stages of a product's or a process' entire life cycle: materials extraction, manufacturing/production, use/operation, and ultimate disposal (or end-of-life). There are many efforts worldwide to produce LCA studies that are comprehensive and useful. The challenge is to map the production processes so that they are accurate and representative of the industry trends. Several LCA tools provide process descriptions and libraries of data to users. Existing studies differ in the number of environmental effects quantified and in the scope of the analysis (where the boundary of the analysis is drawn). Currently, there are two major approaches to boundary setting: a process-based model developed most intensively by the Society of Environmental Toxicology and Chemistry (SETAC) and the U.S. Environmental Protection Agency (EPA) (*6*) and an economic input−output analysis-based model called EIO-LCA (*7, 8*). The SETAC-EPA approach divides each product into individual process flows and strives to quantify their environmental effects. For example, in the manufacturing stage of products, it attempts to go as far back ("upstream") in the flow as possible. This assessment is typically limited by data availability, time, and cost and includes the first tier (direct) suppliers but seldom the complete hierarchy of suppliers, i.e., all the suppliers of suppliers (and thus the indirect effects). In contrast, the EIO-LCA model uses the 498 × 498 economic input−output commodity by commodity matrix of the U.S. economy (a general interdependency model) to identify the entire chain of suppliers (both direct and indirect) of a commodity, thus setting the boundary of the assessment at the level of the national economy. The 498 × 498 matrix is based on

10.1021/es0155884 CCC: $22.00
Published on Web 06/11/2002

commodities such as cement, steel, coal, sugar, etc. To obtain the total (direct plus indirect) economic demand, final purchase (final demand) amounts are input into the model. The results are then multiplied by matrixes of energy use and emission factors calculated on economic sector level (e.g., energy use per dollar). The base year for EIO-LCA data is currently 1992. The EIO-LCA model has been applied to a number of product assessments (see, e.g., refs *9–11*).

The EIO-LCA method was used to estimate the amount *M* of each GHG emissions (CO_2, CH_4, N_2O) from constructing and operating power plants based on the amounts and costs of the materials and energy inputs. The construction assessment included material inputs (extraction, processing, and transportation) and equipment use (combustion of fuel). For the operations stage of the fossil-fueled power plants, fuel inputs were quantified in each year of the service life. Air emissions were estimated from the fuel extraction, transportation, and combustion phases.

The temporal effects of different GHGs on global (climate) change are accounted for by using the global warming effect (GWE), which is the sum of the product of instantaneous GHG emissions (*M*) and their specific time-dependent global warming potential (GWP). Since GWP compares the effect of GHG emissions to the emission of a similar amount of CO_2 over a chosen time horizon, it is "intended for use in studying relative rather than absolute impacts of emissions" (*12*). The GWP for a particular GHG and a given time horizon is (*13*)

$$\mathrm{GWP} = \frac{\int_0^{\mathrm{TH}} a_{\mathrm{x}}[x_{(\mathrm{t})}]\,\mathrm{d}t}{\int_0^{\mathrm{TH}} a_{\mathrm{r}}[x_{(\mathrm{t})}]\,\mathrm{d}t} \tag{1}$$

where a_x is the radiative efficiency of a given GHG, which represents the radiative forcing [radiative forcing measures the importance of a potential climate change mechanism; it represents the perturbation to the energy balance of the atmosphere following a change in the concentration of greenhouse gases] divided by the change in its atmospheric concentration since before the industrial revolution (*14*) up to 1992 (the base year of the EIO-LCA data); a_r is the radiative efficiency of CO_2, which is assumed to be 1 because all other GHGs are compared to CO_2; $x_{(t)}$ in the numerator is a response (decay) function using a GHG-specific *e*-folding time (that represents the time required for a gas to get to 1/*e* of its initial mass) (*14*); $x_{(t)}$ in the denominator represents the CO_2 response function (*13*); and TH is the time horizon between the instantaneous release of the GHG and the end of the analysis period.

Therefore, the global warming effect (in metric tons of CO_2 equivalent**,** MT of CO_2 equiv) is

$$\mathrm{GWE} = \sum M_j \times \mathrm{GWP}_{j,\mathrm{TH}} \tag{2}$$

where M_j is the amount of the instantaneous emission of each GHG_j (in metric tons, MT); $GWP_{j,TH}$ is the global warming potential for each GHG_j over the time period TH calculated using eq 1. For example, the GWE of CH_4 emissions over 20 yr is equal to the amounts of releases in years 1, 2, 3, ... 20 multiplied by methane's GWP when the TH is 20, 19, 18, ..., 1 yr and summed for the total.

Therefore, the global impact of each electricity generation technology over time is a function of the fraction of gas remaining in the atmosphere in the future as compared to the effect of CO_2 remaining in the atmosphere in the future. In addition to GWP calculations for CH_4, it is assumed that after atmospheric decay all CH_4 oxidizes into CO_2, which is captured by the radiative efficiency of CH_4, and thus is accounted for as additional CO_2 (*12*). The CO_2 response function is used to determine the future concentration of carbon in the atmosphere.

The operation of a facility depends on the obsolescence of the structures and technology. Consequently, the analysis periods depend on upgrades, changes in technology, societal preferences, resource availability, etc. To account for different service lives of various power plants, this analysis looked at four periods: 10, 20, 30, and 40 yr after construction. Next, the case studies of the five electricity generation technologies are presented.

Hydroelectric Plant: The Case of Glen Canyon Dam

Hydropower is the United States' leading renewable electricity source (around 7% of generation capacity) (*15*). In 1978, as a direct response to the oil crisis, the U.S. Bureau of Reclamation, the second largest hydroelectricity producer in the nation with 58 power plants (*16*), established a hydroelectric plant upgrade program. The primary goals of upgrading are increased power output and improved reliability of the system. Through October 1995, 55 generator units have been upgraded, corresponding to an added capacity of 1783 MW. Each upgraded unit increased in capacity by an average of 48%, at a cost of \$69/kW, and it has been estimated that three-quarters of the dams operated by the Bureau of Reclamation now contain high-efficiency generator windings (*17*).

The Glen Canyon hydroelectric plant on the Colorado River is the second largest operated by the Bureau (*17*). It began operation in 1964. The reservoir, the 300-km-long Lake Powell, formed by flooding the Glen Canyon and displacing 653 130 000 m^2 of land (*18*), is the second largest in the United States. It provides additional services such as water for irrigation, recreation, and flood control and management. Between 1984 and 1987, the generators were upgraded by 338 MW to 1296 MW. The facility upgrade consisted of rewinding the generators and reducing the size of each penstock (the tube transferring water into a turbine) from 15 to 14 in. diameter (*19*). The facility has 8 units; five generators are presently rated at 165 MW each, and three generators are rated at 157 MW each. The upgrade of the existing dam has resulted in 39% additional power (*17*). Additional energy produced from the upgraded hydroelectric plant corresponded to 1.48 TWh, for a total of 5.55 TWh in 1999 (*19*). The contract cost to upgrade units 1, 3, 5, and 6 was \$7 044 724 (\$26/kW) while it cost \$5 026 724 (\$30/kW) to upgrade units 2, 4, 7, and 8, for a total upgrade cost of \$12 071 448 in 1987 dollars (*17*). The cost calculations do not include the offset in upgrade cost by routine operation and maintenance costs. Namely, normal maintenance costs would have been incurred to replace a worn generator winding even if the upgrade had not occurred. This consideration would make upgrade costs significantly smaller.

On the basis of detailed technical records (*20*), eqs 1 and 2, and the CO_2 response function (*13*), the estimated GWE of Glen Canyon's construction is 500 000 MT of CO_2 equiv (after 20 yr). The contribution of construction materials, processes, and power plant components is shown in Table 1. Emissions from excavation were calculated based on the fuel consumption of the construction equipment, assuming that all fuel was converted to CO_2.

The GHG emissions from the upgrade were estimated assuming that all replaced parts came from the sector that produces turbines and turbine generator sets. Since EIO-LCA in its current version (*7*) uses 1992 dollars, we converted the upgrade costs from 1987 to 1992 dollars using the Consumer Price Index (CPI) (*21*). The upgrade, which increased power capacity by 39%, resulted in 10 000 MT of CO_2 emissions, or about 1% of the estimated CO_2 emissions from Glen Canyon's initial construction (800 000 MT of CO_2).

TABLE 1. Major Construction Inputs and GWE (after 20 yr) for Glen Canyon Hydroelectric Plant[a]

inputs	total MT	unit cost (1992 \$/MT)	total cost (1992 \$)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	$= GWE$
concrete	9 906 809	30[b]	297 652 257	400 792	751	7 898	409 441
excavation (m^3)	4 711 405	na	114 839 000	3 812			3 812
turbines and turbine generator sets	na	na	65 193 084	41 725	45	249	42 019
power distribution and transformers	na	na	13 754 764	12 358	16	79	12 453
steel	32 183	385[c]	12 402 138	43 710	29	244	47 583
copper	90	2 368[c]	214 167	186	0	2	188
aluminum	67	1 268[c]	84 804	157	0	2	159
total			503 240 216	500 000	1 000	9 000	500 000

[a] Total emissions are rounded to one significant digit. MT, metric ton; GWE, global warming effect; na, not available. [b] Ref *39*. [c] Ref *40*.

While hydroelectric plants do not use fossil fuels in operation, they emit GHGs from biomass decay in the dam's reservoir, a subject of debate lately (*22*, *23*, *3*). Yearly biomass emissions are reduced as the flooded vegetation decays over time. Colder climates have slower decay rates and thus lower annual emissions (*23*). For Glen Canyon, the assumptions were that (a) the area of the flooded land is similar to the surface area of the reservoir, Lake Powell (653 130 000 m^2), (b) originally the land was covered by desert scrub that has a carbon density of 0.3 kg of C/m^2 (*24*), (c) the *e*-folding time for the biomass decay is 7 yr, and (d) 10−30% of the carbon was subject to anaerobic decomposition and released as CH_4 (*22*). Accordingly, the GWE is estimated to be 2 000 000−5 000 000 MT of CO_2 equiv (after 20 yr). [The CO_2 response function was used to calculate these values.]

In addition, the formation of Lake Powell displaced an ecosystem and resulted in forgone carbon uptake measured by net ecosystem production (NEP). NEP is the difference between net primary productivity (NPP), which absorbs carbon from the atmosphere, and heterotrophic respiration in the absence of disturbances, which releases carbon to the atmosphere (*25*, *26*). NEP is calculated as

$$\mathrm{NEP} = \mathrm{NPP} - \frac{C}{\tau} \tag{3}$$

where C is the amount of carbon stored in the terrestrial ecosystem; τ is the average turnover time, which is calculated as (*27*, *28*):

$$\tau = 42.8 \times \mathrm{e}^{-1921[1/(283.15 - 139.4) - 1/(\mathrm{MAT} - 139.4)]} \tag{4}$$

Using 298 K for the local mean annual temperature (MAT), τ was calculated as 15 yr. On the basis of annual NPP of 0.032 kg of C/m^2 (*24*) and carbon density in the desert scrub ecosystem (0.3 kg of C/m^2; *24*), the annual NEP was calculated as 12 g of C/m^2. Assuming constant carbon sequestration rates, the estimated GWE due to the forgone carbon uptake of the flooded area is 400 000 MT of CO_2 equiv (after 20 yr).

Summing the two GHG emission sources (construction of the dam and biomass decay from the reservoir) and the forgone NEP, the total GWE of the Glen Canyon Dam after 20 yr (at the time of the upgrade) is estimated at 3 000 000−6 000 000 MT of CO_2 equiv. Decay from flooded biomass accounts for 67−83%, NEP loss accounts for 7−13%, and construction accounts for 8−17% of the total GWE (percentages may not sum due to rounding).

Hydroelectric plants have been intensely criticized for changing and destroying the physical environment, such as destroying natural habitat (e.g., of Pacific Northwest salmon) and species, being unsightly (such as the flooding of Glen Canyon), siltation, dislodging indigenous populations, etc. While undoubtedly important, these issues are not the subject of this paper.

In the following, the comparison of Glen Canyon Dam to two renewable (solar and wind) and two nonrenewable (coal and natural gas) power sources is presented. It was assumed that all the other power plants can meet Glen Canyon's 1999 output (5.55 TWh) and are located in the same geographical area (near the border of Utah and Arizona). This is important for the solar and wind options as the local conditions affect the design and operation of such facilities.

Solar Power Plant

Medium-sized photovoltaic (PV) plants of 1 MW capacity are considered the functional unit (*29*). Ordinarily, large capacity solar plants are designed as thermal systems instead of incorporating photovoltaics. These plants use reflective surfaces to focus sunlight on a collector that contains a working fluid (e.g., an oil-filled tube). The heat from the working fluid is transferred to water, and the resulting steam powers a turbine-generator set to produce electricity (*30*). This setup would be more appropriate at the scale under consideration here; however, solar industry trends point toward PV module production.

Manufacturing and constructing a PV plant for the required annual electricity output (5.55 TWh) would result in a GWE of 10 000 000 MT of CO_2 equiv after 20 yr of operation (Table 2). The total cost of materials and construction energy is \$3 578 458 000 (in 1992 dollars), excluding land purchases, labor/installation, and maintenance costs.

The 100-W panels of dimensions 1.316 × 0.66 m (*31*) are used in a nonconcentrating array (an unrealistic configuration in practice, but suitable for this analysis; such large arrays would almost always take advantage of concentrating lenses), with array units of 3 × 10 panels, each having its own concrete foundation, for a surface area of 3.9 × 6.6 m, sited at 30° latitude, at a 30-deg tilt (approximately 1.2 m of additional width is needed to account for shading by the array due to the sun's angle). There is 0.9 m between each of these array units for personnel access. Each adjacent unit covers a land area of 37.44 m^2 and has a capacity rating of 3 kW. Some 1 372 500 of these 3 kW units are required (*32*). The upgraded Glen Canyon plant yields 5.55 TWh of energy each year from a capacity of 1296 MW. Since the photovoltaic plant will have a smaller capacity factor (due to solar resource availability), the necessary installed capacity to achieve the same delivered energy is 4118 MW, more than three times the hydroelectric plant's capacity. By comparison, the world production of PV modules was 125 MW in 1997 (*33*), thus meeting the capacity with PV is unreachable without major investments in production capacity or new technological breakthroughs.

The PV array required in this analysis would demand approximately 51 386 400 m^2 of land area. Land costs will vary depending on location. A PV plant of this magnitude must be constructed in a remote area such as a desert where land prices are low and solar resource is high. Given a range

TABLE 2. Major Construction Inputs and GWE (after 20 yr) for a Photovoltaic Plant[a]

construction inputs	total MT	unit cost (1992 $/MT)	total cost (1992 $)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	$= GWE$
steel	4 600 276	385[b]	1 772 797 382	6 957 724	4 216	35 924	6 997 865
copper	480 029	2 368[b]	1 136 805 659	984 580	1 617	10 504	996 701
electricity (MWh)	7 556 010	36[c]	268 780 863	2 152 447	1 077	20 407	2 173 931
aluminum	177 788	1 268[b]	225 374 699	428 610	405	6 558	435 573
cement	2 222 356	55[b]	121 362 849	410 263	394	15 497	426 153
glass	1 066 731	50[b]	53 336 538	56 951	67	759	57 777
total			3 578 457 990	10 000 000	8 000	90 000	10 000 000

[a] Total emissions are rounded to one significant digit. [b] Ref *40*. [c] Ref *41*.

TABLE 3. Major Construction Inputs and GWE (after 20 yr) for a Wind Farm[a]

construction inputs	total MT	unit cost (1992 $/MT)	total cost (1992 $)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	$= GWE$
steel	289 987	385[b]	111 751 615	426 296	258	2 201	428 755
electricity (MWh)[c]	1 691 678	36[d]	40 756 138	317 231	158	3 008	320 397
concrete	1 266 172	30[e]	37 927 398	51 225	96	1 009	52 330
aluminum	6 275	1 268[b]	7 954 337	14 703	13	225	14 941
plastics	20 169	220[f]	4 445 273	5 090	7	53	5 150
copper	1 569	2 368[b]	3 715 021	3 127	4	33	3 164
glass	4 930	50[b]	246 511	256	0	3	259
oil	448	106[d]	47 380	204	0	1	205
sand	9 412	4[b]	37 743	55	0	0	55
total			206 881 416	800 000	500	7 000	800 000

[a] Total emissions are rounded to one significant digit. [b] Ref *40*. [c] Derived by assuming that all energy input is electricity, then excluding embedded material energy from Table 6 from ref *36*, assuming 67% construction and 33% decommissioning energy requirements, and scaled up to 4480 turbines. [d] Ref *41*. [e] Ref *39*. [f] Ref *42*.

of prices between $250 and $1200 per ha, the required land would add an additional $1 300 000−6 200 000 to the cost of the PV plant, an insignificant amount given the total life cycle cost of $3.6 billion. The cost of land would be reduced if the PV system were distributed, i.e., the generating capacity required would be spread over a larger number of small systems (e.g., existing rooftops).

The solar plant displaces an ecosystem similar to what Glen Canyon Dam's reservoir flooded. The NEP loss is estimated at 30 000 MT of CO_2 equiv, and the decay of the biomass removed from the site during construction amounts to 40 000 MT CO_2 equiv (assuming the same ecosystem conditions as for the Glen Canyon site, measured after 20 yr). Therefore, the total GWE of the PV plant (accounting for the manufacturing, construction, biomass removal, and NEP loss) would amount to 10 000 000 MT of CO_2 equiv 20 yr after construction.

It was assumed that after 30 yr of operation (*34*) all PV panels had to be replaced (but not the concrete and steel base) and that the required construction energy was 100% of the original due to an energy-intensive PV manufacturing process. The electricity output of the facility remained constant. The refurbishment resulted in 4 000 000 MT of CO_2 emissions, a fifth of the original emissions from manufacturing and construction (20 000 000 MT of CO_2).

Wind Farm

A wind farm producing 5.55 TWh of electricity per year was assumed to be in southern Utah, at an elevation of 2134 m (7000 ft), close to the Escalante Desert where the average wind speed is 6.5 m/s (*35*). A turbine of 600 kW (*36*) was used as the unit for the farm's total of 4480 turbines that would occupy an area of 489 580 000 m^2 (*37*). The total cost of materials and construction of the facility would amount to $206 881 000 (in 1992 dollars) without labor/installation and maintenance costs. Given a range of prices between $250 and $1200 per ha, the required land would add an additional $12 000 000−59 000 000 to the cost. Given the large area, land between the turbines could be used for other activities such as agriculture. No NEP loss was anticipated. The contribution of construction materials and energy to the GWE of the wind farm after 20 yr of operation (800 000 MT of CO_2 equiv) is shown in Table 3.

It was assumed that after 20 yr of operation all turbines had to be replaced (but not the concrete foundations) and that the required construction energy was 30% of the original electricity and 100% of petroleum used. The electricity output of the facility remained constant. The refurbishment resulted in 900 000 MT of CO_2 emissions, two-thirds of the original emissions from manufacturing and constructing the plant (1 300 000 MT of CO_2).

Coal-Fired Power Plant

A 1000 MW coal-fired power plant with 6.08 TWh/yr output (*29*) was scaled down to 5.55 TWh/yr. The technology and design of coal-fired power plants are not site-specific. Their environmental performance depends on coal quality, firing configuration, and technology type. Its location depends on the availability of coal and cooling water. Since this alternative could replace energy from hydropower, it could be installed close to where the demand is (e.g., large cities or industries) or to the current power transmission lines and be accessible by railroad for coal delivery. As shown in Table 4, the GWE for this power plant after 20 yr of operation (including coal burning) was estimated at 90 000 000 MT of CO_2 equiv (*38*).

It was assumed that after 30 yr of operation all boilers had to be replaced (but not the structure of the building) and that the required construction energy was 50% of the original. The electricity output of the facility remained constant. The refurbishment resulted in 70 000 MT of CO_2 emissions, one-third of the original emissions from manufacturing and constructing the plant (200 000 MT of CO_2).

TABLE 4. Major Construction Inputs and GWE (after 20 yr) for a Coal-Fired Power Plant[a]

	total MT	unit cost (1992 \$/MT)	total cost (1992 \$)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	$= GWE$
			Operational Inputs[b]				
coal combustion	2 336 000	28.76[c]	61 180 849	75 825 360	322 383	1 886 309	78 034 052
coal extraction	2 336 000	18.05[c]	38 396 257	7 203 494	25 271	44 197	7 272 962
transportation by railroad	2 336 000	10.71	22 784 592	503 325	5 054	254 597	762 976
			Construction Inputs				
steel	62 200	385.37[d]	21 826 601	83 261	51	430	83 742
concrete	178 320	29.95[e]	4 863 858	6 569	13	130	6 712
aluminum	624	1 267.66[d]	720 289	1 331	2	21	1 354
total[a]				90 000 000	400 000	2 000 000	90 000 000

[a] Total emissions are rounded to one significant digit. [b] Includes fuel consumption over an assumed service life of 20 yr. [c] Ref *43*. [d] Ref *40*. [e] Ref *39*.

TABLE 5. Major Construction Inputs and GWE (after 20 yr) for a Natural Gas Power Plant[a]

	total amount	unit cost (1992 \$/amount)	total cost (1992 \$)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	$= GWE$
			Operational Inputs[b]				
natural gas combustion	1 560 300 000 m^3	0.130[c]	177 347 844	38 800 368	380 506	2 128 974	41 309 848
natural gas transportation	1 560 300 000 m^3	0.068	93 821 050	3 630 894	50 542	221 798	3 903 234
natural gas extraction	1 560 300 000 m^3	0.061[c]	83 526 794	8 552 990	73 285	1 357 117	9 983 392
			Construction Inputs				
steel	51 130	385[d]	17 217 555	65 679	40	339	66 058
concrete	71 270	30[e]	1 865 467	2 520	4	49	2 573
aluminum	230	1 268[d]	254 771	471	0	7	478
total[b]				50 000 000	500 000	4 000 000	50 000 000

[a] Total emissions are rounded to one significant digit. [b] Includes fuel consumption over an assumed service life of 20 yr. [c] Ref *43*. [d] Ref *40*. [e] Ref *39*.

Natural Gas-Fueled Power Plant

The capacity of the facility used as a model for a natural gas power plant is 1000 MW (6.34 TWh/yr output scaled to 5.55 TWh/yr) (*29*). The technology and design of combined cycle gas turbines are not site-specific. Its location depends on the availability of natural gas and cooling water. If this alternative is to replace energy from hydropower, it should be installed close to where the demand is or to the current power transmission lines. As shown in Table 5, after 20 yr, the GWE (including natural gas burning) was estimated at 50 000 000 MT of CO_2 equiv.

It was assumed that after 30 yr of operation all boilers had to be replaced (but not the structure of the building) and that the required construction energy was 50% of the original. The electricity output of the facility remained constant. The refurbishment resulted in 60 000 MT of CO_2 emissions, about 60% of the original emissions from manufacturing and constructing the plant (100 000 MT of CO_2).

Discussion of Results

Meeting the increasing electricity demand is an important strategic goal that should be achieved by building the least economically and environmentally costly new power plants and upgrading existing ones. As the U.S. Bureau of Reclamation has suggested, "upgrading hydroelectric generator and turbine units at existing power plants is one of the most immediate, cost-effective, and environmentally acceptable means for developing additional electrical power" (*17*).

Figure 1 shows a comparison of the GWE/kWh for the alternatives for four time periods after construction. The wind farm's emissions are lower than those of the hydroelectric plant (provided the capacity of the wind farm can be scaled up to a 5.55 TWh annual output), and both have lower impacts than the other options. For the Glen Canyon Dam, the effects associated with the reservoir are the most significant, especially in the short term because the relatively rapid initial decay of biomass in the reservoir releases CH_4 that has a short atmospheric residence time and high GWE in the short run (hence the exponential decrease in GWE/kWh for the hydroelectric plant between years 10 and 20).

This analysis located the plants in the arid Upper Colorado River Basin. The GWE of a reservoir in a region with higher NEP (such as temperate and tropical forests) would further increase the impact of the hydroelectric option. The amounts of materials may also vary from dam to dam depending on design and construction criteria. Technological changes associated with the other electricity generation options (such as increased efficiency of wind and solar energy conversion and lower manufacturing impacts) could change the results as well.

For the Glen Canyon facility, the upgrade 20 yr after the beginning of operation (that increased power capacity by 39%) resulted in a mere 1% of the CO_2 emissions from the initial construction and came with no additional impacts from the reservoir. The upgrade of the other power plants appears in the 30- and 40-yr values in Figure 1. The hydropower upgrade would obviously not result in additional land use. Still, the Glen Canyon Dam uses the most land due to its reservoir, Lake Powell, about one-third more than the wind farm, which in turn would require almost 10 times more land than the PV plant.

Measured after 20 yr (Tables 1−5), the GWE of construction was insignificant for the hydroelectric, coal, and natural gas power plants. (Note: construction inputs were indistinguishable from manufacturing of electricity generation equipment for the solar and wind options.)

Figure 2 shows discounted electricity costs including construction, operation, and maintenance. The hydropower option produces the cheapest energy, followed by

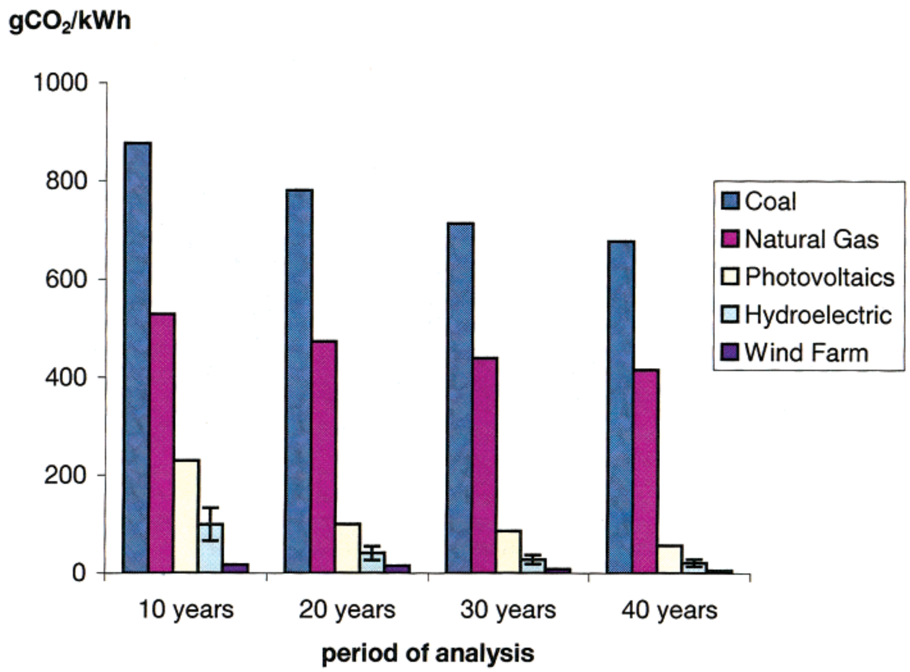

FIGURE 1. Comparison of GWE per electricity output for various alternatives for four time periods after construction (g of CO_2 equiv/kWh).

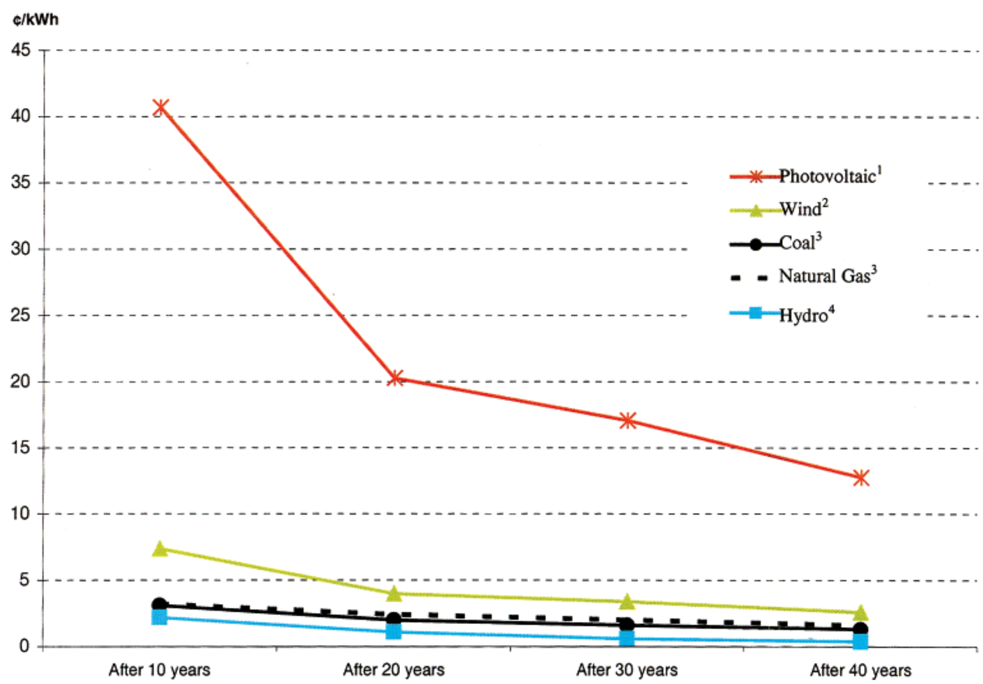

FIGURE 2. Electricity cost in 2000, assuming a constant annual output and a 5% annual discount rate (cents/kWh). Footnotes: (1) ref *34*; (2) refs *37* and *44*; (3) ref *15*, assuming stable prices for fossil fuels; (4) refs *19* and *20*.

coal, natural gas, and wind. The PV plant has the highest costs. For full life cycle costs of the alternatives, the valuation of external effects (such as emissions) should also be included.

Understanding the environmental impacts of electricity generation options from renewable and nonrenewable sources is essential for better policy- and decision-making. This analysis looked at the GWE of GHG emissions (a global concern) from five alternatives. Investment decisions ought to consider a variety of other environmental impacts such as toxic emissions from fossil-fueled power plants, habitat destruction associated with dams, etc. However, a comparison of GWE with other environmental impacts is complicated.

Acknowledgments

Some of the ideas for this research were first explored in a class project at UC Berkeley by S.P., John Galloway, Ahmad Haya, and Jean Ku. S.P. is grateful for the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (National Council for Scientific and Technological Development) fellowship from Brazil.

Literature Cited

(1) Post, N. M. *ENR* **2001**, *247*, 16.
(2) Rosta, P.; Armistead, T.; Ichniowski, T. *ENR* **2001**, *247*, 12.
(3) World Commission on Dams. *Dams and Development: A New Framework for Decision-Making*; Earthscan Publications Ltd: London and Sterling, VA, 2000.

(4) *Carbon Dioxide Emissions from the Generation of Electric Power in the United States: 2000*; U.S. Department of Energy/U.S. Environmental Protection Agency: Washington, DC, 2000.
(5) U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics. *Toxics Release Inventory: 1998*; U.S. Government Printing Office: Washington, DC, 1998.
(6) Curran, M. A. *Life Cycle Analysis*; McGraw-Hill: New York, 1996.
(7) *Economic Input-Output Life Cycle Assessment: 2001*; Green Design Initiative; Carnegie Mellon University: Pittsburgh; http://www.eiolca.net (accessed July 2001).
(8) Hendrickson, C. T.; Horvath, A.; Joshi, S.; Lave, L. B. *Environ. Sci. Technol.* **1998**, *32* (4), 184A−191A.
(9) Lave, L. B.; Maclean, H.; Hendrickson, C. T.; Lankey, R. *Environ. Sci. Technol.* **2000**, *34* (17), 3598−3605.
(10) Horvath, A.; Hendrickson, C. T. *J. Infrastruct. Syst.* **1998**, *4* (3), 111−117.
(11) Horvath, A.; Hendrickson, C. T. *Transp. Res. Rec.* **1998**, *1626*, 105−113.
(12) Houghton, J. T. *Climate Change 2001*: *The Scientific Basis*; Intergovernmental Panel on Climate Change; Cambridge University Press: New York, 2001.
(13) Houghton, J. T. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*; Intergovernmental Panel on Climate Change; Cambridge University Press: New York, 1995.
(14) Houghton, J. T. *Climate Change 1995: The Science of Climate Change*; Intergovernmental Panel on Climate Change; Cambridge University Press: New York, 1996.
(15) *Annual Energy Outlook: 2001*; U.S. Department of Energy, Energy Information Administration: Washington, DC, 2001.
(16) U.S. Bureau of Reclamation. *Reclamation's Role in Hydropower*; http://www.usbr.gov/power/data/role_rpt.htm#power (accessed June 2000).
(17) U.S. Bureau of Reclamation. *Bureau of Reclamation Generator Power Uprate Program Report*; http://www.usbr.gov/power/data/uprate/uprate.htm (accessed June 2000).
(18) U.S. Bureau of Reclamation. *Glen Canyon Dam Facts*; http://www.uc.usbr.gov/information/gcdfacts.html (accessed June 2001).
(19) U.S. Bureau of Reclamation. *Glen Canyon Power Plant*; http://www.usbr.gov/power/data/sites/glencany/glencany.htm (accessed June 2001).
(20) *Glen Canyon Dam and Power Plant: Technical Record of Design and Construction*; U.S. Bureau of Reclamation: Denver, CO, 1970.
(21) *Consumer Price Indexes: 2000*; U.S. Department of Labor, Bureau of Labor Statistics: Washington, DC, 2000.
(22) Pinguelli Rosa, L.; Schaeffer, R. *Energy Policy* **1995**, *23* (2), 149−158.
(23) Gagnon, L.; van de Vate, J. *Energy Policy* **1997**, *25* (1), 7−13.
(24) Harte, J. *Consider a Spherical Cow*; University Science Books: Sausalito, CA, 1988.
(25) Baldocchi, D. Carbon and Energy: Terrestrial Stores and Fluxes. In *Encyclopedia of Global Environmental Change*, Vol. 2; John Wiley & Sons: New York, 2001.
(26) Watson, R. T.; et al. *Land Use, Land-Use Change and Forestry*; IPCC, WMO, UNEP/GRID-Arendal: The Hague, Netherlands, 2001 (CD-ROM).
(27) Sanderman, J.; Amundson, R.; Baldocchi, D. University of California, Berkeley, unpublished results.
(28) Lloyd, J.; Taylor, A. *Funct. Ecol.* **1994**, *8* (3), 315−323.
(29) Tahara, K.; et al. *Energy Convers. Manage.* **1997**, *38*, S615−620.
(30) Johansson, T. B.; et al. *Renewable Energy*: *Sources for Fuels and Electricity*; Island Press: Washington, DC, 1993.
(31) Siemens Solar. *Siemens Solar Module Details and Specifications*; http://www.siemenssolar.com/sm110_sm100.html (accessed June 2001).
(32) *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors: 1991*; National Renewable Energy Laboratory, Analytic Studies Division: Golden, CO, 1991.
(33) Eckhart, M. T. *Financing Solar Energy in the U.S.*; Technical Report; Renewable Energy Policy Project: Washington, DC, 1999.
(34) Stronberg, J.; Virinder, S. *Government Procurement to Expand PV Markets*; Technical Report; Renewable Energy Policy Project: Washington, DC, 1998.
(35) *Wind Energy Resource Atlas of the United States*; Pacific Northwest National Laboratory, Solar Technical Information Program; Solar Energy Research Institute: Richland, WA, 1986.
(36) Schleisner, L. *Renewable Energy* **2000**, 20 (3), 279−288.
(37) Natural Resources Canada, Energy Diversification Research Laboratory. *Wind Energy Project RETScreen Energy Model*; 1998; http://cedrl.mets.nrcan.gc.ca/e/412/retscreen/retscreen_new_1.html (accessed May 2000).
(38) U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics. *Compilation of Air Pollutant Emission Factors AP-42*; U.S. Government Printing Office: Washington, DC, 2002.
(39) *R. S. Means Building Construction Cost Data*; R. S. Means Co.: Kingston, MA, 1995.
(40) U.S. Geological Survey, Mineral Resources Program. *USGS Minerals Information, Publications and Data Products*; 2002; http://minerals.usgs.gov/minerals/pubs/ (accessed January 2002).
(41) *Retail Energy Prices in Selected Countries in US Dollars/Unit*; International Energy Agency: 2000.
(42) Joshi, S. Unpublished Ph.D. Dissertation, Carnegie Mellon University, Heinz School of Public Policy and Management, 1998.
(43) *Energy Prices*; U.S. Department of Energy, Energy Information Administration: Washington, DC, 2002.
(44) Sezgen, O.; et al. *Wind Generation in the Future Competitive California Power Market*; Technical Report; Lawrence Berkeley National Laboratory: Berkeley, CA, 1998.

Received for review June 27, 2001. Revised manuscript received March 20, 2002. Accepted May 1, 2002.

ES0155884