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

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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 CO₂ 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.

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 CO₂ 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...
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 matrices 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 of greenhouse emissions (CO₂, CH₄, N₂O) 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 global warming potentials (M) and their specific time-dependent global warming potential potential (GWP). Since GWP compares the effect of GHG emissions to the emission of a similar amount of CO₂ 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)

\[
GWP = \frac{\int_{0}^{TH} a_j [x_j(t)] dt}{\int_{0}^{TH} a_j [x_j(t)] dt}
\]

where \(a_j\) 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); \(a_j\) is the radiative efficiency of CO₂, which is assumed to be 1 because all other GHGs are compared to CO₂; \(x_j\) 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); \(x_j\) in the denominator represents the CO₂ 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 CO₂ equivalent, MT of CO₂ equiv) is

\[
GWE = \sum M_j \times GWP_{j,TH}
\]

where \(M_j\) is the amount of the instantaneous emission of each GHG (in metric tons, MT); \(GWP_{j,TH}\) is the global warming potential for each GHG over the time period \(TH\) calculated using eq 1. For example, the GWE of CH₄ 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 CO₂ remaining in the atmosphere in the future. In addition to GWP calculations for CH₄, it is assumed that after atmospheric decay all CH₄ oxidizes into CO₂, which is captured by the radiative efficiency of CH₄, and thus is accounted for as additional CO₂ (12). The CO₂ 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 hydropower producer in the nation with 56 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 m² 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, 17 219 319, $4 229 195, and $7 673 175, for a total of $12 071 448 in 1987 (21). The contract cost 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 CO₂ response function (13), the estimated GWE of Glen Canyon’s construction is 500 000 MT of CO₂ 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 CO₂.

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 CO₂ emissions, or about 1% of the estimated CO₂ emissions from Glen Canyon’s initial construction (800 000 MT of CO₂).
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 emissions are reduced as the flooded vegetation decays over time. 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

\[ NEP = NPP - \frac{C}{\tau} \]  

(3)

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

\[ \tau = 42.8 \times e^{-192.1/[283.15 - 139.4 - 1/\text{MAT} - 139.4]} \]  

(4)

Using 298 K for the local mean annual temperature (MAT), \( \tau \) was calculated as 15 yr. On the basis of annual NPP of 0.032 kg of C/m² (24) and carbon density in the desert scrub ecosystem (0.3 kg of C/m²; 24), the annual NEP was calculated as 12 g of C/m². Assuming constant carbon sequestration rates, the estimated GWE due to theforgone carbon uptake of the flooded area is 400 000 MT of CO₂ 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 3 000 000–5 000 000 MT of CO₂ equiv (after 20 yr). [The CO₂ response function was used to calculate these values.]

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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 3 000 000–5 000 000 MT of CO₂ 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 CO₂ 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 \( \times 3 \) 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 m² 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 \( \times 118 \) 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 m² 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 1. Major Construction Inputs and GWE (after 20 yr) for Glen Canyon Hydroelectric Plant

<table>
<thead>
<tr>
<th>inputs</th>
<th>total MT</th>
<th>unit cost (1992 $/MT)</th>
<th>total cost (1992 $)</th>
<th>GHG emissions (MT of CO₂ equiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>concrete</td>
<td>9 906 809</td>
<td>30(^{b})</td>
<td>297 652 257</td>
<td>400 792 + CH₄ + N₂O = GWE</td>
</tr>
<tr>
<td>excavation (m²)</td>
<td>4 711 405</td>
<td>na</td>
<td>114 839 000</td>
<td>3 812</td>
</tr>
<tr>
<td>turbines and turbine generator sets</td>
<td>na</td>
<td>na</td>
<td>65 193 084</td>
<td>41 725 + CH₄ + N₂O = GWE</td>
</tr>
<tr>
<td>power distribution and transformers</td>
<td>na</td>
<td>na</td>
<td>13 754 764</td>
<td>12 358 + CH₄ + N₂O = GWE</td>
</tr>
<tr>
<td>steel</td>
<td>32 183</td>
<td>385(^{c})</td>
<td>12 402 138</td>
<td>43 710 + CH₄ + N₂O = GWE</td>
</tr>
<tr>
<td>copper</td>
<td>90</td>
<td>2 368(^{c})</td>
<td>214 167</td>
<td>29 + CH₄ + N₂O = GWE</td>
</tr>
<tr>
<td>aluminum</td>
<td>67</td>
<td>1 268(^{c})</td>
<td>84 804</td>
<td>2 + CH₄ + N₂O = GWE</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
<td>503 240 216</td>
<td>500 000 + 1 000 + 9 000 = 500 000</td>
</tr>
</tbody>
</table>

\(^{a}\) Total emissions are rounded to one significant digit. MT, metric ton; GWE, global warming effect; na, not available. \(^{b}\) Ref 39. \(^{c}\) Ref 40.
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 CO2 equiv, and the decay of the biomass removed from the site during construction amounts to 40 000 MT CO2 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 CO2 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 70 000 MT of CO2 emissions, one-third of the original emissions from manufacturing and constructing the plant (1 300 000 MT of CO2).

**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 m2 (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 CO2 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 CO2 emissions, two-thirds of the original emissions from manufacturing and constructing the plant (1 300 000 MT of CO2).

**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 CO2 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 CO2 emissions, one-third of the original emissions from manufacturing and constructing the plant (200 000 MT of CO2).
TABLE 4. Major Construction Inputs and GWE (after 20 yr) for a Coal-Fired Power Plant

<table>
<thead>
<tr>
<th>Construction Inputs</th>
<th>total MT</th>
<th>unit cost (1992 $/MT)</th>
<th>total cost (1992 $)</th>
<th>GHG emissions (MT of CO₂ equiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ CH₄</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ N₂O</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= GWE</td>
</tr>
<tr>
<td>Operational Inputs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coal combustion</td>
<td>2 336 000</td>
<td>28.76c</td>
<td>61 180 849</td>
<td>75 825 360</td>
</tr>
<tr>
<td>natural gas extraction</td>
<td>1 560 300</td>
<td>0.130c</td>
<td>177 347 844</td>
<td>38 800 368</td>
</tr>
<tr>
<td>natural gas transportation</td>
<td>1 560 300</td>
<td>0.068</td>
<td>93 821 050</td>
<td>3 630 894</td>
</tr>
<tr>
<td>concrete</td>
<td>3 000 000</td>
<td>0.061c</td>
<td>83 526 794</td>
<td>8 552 990</td>
</tr>
<tr>
<td>steel</td>
<td>62 200</td>
<td>385.37a</td>
<td>21 826 601</td>
<td>83 261</td>
</tr>
<tr>
<td>concrete</td>
<td>178 320</td>
<td>29.95c</td>
<td>4 863 858</td>
<td>6 569</td>
</tr>
<tr>
<td>aluminum</td>
<td>624</td>
<td>1 267.66d</td>
<td>720 289</td>
<td>1 331</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>90 000 000</td>
<td>400 000</td>
<td>2 000 000</td>
<td>90 000 000</td>
</tr>
</tbody>
</table>

* Total emissions are rounded to one significant digit. a Includes fuel consumption over an assumed service life of 20 yr. b Ref 39.

table columns

1. 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 CO₂ equival.

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 60 000 000 MT of CO₂ emissions, about 60% of the original emissions from manufacturing and constructing the plant (100 000 000 MT of CO₂).

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 CH₄ 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 CO₂ 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...
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.

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Literature Cited
(1) Post, N. M. ENR 2001, 247, 16.