Life-Cycle Energy Requirements and Greenhouse Gas Emissions for Building-Integrated Photovoltaics

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FUSION TECHNOLOGY INSTITUTE

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ABSTRACT

This study performs a life-cycle assessment on a building-integrated photovoltaic (PV) power system and evaluates the net energy payback and greenhouse gas emission rates. The system studied utilizes 8 kilowatts (kW) of amorphous silicon PV material incorporated into standard metal roofing panels. The PV system, located in Silverthorne, Colorado, converts sunlight to direct current (DC) electricity at 6% efficiency.

Life-cycle assessment considers "upstream" and "downstream" processes, such as raw materials production, fabrication of system components, transportation, installation, operation and maintenance, and decommissioning. The energy payback ratio (EPR) is the ratio of useful electrical output to the total energy inputs. The PV system EPR is 6, higher than gas turbine technology (4), but lower than coal (11), fission (16), fusion (27), and wind turbine (23) technologies.

Net energy analysis is utilized as the basis for calculating a greenhouse gas emission rate. The PV life-cycle emits 39 tonnes of carbon dioxide equivalent for every gigawatt-hour of electricity produced (T/GW_eh). This emission rate is substantially lower than conventional coal (974 T/GW_eh) and gas turbine (464 T/GW_eh) technologies, and higher than fission (15 T/GW_eh), fusion (9 T/GW_eh), and wind (14 T/GW_eh) technologies.

1.0 INTRODUCTION

Studies in the 1970's argued that the energy required to produce a photovoltaic (PV) system was greater than the energy generated by the system over its lifetime.[1] More recent studies have revealed that current PV systems are in fact net energy producers, but they are an expensive alternative when compared to conventional sources. Utilizing building-integrated PV systems reduces the net system cost by replacing conventional building materials and avoiding the cost of land acquisition. In addition, generating electricity at the point of use avoids the cost of transmission and distribution. Perhaps most importantly, PV systems generate electricity with minimal associated emissions by relying on solar radiation as their source of energy.

This study performs a life-cycle assessment on a building-integrated PV system and evaluates the net energy payback and greenhouse gas emission rates. The PV system, located in Silverthorne, Colorado, utilizes 8 kilowatts (kW) of amorphous silicon PV material incorporated into standard metal roofing panels. The net energy requirements and greenhouse gas emissions from the PV system are compared against previous studies of gas turbine, coal, fission, fusion, and wind turbine technologies.

2.0 BACKGROUND

The two metrics developed in this study are the life-cycle energy payback ratio (EPR) and the life-cycle greenhouse gas emission rate. The EPR is the ratio of useful electrical output to the total energy inputs, which is one method to evaluate the efficiency of a system. Energy choices are typically based on economic cost and not energy efficiency; however, the EPR is a relevant metric when considering ultimate energy resource availability in a global sense. The EPR provides a long-term perspective on how to maximize the productivity of our combined energy resources. This perspective is especially important in the United States, which consumes 25% of the world's energy annually.[2]

The U.S. emits almost one-quarter of the world's anthropogenic (human generated) greenhouse gas emissions[3], in relative proportion to energy consumption. The correlation between greenhouse gas emissions and global warming has continued to improve. Recent observations confirm the warming of each major component of the earth's climate: the atmosphere, oceans, and cryosphere.[4,5] Most of the warming of the last 50 years is believed to be the result of increased greenhouse gas concentrations.[6] A host of adverse impacts are expected to accompany climatic change, including increased floods and droughts, sea-level rise, damaged ecosystems, and increased heat-stress mortality.[7]

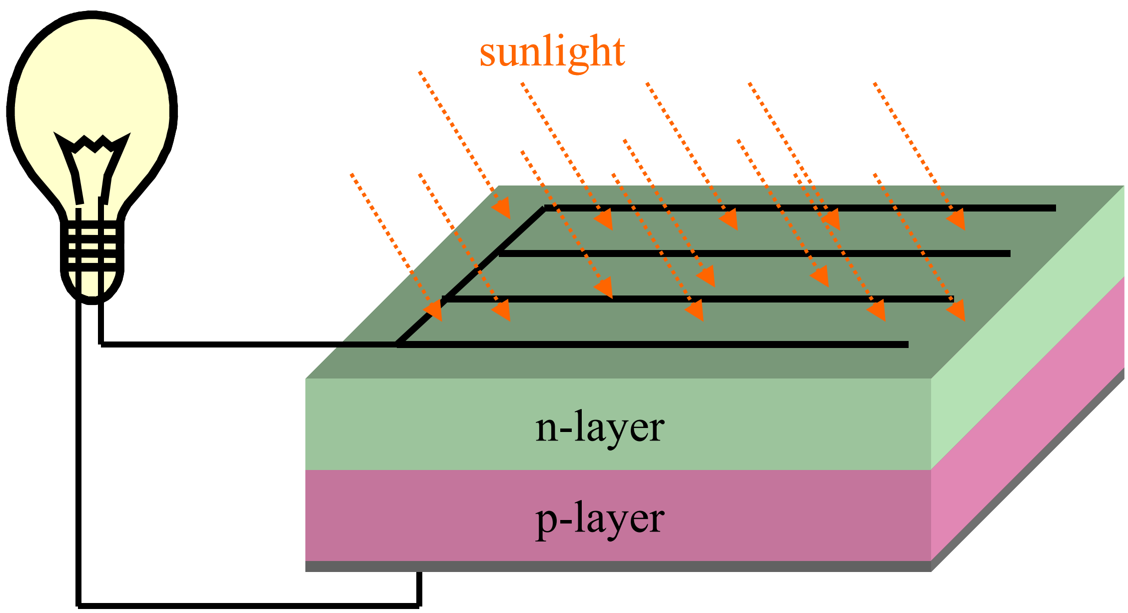
This study illustrates the greenhouse gas impact associated with electricity generation technologies. U.S. electricity generation represents the largest single source of greenhouse gases, contributing 40% of domestic emissions and 9% of the global emissions.[2] Accordingly, minimizing the impact of electricity generation is a key component for successful climate change mitigation. Building-integrated PV is an emerging alternative for generating electricity with minimal associated emissions.

3.0 BUILDING-INTEGRATED PHOTOVOLTAICS

3.1 Photovoltaic Principles

PV devices convert sunlight directly into electricity.[8] When solar radiation (in approximately the same spectrum as visible light) strikes a semiconductor material such as silicon, it provides enough energy to mobilize electrons. A simple photovoltaic cell (Figure 1) consists of two silicon layers, one doped with phosphorous to provide excess electrons (n-layer), and one doped with boron to create an electron deficiency (p-layer).[9] When the p and n layers are connected into a circuit, electrons mobilized by incident solar radiation move across the p-n potential, creating electricity.

Figure 1: Simple Photovoltaic Cell



3.2 PV Technologies

PV technologies were initially developed for space applications and utilized crystalline silicon technology. The single-crystal and multicrystalline technologies both require the manufacture of silicon ingots that are sliced into thin wafers to create silicon solar cells.[9]

Crystalline PV modules provide the best available conversion efficiencies and currently comprise nearly 90% of the PV market.[10] However, the high material costs and expensive manufacturing make it difficult for crystalline technologies to compete with conventional electricity generation except in remote applications. For this reason, future applications of PV will likely utilize "thin film" technology.[9]

Thin film PV modules have lower conversion efficiencies than crystalline wafers, but have the advantage of cheaper manufacturing costs. The leading candidates for low-cost PV are amorphous silicon, polycrystalline compounds, and thin-film silicon.[10] Amorphous silicon was the first thin-film material commercially available and is better suited to high volume manufacturing than its crystalline predecessors.[9] Amorphous silicon lacks perfect crystalline geometry; consequently, electronic performance is lower than crystalline cells.[9] Currently, the best commercial modules utilize three cell layers and have conversion efficiencies around 6-7%.[9]

Polycrystalline compound technology provides higher conversion efficiencies than amorphous silicon by introducing more efficient semiconductor materials. Cadmium telluride modules currently reach efficiencies beyond 9%, and copper indium diselenide modules reach efficiencies greater than 11%.[10] Unfortunately, this technology has some disadvantages compared to amorphous silicon, including reliance on toxic and scarce materials, and more complicated manufacturing.[9]

Thin-film silicon is a promising future technology that attempts to improve on silicon conversion efficiency while still using low-cost polycrystalline silicon. Design techniques are utilized that trap light in silicon for total absorption, allowing for thin cells with high efficiencies. Laboratory-scale cells have demonstrated conversion efficiencies as high as 17%.[11] This technology is not yet commercially available, but may be utilized in conjunction with amorphous silicon as early as 2002.[9]

3.3 Building Integration

When first developed for ground-based applications, large centralized PV systems were intended to compete with conventional electricity generation. Despite continuous efficiency improvement, the cost of generating electricity from such systems is usually considered cost prohibitive.[12] Building integration of photovoltaics began in the 1980's, as a method to reduce the economic and energy costs of these systems by incorporating PV modules into the building design.[13] Conventional building components, such as roofing, façade, and windows, can be replaced with PV panels or coated with thin-film PV material. The building used as the basis for this study utilizes amorphous silicon PV material bonded onto standing-seam metal roof panels. This system is described in more detail in Section 5.1.

3.4 Installed Capacity and Growth

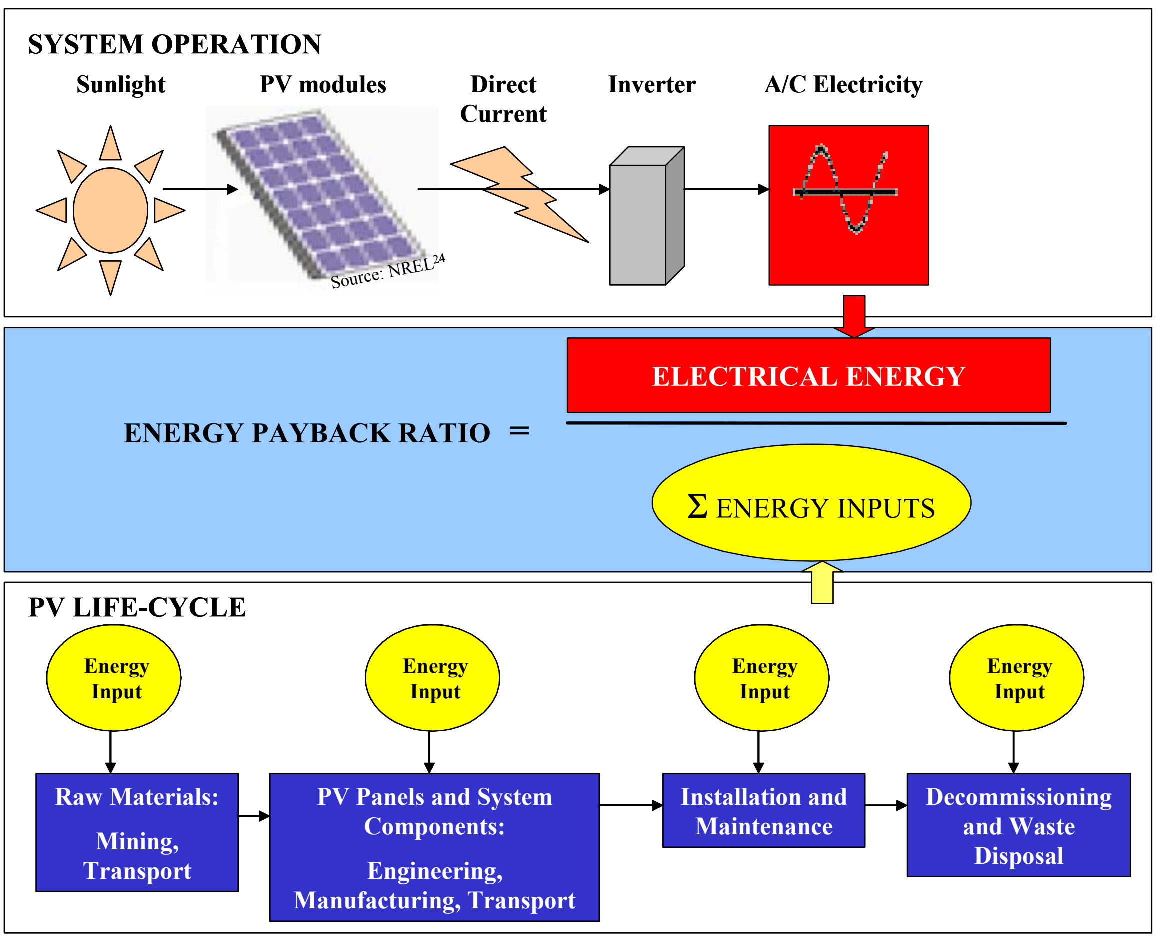
Worldwide grid-connected PV applications have grown over 20% per year from 1982 to 1997.[8] The United States currently has 21 megawatts (MW) of installed photovoltaic capacity in 1999, of which approximately 0.3 MW are located in Wisconsin.[13,14] Growth in PV power in the near future is highly dependent on improvements in installed cost, availability of government subsidy, and the future cost of competitive sources of electricity.[9]

4.0 METHODS OF ANALYSIS

4.1 Net Energy Analysis

Net Energy Analysis (NEA) is a comparison of the useful energy output of a system to the total energy consumed by the system over its life-cycle. The PV life-cycle, shown in Figure 2, includes mining and transporting raw materials, manufacturing and transportation of PV panels and other system components, transportation of the finished product, installation and maintenance, and system decommissioning. NEA compares the energy inputs from each of these phases to the useful electrical output.[15] The resulting ratio of the useful energy output to the total energy input is termed the "Energy Payback Ratio" (EPR).[16]

Figure 2: Photovoltaic Life-Cycle and Energy Payback Ratio



The output energy for a PV system can be based on actual performance data, or estimated using the average solar insolation rate and the module conversion efficiency. The input energy can be estimated by two methods, called Process Chain Analysis (PCA) and Input/Output (I/O).[17] PCA evaluates the material and energy flows for each process within the system life-cycle. This methodology relies on actual data for the primary energy expended during each step, such as the electricity (converted to primary energy) to manufacture the PV module, or the diesel fuel consumed in transporting the completed modules to the building site. The PCA method requires defining a system boundary for analysis. PCA cannot practically consider the entire economy and is therefore subject to truncation error, a slight underestimation of energy inputs.[17]

The Input/Output (I/O) method correlates dollar cost to energy use. The input/output model used in this study divides the U.S. economy into 485 distinct sectors.[18,19] These sectors are the basis for a matrix, which distributes the total cost of outputs and total energy inputs of the U.S. economy.[20] The model estimates the total energy consumed directly and indirectly throughout the economy based on the cost of goods or services procured from a given sector. The I/O method averages prices across sectors and therefore introduces inaccuracies when the actual energy intensity of a process differs from the sector average.

PCA is highly reliable with small truncation errors for many processes.[17] However, it is difficult to evaluate an entire life cycle using PCA, because data on energy consumption is not always readily available. Cost data is frequently available; therefore, the input/output method is more easily applied to many processes. In most cases, a combination of PCA and I/O is the preferred approach to net energy analysis.[17] This study utilizes PCA primarily, but relies on the I/O method to provide estimates of energy requirements for installation, maintenance, and decommissioning.

4.2 Greenhouse Gas Emission Rate

PV systems generate electricity using the photovoltaic effect, which in itself has no associated emissions. However, the greenhouse gas emission rates calculated in this study incorporate all components of the system life-cycle such as manufacturing, transportation, and maintenance. As a result, non-fossil fuel electricity systems have a greenhouse gas impact due to their reliance on the existing fossil fuel infrastructure. Carbon dioxide, a byproduct of fossil fuel combustion, is the most important greenhouse gas based on total global emissions. Methane and nitrous oxide emissions occur in much smaller quantities but are respectively 21 and 310 times stronger global warming agents. Emissions of the lesser greenhouse gases are accounted for in terms of CO_2-equivalent emissions.

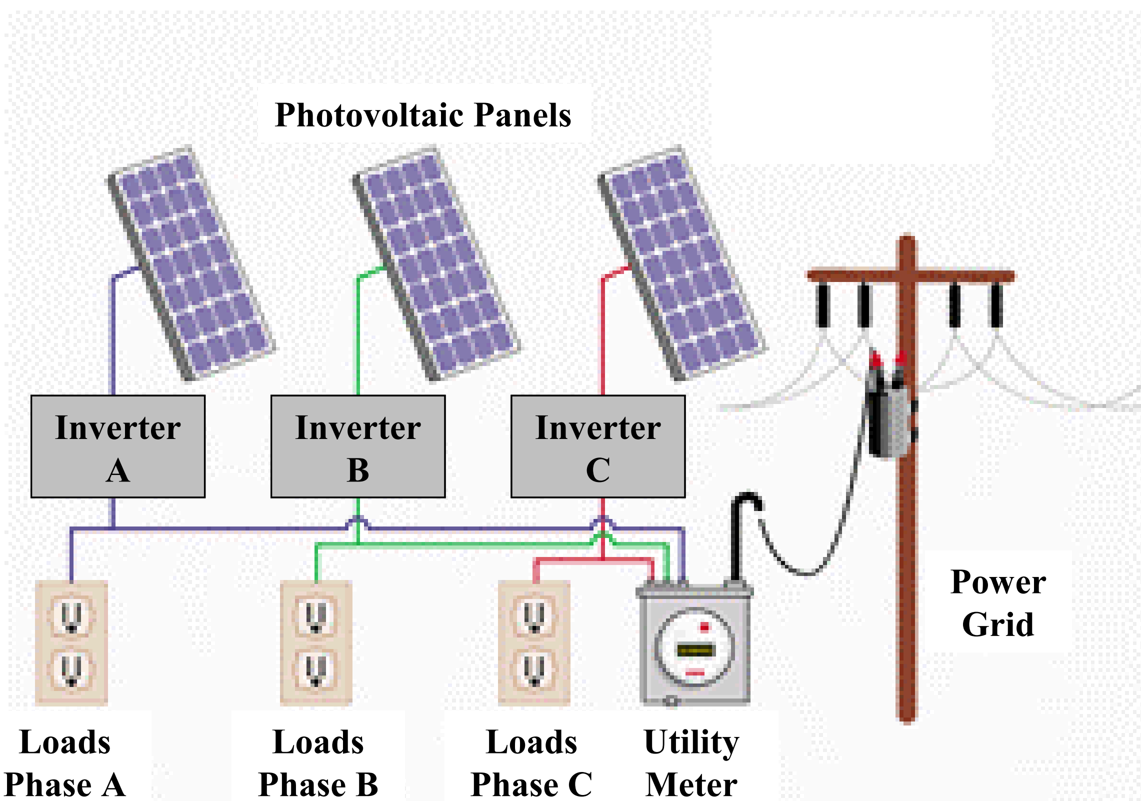
Net energy analysis provides a convenient and accurate basis for estimating greenhouse gas emissions. The relationship between the type and quantity of the fuel consumed and the resulting emissions is well established. Multiplying the individual energy inputs by a corresponding emission factor provides greenhouse gas emission estimates for each component of the life-cycle. The total emissions are normalized in terms of tonnes CO_2-equivalent emitted per gigawatt-hour electricity produced (T/GW_eh), allowing for comparison against alternative technologies.

5.0 PHOTOVOLTAIC LIFE-CYCLE ASSESSMENT

5.1 System Description

The BigHorn Center, located in Silverthorne, Colorado, is site to a building-integrated photovoltaic (PV) system utilizing thin-film amorphous silicon technology.[21] 157 m^2 of Uni-Solar® PV material is laminated onto the building's south facing roof panels. Under peak sunlight, these modules generate up to 8 kW of direct current (DC) electricity, collected at three combiner boxes.[22] Each combiner box connects to a separate inverter, which converts the DC current to alternating current (AC) tied directly to the building's three-phase electrical system (Figure 3).[23] The system is also grid-tied, and excess electricity may be sold to the local utility under a net-metering agreement.[24]

Figure 3: Three-Phase Photovoltaic System (Source: NREL[24])



5.2 Energy Output

The output of the PV life-cycle is defined as the total AC electricity generated over the lifetime of the system. At high altitude in Colorado, the amount of solar radiation incident on the PV modules will average about 5.3 kWh/m^2-day. The output for the system is largely controlled by the efficiency at which the modules convert this sunlight to electricity. The Uni-Solar® PV modules are factory rated to convert solar radiation to DC electricity at 5.7% efficiency.[26] At this efficiency, the BigHorn Center array could generate 17,000 kWh of DC electricity each year (61 GJ/year) assuming optimal orientation. Approximately 10% of the potential solar energy is unavailable due to the slightly less than optimal orientation of the BigHorn Center PV modules.

The BigHorn Center array generates 8 kW of DC power during peak insolation; however, electrical system losses at the inverters (converting DC to AC) and throughout the system (line losses) reduce the available AC power by approximately 20% to 6.4 kW.[22] Environmental deterioration will reduce module performance by an estimated 15% by the end of its useful life.[25] Assuming degradation occurs at a constant rate over 30 years (0.55%/yr), the cumulative impact of module degradation will reduce the average annual output by 8%. Therefore, the expected output for the BigHorn Center system is approximately 10,800 kWh per year (39 GJ/year), after consideration of system losses and degradation. Over a 30 year lifetime, the total expected energy output is 1,160 GJ.

The performance of any new PV system is somewhat uncertain. Preliminary data during March 2001 showed the system to underperform design expectations by about 25%. This is not uncommon for PV systems during the first months of operation, and system performance is expected to meet design expectations following a short period of system optimization.[22] The expected 30-year output (1,160 GJ) is therefore considered to provide the best estimate of long-term performance for this study and is used to calculate the Energy Payback Ratio in Section 6.1.

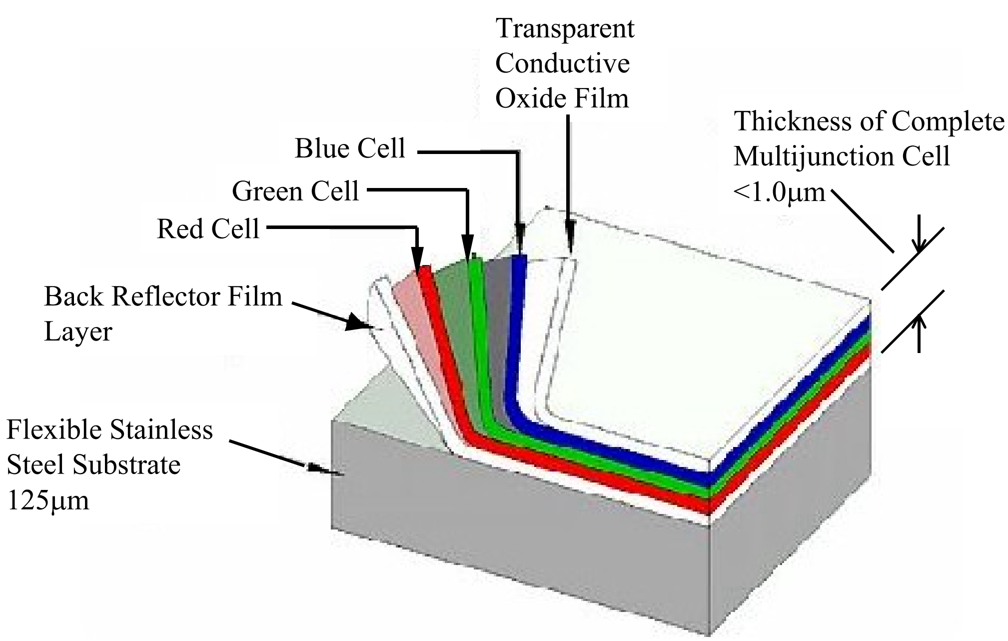
5.3 Energy Inputs and Greenhouse Gas Emissions

The following sections describe the components of the PV life-cycle. Energy inputs and greenhouse gas emissions are estimated for each component.

5.3.1 PV Modules

The Uni-Solar® PV modules consist of a thin sheet of stainless steel substrate onto which various thin-film layers are sequentially deposited.[26] Three separate amorphous silicon cells (Figure 4) are used to convert visible and near-infrared solar radiation to electricity. Each layer responds optimally to a different spectral distribution, improving overall conversion efficiency. A transparent conductive oxide film conducts the mobilized electrons to the module terminal. Solar energy that passes through without absorption is reflected back through the cells by the back reflector layer. A polymer matrix encapsulates the finished module and inhibits environmental deterioration.

Figure 4: Uni-Solar® Triple Junction Amorphous Silicon Thin Film PV Cell[26]



The BigHorn Center system consists of 123 PV modules laminated onto standard galvanized aluminum standing seam roofing panels, providing 157 m^2 of surface area. The energy inputs associated with the PV modules (Table 1A) include acquisition and processing of primary materials, intermediate transportation, module manufacturing, engineering and administration, and final transportation. The energy required to manufacture and install the roofing panels is intentionally excluded, assuming that the building would require a similar roof regardless of the addition of the PV system. However, the energy required to transport the module (roofing panel and PV material) from San Diego to Silverthorne is included (1000 miles), assuming that alternative roofing material could otherwise be obtained from Denver (70 miles). Details on energy inputs and emissions are included in Appendix A.

Table 1A: PV Module Life-cycle Energy Requirements

Process	**Energy Input (GJ)**	**% of Total**	**Method**
Materials and Manufacturing	123	73%	PCA
Engineering and Administration	39	23%	PCA
Finished Product Transportation	7	4%	PCA
Total PV Module Energy Input	**170**		

Greenhouse gas emissions (Table 1B) are estimated by multiplying the energy requirements (Table 1A) by fuel-specific emission factors. Energy and emissions associated with materials and manufacturing are based on a detailed study of a similar Uni-Solar® PV module (Keoleian and Lewis 1997).[27]

Table 1B: PV Module Life-cycle Greenhouse Gas Emissions

Process	**Tonnes CO_2-equivalent**	**% of Total**
Materials and Manufacturing	7.3	73%
Engineering and Administration	2.2	22%
Finished Product Transportation	0.5	5%
Total PV Module Emissions	**10.1**	

5.3.2 Balance of System

The PV system components, excluding the modules themselves, are collectively referred to as the Balance-of-System (BOS). The BOS consists of combiner boxes, inverters, circuit breakers, lightning arrestors, and several hundred feet of electrical wiring and conduit.[22] Modules are laminated directly onto roofing panels; therefore no array support is required. The majority of the BOS energy consumption occurs during inverter manufacturing. Lesser energy requirements are associated with system electrical wiring. The energy associated with remaining components is presumably small.[36] The BOS energy inputs (Table 2A) are estimated using PCA methods based on material requirements. The associated greenhouse gas emissions are shown in Table 2B. Emissions from electricity consumption are based on the average U.S. emissions from electricity generation.

5.3.3 Installation, Operation and Maintenance

Installing the building-integrated PV system involves mounting the roofing panels, connecting the PV modules, and installing and connecting the BOS. A portion of the installation energy is excluded from the NEA, assuming builders would install a similar roof regardless of the addition of the PV system. The reliability of power conditioning equipment is the primary consideration for determining operation and maintenance (O&M) energy requirements.[28,29] This study assumes a 15-year inverter lifetime (i.e., inverters are replaced once). The energy inputs for O&M are shown in Table 2A, and the associated greenhouse gas emissions are shown in Table 2B.

5.3.4 Decommissioning and Disposal

Decommissioning and disposal is generally considered a negligible component of the energy input requirements and is frequently omitted from analysis. While future recycling programs are viable for some PV technologies,[30] it is likely that amorphous silicon modules would be disposed of at the end of their useful life. The PV modules in the BigHorn Center system contain no toxic semiconductor materials and are therefore suitable for sanitary landfill disposal. Energy requirements and emissions are estimated for landfilling of the PV system components and disposing of wastes associated with manufacturing (See Tables 2A and 2B).[30,31]

Table 2A: BigHorn Center PV System Life-cycle Energy Requirements

Process	Energy Input* (GJ)	% of Total	Method
PV Modules (See Table 1A)	169.6	82.8%	PCA
Balance of System	6.9	3.4%	PCA
Installation, Operation & Maintenance	24.0	11.7%	I/O & PCA
Decommissioning	4.3	2.1%	PCA
Total PV Life-cycle Energy Input	**205**	**100%**	

*Details are included in Appendix A.

Table 2B: BigHorn Center PV System Life-cycle Greenhouse Gas Emissions

Process	Tonnes CO_2-equivalent*	% of Total
PV Modules (See Table 1B)	10.07	80.5%
Balance of System	0.47	3.8%
Installation, Operation & Maintenance	1.67	13.4%
Decommissioning	0.30	2.4%
Total PV Life-cycle Emissions	**12.5**	**100%**

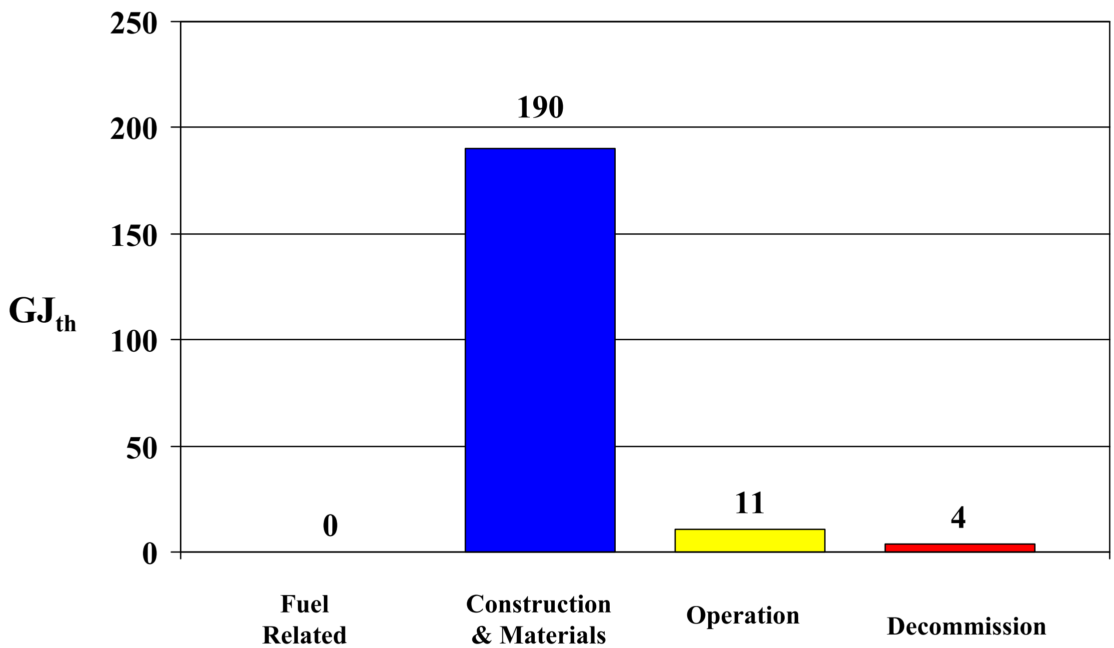
*Details are included in Appendix A.

6.0 DISCUSSION

6.1 Net Energy Analysis

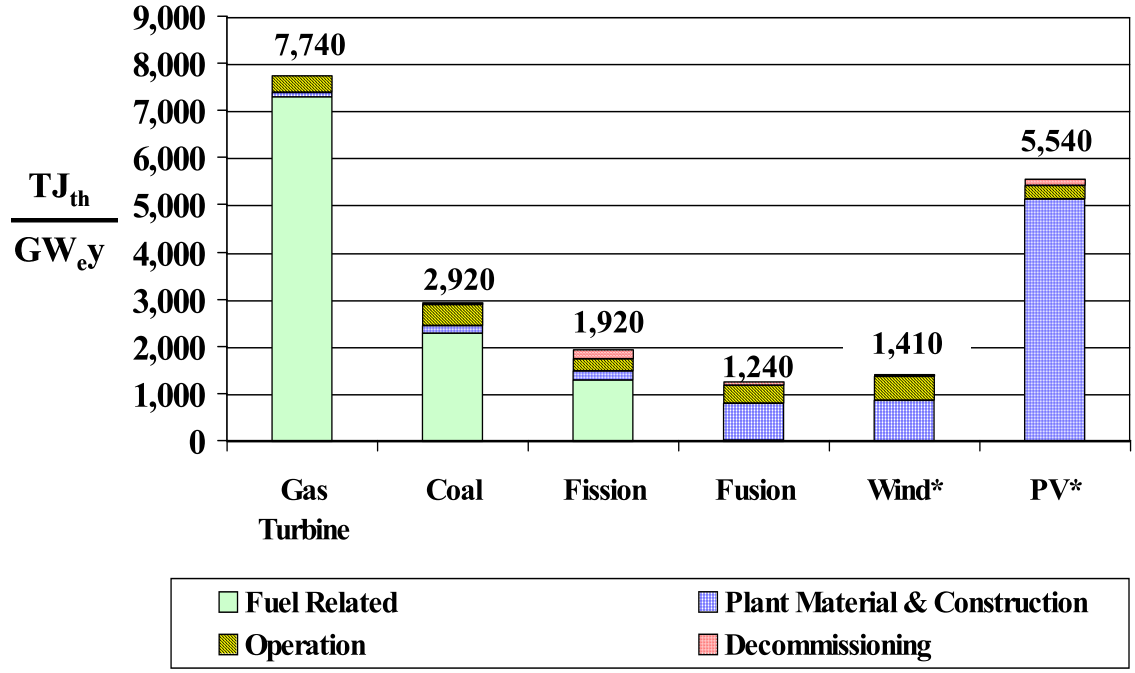
As discussed in Section 5, a total of 205 GJ of energy is consumed throughout the life-cycle of the PV system. These inputs are grouped into 4 categories shown in Figure 5. Almost 90% of the PV energy input is associated with system materials and construction (installation). Most of the remainder is consumed during operation and maintenance, with a negligible fraction consumed for decommissioning and disposal.

Figure 5: Life-cycle Energy Requirements



Normalizing the inputs in units of terajoules input per gigawatt-year of electric output (Figure 6) allows for comparison to alternative technologies. Materials and construction constitute the majority of energy inputs for PV, wind and fusion technologies. Gas turbine, coal, and fission technologies consume the majority of their energy inputs during fuel acquisition and fuel transportation.[32,33] Because PV technology relies on sunlight, there is no energy required to procure "fuel". Radiation that is reflected or lost to waste heat is not considered an energy input. The analogous convention was applied to each of the technologies described in this study (e.g., the energy in natural gas consumed at the gas turbine plant, the energy content of coal, and the energy content of the enriched uranium at the fission plant is also excluded).

Figure 6: Normalized Energy Requirements Comparison to Previous Work[33,34]



*Wind and PV analysis excludes energy storage

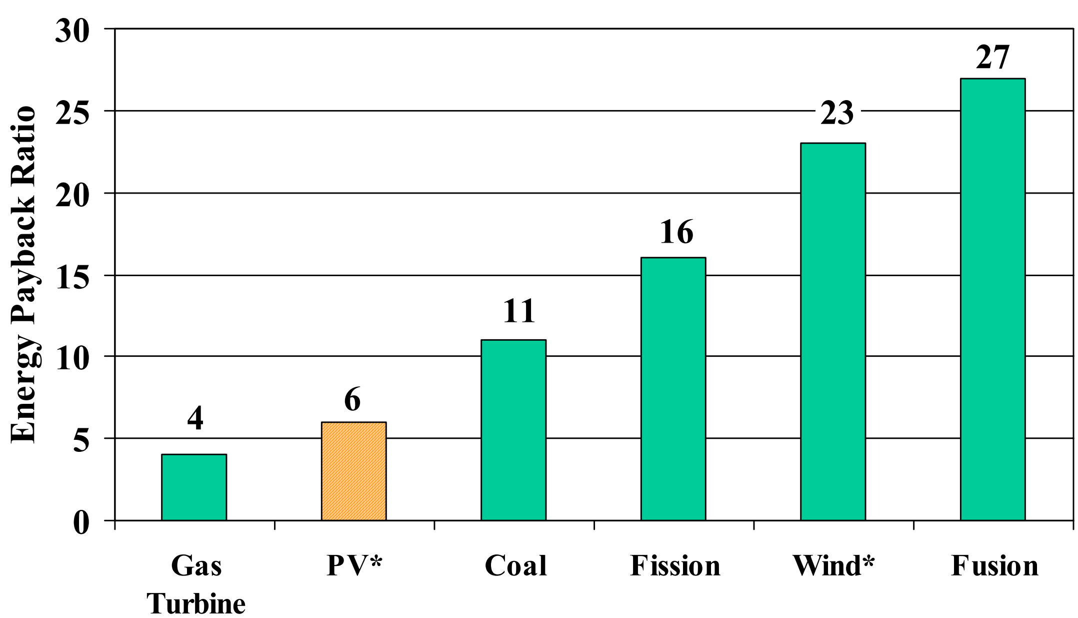
The Energy Payback Ratio for the BigHorn Center PV system is 6, calculated by the procedure shown in Figure 7. This EPR is higher than gas turbine technology (4), but lower than coal (11), fission (16), fusion (27) and wind (23) technologies (Figure 8).[34,35] Fundamental differences between technologies make more precise comparisons difficult, such as intermittent versus continuous (base load) sources, and distributed versus centralized generation. Coal, fission, and fusion technologies all assume a plant capacity factor of 75%, while the wind and PV systems have capacity factors of about 30% and 20% respectively. PV and wind analysis exclude provisions for electrical storage, which would allow for a continuous power supply and make these systems more comparable to base load systems. Consideration of storage would reduce the EPR for wind and PV systems. On the other hand, the electricity generated by the PV system is utilized onsite. This is an advantage over centralized power plants that will incur an average transmission loss of 3% prior to end use, in addition to the life-cycle energy requirements of the transmission system. Consideration of transmission would reduce the EPR of centralized generation relative to distributed systems like PV.

Figure 7: Energy Payback Ratio Calculation for Photovoltaics

Life-cycle Energy Inputs (GJ_{th})	Life-cycle Output (GJ_e)
Fuel Related: 0	Net Electrical Output: 1,164
Materials & Installation: 190	
Operation & Maintenance: 11	
Decommission: 4	
Total: 205	

$$\text{Energy Payback Ratio (EPR)} = \frac{\text{Output}}{\text{Input}} = \frac{1{,}164}{205} = 6$$

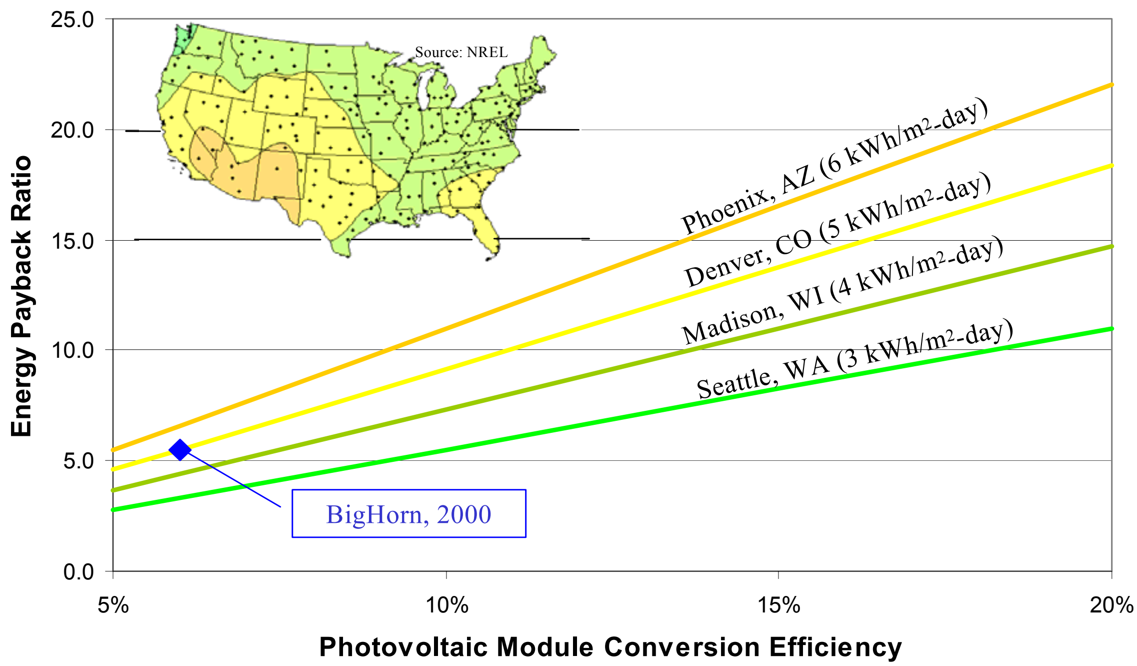
Figure 8: Energy Payback Ratio Comparison to Previous Work[33,34]



*Wind and PV analysis excludes energy storage

The EPR for the BigHorn Center PV system is limited by the module's 6% conversion efficiency. Thin-film PV is an emerging technology, with conversion efficiencies potentially exceeding 20% in the next two decades.[10] In addition to conversion efficiency, the amount of available solar energy (Figure 9) directly affects the PV output. Depending on its location and conversion efficiency, the EPR of a comparable system could reach 22 (Figure 9).

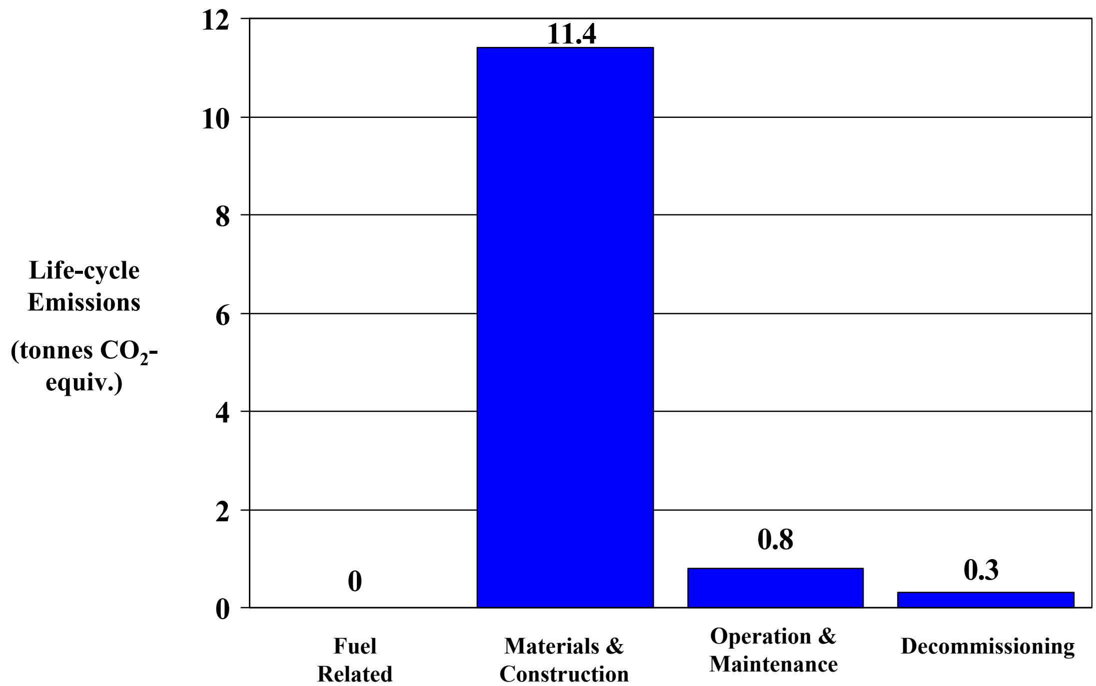
Figure 9: Correlation of Conversion Efficiency and Insolation to EPR



6.2 Greenhouse Gas Emission Rate

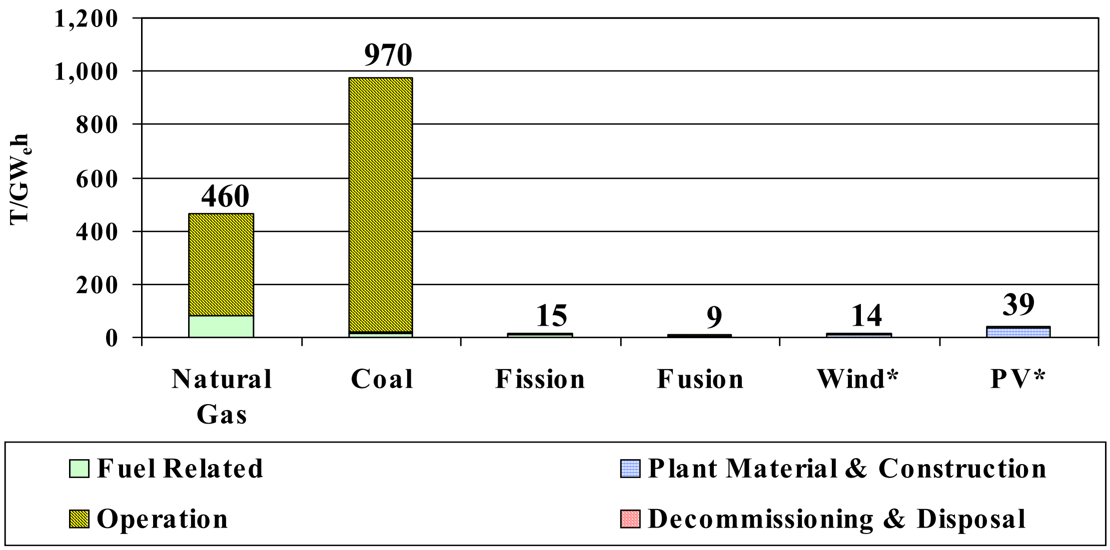
The energy inputs calculated for the net energy analysis provide the basis for estimating greenhouse gas emissions. As shown in Section 5, approximately 12.5 tonnes of CO_2-equivalent greenhouse gases are emitted throughout the life-cycle of the BigHorn Center PV system. The majority (91%) of the life-cycle greenhouse gas emissions are associated with materials and construction (Figure 10), in direct correlation to energy consumption. The O&M and decommissioning contribute 6% and 2% of life-cycle emissions respectively.

Figure 10: Life-cycle Emissions for Photovoltaic Electrical Energy Generation (BigHorn Center PV System)



Dividing life-cycle emissions by the useful electricity produced normalizes life-cycle emissions and allows for comparison to other technologies. Figure 11 compares the PV life-cycle emission rate to other technologies in terms of tonnes of CO_2-equivalent emissions per gigawatt-hour of electricity produced (T/GW_eh). The PV emission rate of 39 tonne/GW_eh is higher than fusion (9), wind (14), and fission (15). However, because the PV conversion efficiency relates directly to the emission rate, a comparable PV system with 12% conversion efficiency would have an emission rate of only 19 T/GW_eh.

Figure 11: Emissions Comparison to Previous Work[33,34] (Tonnes CO_2-equiv. / GW_eh)

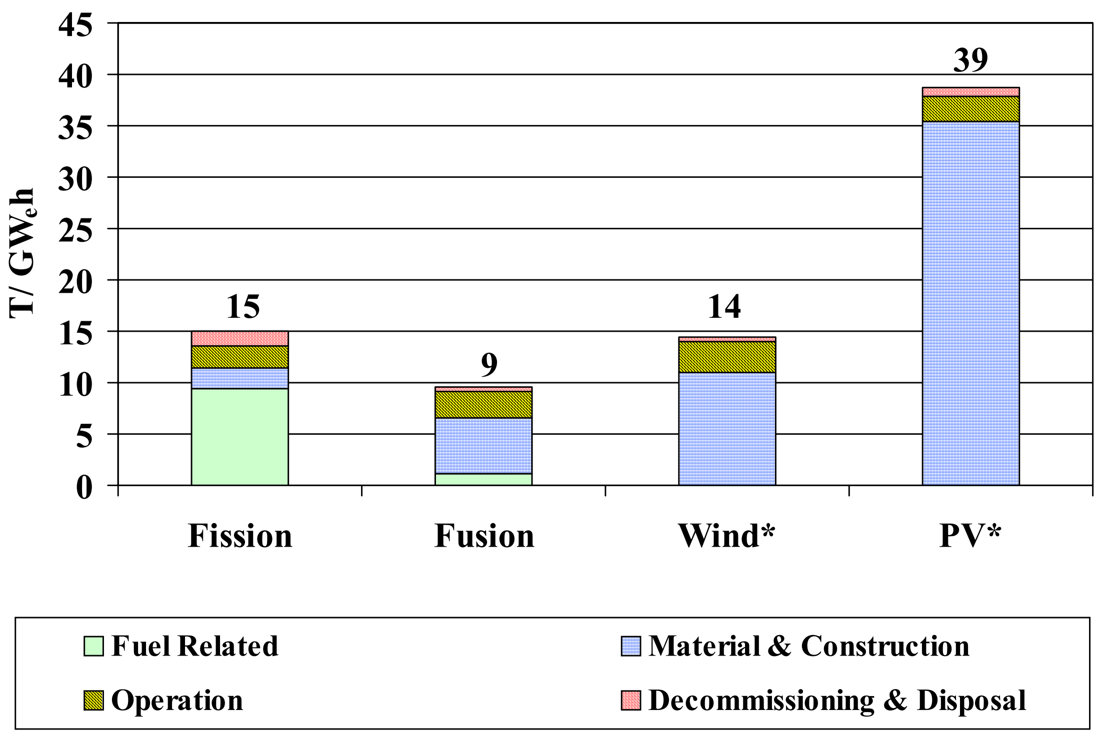


*Wind and PV analysis exclude energy storage.

Unlike the net energy analysis, greenhouse gas emission rates include the fuel consumed during plant operation. As a result, nuclear and renewable technologies have drastically lower emission rates than the fossil fuel technologies. Coal and gas turbine technologies emit considerable CO_2 during fuel combustion, resulting in high emission rates of 970 and 460 tonne/GW_eh respectively.[33,34]

Figure 12 compares the emissions from the nuclear and renewable technologies. Fusion, wind, and PV technologies have similar life-cycle emission profiles. The majority of greenhouse gases for these technologies are generated from materials and construction, with some contribution from O&M and minimal emissions from decommissioning. In contrast, the majority of emissions from fission plants are associated with the fuel cycle. Fission also has relatively significant emissions associated with decommissioning and waste disposal.

Figure 12: Nuclear and Renewable Emission Comparison[34] (Tonne CO_2-equiv. / GW_eh)



*Wind and PV analysis exclude energy storage.

Greenhouse gas emissions from nuclear and renewable technologies occur as a result of their reliance on the U.S. fossil fuel infrastructure. The United States generates 70% of its electricity from fossil fuels. Reducing the fossil fuel component of electricity to 50%, comparable to some European nations, would lower the nuclear and renewable emission rates by about 30%. For PV, the heaviest reliance on fossil fuels occurs due to the consumption of electrical energy during manufacturing. Therefore, as the U.S. electrical generating profile changes, so will the effective greenhouse gas emission rates.

6.3 Comparison to Other Photovoltaic Studies

The energy requirements for amorphous silicon PV module production is reported in the literature between 710 to 1,980 MJ/m^2 over widely varying study parameters.[36] Kato and Alsema report energy requirements of 1,180 and 1,200 MJ/m^2 respectively, for modules similar to those at the BigHorn Center.[37,38] These estimates consider module production only, and exclude final product transport, installation, maintenance, and disposal. Module manufacturing for the BigHorn Center system required 1,100 MJ/m^2 including engineering, administration, and final transportation to site.[27,36] Consideration of the remaining life-cycle components (balance of system, installation, maintenance, and disposal) increased the BigHorn Center energy requirements to 1300 MJ/m^2 in this study. This is well within the range of previous studies and slightly higher than reported by Alsema and Kato.

Comparing emission rates between studies is difficult due to the variance of multiple factors, including the carbon intensity of primary energy, insolation rate, PV conversion efficiency, and system lifetime. Alsema reports a greenhouse gas emission rate of 50 g/kWh, slightly higher than the BigHorn Center system (39 g/kWh).[37] Kato reports a greenhouse gas emissions of 18 kg C/m^2.[38] This is slightly lower than the BigHorn Center, with emissions of 21 kg C/m^2.

6.4 Conclusions

The energy payback ratio (EPR) for a photovoltaic (PV) electrical generating system is controlled largely by the module conversion efficiency. The BigHorn Center PV system has an EPR of 6, lower than coal (11), fission (16), fusion (27), and wind turbine (23) technologies, but higher than gas turbine technologies (4). Considering future improvements in PV conversion efficiency could increase the EPR to as high as 22 in favorable locations. The greenhouse gas emission rate for the PV life-cycle (39 tonnes CO_2-equivalent per GW_eh) is higher than for fusion (9), wind (14), and fission (15), but drastically lower then fossil fuel technologies (460-970). This value is also dependent on conversion efficiency. A comparable system with 12% conversion efficiency would have an emission rate of 19 T/GW_eh.

6.5 Acknowledgments

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SUMMARY OF DATA AND CALCULATIONS

BUILDING INTEGRATED PV LIFE-CYCLE - ENERGY REQUIREMENTS			
Item		**GJ**	**Reference Page**
PV Modules			
	Materials and Manufacturing	123.0	A2
	Engineering & Administration	39.3	A2
	Finished Product Transport	7.2	A2
Balance of System			
	Inverters	4.0	A5
	Wiring	2.9	A5
Installation		12.9	A6
Operation and Maintenance		11.0	A6
Decommissioning and Disposal		4.3	A7
TOTAL LIFE-CYCLE ENERGY (GJ)		**205**	

Energy Payback Ratio Calculation		**Reference Page**
Energy Input (GJ) =	205	A1
Energy Output (GJ) =	1,164	A8
EPR Expected = Output / Input =	**5.7**	

BUILDING INTEGRATED PV LIFE-CYCLE - CO_2-Equivalent Emissions			
Item		**kgCO_2-Equiv**	**Reference Page**
PV Modules			
	Materials and Manufacturing	7,315	A3
	Engineering & Administration	2,221	A4
	Finished Product Transport	534	A4
Balance of System			
	Inverters	290	A5
	Wiring	179	A5
Installation		896.6	A6
Operation and Maintenance		776.5	A6
Decommissioning and Disposal		296.7	A7
TOTAL LIFE-CYCLE EMISSION (tonnes)		**12,508**	

Greenhouse Gas Emission Factor Calculation		**Reference Page**
Life-Cycle Emission (tonnes CO_2) =	12.508	A1
Energy Output (GW_eh) =	0.323	A8
Emission Rate = Emission / Output (T/GW_eh) =	**38.7**	

ENERGY INPUT REQUIREMENTS FOR PV MODULES

	Unit Energy GJ/m^2	Module Area m^2	Total GJ
Materials & Manufacturing[1]	0.782	157	**123**
Engineering & Administration[2]	0.250	157	**39**
Transportation to Site	0.046	157	**7**
		Total Energy	**170**

Material & Manufacturing Energy[1]

	Energy Per Module Area (GJ/m^2)			
Activity	**Material**	**Manufacturing**	**Mat. Transport**	**Total**
Encapsulation	0.2119	0.1372	0.0188	0.3680
Substrate	0.0256	0.0564	0.0093	0.0913
Deposition Materials	0.0188	0.0925	0.0002	0.1116
Busbar	0.0051	0.0000	0.0002	0.0054
Back Reflector	0.0007	0.0740	--	0.0747
Grid	--	0.0342	--	0.0342
Conductive Oxide	--	0.0969	--	0.0969
Total	0.262	0.491	0.029	**0.782**

Transportation to Site Energy

Distance	miles	928
Energy Intensity[3]	BTU/ton Mile	4359
Mass	tons	1.69
Transport Energy	GJ	7.22
Area	m^2	157
Unit Transport Energy	GJ/m^2	**0.046**

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1. Keoleian, G. and Lewis, G. (1997) *Application of Life-cycle Energy Analysis to Photovoltaic Module Design* . Progress in Photovoltaics: Research and Applications. 5: pp. 287-300.
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GREENHOUSE GAS EMISSIONS FOR PV MODULES (Page 1 of 2)

	Reference Page	Unit Emission kg CO_2/m^2	Module Area m^2	Total kg CO_2-Equiv
Materials & Manufacturing	A3			
Material		16.7		
Manufacturing		27.7		
Intermediate Transport		2.1		
Subtotal		***46.5***	***157***	***7,315***
Engineering & Administration	A4	14.121	157	2,221
Transportation to Site	A4	3.394	157	534
			Total Emissions	**10,070**

Material Emissions

Activity	Material	Unit Energy[1] MJ/m^2	Emis. Factor[2,3] kg CO_2/MJ	Unit Emission kg CO_2/m^2
Encapsulation	Various	211.94	0.064	13.504
Substrate	Stainless Steel	25.64	0.062	1.579
Deposition Materials	Various	18.80	0.064	1.198
Busbar	Various	5.13	0.064	0.327
Back Reflector	Various	0.73	0.064	0.047
Grid	Various	--	--	--
Conductive Oxide	Various	--	--	--
Total				**16.7**

Manufacturing Emissions

Activity	Unit Energy[1] MJ/m^2	Emis. Factor[2,3] kg CO_2/MJ	Unit Emission kg CO_2/m^2
Encapsulation	137.23	0.056	7.75
Substrate	56.40	0.056	3.19
Deposition Materials	92.54	0.056	5.23
Back Reflector	73.99	0.056	4.18
Grid	34.18	0.056	1.93
Conductive Oxide	96.94	0.056	5.48
Total			**27.75**

Intermediate Transport Emissions

Activity	Unit Energy[1] MJ/m^2	Emission Factor[5] kg CO_2/MJ	Unit Emission kg CO_2/m^2
Encapsulation	18.80	0.0738	1.39
Substrate	9.28	0.0738	0.68
Deposition Materials	0.24	0.0738	0.02
Busbar	0.24	0.0738	0.02
Back Reflector	--	--	--
Grid	--	--	--
Conductive Oxide	--	--	--
Total			**2.11**

References - See Page A4

GREENHOUSE GAS EMISSIONS FOR PV MODULES (Page 2 of 2)

Engineering & Administration Emissions

Activity	Unit Energy[6] MJ/m^2	Emis. Factor[2,4] kg CO_2/MJ	Unit Emission kg CO_2/m^2
Engineering & Administration	250	0.056	**14.12**

Transportation to Site Emissions

Activity	Unit Energy MJ/m^2	Emis. Factor[5] kg CO_2/MJ	Unit Emission kg CO_2/m^2
Transportation to Site	46	0.0738	**3.39**

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BALANCE OF SYSTEM
ENERGY REQUIREMENTS AND CO_2-Equiv. EMISSIONS

INVERTERS

Inverter Capacity[1]	4000	W
Energy Intensity[2]	0.001	GJ/W
Number of System Inverters[3]	3	
Energy Required	**4.0**	**GJ**
CO_2 Intensity[4]	72.5	kg CO_2/GJ
CO_2-equiv. Emissions	**290**	**kg**

WIRING

AC Wiring[3]	100	feet
DC Wiring[3]	400	feet
Copper Required	24	kg
Energy Intensity[5]	0.12	GJ/kg
Energy Required	**2.9**	**GJ**
CO_2 Intensity[5]	62.4	kg CO_2/GJ
CO_2-equiv. Emissions	**179**	**kg**

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INSTALLATION, OPERATION & MAINTENANCE
ENERGY REQUIREMENTS AND CO_2-Equiv. EMISSIONS

Installation	Cost[1,2] ($)	Energy Intensity[3] GJ/$	GJ	CO_2-Equiv. Intensity[3] kg CO_2/GJ	CO_2-equiv. Emission kg
Installation (excludes roofing)	5667	0.00228	12.9	69.25	897
TOTAL			**12.9**		**897**

OPERATION & MAINTENANCE	Cost[1,2] ($)	Energy Intensity[3] GJ/$	GJ	CO_2-Equiv. Intensity[3] kg CO_2/GJ	CO_2-Equiv. Emission kg
Year 1 - System Optimization	1000	0.00228	2.3	69.25	158
Year 15 - Inverter Replacement*			4.0		290
Miscellaneous	1500	0.00315	4.7	69.55	328
TOTAL			**11.0**		**776**

*See Balance of System Page A4

References:

1. Burdick, J. (September 1,2000 - June 29, 2001) President, Burdick Technologies Unlimited, LLC, Personal Communications.
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DECOMMISSIONING AND DISPOSAL
ENERGY REQUIREMENTS AND CO_2-Equiv. EMISSIONS

Item	Energy GJ	CO_2-Equiv. Emission (kg)
Decommissioning[1]	2.59	179.32
Transportation	0.257	18.94
Disposal	1.455	98.39
Total Decom. and Disposal	**4.30**	**296.7**

TRANSPORTATION					
Component	**Mass kg**	**Transport Intensity[2] GJ/kg**	**Transport Energy* GJ**	**Transport Emis. Fctr[6] kg CO_2/GJ**	**Transport Emission kg CO_2**
Decommission[1]					
Disposal					
Modules	1535	0.00015	0.233	73.80	17.23
Inverter	48	0.00015	0.007	73.80	0.54
Wiring	24	0.00015	0.004	73.80	0.27
Manufacturing Solid Waste[4]	77	0.00015	0.012	73.80	0.86
Manufacturing Chemical Waste[5]	4	0.00015	0.001	73.80	0.05
Total			**0.257**		**18.94**

* Assumes 30-mile transport distance.

DISPOSAL					
Component	**Mass kg**	**Disposal Intensity[3,4] GJ/kg**	**Disposal Energy GJ**	**Disposal Emis. Fctr[3,4] kg CO_2/GJ**	**Disposal Emission kg CO_2**
Disposal					
Modules	1535	0.00072	1.11	70.763	78.61
Inverter	48	0.00072	0.03	70.763	2.46
Wiring	24	0.00072	0.02	70.763	1.23
Manufacturing Solid Waste[4]	77	0.00072	0.06	70.763	3.93
Manufacturing Chemical Waste[5]	4	0.05804	0.24	51.397	12.17
			1.455		**98.39**

References and Notes:

1. Decommissioning energy and emissions estimated as 20% of installation energy and emissions.
2. Energy Information Administration (1995) *Measuring Energy Efficiency in the United States' Economy: A Beginning.* DOE/EIA-0555(95)/2.
3. Fthenakis, V. (2000) *End-of-life management and recycling of PV modules.* Energy Policy. 28: pp. 1051-1058.
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6. Organisation for Economic Cooperation and Development (1991) *Greenhouse Gas Emissions: The Energy Dimension.* OECD611990091P1.

LIFE-CYCLE ENERGY OUTPUT

OUTPUT ESTIMATION		
Peak Output[1]	8	kW
Electrical System Efficiency[1]	80%	
Degradation Losses[2]	7.6%	
Lifetime	30	years
Life-cycle Output[3,4]	323,434	kWh
Life-cycle Output	1,164	GJ
Life-cycle Output	0.323	GW_eh
Life-cycle Output	3.69E-05	GW-full power year

References and Notes:

1. Burdick, J. (September 1, 2000 - June 29, 2001) President, Burdick Technologies Unlimited, LLC, Personal Communications.
2. Based on a 15% total degradation over 30 year module lifetime. Bertsche, G. (June 14, 2001) Regional Sales Manager, United Solar Systems Corporation, Personal Communications.
3. Output estimation based on 5 peak hours per day in Colorado (Burdick).
4. (8 kW) x 80% x (5 hr/day) x (365 day/yr) x (1 - 7.6%) (30 yr) = 323,434 kWh