Progress in Photovoltaics Research and Applications, 14:179-190, 2006

Energy Pay-Back and Life Cycle CO_2 Emissions of the BOS in an Optimized 3.5 MW PV Installation

J.M. Mason[1], V.M. Fthenakis[2], T. Hansen[3] and H.C. Kim[2]
[1] Solar Energy Campaign, 52 Columbia Street, Farmingdale, NY 11735, E-mail: cjjmason5@earthlink.net
[2] PV EH&S Research Center, Brookhaven National Laboratory, Bldg. 830, Upton, NY 11973, Email: vmf@bnl.gov
[3] Tucson Electric Power, PO Box 711, Tucson, AZ, 85702, E-mail: thansen@tep.com

Abstract

This study is a life-cycle analysis of the balance of system (BOS) components of the 3.5 MW_p multi-crystalline PV installation at Tucson Electric Power's (TEP) Springerville, AZ field PV plant. TEP instituted an innovative PV installation program guided by design optimization and cost minimization. The advanced design of the PV structure incorporated the weight of the PV modules as an element of support design, thereby eliminating the need for concrete foundations. The estimate of the life-cycle energy requirements embodied in the BOS is 542 MJ/m^2, a 71% reduction from those of an older central plant; the corresponding life-cycle greenhouse gas emissions are 29 kg $CO_{2\text{-eq.}}$ $/m^2$. From field measurements, the energy payback time (EPT) of the BOS is 0.21 years for the actual location of this plant, and 0.37 years for average US insolation/temperature conditions. This is a great improvement from the EPT of about 1.3 years estimated for an older central plant. The total cost of the balance of system components was \$940 US per kW_p of installed PV, another milestone in improvement. These results were verified with data from different databases and further tested with sensitivity- and data-uncertainty analyses.

Key Words: PV plant; balance of system; life cycle assessment, energy payback, greenhouse gas emissions

INTRODUCTION

This study is a life-cycle analysis of the energy requirements and greenhouse-gas (GHG) emissions of the balance of system (BOS) components at Tucson Electric Power's (TEP) Springerville photovoltaic (PV) plant. The Springerville PV plant, located in eastern Arizona, USA, currently has 4.6 MW_p of installed PV modules of which 3.5 MW are mc-Si PV modules. Electricity from the PV modules is used to power the 10-$MW_{ac\text{-}el}$ water pump load at the Springerville coal-fired electricity-generating plant. When the water pumps are not operating, the PV electricity is distributed over the transmission grid for general consumption. While PV plants produce fossil-fuel-free and non-polluting electricity, the life-cycle of PV plant components from production through disposal does consume fossil fuels, which causes the release of greenhouse gases (GHGs). With the growing need to conserve fossil fuel and mitigate GHG emissions, this evaluation of a large field PV plant in terms of its potential to achieve such savings and lower emissions is timely.

Previous life-cycle assessments of field and rooftop PV systems indicated that the energy embodied in the BOS components and their installation in ground-mounted utility plants is much greater than the energy requirements in rooftop and facade installations.[1,2,3,4] These assessments were based on a single plant, the Serre plant in Italy, whose BOS life-cycle energy was estimated to be 1850 MJ of primary energy per m^2 of installed PV modules, and the energy payback time (EPT) was around 1.3 years. By comparison, several studies of the BOS in rooftop and facade PV installations showed their energy requirements to be only about 600 MJ/m^2. The much higher energy requirement of field PV plants compared to residential PV systems was attributed to the need for concrete foundations and metal support structures. Further, projections of the energy requirements for BOS of central plants predicted only small reductions with time (e.g., 1700 MJ/m^2 by 2010, and 1500 MJ/m^2 by 2020).[4]

This study discusses an actual installation where the life-cycle energy requirements are drastically lower than the predicted numbers. The optimized design and innovative installation of the Springerville central PV plant have lowered its energy requirements by 71% compared with the Serre plant.

DESCRIPTION AND COST OF THE SPRINGERVILLE PV PLANT

TEP has designed the Springerville PV plant for 8-MW_p of field-mounted PV. To date, 4.6 MW_p of PV modules have been installed, of which 3.5 MW_p is framed mc-Si PV and 1.1 MW_p is framed and frameless thin-film PV modules. Figure 1a shows an aerial view of the PV plant, with a close-up in Figure 2b. TEP's philosophy guiding all phases of the PV plant installations is to optimize its design so as to minimize labor, materials, and costs. In the design phase of the PV plant, small prototype PV installations were evaluated to assess the appropriate electrical configurations and optimize the performance of standard utility-scale power conditioning equipment. Having determined the size and design of the PV plant, TEP staged construction in phases to realize benefits from synergies in utilizing labor and equipment. Time and motion studies were conducted to make the best use of construction personnel and equipment. In the site-preparation construction stage, TEP installed infrastructure for the electrical connections that is sized to accommodate the addition of planned PV installations until it attains its intended size. Site preparation included leveling the ground, applying soil stabilizer, installing underground conduits, concrete foundations for inverter and transformer pads, high-voltage wiring, high-voltage disconnects, transformers, and a grounding system, all to power plant specifications.

The sizing and wiring configuration of the PV arrays is fashioned to produce electricity flows that match the performance characteristics of standard utility electrical equipment. The objective is to maximize the amount of PV capacity per connection point, which minimizes electrical costs per PV W_p. In addition, the configuration of the PV arrays is designed to maintain operation in defined voltage ranges, enabling the inverters and transformers to operate in their performance "sweet spot," which also maximizes the amount of ac electricity flowing onto the transmission grid. The optimized layout of the PV installations is 135 kW_p arrays. Four construction workers installed each of the arrays in forty hours, from ground level to a standing array. The PV support structures rely on the mass of the PV modules that are anchored into the ground with one-foot-long nails, thereby eliminating the need for concrete foundations. The PV support structures can withstand 193 km/hour (120 mph) winds; to date, they successfully withstood sustained winds of 160 km/hour (100 mph).

The performance of the system is monitored with computer software. Detailed records show that the annual average (in 2004) of ac electricity output from the mc-Si section of the plant was 1730 $kWh_{ac\text{-}el}/kW_p$ (214 $kWh_{ac\text{-}el}/m^2$) of installed PV modules, with an effective system availability greater than 99%. This electricity output is measured at the grid connection on the 480 V side of the isolation transformer and accounts for all losses. The current real-time day-to-date performance of the plant can be seen in www.GreenWatts.com. The 3.5 MWp system was installed in stages between 2001 and 2004 and uses ASE 300DG/50 modules the specifications of which are the following: 46.6 kg weight (including 5.9 kg of Al frame), 2.456 m^2 area, and 12.2% rated efficiency. The thin film PV installation are being optimized and their performance evaluated.

TEP's optimization of design and forward construction staging enabled them to reduce costs by developing "cookie-cutter" installation procedures. To minimize the system costs, the timing and sizing of the installations are scheduled to take advantage of volume purchasing and partnership contracts with the manufacturers of the major components. TEP reported that the total installed cost of BOS components is $940/kW_p$[5], a great improvement from previous estimates of $1700/kWp[6] (see Figure 2). These costs do not include financing or end-of-life dismantling and disposal expenses. The end-of-life salvage value of the BOS components is assumed to equal the costs of dismantling and disposal. Inverters and their support software are the single largest most expensive BOS component, with an installed cost of $400/kW_p$. The next largest is the electrical wiring system with an installed cost of $300/kW_p$. TEP states that their detailed attention to designing the dc trunk electrical connections and to the pre-planned construction staging significantly lowered the costs for installing the electrical system. The installed cost of the PV support structures was $150/kW_p$; this low value resulted from simplifying the design, which minimized labor, equipment, and materials, and using relatively inexpensive, powder-coated, angle iron. The site preparation costs were $80/kW_p$.

METHODOLOGY

BOS Life Cycle Inventory and Boundary Conditions

TEP provided an itemized BOS bill of materials for their mc-Si PV installations. Table 1 is a categorized list of the BOS components. Aluminum frames are shown separately, since they are part of the module, not of the BOS inventory, and there are both framed and frameless modules on the market. The BOS component inventory is scaled to 1-MW_p of installed PV and a thirty- year operating life. The material composition of the BOS components is estimated from information provided by the manufacturers, TEP, and published studies. The life expectancy of the PV metal support structures is assumed to be sixty years. Inverters and transformers are considered to have a life of thirty years but parts must be replaced every ten years, amounting to 10% of their total mass according to well-established data from the power industry on transformers and electronic components. The inverters are the utility-scale, Xantrec PV-150 models, which have a wide open frame, so that a failed part can be easily replaced. We also explored the assumption of total replacement of the inverters every ten and fifteen years as part of the sensitivity analysis.

Although the PV system is currently unmanned, for consistency the material inventory includes an allocation of office facility materials for administrative-, maintenance-, and security-staff, as well as staff vehicles for PV plant maintenance.

.

The boundaries of the life cycle energy and GHG emissions analysis extend from materials production to product end-of-life disposal. Five life-cycle stages are evaluated: Stage 1 – BOS part production, including extraction of raw materials, materials processing, manufacturing, and assembly; Stage 2 – BOS part transportation; Stage 3 – PV plant construction including BOS installation and office building construction; Stage 4 – PV plant administrative; and, Stage 5 – product end-of-life management. The geographic system boundary of this study is North America and the time period of the technology and data covers the late 1990s and later.

Estimation of Life Cycle Energy and GHG Emissions

The life-cycle energy uses and GHG emissions over the complete life cycle of PV BOS were determined from the commercial Life Cycle Inventory (LCI) databases, Franklin[7] and Ecoinvent[8] , and public-domain sources from National Renewable Energy Laboratory (NREL)[9] and the Aluminum Association.[10] Supplementary data sources include those from the U.S. Energy Information Administration[11], the U.S. Department of Energy[12] and a European study.[13]–The LCA software tool Simapro 6 was used for detailed energy payback and greenhouse emissions analyses. The assumptions for the reference-case scenario of the LCI were as follows:

- 33% of secondary material content in aluminum parts.
- 30 years of inverter lifetime with 10% of materials' replaced every 10 years.
- Transport range of BOS components: 1600 km with 50% of the transport made by railroads and 50% by trucks.
- Transport range for disposal: 160 km by trucks.

The following, well-established data were used:

The U.S. electricity production mixture was used for power in manufacturing BOS components except for the aluminum products for which more site-specific grid mixture was used. Conventional diesel fuel was used for rail and truck transport. The PV plant utilization/administrative functions are a pickup truck for plant maintenance, and energy to heat, cool, and power office facilities for the staff. The energy sources were gasoline for vehicles, and electricity and natural gas for office facilities. The disposal of field PV plant components is based on transporting them a distance of 160 km by heavy truck. The distribution and disposal of concrete is based on transporting it 50 km. The energy to shred and separate PV plant components is 0.34 MJ/kg.[14] The energy source for dismantling, transporting, and shredding the PV components is assumed to be conventional diesel fuel.

Sensitivity analyses also were conducted with variations in the secondary aluminum content of the BOS components (100% and 0%), and lifetimes of inverters (10 years and 15 years without replacing parts). In addition, to verify our findings, we employed GREET[15], a model and database widely used for automobile LCA, in conjunction with data on the production of materials from Weiss et al.[16] and from Environdec's environmental product declarations.[17]

All energy values are reported in terms of primary energy in units of GJ/kW$_p$ of rated peak dc electricity output, or MJ/m^2 of installed PV modules. Primary energy is the total fuel-cycle energy per unit of energy consumed, and accounts for that expended to extract, refine, and deliver fuels. Energy values are reported at their gross heating value. The electricity estimates are based on a U.S. average fuel mix and power-plant efficiency, corresponding to a conversion efficiency of 33% [11]. The GHG emissions are carbon dioxide, nitrous oxide, methane, sulfur hexafluoride, PFCs, and CFCs, which are reported in kg of CO_2 equivalencies per kW$_p$ (or per m^2) of installed PV modules.

Life-Cycle Energy and GHG Emissions Payback Times

The concept of payback time is used to evaluate the time it takes to recover the life-cycle energy and GHG emissions embodied in PV installations. Payback time is based on the assumption that the ac electricity produced by PV plants displaces an equal quantity of electricity generated by the current US energy mixture. The energy payback time (EPT) is calculated by dividing the life-cycle energy requirements of the BOS components (converted to kWh of equivalent electricity) with the actual annual electricity output of the system, after all losses, at the grid connection (i.e., 1730 kWh$_{ac\text{-}el}$ per kW$_{p)}$. The actual performance and the most likely values of input parameters comprise our "reference case". We also present, as the "US average case", the expected performance under average U.S. insolation conditions

RESULTS

Reference Case

Table 2, and Figures 3 and 4, show the results of calculating BOS life-cycle energy and GHG emissions by categories of BOS components. The total primary energy in the BOS life cycle is 542 MJ/m^2 of installed PV modules. This finding contrasts sharply with the previous central PV plant BOS estimate (i.e., 1850 MJ/m^2) that was based on the Serre, Italy plant, and reveals the energy savings from eliminating concrete foundations and roads. PV support structures account for only 12% of the total BOS energy, while that of inverters and transformers combined accounts for 31%. This is followed by electrical connections and PV module frames at 20% and 19% of total BOS energy, respectively.

Using the average U.S. energy conversion efficiency of 33%[11], this gives an electricity equivalent of 50 kWh/m^2 that, after annualizing the administrative and disposal conntributions, results in an EPT of 0.21 years.

The Springerville site combines high insolation (e.g., ~2100 $kWh/m^2/yr$) with relatively low ambient temperatures which increases the system's efficiency; the measured system efficiency of the mc-Si PV modules at Springerville is 83.5%.
The assessments of installations under US average conditions are based on 1800 $kWh/m^2/yr$ insolation, a rated module efficiency of 12.2%, and a system efficiency of 80%. This corresponds to annual electricity production of 1420 kWh/KWp installed PV. The corresponding EPT of the BOS for an average U.S. installation is 0.37 years.

For comparison, Figures 3 and 4 also show the energy consumption and corresponding GHG emissions of the aluminum frames, which are part of the mc-Si PV modules used at Springerville. The calculated energy consumption for the Al frames under reference conditions (i.e., 33% recycled Al) was 331 MJ/m^2; producing them consumes 99% of this energy. As discussed in the sensitivity section, the energy consumption if all the aluminum is from primary sources, is 457 MJ/m^2. These estimates agree with previous publications attributing 400 MJ/m^2 to Al frames, which did not, however, cite the fraction, if any, of recycled aluminum.[4] This comparison shows that the environmental impact from the life cycle of the frames is of the same magnitude as that from the total BOS components and their installation. This highlights the need for frameless PV modules to reduce the environmental impacts of the whole (modules+BOS) PV plant.

Verification Analysis

A common exercise to verify the results from a multifaceted assessment, like this one, is for different analysts to assess the same system with different tools. An earlier assessment, undertaken by the first author of this paper was based on GREET[15], along with data on materials' production from Weiss et al.[16] and from Environdec's environmental product declarations.[17] This is labeled "Assessment 1" and the previously discussed reference case is labeled "Assessment 2".

A comparison of the results from the two assessments is shown in Figures 5 and 6. According to Assessment 1, the BOS life cycle energy is 526 MJ/m^2 which is 3% lower than the reference case, whereas the corresponding GHG emissions are 31 kg $CO_{2\text{-eq}}/m^2$, which is 7% higher than the reference case. As shown in these figures, the differences between the two assessments are greater for the frame than for the BOS. These differences are mainly due to the different energy intensity and emission factors adopted in each assessment for aluminum part production. Energy intensity data of primary aluminum production from Weiss et al (220 MJ/kg)[16] used in Assessment 1, are 5-10% higher than those from other studies including the current Assessment 2. The GHG emission factors in the earlier assessment were based on the average US grid mix while Assessment 2 uses emission factors of the electricity grid mixture specifically used by the U.S. aluminum industry. Thus, the GHG emissions of Assessment 2 reflect the actual energy consumption of the aluminum industry, which primarily relies on hydroelectric power as the main energy source.[18] Further analysis shows that differences in other assumptions including emissions factors of transportation and part fabrication, had a negligible impact.

Sensitivity Analysis

This assessment is based on actual field-performance data and accurate records for the BOS components and their installation. However, some of our assumptions carry uncertainty that needs to be quantified. It pertains to the life expectancy of the inverters and the fraction of recycled aluminum used in the BOS components. The results presented below are based on the Assessment 2 data bases (i.e.,: Franklin; NREL US LCI; Aluminum Association LCI; Ecoinvent; Annual Energy Review, EIA; DOE LCI of Biodiesel, and ETH-ESU)

As discussed earlier, the open-frame utility-grade inverters used in Springville are expected to have the same life as utility transformers; industry data on the latter show a 30-year useful lifetime. Electronic components may need to be replaced earlier; hence, we adopted a 10% replacement of parts every 10 years in our reference case. However, the integrated inverters commonly used in small installations typically are assumed to last 10- to 15-years. In our sensitivity analysis, we explored the impact on our estimates of such shorter lives; Figures 7 and 8 give the resulting life-cycle energy and GHG factors. For the plant at Springerville, the EPTs of the BOS increase to 0.23 and 0.25 yrs, corresponding to 15-yr and 10-yr inverter lives. For U.S. average conditions, the EPTs increase to 0.40 and 0.43 yrs correspondingly.

Both global and US production of aluminum includes ~1/3 from secondary (recycled) metals; this mixture was used in our reference case. Aluminum from ore (primary source) uses ten- to twenty-times more energy than that from recycled metal. In the following, we also examined the impact of using a) 100% primary Al (0% recycled) and b) 100% recycled Al (Figures 9 and 10). The impact on the BOS components is very small, since only small amounts of Al are imbedded in transformers, inverters, and supports. However, there is a significant impact of using either totally primary or totally secondary aluminum for producing PV module frames.

Data Uncertainty Analysis

As shown by the comparison of Assessments 1 and 2, a choice of data sources can produce slightly different results. An interesting example of the impact of different values in a component's life cycle inventory, is the case with the transformer oil. The transformer oil used in the Springerville PV power plant consists of mostly soybean oil (>98.5%).[19] The life cycle GHG emissions from the PV BOS using Ecoinvent LCI data for soybean oil, is 6% higher than the reference case based on US Department of Energy's LCI study of soybean oil [12] (Figure 11). These two LCI studies adopt different assumptions on the methods of soy agriculture and in the allocations rule of energy and emissions between the soybean oil and soy meal, a co-product.[12,20] However, the difference in the life cycle energy consumption for the two cases is negligible

CONCLUSIONS

The Springerville mc-Si field PV plant achieves two important advances in field PV plants: a reduction in BOS life-cycle energy and GHG emissions; and, a decrease in the cost of the installation.

The total primary energy for the BOS life cycle was estimated, by using different data-bases and analysts, to be only 526-542 MJ/m^2, which is 71% lower than the previously published estimates based on the Serre plant. The main difference is due to design optimization, that eliminated reinforced cement foundations, and decreased the quantity of expensive metal supports. For the Springerville site, the actual energy payback is 0.21 years; for U.S. average conditions, the estimated EPT is 0.37 years. The GHG emissions during the life cycle of the BOS are 29-31 kg $CO_{2}\text{-}_{eq}/m^2$. This study indicates that PV plants potentially may approach near-zero GHG emission values with the development of advanced PV technologies and installations. The total installed cost of the BOS components is \$940/kW$_p$, representing a 45% reduction from the previously reported lowest estimate for field PV plants, and brings the cost of PV electricity a step closer to being a cost- competitive source of distributed electricity generation. Undoubtedly, more decreases in the life-cycle energy, GHG emissions and costs of field PV plants will occur with advances in PV manufacturing technologies, the large-scale manufacture of standardized BOS components and utility-scale inverters, and the development of more effective installation techniques.

ACKNOWLEDGEMENTS

We would want to thank the Arizona Corporation Commission through whose leadership the TEP Springerville PV project funding was made available. The Brookhaven investigators were supported by the Solar Technologies Program, Conservation and Renewable Energy, under Contract DE-AC02-76CH000016 with the US Department of Energy.

REFERENCES

1. Alsema EA. Energy pay-back time and CO_2 emissions of PV systems. *Progress in Photovoltaics: Research and Applications* 2000; 8(1):17-25. DOI: 10.1002/pip295

2. Frankl P, Masini A, Gamberale M, Toccaceli D. Simplified life-cycle analysis of PV systems in buildings – present situation and future trends. *Progress in Photovoltaics: Research and Applications* 1998; 6(2):137-146. DOI: 10.1002/pip214

3. Alsema EA, Frankl P, Kato K, Energy pay-back time of photovoltaic energy systems; Present status and prospects, Presented at the 2nd World Conference Solar Energy Conversion, Vienna, 6-10 July 1998.

4. Alsema EA. Energy Pay-Back and CO_2 Emissions of PV Systems, chapter V-2, pp. 869-886, in *Practical Handbook of Photovoltaics Fundamentals and Applications* (ed. Markvart T, Castaner L), Elsevier, Oxford, UK, 2003.

5. Hansen TN. The promise of utility scale solar photovoltaic (PV) distributed generation. Paper presented at POWER-GEN International, Las Vegas, NV, 10 December 2003.

6. Zweibel K. PV as a major source of global electricity. Paper presented at the University of Toledo, 24 February 2004.
http://www.nrel.gov/ncpv/thin_film/docs/zweibel_t_club_feb_04_pv_global_energy_needs.ppt

7. USA LCI Database Documentation. Franklin Associates, Prairie Village, Kansas, USA, 1998.

8. Althaus H-J, Blaser S, Classen M, Jungbluth N. *Life Cycle Inventories of Metals. Final report Ecoinvent 2000*. Editors: 0. Volume: 10. Swiss Centre for LCI, EMPA-DU. Dübendorf, CH, 2003.

9. US Life-Cycle Inventory Database Project data. National Renewable Energy Laboratory, 2004. www.nrel.gov/lci

10. *Life Cycle Inventory Report for the North American Aluminum Industry*. Aluminum Association, Inc. Washington, DC, 1998.

11. Annual Energy Review 2003. Energy Information Administration, DOE/EIA-0384, 2003. http://www.eia.doe.gov/aer.

12. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*. US DOE, NREL/SR-580-24089, 1998.

13. Frischknecht R, Hofstetter P, Knoepfel I, Ménard M, Dones R, Zollinger E. *Öko-inventare von Energiesystemen*. ETH-ESU. Zürich, Switzerland, 1996.

14. Staudinger J, Keoleian GA. *Management of End-of Life Vehicles (ELVs) in the US. Center for Sustainable Systems.* University of Michigan. Report No. CSS01-01. 2001.

15. Wang M. GREET Version 1.6. Center for Transportation Research, Argonne National Laboratory, University of Chicago, Chicago, IL, 2001.

16. Weiss MA, Heywood JB, Drake EM, Schafer A, AuYeung FF. *On the Road in 2020: A life cycle analysis of new automobile technologies*. Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA. Energy Laboratory Report # MIT EL 00-003, 2000. http://lfee.mit.edu/publications/PDF/el00-003.pdf

17. Environmental Product Declarations, Swedish Environmental Management Council, Stockholm, Sweden, 2004. http//:www.environdec.com

18. *Life Cycle Assessment of Aluminum: Inventory Data for the Worldwide Primary Aluminum Industry.* International Aluminum Institute. London, UK, 2003. http://www.world-aluminium.org/iai/publications/documents/lca.pdf.

19. Joint Verification Statement: The Environmental Technology Verification Program. Department of Toxic Substance Control, US. EPA, 2002. http://www.epa.gov/etv/library.htm.

20. Althaus H-J, Chudacoff M, Hischier R, Jungbluth N, Osses M, Primas A. *Life Cycle Inventories of Chemicals.* Final report Ecoinvent 2000. Volume: 8. Swiss Centre for LCI, EMPA-DU. Dübendorf, CH, 2003.

21. Gaines L, Stodolsky F, Cuenca R, Eberhardt J. Life-cycle analysis for heavy vehicles. Argonne National Laboratory, Argonne, IL and Office of Heavy Vehicle Technologies, U.S. Department of Energy, 1998.

22. Wibberley L. LCA in Sustainable Architecture (LISA). Developed by Sustainable Technology, BHP Billiton Technology, BlueScope Steel, Melbourne, Australia, 2002. http//:www.lisa.au.com

Table 1. Material Inventory (kg) of the BOS Components for a 1-MW_p Field PV Plant

BOS Components	Steel	Aluminum	Copper	Plastics	Other	Total Weight
Frames for PV Modules	0	18144	0	0	0	18144
Support Structure Frames	30906	0	0	0	0	30906
Support Structure Hardware	1333	0	0	0	0	1333
Bare Copper Wire	0	0	445	0	0	445
Insulated Copper Wire	0	0	2071	323	0	2394
PVC Conduit	0	0	0	3425	0	3425
IMC Conduit	4799	0	0	0	0	4799
Concrete	0	0	0	0	47405	47405
Connections	1296	126	3	36	0	1462
Inverters	3036	894	625	485	0	5040
Transformers	6756	0	1652	300	300	9008
Transformer Oil (Vegetable)	0	0	0	0	6001	6001
Concrete Pad Foundations	562	0	0	0	18350	18912
Grounding and Disconnects	178	214	2721	190	67	3370
Miscellaneous Components	437	0	1	516	0	955
Fence (Perimeter)	4291	0	0	0	10502	14793
Water for Soil Stabilizer	0	0	0	0	60564	60564
Vehicles and Construction[1]	330	57	5	23	89	505
Office Facilities PV Plant Staff[2]	1968	2	4	532	18190	20697
Totals	55893	19437	7527	5832	161469	250158

Energy Consumption	Total	Energy (GJ)
Diesel (liter) – Construction	1472	53
Natural Gas (m^3) – Office	1480	54
Electricity (kWh) – Office	5168	19

Data Source: Tucson Electric Power, 2004.

Notes:
1. Truck/construction equipment material composition are derived from Gaines *et al*. study of heavy trucks for material proportions,[21] which is applied to manufacturers' advertised mass for types of construction equipment specified by Tucson Electric and Power.
2. The composition of the office building material is estimated from data provided by the LCA software LISA from the case study of a multi-story office building with LISA default values.[22]

.

Table 2. Energy Use and GHG Emissions for BOS Production for Reference Case (33% secondary aluminum, and a 30-yr lifetime of inverters, with 10% part replacement every 10-years)

	Balance of System	Mass (kg/MW$_p$)	% of total	Energy (GJ/MW$_p$)	% of total	GHG emissions (t CO_2 eq./MWp)
BOS	PV Support Structure	16821	10.3	699	18.7	47
	PV Module Interconnections	453	0.3	53	1.4	2
	Junction Boxes	1385	0.8	51	1.4	4
	Conduits and Fittings	6561	4.0	328	8.8	20
	Wire and Grounding Devices	5648	3.4	769	20.6	35
	Inverters and Transformers	28320	17.3	1321	35.3	55
	Grid Connections	1726	1.1	127	3.4	5
	Office facilities	20697	12.6	90	2.4	8
	Concrete	76417	46.6	66	1.8	10
	Miscellaneous	5806	3.5	236	6.3	16
	Total	163834	100.0	3740	100.0	204
Frame		18141		2650		184

Figure 1. Photographs of TEP's Springerville PV Plant (source: www.greenwatts.com)
(a) overview of the whole installation; (b) close-up on part of the installation

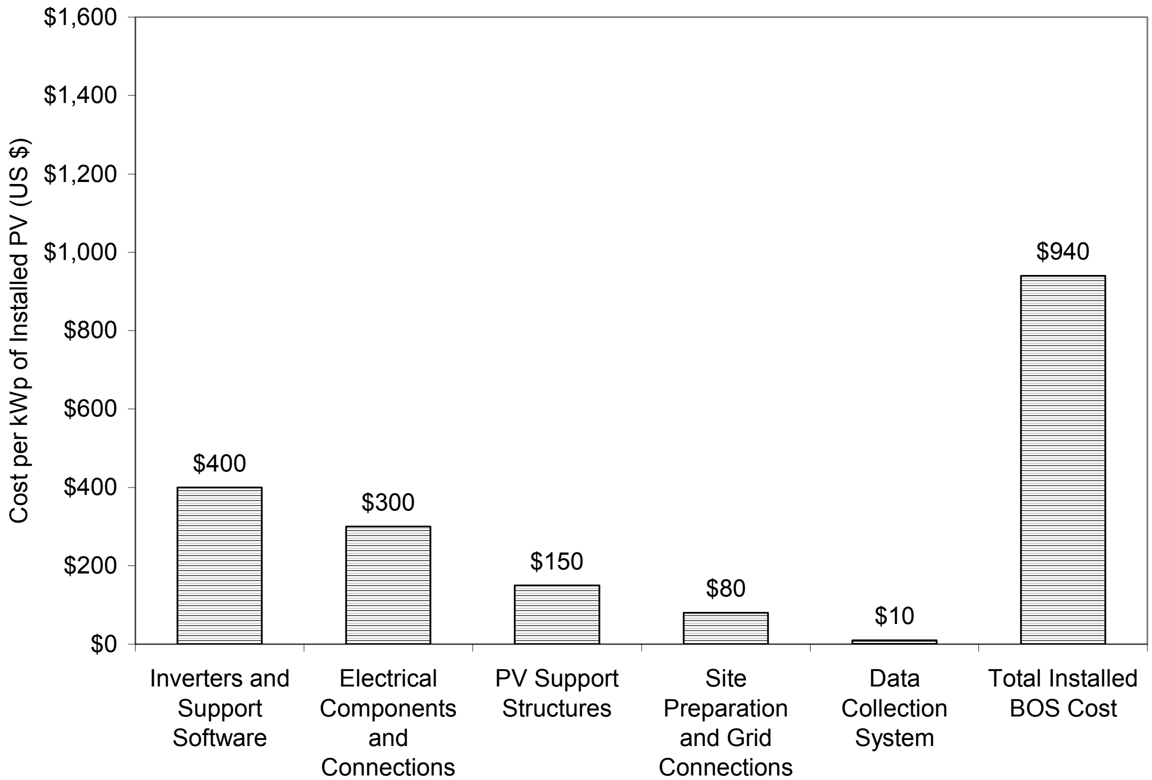


Figure 2. Installed BOS Costs for the mc-Si PV Installations (Source: Hansen, 2003; costs in 2003 US dollars

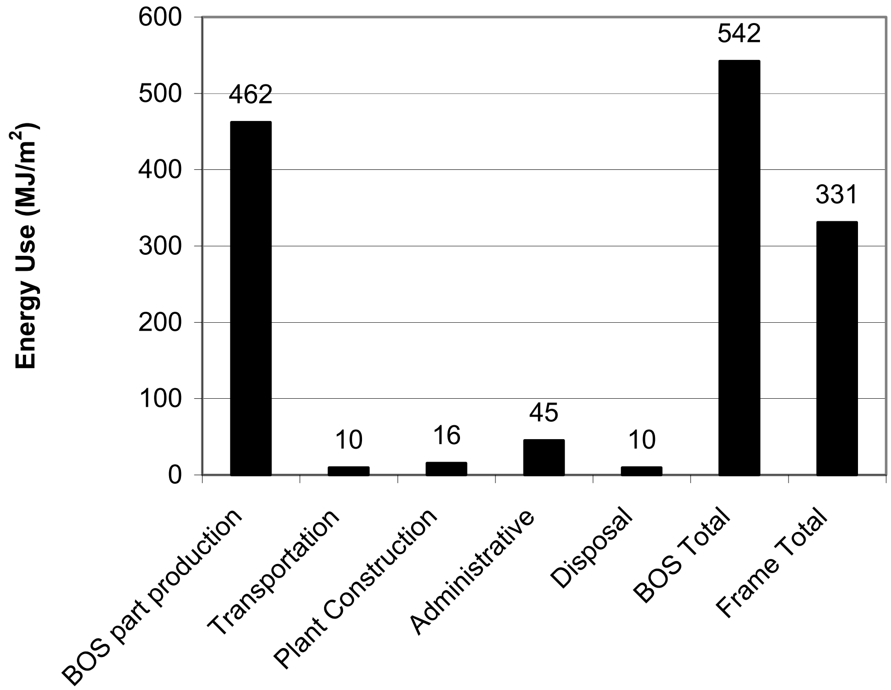


Figure 3. Life Cycle Energy Consumption of BOS: Reference Case

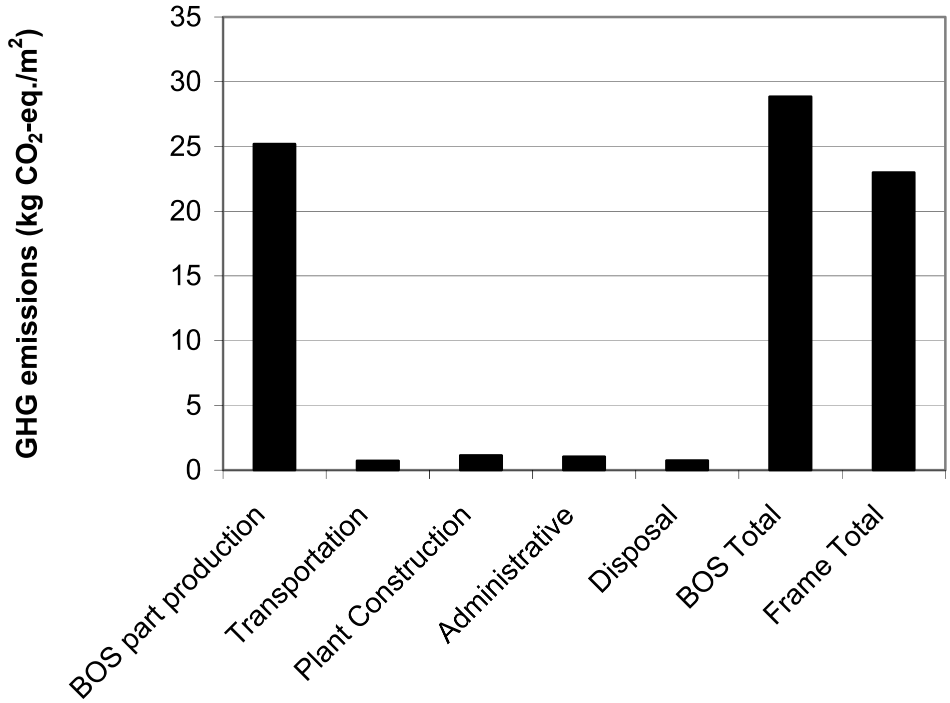


Figure 4. Life-Cycle GHG Emissions of BOS: Reference Case

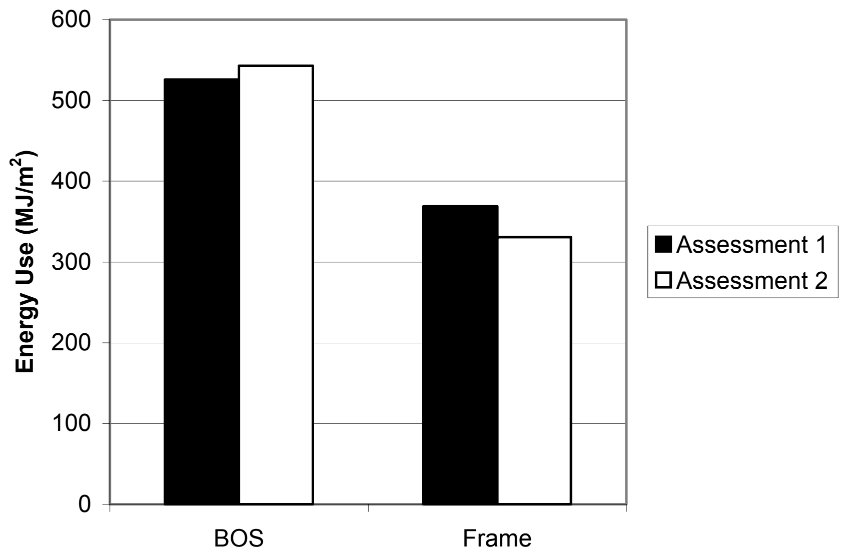


Figure 5: Comparison of Life Cycle Energy Use between Assessments 1 and 2.

(Assessment 1 is based on data from: GREET 1.6; Weiss et al.; EPD SEMC.

Assessment 2 is based on data from: Franklin Associates; NREL US LCI; Aluminum Association LCI; Ecoinvent; Annual Energy Review, EIA; DOE LCI of Biodiesel; ETH-ESU)

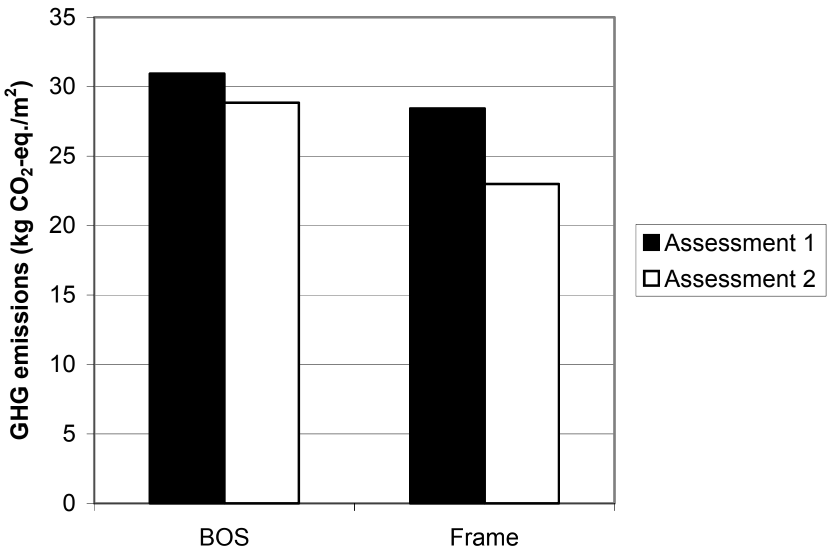
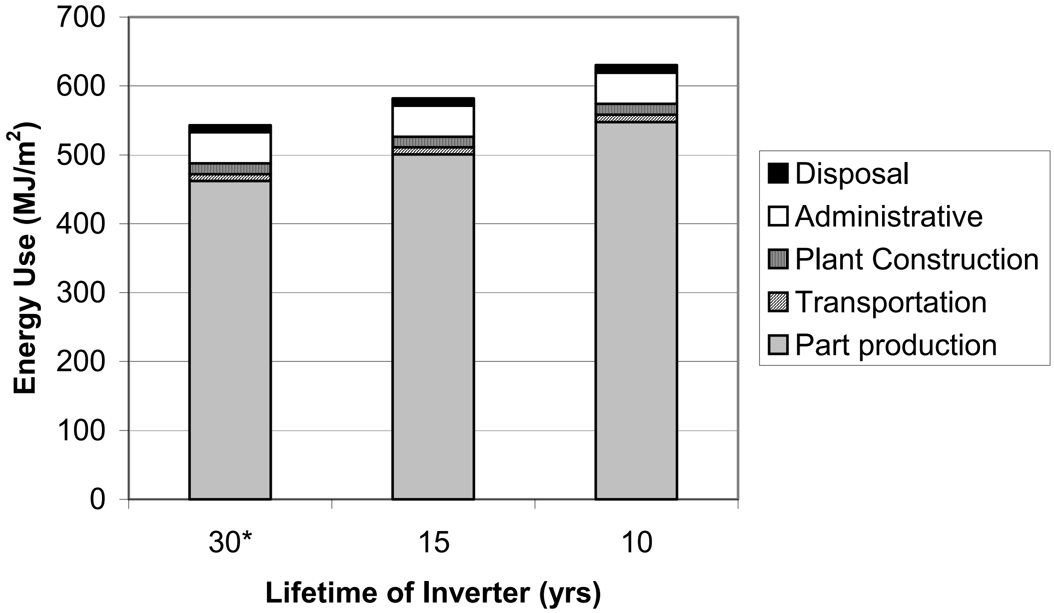


Figure 6: Comparison of GHG Emissions Between Assessments 1 and 2.

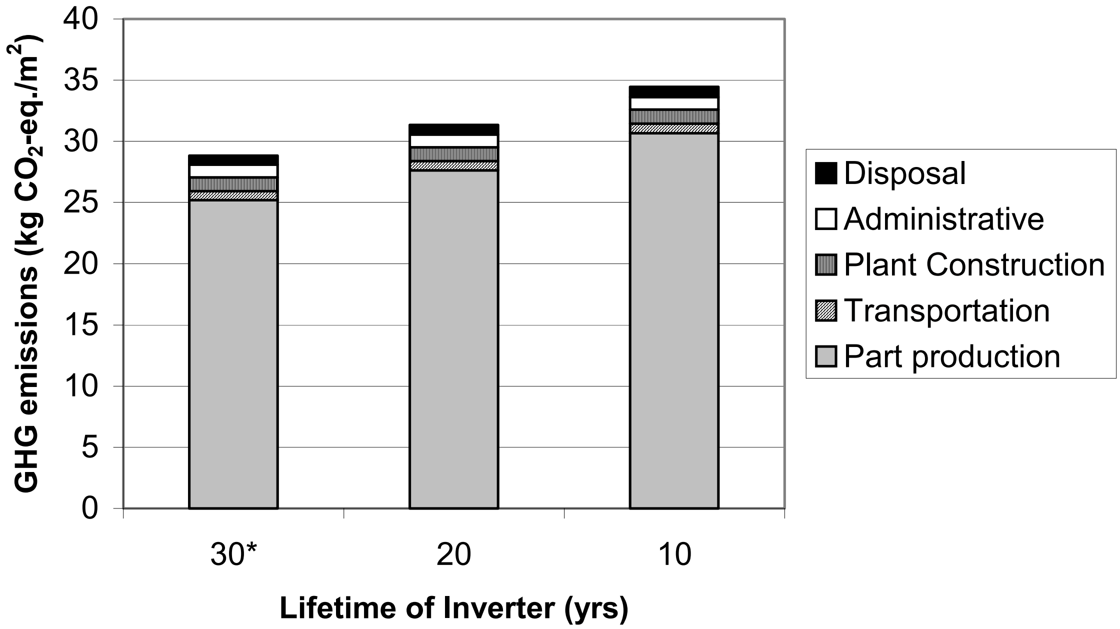
(Assessment 1 is based on data from: GREET 1.6; Weiss et al.; EPD SEMC.

Assessment 2 is based on data from: Franklin; NREL US LCI; Aluminum Association LCI; Ecoinvent; Annual Energy Review, EIA; DOE LCI of Biodiesel; ETH-ESU)



* with 10% parts replacement every 10 years

Figure 7. Life-Cycle Energy Consumption of BOS: Impact of Inverters' Life-Expectancy



* with 10% parts replacement every 10 years

Figure 8. Life-Cycle GHG Emissions of BOS: Impact of Inverters' Life-Expectancy

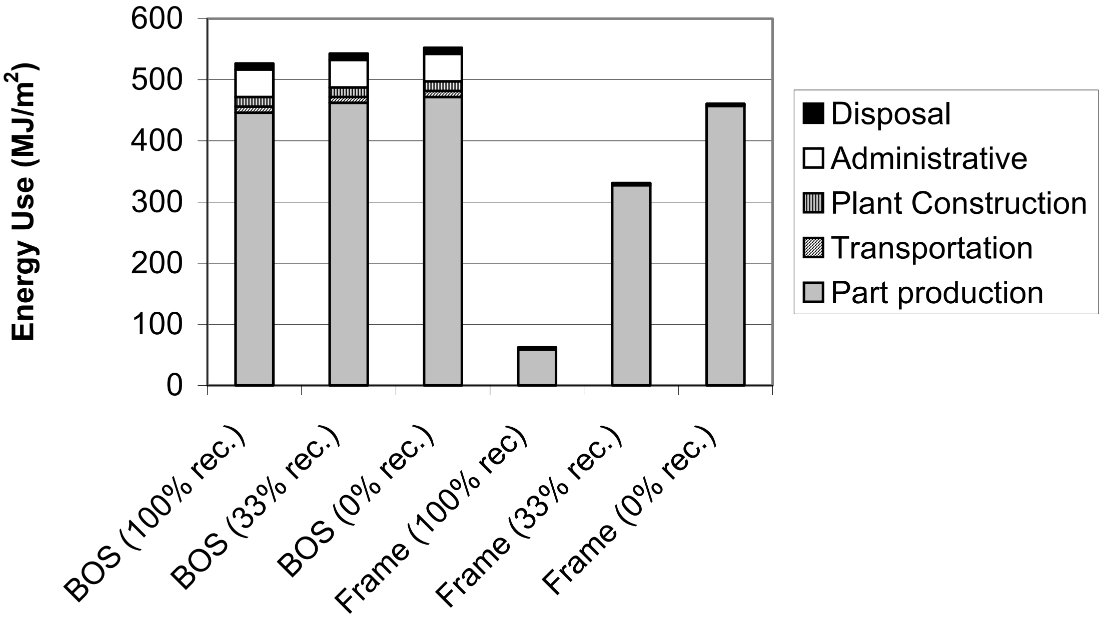


Figure 9. Life-Cycle Energy Consumption of BOS: Impact of Recycled Aluminum

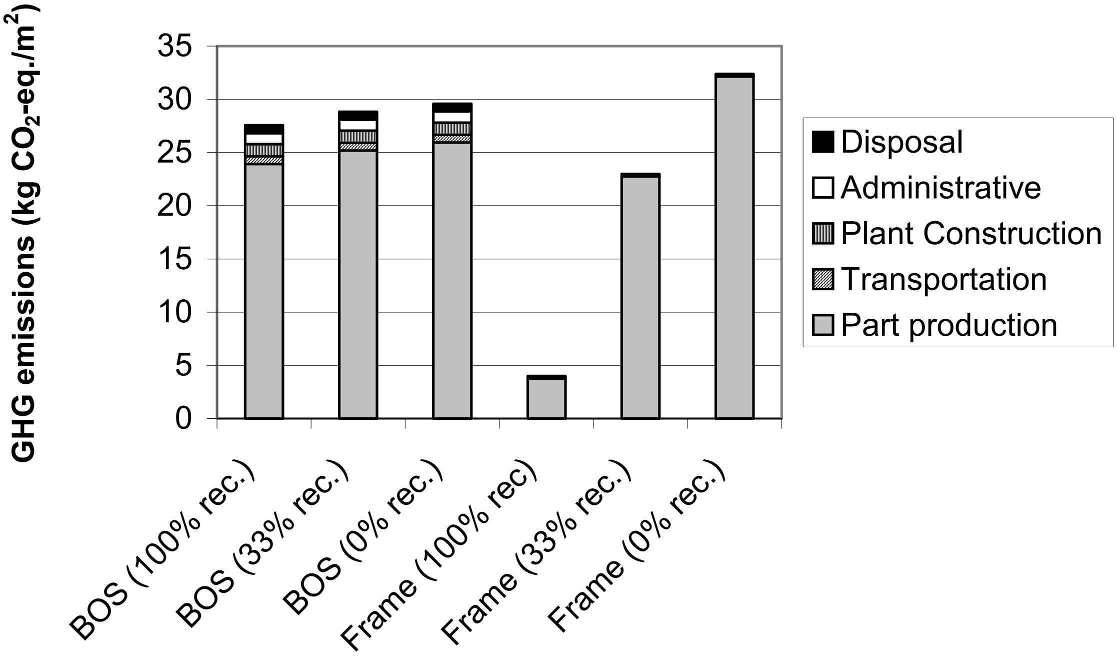


Figure 10. Life-Cycle GHG Emissions of BOS: Impact of Recycled Aluminum

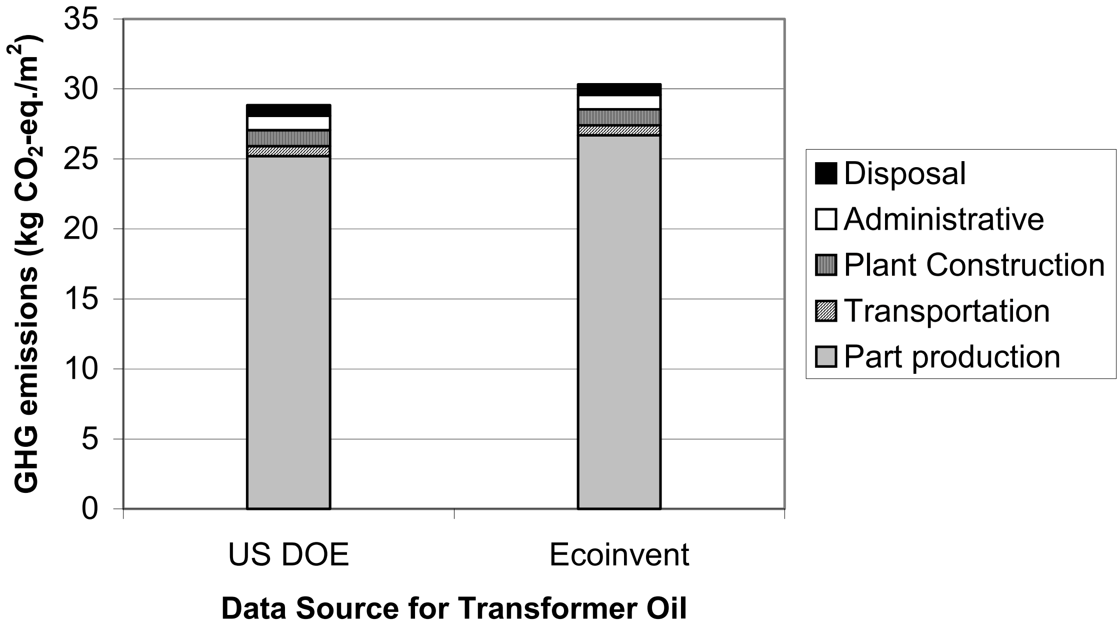


Figure 11. Life Cycle GHG Emissions of BOS: Impact of Transformer Oil LCI Data