Journal Code				Article ID				Dispatch: 14.09.11	CE: Lombart, Ma. Cristina
P	I	P		1	1	8	6	No. of Pages: 10	ME:

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1186

BROADER PERSPECTIVES

Life cycle assessment of high-concentration photovoltaic systems

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ABSTRACT

The environmental profiles of photovoltaic (PV) systems are becoming better as materials are used more efficiently in their production, and overall system performance improves. Our analysis details the material and energy inventories in the life cycle of high-concentration PV systems, and, based on measured field-performances, evaluates their energy payback times, life cycle greenhouse gas emissions, and usage of land and water. Although operating high-concentration PV systems require considerable maintenance, their life cycle environmental burden is much lower than that of the flat-plate c-Si systems operating in the same high-insolation regions. The estimated energy payback times of the Amonix 7700 PV system in operation at Phoenix, AZ, is only 0.9 year, and its estimated greenhouse gas emissions are 27 g CO_2-eq./kWh over 30 years, or approximately 16 g CO_2-eq./kWh over 50 years. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
HCPV; LCA; photovoltaics; environmental

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Received 21 April 2010; Revised 14 March 2011

1. INTRODUCTION

By employing concentrating and tracking technologies, concentrated photovoltaics (CPVs) lower the use of highly efficient but expensive photovoltaic (PV) materials, like III–V semiconductors, while achieving efficient energy-conversion. Their prospective contribution to renewable electricity portfolio seems substantial, especially in the Southwestern USA where direct normal irradiation is plentiful. Recent progress in photovoltaic cells, concentrator design, and component reliability dramatically increased the lifetime electricity generation capability of CPVs [1–5]. However, sustainability indicators of these technologies such as emissions and energy use over the life cycle are less completely understood than flat fixed PV systems, for which a number of life cycle assessments (LCAs) have been conducted to measure the environmental impacts associated with the whole life, from cradle to grave, of PV module and balance-of-system [6–9].

Life cycle assessment is an analytical tool used to measure material and energy inputs and emissions and waste outputs throughout the life cycle stages of a product or process, ultimately aiming to evaluate the system's environmental and health impacts. LCA particularly is useful in comparing energy-generation technologies. Although the operation of power plants is the most polluting stage for fossil-fuel burning technologies (coal, gas, and oil), manufacturing the device often is the key stage for renewable technologies, such as solar and wind-power.

In our earlier LCA study (Kim and Fthenakis, 2006), we reported greenhouse gas (GHG) emissions of 38 CO2-eq./kWh and an energy payback time (EPBT) of 1.3 years for the 24-kW Amonix high concentration photovoltaic (HCPV) system, equipped with single-crystal Si cells under the environmental conditions at Phoenix, AZ, USA [10]. Our data revealed that the concentrator unit and tracker accounted for 91% of the GHG emissions and the primary energy demand. The annual electricity generation by 24-kW Amonix HCPV installed in Phoenix, AZ, USA was 49.2 MWh at the time of this previous study. This performance was ~30% less than the ideal generation, 72 MWh/year calculated from the direct normal irradiation with a two-axis, 2500 kWh/m2/year in Phoenix, AZ, USA, the aperture area of 182 m^2 and the rated AC efficiency of 16%. Peharz and Dimroth (2005) reported a much shorter EPBT, that is, 0.5–0.6 year for a prototype module of the

FLATCON HCPV system with III–V solar cells, after normalizing their results to Phoenix insolation [11].

The Amonix 7700 system is equipped with III–V solar cells that have much higher efficiency (37%) than single crystal Si cells (26.5%) used in the previous system from the same company. The latest HCPV system is expected to produce electricity at under \$0.1/kWh of levelized cost, if the ongoing improvement in performance and durability is coupled with a manufacturing scale of about 100 MW/year, which would allow reduced material use and efficient design of tracker and inverter [4]. The timely update of such information is important in view of the rapid developments in the solar industry. In this paper, we discuss the life cycle emissions and energy payback time of the Amonix 7700 HCPV with III–V solar cells (Figure 1) based on their most recent operational records and data on the usage of materials and energy. Besides, this study aims to improve the previous LCAs on HCPVs by conducting detailed analyses on manufacturing III–V solar cells and scheduled maintenance as well as on electricity generation performance. We detail the flows of material and energy for each major process from cradle-to-grave and project the environmental benefits that would accrue from wide-scale deployment of the Amonix 7700 HCPV systems in the USA.

2. METHODOLOGY

We undertook a life cycle assessment of Amonix 7700 CPV following the process-based approach under which we measured, estimated, and detailed the input-physical and output-physical flows for each stage from the bill of materials, fuel and electricity usage, and operational data from Amonix Corporation. The spatial-system boundary for this LCA study is the USA for which the major energy and emissions flows are evaluated.

The life cycle of Amonix 7700 CPV starts with the acquisition of materials, encompasses their production, the manufacturing of components, their assembly/installation, their operation/maintenance, and then ends with their disposal (Figure 2). The upstream inventory data (i.e., energy and materials inputs and outputs during the materials-acquisition and production stages), come from commercial databases, including those of Franklin and Ecoinvent [12,13]. For life cycle land and water use assessment, we employed the resource use factors for upstream electricity usages from our earlier studies, along with the database listed previously [14,15]. The LCA software SIMAPRO 7.1.7 was used to determine the life cycle primary energy consumption and greenhouse gas emissions. The cumulative energy demand 1.04 method was used for the former and 2007 Intergovernmental Panel on Climate Change global warming potential values with an integrated time horizon of 100 years are used for the latter [16].

We collected the inventory data for the component-manufacturing stage from measurements and estimates in the manufacturing lines of Amonix and Spectrolab, a major producer of III/V solar cells [17,18]. For other system components (i.e., hydraulic drive, pedestal, and torque tube), the environmental burdens for the corresponding machining processes are assessed based on the previously mentioned LCA databases and were added to the impacts

Figure 1. The Amonix 7700 system (source: Amonix Corporation, with permission).

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DOI: 10.1002/pip

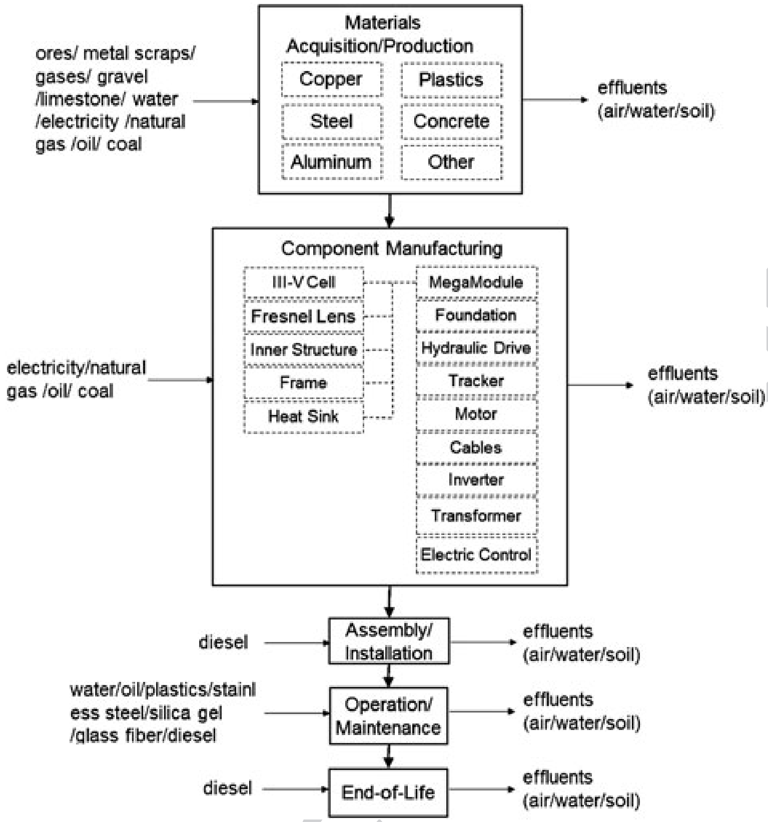

Figure 2. Life cycle flow of Amonix 7700 concentrated photovoltaic.

from materials' production. For LCA data of electrical parts including inverter, cables, and transformer, literature values for a utility flat panel PV power plant are used [7]. Detailed inputs of precursor gases, contact metals, and chemicals along with electricity usage have been investigated for manufacturing the III–V solar cell, GaInP/GaInAs/Ge. Energy and emissions inputs of similar data have been assumed for inventory items whose environmental aspects are not available in the previously mentioned databases. For example, the LCA data of single crystal silicon were used as a surrogate of the germanium substrate in the III–V solar cell. Likewise, the LCA data of acetone, a common industry solvent, were used for unspecified solvents in the III–V solar cell production.

The end-of-life (EOL) management of this system consists of decommissioning and disposal stages, which we modeled by scenario analyses based on industrial practices (e.g., recycling of automobiles). Because we employ the 'open-loop' recycling scheme wherein recycled materials are not returned to the original system, the energy and emissions credits from recycling were not accounted for. We estimated the energy usages of transporting parts from suppliers to Amonix or directly to the installation site and of delivering subassemblies from Amonix to the installation site from records of actual distance and tonnage. We also included the maintenance stage, during which oils and filters are replaced, and the mirror surface is washed.

3. LIFE CYCLE INVENTORY ANALYSIS

The Amonix 7700 HCPV system consists of seven concentrating module units called MegaModules mounted on a two axis tracker. Sunlight is concentrated on to 7560 focal spots at a ratio of 500:1. This system uses multijunction GaInP/GaInAs/Ge cells grown on a germanium substrate rated at 37% efficiency under the test condition of 50 W/cm^2, 25 °C, and AM 1.5D. We presented a full life cycle analysis on this III–V cell elsewhere [19]. With an aperture area of 267 m^2, the capacity of this unit corresponds to 53 kW$_p$ AC power under the Photovoltaics for Utility Scale Applications test conditions; that is, 850 W/m^2 direct normal insolation (DNI), 20 °C ambient temperature, and 1 m/s wind velocity. Because of increases in the efficiency of the cells, improvements in the optical path and tuning the lens to the properties of the cells, Amonix expects that the same unit will produce 62 kW$_p$ AC power in 2011 under the same test condition.

3.1. Materials breakdown

Table I gives the materials composition and mass balance **T1** of the Amonix 7700 system. Although the measurements of the mass of manufactured parts were taken directly from the assembly line, the quantity of concrete used was

DOI: 10.1002/pip

Table I. Material breakdown of the Amonix 7700. Q8

Submodule	Components	Materials	Mass (kg)	Fraction (%)
MegaModules	Cell	Semiconductor	0.2	0.001
	Frame	Steel (galvanized)	6566	23.0
	Fresnel lenses	PMMA	1143	4.0
	Heat sink	Aluminum	3086	10.8
Tracker	Foundation	Concrete	3126	10.9
	Hydraulic drive	Steel	2724	9.5
	Pedestal and torque tube	Steel	11 260	39.4
	Motor	Various	16	0.1
Electrical	Inverter	Various	500	1.7
	Transformer	Various	100	0.3
	Cables	Copper/PVC	35	0.1
Other	Controller	Various	18	0.1
	Sensor	Various	1.4	0.005
	Anemometer	Various	0.1	0.0003

PMMA, polymethyl methacrylate; PVC, polyvinyl chloride. Q9

calculated by the dimensions of the foundation, that is, 5.5 m deep and 1.1 m diameter. The detailed material compositions of electrical parts, that is, motor, transformer, and inverter, were estimated from Mason *et al* (2006) [7]. The MegaModules (36%) and tracker (58%) account for most of the components, whereas steel (75%), concrete (11%), and aluminum (11%) dominate the material usages.

3.2. Cell manufacturing

The process of cell manufacturing starts from Ge ingot and substrate fabrication. Because there is no LCA data available on Ge ingot production, the data for single crystal Si were used as a surrogate during the calculation of environmental impacts. The cell supplier, Spectrolab grows the semiconductor layers on Ge substrate through metal-organic vapor-phase epitaxy (MOVPE) and fabricates the triple-junction structure. Assumptions were made in estimating environmental impacts for unspecified chemicals and the chemicals whose LCA data are unavailable, and their validity was later tested by a sensitivity analysis. For example, LCA data for generic metal-organics were used for trimethylgallium, a precursor gas T2 for the semiconductor layers. Table II presents the input energy and materials required to manufacture the III–V solar cells scaled for Amonix 7700. A 10% loss of inputs during the solar cell production/dicing and assembly was assumed.

3.3. Part manufacturing

We assessed the energy, and materials used, and the emissions during manufacturing of major parts from information in commercial databases. The processes considered include galvanizing the steel used in the MegaModule and tracker parts, wire drawing and pipe drawing for the cables and tubes, injection-molding for the Fresnel lenses, and using a cutting tool with computer numerical control for manufacturing the hydraulic drive. The manufacturing process of the III–V cell is also assessed in detail, based on our previous investigation [19].

Table II. Inputs for processing GaInP/GaInAs/Ge terrestrial concentrator solar cell for Amonix 7700 (adapted from (Kim *et al.* 2008) [19]).

Inputs	Amount
Materials for components (kg)	
Ge substrate	0.9
Precursors	1.4
Contact metals	0.4
Antireflection coating	0.002
Materials use for process (kg)	
Hydrogen	6.6
Nitrogen	0.02
Photoresist	0.3
Solvents	124.3
Acids	29.6
Bases	18.7
Electricity (kWh)	
MOVPE	274.0
Gas scrubbing and cell processing	54.4

MOVPE, metal-organic vapor-phase epitaxy.
[a]at 37% rated efficiency.

3.4. Assembly and installation

The electricity usages by the crane and robot for assembling the MegaModule were measured in the assembly factory in Torrence, CA, USA; fuel and electricity usages for installing the Amonix 7700 system, that is, drilling its foundation hole, lifting and placing the MegaModule and tracker, and welding the hydraulic drive to the pedestal, were assessed from actual installations [17]. We assumed that no site clearance is required before installing the system.

3.5. Transportation

MegaModules are manufactured in Las Vegas, NV, USA and shipped to the installation site, whereas other parts are sent directly to the site from suppliers. We include three stages of transportation: (i) MegaModule components from suppliers to Amonix; (ii) MegaModule from Amonix to the installation site; and (iii) other parts from suppliers to installation site. Table III summarizes the transportation distance for parts, assuming that the site is located in Phoenix, AZ, USA. A trailer transports the parts, except for the hydraulic drive that is shipped from a European supplier via an ocean freighter.

3.6. Maintenance/operation

Using the data from the Tucson Electric PV plant, Springerville, AZ, USA [7], we estimated the demand for materials and energy for building and running an office needed for monitoring and maintaining the system. We also assessed the materials used in scheduled maintenance, which include changing the hydraulic and bearing oils, cleaning the lens, changing the air and oil filters, and general inspection. Table IV presents the materials and quantity of the consumables used during maintenance over an expected lifetime of 30 years.

3.7. End-of-life

The EOL stage of the Amonix 7700 HCPV components involves decommissioning the system and transporting its components elsewhere, shredding and separating parts for recycling, and disposing of the unrecyclable residue. For decommissioning, the energy inputs are determined from the installation stage. It is assumed that the dismantled components, except for the foundation, are shredded in a local scrap processor located 100 km away where recyclable metals are separated, and non-recyclable residues are sent to landfill facility, also 100 km away. The energy usages during the shredding and separation stages were taken from a publication on recycling automobiles [20]. Shredding requires 0.1 MJ/kg energy, and separation uses 0.24 MJ/kg. We assumed that separation is unnecessary for parts with homogeneous material composition, for example, the foundation, pedestal, and torque tube. The metals are recycled at the EOL stage, but we did not consider the processes that occur after shredding and separation; we assumed an open-loop recycling scheme for this analysis.

4. PHOTOVOLTAIC SYSTEM PERFORMANCE DATA AND ESTIMATES

We determined the electricity generation of the new Amonix 7700 based on the energy production of a 7500 HCPV system in Las Vegas over a year. The annual AC-generated energy at the test site, y (kWh/year) is approximated as proportional to the DNI with a two axis tracker, x (kWh/m^2/year) as follows [21]:

$$y\ (\mathrm{kWh/year}) = Ax\ (\mathrm{kWh/m^2/year}), \quad \text{where} = 42.429\ \mathrm{m}^2 \qquad (1)$$

The coefficient A was determined using linear regression from the field data of energy generation per day (kWh) and the corresponding DNI (kWh/m^2) and represents the relationship between incident sun energy and energy generation. The

Table IV. Materials required for maintaining Amonix 7700 over 30 years.

Item	Quantity (kg)
Water ,demineralized	106 000
Hydraulic oil	900
Lubricating oil	25
Poly carbonate	3
Polyester	60
Polyurethane	9
ABS (co-polymer plastic)	40
Poly amide	1
Silica gel	9
Stainless steel	7
Glass fiber	7

Table III. Details of parts transportation.

Submodule	Components	Route	Tonnage-distance (tkm)
MegaModules	Cell	Supplier-Amonix-site	0.1
	Frame	Supplier-Amonix-site	18 800
	Fresnel lenses	Supplier-Amonix-site	4300
	Heat sink	Supplier-Amonix-site	3880
Tracker	Foundation	Supplier-site	100
	Hydraulic drive	Supplier-site	26 300
	Pedestal and torque tube	Supplier-site	18 200
	Motor	Supplier-site	10
Electrical	Inverter	Supplier-site	500
	Transformer	Supplier-site	60
	Cables	Supplier-site	20
Other	Controller	Supplier-Amonix-site	22
	Sensor	Supplier-Amonix-site	1.7
	Anemometer	Supplier-Amonix-site	0.2

Amonix 7700 has seven MegaModule units, two more than the 7500 version, thereby producing 1.4 times more electricity. Note that this estimate does not include losses in field performance. Using the annual average direct solar radiation in Las Vegas with this equation gave us the ideal annual energy generation in this location. Amonix conducted an extensive analysis of a variety of losses in field performance of multiple 7700 units operating in three locations. Their analysis yielded the following information: additional soiling (2%), ac wiring and transformer losses (2%), availability (1%), wind stow (0.5%), shading (0.5%), and losses from limit on elevation angle (0.8%). Therefore, the ideal energy generation of a single unit of the Amonix HCPV system operating in the field is lowered by 6.8%. Adding these modifications, the electricity generation of Amonix 7700 (Y) is formulated in the following equation:

$$Y(\text{kWh/year}) = A'x\ (\text{kWh/m}^2/\text{year}), \quad \text{where } A' = A\ (1.4)\ (1\text{-}0.068) = 55.361\ \text{m}^2 \tag{2}$$

Extrapolating this correlation to Amonix 7700, with a performance loss of 6.8%, yields 144 000 kWh/year of electricity generation for Las Vegas where the DNI with a two axis tracker is 2600 kWh/m^2/year. The energy generation from this system operating elsewhere is derived likewise, with a minor adjustment for differing environmental conditions such as average site temperature and soiling factor. The ambient temperature effect on the efficiency of concentrated PV modules was recently documented by Kurtz *et al*. [22]. The study estimates that the ambient temperature coefficient for thin film concentrated PV modules to be about −0.2%/°C over an ambient temperature range of −10 °C to 40 °C, which corresponds to a cell operation temperature range of 15 °C–100 °C. In a separate study by Verlinden *et al*, the power temperature coefficient for a Spectrolab III–V cell is reported to be −0.171%/°C under irradiance of 50 W/cm^2 [23]. Amonix has implemented several improvements in efficiency because we used their data from the 7500 system for this regression, and has more planned, now which are progressing from the laboratory to field operation. Based on these improvements, the expected generation for Las Vegas and Phoenix, with the 2011 version of the 7700, respectively, will be 168 000 kWh/year and 159 000 kWh/year.

5. ENERGY PAYBACK TIME

The EPBT is defined as the period required for a renewable energy system to generate the same amount of energy as that used by the system from cradle to grave. For a PV system, it is quantified as follows:

$$\text{Energy Payback Time (EPBT)} = \frac{E_{comp.} + E_{inst.} + E_{EOL}}{E_{a.gen.} - E_{a.oper.}} \tag{3}$$

where

$E_{comp.}$ Primary energy demand to produce the components
$E_{inst.}$ Primary energy demand to assemble and install the system
E_{EOL} Primary energy demand for EOL management
$E_{a.\ gen.}$ Annual electricity generation (primary energy equivalent)
$E_{a.\ oper}$ Annual energy demand for operation and maintenance (primary energy equivalent)

Table V breaks down the primary energy demand during the life cycle of the Amonix 7700 HCPV system. Parts

Table V. Breakdown of the life cycle primary energy demand.

Stage	Energy (MJ)	%	GHG (kg CO_2-eq.)	%
Parts	1 470 633	88.3	102 108	92.4
Cells	14 562	0.9	615	0.6
Foundation	2341	0.1	430	0.4
Frame	234 218	14.1	16 836	15.2
Fresnel lenses	171 974	10.3	9086	8.2
Heat sink	440 089	26.4	31 194	28.2
Tracker (pedestal and tube)	427 106	25.7	31 420	28.4
Inverter	33 395	2.0	2130	1.9
Transformer	11 973	0.7	566	0.5
Hydraulic drive	117 972	7.1	8912	8.1
Motor	2056	0.1	113	0.1
Cables	5278	0.3	265	0.2
Controller	8907	0.5	498	0.5
Anemometer and sensor	762	0.05	43	0.04
Assembly/installation	162	0.01	12	0.01
Operation/maintenance	111 830	6.7	2463	2.2
Transportation	61 364	3.7	4480	4.1
End-of-life	20 745	1.2	1512	1.4
Total	1 664 733	100.0	110 575	100.0

GHG, greenhouse gas.

production dominates this demand, accounting for 88.3% of the total primary energy, followed by the operation/maintenance stage that represents 6.7%. Calculating the primary energy equivalent requires country-specific, energy-conversion parameters for the fuels and technologies used to produce energy and feedstock. The annual electricity generation ($E_{a.gen.}$) is represented as primary energy based on the efficiency of electricity conversion at the demand side. We adopted the USA's average energy-mixture efficiency of 0.29 in converting the electricity generated into primary energy.

Because the use of III–V solar cells noticeably increases the electricity conversion efficiency over an earlier system based on crystalline-Si cells, it would be important to examine in detail the energy requirement during production of these solar cells. Figure 3 presents detailed breakdown of primary energy demand from cradle-to-gate of the III–V solar cells used in Amonix 7700. Energy imbedded in solvents accounts for the largest energy demand, followed by process electricity usages during MOVPE process and manufacture of germanium substrate. We found that the energy usage of III–V solar cells contributes only ~1% of the total energy demand as shown in Table V. Although we note that, as discussed before, these figures bear uncertainties because of the absence of LCA data for germanium substrate and precursor gases, their impact may be negligible for determining the EPBT of Amonix 7700 system considering the relatively small amount of energy demand associated with the III–V solar cell manufacturing.

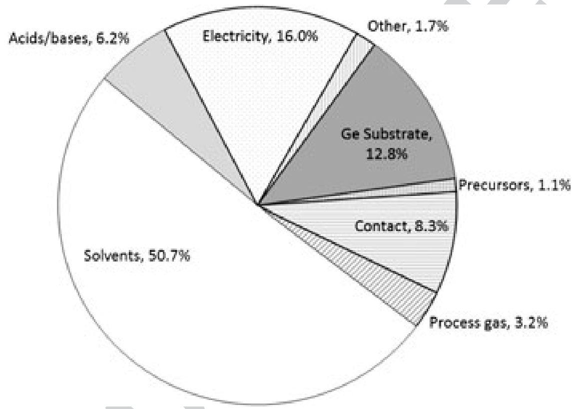

Figure 3. Breakdown of primary energy demand to manufacture III–V solar cells used in Amonix 7700 (total = 14 562 MJ_p).

We estimated the EPBTs for the sites where Amonix 7700 systems currently are operating (Table VI). We note that these EPBTs (~0.9 year) are comparable with the EPBT of the European FLATCON system, normalized for operating at the same sites [11]. Compared with our previous analysis based on the 24 kW Amonix HCPV system, the EPBT of 53 kW Amonix 7700 decreased by 0.4 year for the same location, Phoenix, AZ, USA [10]. The latter annually generates 2.8 times as much electricity as the former does, that is, 136 vs. 49 MWh because of upgrades in module design such as enhanced concentration ratio (from 250:1 to 500:1), switching to III–V solar cells with a 37% efficiency (under 50 W/cm^2) from single crystal silicon cells with a 26.5% efficiency, and accommodation of two more MegaModule units in one tracker, as well as reduced field losses. On the other hand, the increased number of MegaModule units in the latter, together with detailed material and energy accounting, especially on the operation/maintenance and transportation stages, resulted in a doubled primary energy demand compared with the former, that is, 1665 vs. 817 GJ. The net effect of these changes explains the 30% reduction in EPBT (i.e., 0.9 year) from the previous EPBT of the 24 kW Amonix system (i.e., 1.3 years).

6. GREENHOUSE GAS EMISSIONS

The greenhouse gas emissions during the life cycle stages of the Amonix 7700 HCPV system are estimated as an equivalent of CO_2, using an integrated time horizon of 100 years. Those considered for calculating GHG emissions are CO_2, CH_4, N_2O, and chlorofluorocarbons. Unlike fixed, standard PV configurations in which the emissions mostly are evolved during the production of solar cells, the tracking and concentrating equipment contributes the majority of the GHG emissions from this HCPV system. After normalizing for the electricity generated, the current system generates 26–27 g CO_2-eq./kWh during its 30-year life cycle (Table VI) in its current operating locations. Extending the system's life to 50 years by properly maintaining it, and replacing the solar cells and Fresnel lenses every 25 years, will lower its life cycle emissions approximately to 16 g CO_2-eq./kWh. The expected system for 2011 offers further gains. Part production accounts for the major share of the GHG emissions, that is, 92.4%;

Table VI. Energy payback time and greenhouse gas emissions of Amonix 7700 for 2009 and 2011.

Location	DNI with a two-axis tracker (kWh/m2/year)	Energy generation (MWh/year)		EPBT (years)		GHG emissions (g CO_2-eq./kWh)	
		Current (2009)	Future (2011)	Current (2009)	Future (2011)	Current (2009)	Future (2011)
Las Vegas, NV, USA	2600	144	168	0.9	0.8	26	22
Phoenix, AZ, USA	2480	136	159	0.9	0.8	27	23
Glendale, AZ, USA	2570	139	163	0.9	0.8	27	23

DNI, direct normal irradiation; EPBT, energy payback time; GHG, greenhouse gas.

DOI: 10.1002/pip

those from maintenance represent only 2.2% of the total, a much smaller proportion than accounted for by the primary energy demand, that is, 6.7%. The latter amount reflects the considerable usage of hydraulic oil derived from biomass-based natural ether: CO2 is sequestered during biomass growth.

7. LAND AND WATER USAGE

We assessed the life cycle usages of land and water for Amonix 7700. Detailed descriptions of resource-use indicators associated with electricity generation technologies are given elsewhere [14,15]. For our study, the land transformation (m2) and water withdrawal (m3) indicators were estimated for both upstream and on-site usages. For upstream usages, we took information from the Ecoinvent database [13]; for on-site data, we used actual field data. The currently operating Amonix 7700 units occupy 4–6 acres per 1 MW of AC power, which translates into 266 m2 of direct land transformation per GWh of electricity in Phoenix. The indirect land transformation that is linked to the energy and materials inputs to build Amonix 7700 corresponds to only 32 m2/GWh. Contrastingly, for water usages, the indirect component dominates: Direct water withdrawal for cleaning Amonix 7700 is only 26 L/MWh under the solar radiation of Phoenix, whereas, correspondingly, indirect water withdrawal for materials and energy inputs is 682 L/MWh. We note that we excluded the water withdrawal of the hydroelectric power plant in our accounting, in accordance with the convention of the US Geological Survey [24]. We compare in Figures 4 and 5 these usages of resource across PV technologies under the solar radiation of Phoenix, that is, 2370 kWh/m2/year for optimal tilt flat PV and 2480 kWh/m2/year of DNI for collectors with a two-axis tracker. We assumed that flat PV is installed with the BOS of TEC's Springerville power plant [7]. Accordingly, the land use for Amonix 7700 is less than

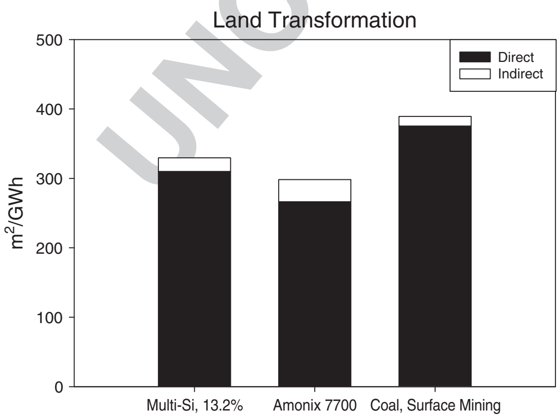

Figure 4. Comparison of land transformation. Photovoltaic technologies are assessed under the environmental conditions of Phoenix, AZ, USA, whereas the coal case refers to surface mining in the Eastern USA (case 1, Table I in Ref.[14]).

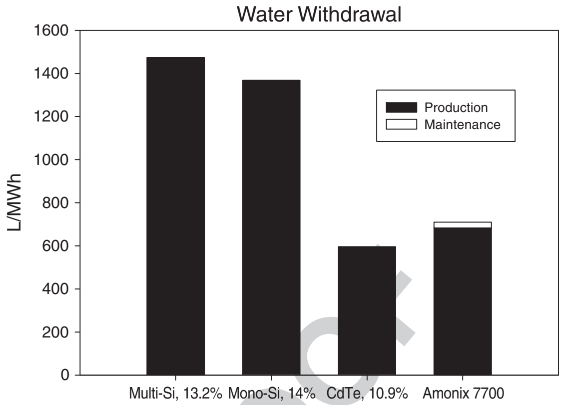

Figure 5. Comparison of water withdrawal across photovoltaic technologies under the environmental conditions of Phoenix, AZ, USA [15].

that of multi-Si PV. The indirect land use for this system is unknown. Similarly, the water use of Amonix 7700 is less than that of multi-PVs and mono-PVs, whereas comparable with that of CdTe PV. We point out that estimates of land and water usage carry a larger uncertainty than those for emissions and energy payback because the availability and quality of data is poorer for the former.

DISCUSSION

Fthenakis and Alsema (2006) and Fthenakis *et al* (2008) reported the EPBT and the GHG-emissions of crystalline Si and CdTe PV technologies [6,8]. Fthenakis *et al* (2009) recently updated the environmental impacts of thin film CdTe PV [9]. The EPBT and the GHG-emissions of 14% efficient monocrystalline silicon, ground-mount PV modules produced in the USA correspond to 1.8 years and 39 g CO_2-eq./kWh, respectively, when operating in south-facing latitude tilt under the optimal angle insolation of Phoenix—2370 kWh/m^2/year. In the same location, the EPBT and the GHG-emissions of a CdTe PV system are 0.6 year and 13 g CO_2-eq./kWh, respectively; these are the lowest numbers reported in the peer-reviewed literature. The Amonix 7700 HCPV has a significant advantage over the flat, fixed crystalline silicon solar cell in terms of both these parameters.

The life expectancy of the HCPV system could be extended to 50 years by replacing the III-V solar cells in the field, assuming that the Fresnel lenses and the overall structure would last 50 years. Replacing them would not add significantly to the EPBT or the GHG burden because the cells account for only about 1% of the total energy burden. However, a detailed analysis of this scenario must take into account potential losses from breakage of cells in the field and increased maintenance requirements associated with an operational life of over 30 years. If the life of the 7700 HCPV is extended to 50 years, then its life cycle GHG emissions would fall to 16 g CO_2-eq./kWh.

Prog. Photovolt: Res. Appl. (2011) © 2011 John Wiley & Sons, Ltd.
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A recent study on the FLATCON concentrating PV system that employs a similar design, that is, Fresnel lenses over III–V cells with a two-axis tracker, reports 1.2 years of EPBT, and 30 g CO_2-eq./kWh of GHG emissions during its 25-year lifetime, under southern European conditions with DNI of 1900 kWh/m^2/year [25]. These results correspond to 0.9 year of EPBT and 19 g CO_2-eq./kWh of GHG emissions under the DNI of Phoenix, AZ, USA of 2480 kWh/m^2/year. The comparable EPBTs of these two systems probably reflect their similar design concept, even though they differ in size and power. The FLATCON system has a much smaller aperture area than the Amonix 7700 system, that is, 28.8 vs. 267 m^2 and has a lower life cycle primary energy demand of 160 vs. 1665 GJ. The former generates much less electricity than the latter, 16.4 MWh/year vs. 136 MWh/year, nearly proportional to the apertures' areas. According to equation (3), these parameters result in comparable EPBTs. On the other hand, the lower GHG emissions for the FLATCON CPV compared with our estimates in Table VI may be related to the cleaner European electricity mix (i.e., less CO_2 emissions per kWh) used during its production than the mix in the USA, where coal is the dominant source of electrical energy.

The current investigation did not include other environmental and human health impact indicators such as human toxicity and eco-toxicity potentials. Although the quantities of toxic elements used in III–V cells (e.g., gallium, indium and arsenic), are minute in comparison to the mass of the HCPV system, the high toxicity of these elements [26,27] warrants the need for further life cycle investigations that include EOL management and fate.

CONCLUSIONS

We investigated selected environmental indicators, that is, EPBT, GHG emissions, land transformation, and water withdrawal during the life cycle of the Amonix 7700 HCPV system. The estimated EPBT of the current system operating in Phoenix, AZ, USA is 0.9 year, and the estimated GHG emissions are 27 g CO_2-eq./kWh over a 30-year operation, or approximately 16 g CO_2-eq./kWh over 50 years. Both values are much less than that of typical flat-plate c-Si PV ground-mount system normalized for the same manufacturing conditions (i.e., upstream grid mix) and solar radiation. In addition, we also estimate that Amonix 7700 will use less land and water than Si PV modules. The MegaModule and the tracker account for the largest part of its life cycle energy use and emissions; the multijunction cells have negligible environmental impacts. Unlike flat fixed PV, this system requires a considerable amount of materials and resources during its maintenance stage, translating into 7% of the total life cycle energy use. As this system offers opportunities for further increasing electricity generation and the device's lifetime, updated studies are warranted in the future as new performance data are generated.

Note in Press

Amonix informed the authors during this article's final review that the company's product today has several significant improvements over the original 7700 evaluated in this article a year ago. Amonix claims the 7700 product today has higher cell efficiencies, higher power ratings, and lower costs because of improved design and manufacturing benefits. Amonix has an improved energy production methodology for greater confidence in energy generation estimates and has identified concepts for extending operation life by a factor of two or more. Amonix claims that these changes will reduce GHG emissions by approximately a factor of two from those estimated in this paper for the first 7700 and reduce the EPBT from 0.9 year to 0.7 year. These preliminary results will be reviewed and refined in a future publication.

ACKNOWLEDGEMENTS

The authors thank Matthew Meares and Bob McConnell for providing energy production and materials breakdown of the Amonix 7700 needed for this analysis. This work was partially supported by the Solar Technologies Program, US Department of Energy, under Contract DE-AC02-76CH000016 with the US-DOE.

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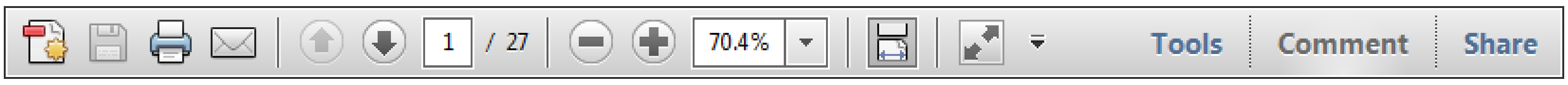

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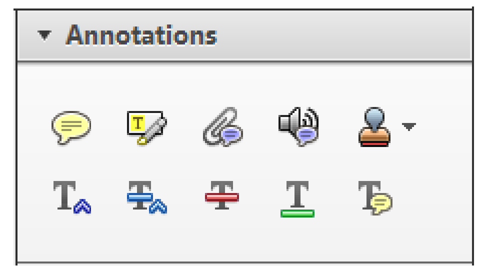

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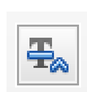

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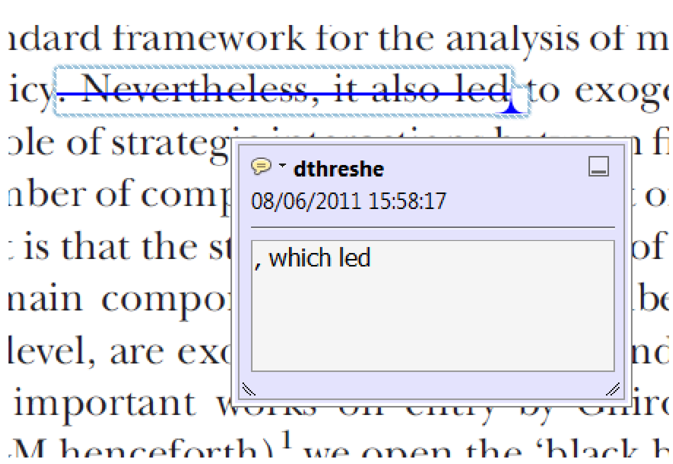

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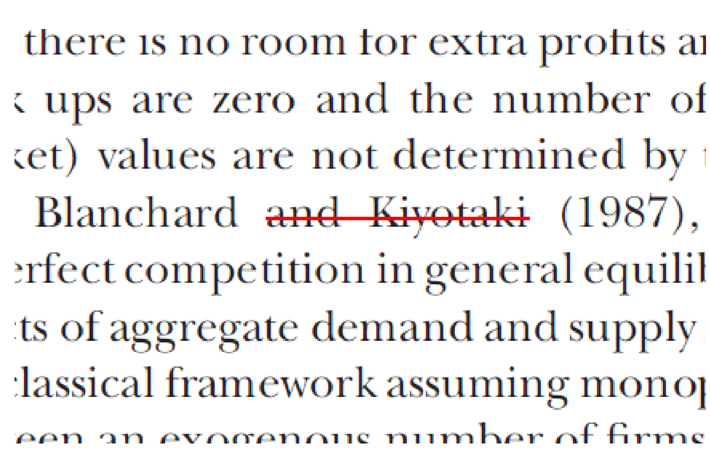

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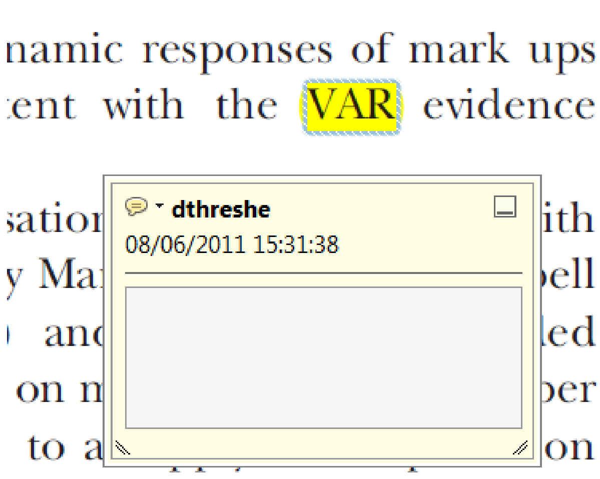

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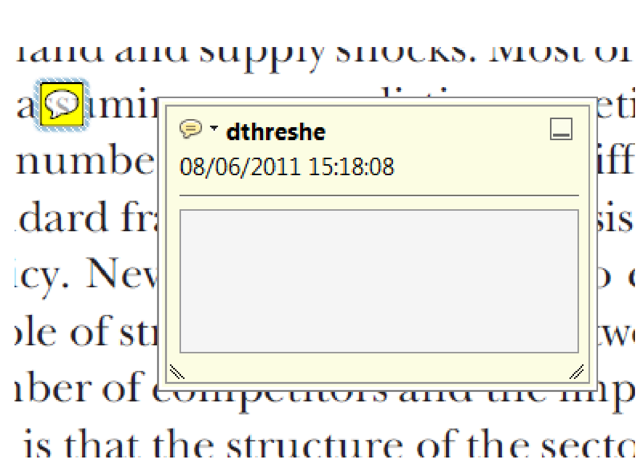

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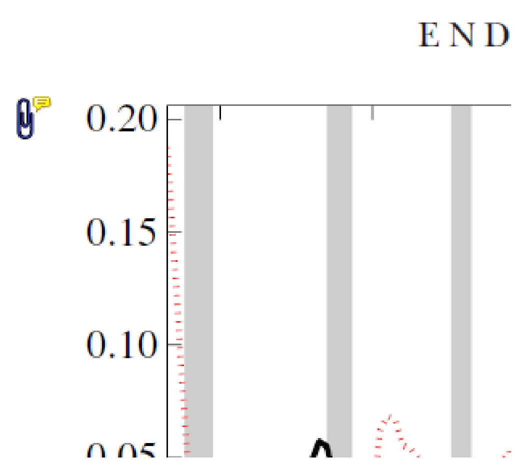

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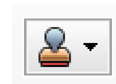

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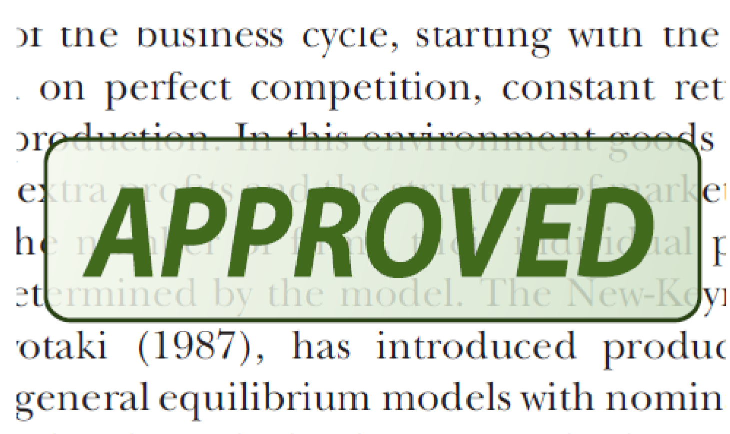

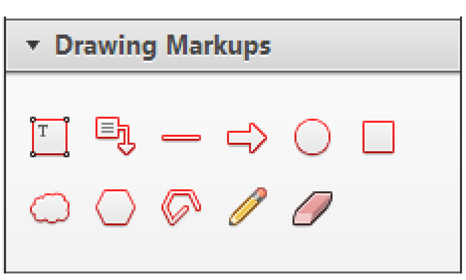

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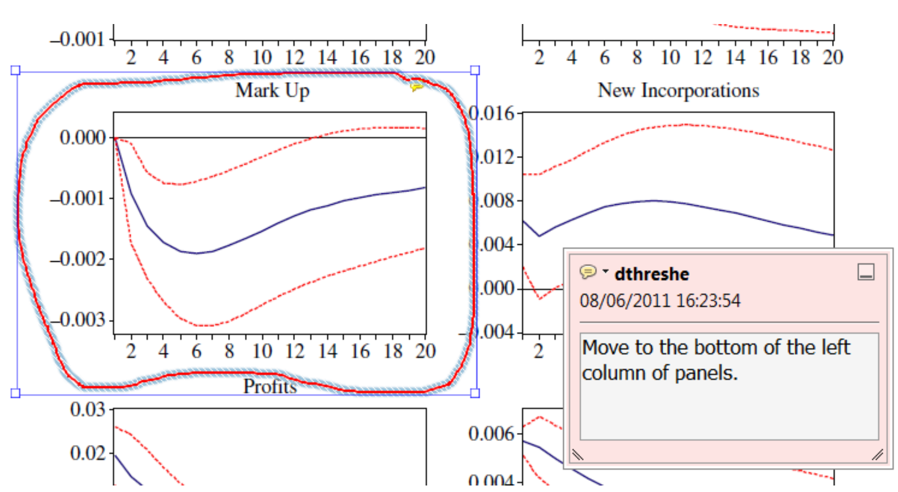

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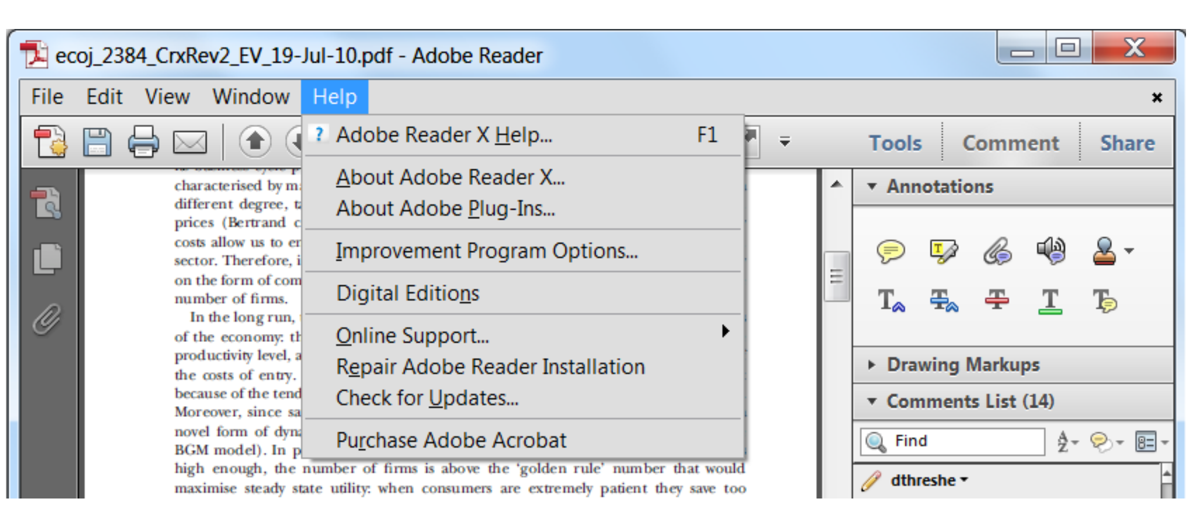

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