IMPACT OF CELL TECHNOLOGY, INSTALLATION TYPES AND SCALES ON ENERGY EVALUATION METRICS OF PV SYSTEMS

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Abstract

We evaluate the impact of system installation types, cell material and tracking strategies on the evaluation metrics of PV systems such as energy payback time (EPBT), return factor (ERF) and CO_2 emissions offset. As candidate power producing systems we consider a range of PV cell materials, different tracking strategies, as well as concentrating photovoltaic. We conclude that utilizing existing structures significantly reduces the energy payback time of flat-plate PV. High-efficiency concentrating PV installations yielded the shortest EPBT, the highest ERF and the largest life-cycle CO_2 offsets. Considering the use of land, we find that a greater life-cycle energy return and carbon offset per unit *land* area is yielded by locally-integrated non-concentrating systems.

1. Introduction

PV systems are inherently scalable and can be deployed in a wide range of settings, from small systems installed on individual building roofs to commercial-scale generating plants (Alsema, 1997). The process of PV manufacturing and installation consumes energy and generates pollutants (Frankl *et al*., 1998). Studies over the past decade (Boyd and Dornfeld, 2005; Pacca and Horvath, 2002) have shown that while the carbon emissions resulting from PV power generation are an order of magnitude lower than for coal-fired plants, they are still significantly higher than for hydroelectric and wind generation. The overall energy efficiency of PV systems may therefore be improved not only by increasing their electrical output, but by reducing their embodied energy – which is consumed not only in the production of PV modules (including the specific solar cell), but in the other balance-of-system (BOS) components such as supporting structures. The deployment of the PV system – be it building-integrated, requiring little or no additional support, or constructed in the open field – may thus have considerable importance for its net energy yield. In addition to the potential savings offered by building-mounted PV through the avoidance of new support structures, access roads, fencing, and cabling, which can represent substantial costs (both monetary and energetic) at remote sites, other advantages over centralized ground-based PV have been cited (Oliver and Jackson, 2001). PV systems on buildings may produce electricity at or near the point of use, avoiding transmission and distribution of electricity and the costs and losses associated with this.

In this study, we evaluate these impacts via a case study of PV-supplied electricity for a specific region while considering different possibilities of system deployment as well as different PV systems ranging from stationary flat plate collectors of different cell materials to various tracking strategies and to concentrator photovoltaic systems requiring two-axis tracking. The study analyses the case of the Arava region (population ca. 4000), a part of the Negev desert of southern Israel (Figure 1), which includes the valley stretching from the Dead Sea to the Gulf of Aqaba (Eilat) and is considered a prime location for large-scale solar generation, with its average annual insolation equaling 2150 kWh/m^2 (Faiman et al., 2006). We perform a comparative life-cycle energy analysis of a variety of PV electricity generating systems at three different scales, from the most localized (integration with individual buildings) to the most centralized (a commercial-scale field array). An intermediate scale scenario of "urban-integrated" PV is also considered, in which available buildings, allied support structures (such as shading structures for parking and other open spaces), and open land *within* a given settlement are all utilized for PV installation.

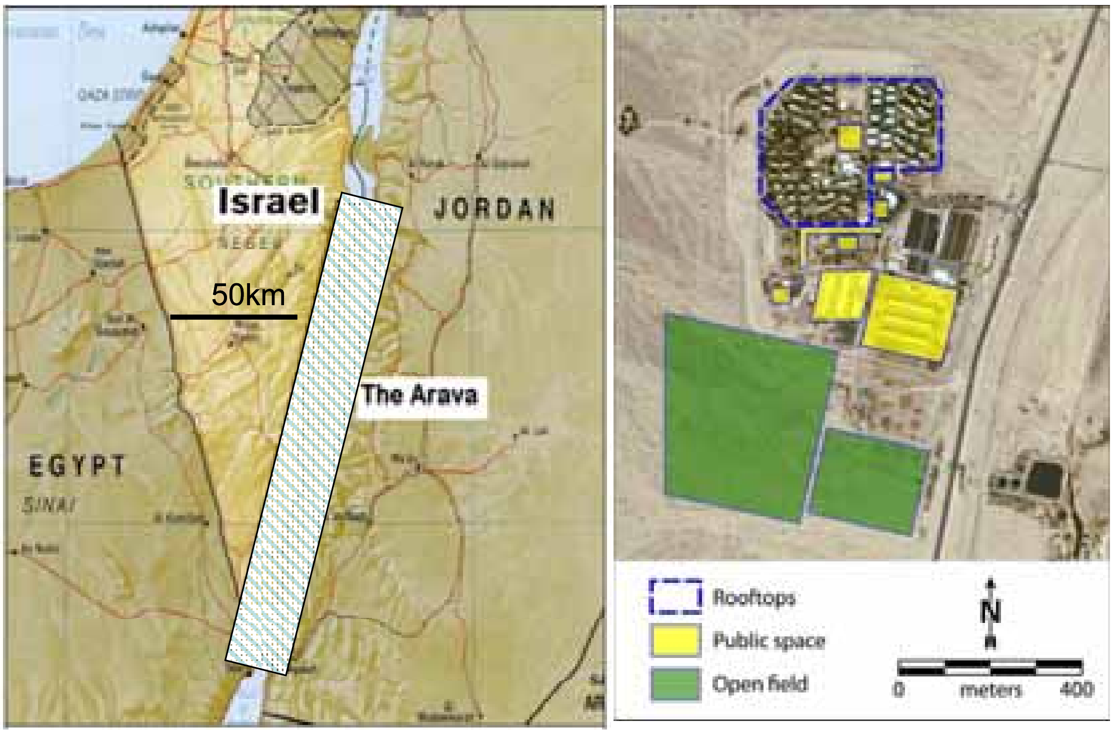

Fig. 1. Left: the Arava region of southern Israel. Right: Kibbutz Ketura, a typical community of the region, the plan indicates potential areas for PV deployment.

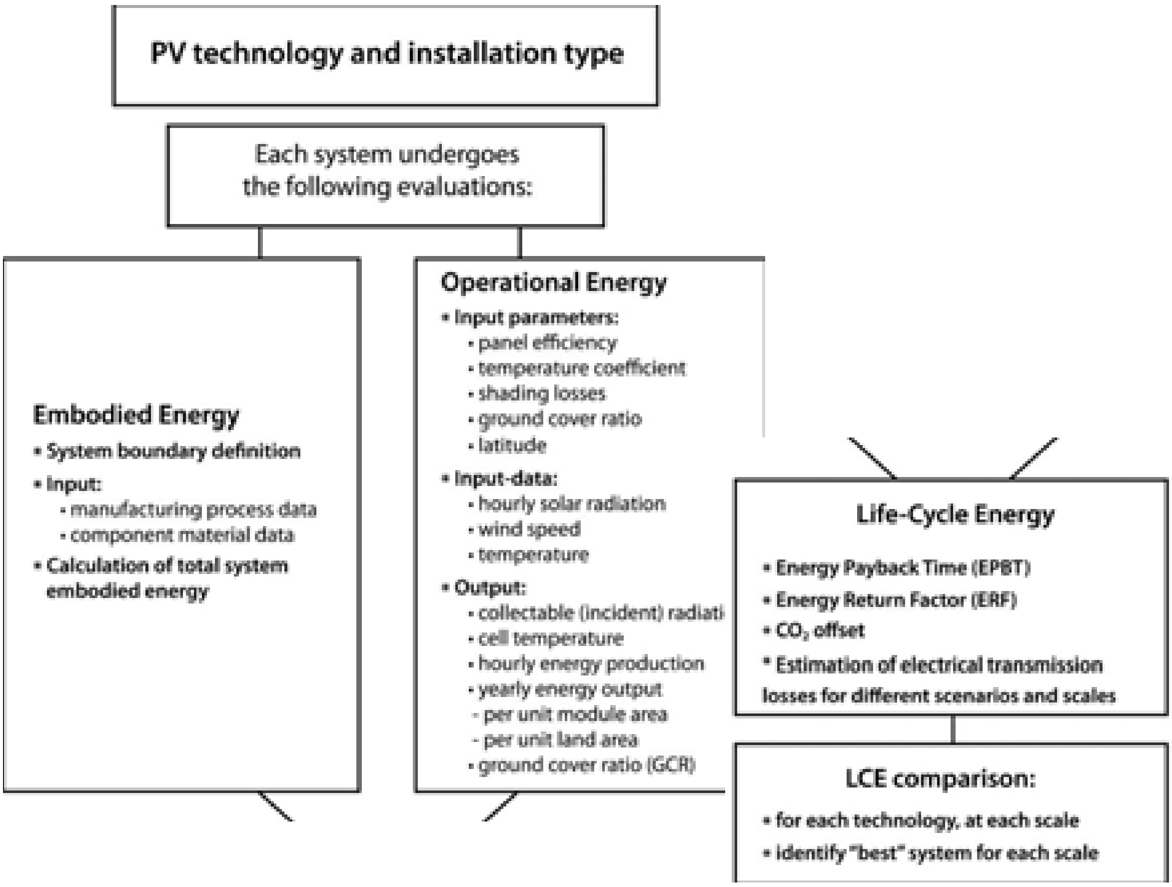

Fig. 2. Each PV system is evaluated following this flow chart.

2. Methodology

The relative weight of embodied energy for the different components within a PV system's lifetime and net energy yield may be quantified using Life-Cycle Energy Analysis (LCEA). The methods for performing such life-cycle analyses, including standardization in the definition of system boundaries and accounting procedures, have been refined over the last two decades (Alsema, 1997; Fthenakis and Alsema, 2006). The ratio of the total primary energy input to the yearly primary energy-equivalent generated by the system represents the energy pay-back time (EPBT) of the PV system, the EPBT being a key measure of a PV system's appropriateness as an alternative to fossil fuel-based generation. A second metric is the Energy Return Factor (ERF) of the system which represents the ratio between the total energy generated by the PV system to the total energy consumed over its entire life cycle. Similar analyses can be made for greenhouse gases emissions, by evaluating the quantities of CO_2, SF_6, CF_4 and other greenhouse gases emitted in the PV system life-cycle and comparing these values to emissions from fossil fuel-based electricity generation options (Alsema, 1997).

Three distinctive scales and a number of PV technologies create a matrix of system possibilities, each of which requires the analysis of energy input (embodied energy) and output, from which in turn the other metrics can be derived. Figure 2 schematically describes the process for determining the metrics for each combination of technology and type of deployment.

Energy output

Eight different PV systems were chosen for the case study based on their commercial availability as well as the accessibility of their embodied energy data. Table 1 lists these PV systems with their key performance data and essential characteristics (such as temperature coefficient, positioning, and tracking strategy). The determination of the energy output of each technology is performed by simulation (Halassah, 2010) using hourly meteorological data from a weather station located in the area with the appropriate equations accounting for solar geometry. It was assumed that flat plate systems suffer a total of 15% losses due to mutual shading over the year, assuming a 50% ground cover ratio (40% for polar axis tracking systems). No shading was assumed for fixed horizontal (tilt=0) collectors. The losses for concentrating collectors due to shading were taken to be 2.6% (Hakenjos et al. 2008) due to their low ground cover ratios (GCR). The simulation results were verified against experimental output data from stationary flat plate PV panels measured over a one-year period at Keturah (Halasah, 2010).

Table 1: PV technologies and types of installations included in the case study, with key performance parameters.

Module type (installation options)	PV cell type	Nominal module efficiency (%)	Temperature coefficient (%/°C)
Flat plate (Fixed position with tilt angle = latitude; Fixed position with tilt angle = 0; or Single-axis tracking)	Single Crystalline Silicon (s-Si)	19.3	-0.38
	Multi Crystalline Silicon (m-Si)	14	-0.4
	Ribbon Cast Silicon (r-Si)	13.2	-0.47
	Amorphous Silicon Thin Film (a-Si)	6	-0.25
	Cadmium Telluride Thin Film (CdTe)	10.8	-0.25
	Copper Indium Selenide thin film (CIS)	12	-0.35
Concentrator (Two-axis tracking)	SolFocus (dual mirror design)	25	-0.046
	Flatcon (Fresnel lens design)	26	-0.046

Embodied Energy

The embodied energy calculation relies on published data or on data provided by the manufacturer and takes into account the support structure of the system, which in turn depends on the type of installation, such as building integrated or free-standing. Based on the initial embodied energy and yearly energy output, the life-cycle metrics – energy pay-back time (EBPT), energy return factor (ERF) and CO_2 offset – are calculated for each system configuration, accounting for a 1% nominal yearly system degradation.

Embodied energy data were collected from published studies on the relevant manufacturing processes involved in PV system production as well as from manufacturers' data sheets. All electrical energy inputs (in kWh/m^2 of panel surface) were converted to primary energy units based on the UCPTE[1] average electricity generation efficiency of 32% (Raugei et al, 2007). The system boundaries were defined in terms of the International Federation of Institutes for Advanced Study (IFIAS) scheme of orders as adopted by ISO 14040 (Wilting, 1996). This study included processes included in Level 2, which incorporates direct energy for processes, material manufacturing, and transportation, and which together are estimated to cover up to 90% of direct energy inputs (Huberman and Pearlmutter, 2008). Several studies provided data for crystalline and Ribbon-Si cells (Nawaz and Tiwari, 2006; Jungbluth et. al, 2008; de Wild-Scholten and Alsema, 2006) that were based on the ‘Ecoinvent‘ data base published by the Swiss Center for Life Cycle Inventories (Dübendorf, Switzerland, 2008: http://www.ecoinvent.org). The processes involved in the different stages of silicon cell material preparation were adopted from Jungbluth et.al. (2008), and it was assumed that solar-grade silicon, produced by a modified Siemens process for metallurgical grade silicon, was used for the cells considered. For crystalline Si cells, this study assumes a cell area of 156 cm^2, or about 60 cells per m^2 of module area, with 6% of the wafer area being lost due to sawing. Embodied energy data for thin film modules were taken from a number of published studies (Raugei, et. al, 2007; Hynes, et al. 1994; Knapp and Jester, 2001a; and Knapp et. al. 2000).

The embodied energy for the cell material of concentrator systems is relatively minor, as the concentration ratio is on the order of 500. Data for these systems were taken from Peharz and Dimroth (2005) and Der Minassians (2006). Aluminum used for the PV module frame was assumed to contain 15-25% recycled content (Pacca et. al., 2006). The balance-of-system (BOS) was assumed to contribute a fixed amount of embodied energy to each type of module to account for the operation and maintenance of the system, and the inverter was assumed to require two replacements during the system‘s life time. The BOS also includes embodied energy for the support structures, whose value varies with the type of installation. An input of 200kWh/m^2 was estimated for the rooftop installation, and 500 kWh/m^2 for installations in the open field (Nawaz and Tiwari, 2006) due to the embodied energy of concrete foundations. The additional energy required for tracking systems is negligible (Perpiñan et. al., 2009), and is estimated at 2 kWh/m^2. For simplicity, it was assumed that all systems would be shipped from the same port in Europe (Hamburg, GE) to an Israeli port (Ashdod) by cargo vessels with average fuel consumption of 6.7 grams of oil per ton-km. An energy expense for the 268km distance from the port to the final destination in the Arava by truck was added and converted into kWh.

Life-cycle energy metrics

The energy payback time (EPBT) is calculated in years by (Alsema, 1997):

$$EPBT = \frac{E_{input}}{E_{gen}} \qquad \text{(eq. 1)}$$

where E_{input} is the embodied energy and E_{gen} is the yearly primary energy savings due to the electricity generated by the PV system. E_{gen} is converted into primary energy (i.e. avoided generation by conventional means) via the UCPTE[1] average generation efficiency of 32% (Raugei et. al., 2007). The energy return factor (ERF) gives the energy balance of the system, in terms of the ratio between its total lifetime output ($E_{gen,L}$) and its initial embodied energy (Alsema, 1997):

$$ERF = \frac{E_{gen,L}}{E_{input}} \qquad \text{(eq. 2)}$$

[1] UCPTE European Union for the co-ordination of production and transmission of Electricity.

For calculating the lifetime output, an operational lifespan of 20 years was assumed for thin-film technologies, and for all other systems a period of 30 years was assumed. All calculations included a 1% yearly output degradation. The CO_2 emissions offset was calculated from the net energy abatement ($E_{gen,L}$ - E_{input}) based on an electrical generation mix of 75% coal, 11% natural gas and 14% heavy fuel and gasoil (Mor and Seroussi, 2007), yielding an average CO_2 emissions intensity of 0.904 kg/kWh of generated electric power.

3. Results

Energy output

The energy output for the eight PV systems is shown in Figure 3. The dual-axis concentrating PV systems have the highest output per module area due to their highly efficient solar cells, which also have a relatively low temperature coefficient. This is despite the fact that their collectible energy is limited to direct radiation only, whereas flat plate systems exploit diffuse radiation as well. For flat plate systems, the yearly collectible energy is highest for polar axis tracking, followed by North-South axis and East-West axis tracking. Dual axis tracking for flat plate collectors is excluded due to the low increase in collectable energy compared to polar axis tracking (Rabl 1985) and the added complication of dual axis tracking. In terms of cell type, the single crystalline silicon technology (Single-Si) yields the highest output, and amorphous silicon (a-Si) the lowest.

PV type	Tracking installations polar	N-S axis	E-W axis	Stationary tilt=lat.	tilt=0
CIS	271	259	234	223	205
CdTe	246	235	213	203	186
Ribbon-Si	294	282	254	242	222
Single-Si	434	416	376	358	328
Multi-Si	314	301	272	259	238
a-Si	137	131	119	113	104
III-V semi-conductor material	Two-axis tracking concentrators: FLATCON 501	SolFocus 482			

100 150 200 250 300 350 400 450 500
Energy output [kWh m⁻²]

Fig. 3. Total yearly energy output for different Photovoltaic modules.

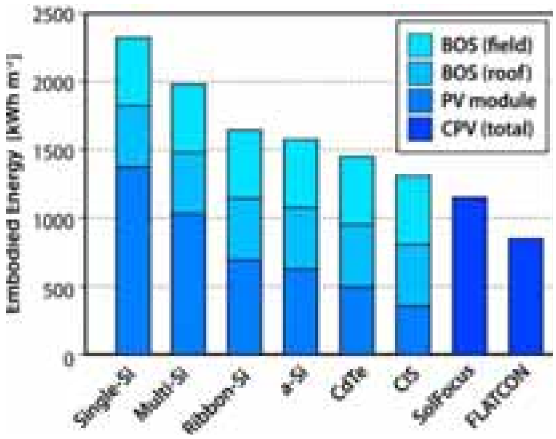

Figure 4: Total initial embodied energy for different Photovoltaic modules. For flat-plate systems, values are broken down for PV module, BOS for rooftop installation, and additional BOS for field installation, while for CPV (FLATCON and SolFocus) systems the values are inclusive. Sources: de Wild-Scholten and Alsema, 2006 (single-Si, multi-Si and ribbon); Lewis et al., 1997 (a-Si); Kato et al., 2001(CdTe); Knapp and Jester, 2001b(CIS); Peharz and Dimroth, 2005(FLATCON); and Der Minassians et al., 2006 (SolFocus).

Embodied Energy

The embodied energy for the different PV technologies considered in this study is shown in Figure 4. In the case of flat panels, cumulative values are shown for (a) the embodied energy required for the production of the PV modules, (b) the balance of system (inverter, tracking system, support structure) when PV panels are installed on existing roof structures, and (c) additional BOS (primarily foundations) when panels are installed in the open field. Values for the CPV technologies include the embodied energy for the whole system, per square meter of aperture area. By this comparison the CPV technology systems have a lower embodied energy than all of the flat plate systems when the latter are installed in the field, and lower than some of the flat-plate technologies with rooftop installations.

Evaluation

Figure 5 (left) shows that the energy payback time (EPBT) for flat-plate systems ranges from 1.1 to 5.0 years, with rooftop installations having a payback time which is consistently, and in some cases significantly, shorter than those in the open field. This is due to the additional balance-of-system energy that is embodied in field arrays, primarily for concrete foundations. In terms of PV cell technologies, the two non-silicon thin-film options (CIS and CdTe) have the shortest payback periods due to their low embodied energy (see Fig. 4) while the amorphous silicon (a-Si) thin-film has by far the highest EPBT due to its low output. While the EPBT of most flat plate panels fall in the range of 1.5 to 2.5 years, the concentrator systems have a much shorter EPBT – of 0.6 and 0.8 years for the Flatcon and SolFocus systems, respectively.

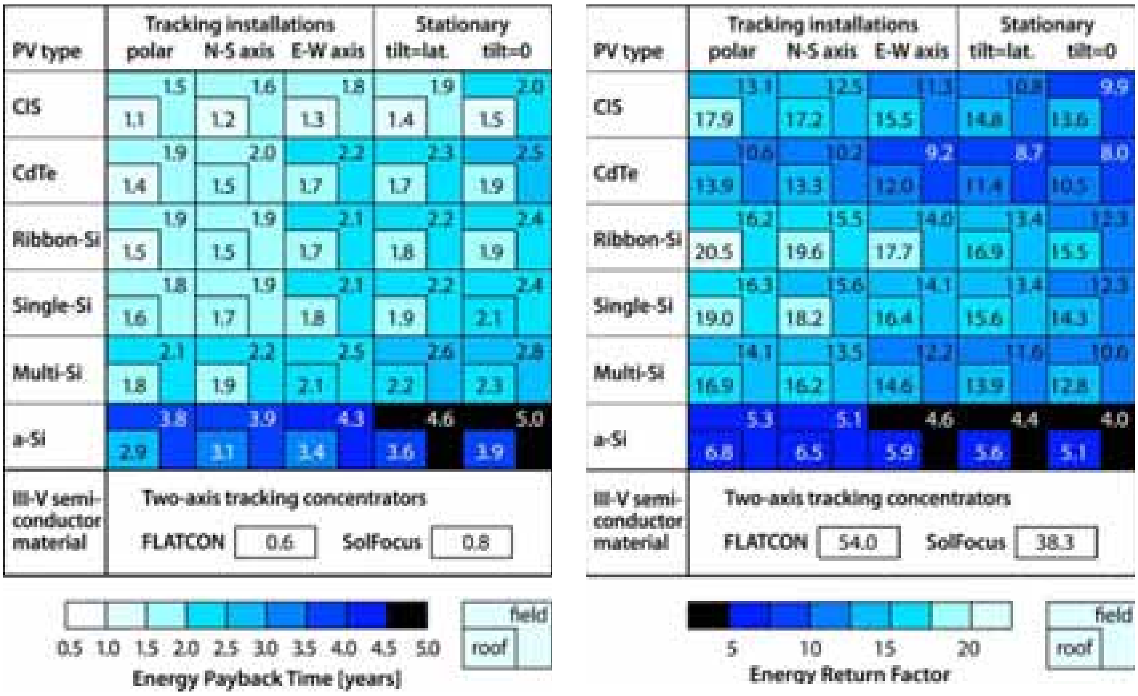

Fig. 5. Left: Energy Payback Time (EPBT) for flat-plate PV systems by type of cell and installation, on building rooftops and in open field, and concentrating PV systems with 2-axis tracking (field installation only). Right: Energy Return Factor (ERF) for flat-plate PV systems by type of cell and installation, on building rooftops and in open field, and concentrating PV systems with 2-axis tracking (field installation only).

The energy return factor (ERF) expresses the energy balance of the PV system over its full life time (Fig. 5 right). Both for roof-top and field installations, a life time of 20 years was assumed for thin-film systems (CIS, CdTe and a-Si), while 30 years was taken for all the other silicon-based systems (a degradation of 1% per year was assumed for all systems). For flat plate technologies the ERF ranges between approximately 4 (stationary a-Si, field installation) and 20 (polar tracking Ribbon-Si, roof installation), while the concentrator systems showed values of 54 for Flatcon and 38 for SolFocus, thanks to their higher output efficiency. The relative performance shown by the ERF results differ from those for the EPBT mainly because of the different life spans of the systems: in the case of ERF, the thin-film technologies are disadvantaged due to their shorter life span, and thus the highest return factors for flat-plate systems are found for the silicon-based cells.

Figure 6 (left) shows the lifetime carbon offset of each PV system, per unit *aperture* area. The comparative results are similar to those for ERF, with the main difference stemming from the fact that the CO_2 offset expresses a difference, rather than a ratio, between embodied and operational energy. Thus the quantitative advantage of the systems with the most efficient output is less pronounced for CO_2 offset than it is for ERF. Figure 6 (right) shows the lifetime carbon offset per unit area of *land*, whose availability in many cases is limited. Varying from a high of 6.1 tCO_2/m^2 for a single crystalline Si panel with no tilt angle (and a ground cover ratio of unity, since overshadowing is eliminated) to only 0.3-0.7 tCO_2/m^2 for a-Si panels, the spread is indeed large. The concentrator systems require significant land use, because of the large spacing between the individual modules to prevent mutual shading (though in such field installations the available land between the modules may also serve additional functions).

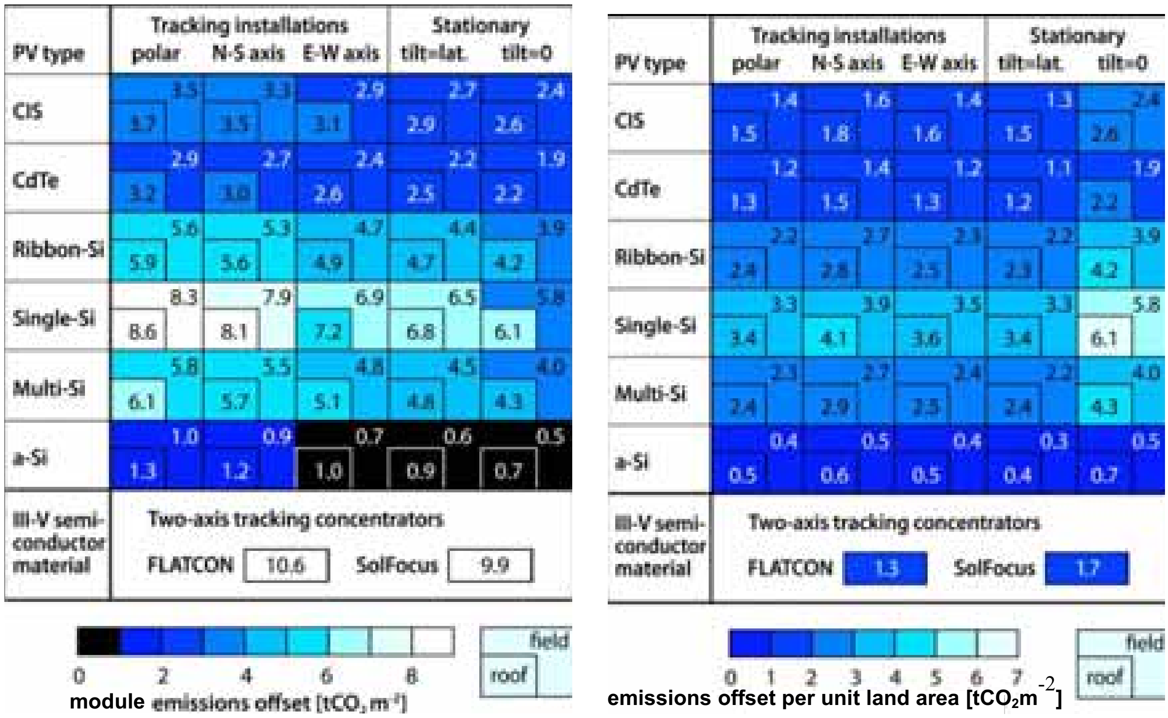

Figure 6. Left: CO_2 emissions offset by *aperture area* for flat-plate PV modules by type of cell and installation, on building rooftops and in open field, and concentrating PV systems with 2-axis tracking (field installation only). Right: CO_2 emissions offset by *land area* for flat-plate PV systems by type of cell and installation, on building rooftops and in open field, and concentrating PV systems with 2-axis tracking (field installation only).

4. System Scale Comparison

In order to evaluate the life-cycle energy efficiency of PV systems at different scales of deployment, from the most highly distributed to the most highly centralized, this study establishes three different scenarios: 1) Building-integrated PV, utilizing individual existing rooftops in the built-up area of a representative settlement; 2) Locally-integrated PV, using both rooftops and other available infrastructure within the same settlement; and 3) Regionally-integrated PV, in the form of a large-scale field installation serving all settlements in the area. It is assumed that all systems are grid-connected, such that there is no need for storage of energy. The first two scenarios, which represent different levels of distributed power generation at the local scale, are based on the above-mentioned case study the *kibbutz*, which is typical of the development in the Arava Valley. Kibbutz Ketura, a settlement with a population of approximately 300 residents, was selected for the purpose of quantifying the available area for potential PV installation, since its population size and electricity consumption are representative of the region (Cohen, et al. 2009). As shown in Figure 1, these areas include the rooftops of existing buildings (with typical multi-unit residential structures having a useful rooftop area of 144 m^2), and, for the "locally-integrated" scenario, also public areas which are assumed to have structures for shading and open areas that may be adapted for the deployment of PV panels.

The third scale is the centralized regional power plant, which is sized to generate 12.5 MWp in order to match the total annual electricity demand of the *kibbutz* communities in the Arava region (equal to approximately 25 GWh/yr or an installed capacity of 12.5 MWp). It is assumed here that land availability in the Arava is not the limiting factor in determining system size. Implementation at this scale allows for centralized maintenance, but it introduces transmission losses as a function of the average distance to the point of end use (estimated as 0.02%/km). Transmission losses were found to be negligible for transmission within the region itself (Sørensen 2007), and only the reduction in the high voltage line losses were considered as an additional benefit for regional production of electricity. Given that the next major power station is distanced from the region by about 200 km, and the transmission lines are at a high standard, the saving due to avoided transmission losses were estimated at 4% (Halasah, 2010) and are the same regardless of technology or type of deployment.

The comparison between these scales of deployment is made using two models. The first employs a *single* PV technology, which is judged to be adaptable to each of the different scales, and the second employs *multiple* PV technologies by identifying the most suitable option for each of the different scales. In both models, the selected technology is chosen based on criteria of applicability, market availability and total output per unit area.

Single-technology comparison

By using the different metrics discussed previously, the Single-crystalline silicon flat plate technology was chosen as the most suitable *single* technology for implementation at *all* scales (the CPV options were eliminated in this case as unsuitable for rooftop installation). Per unit aperture area, Single-Si has the highest electrical output of all flat-plate options (Fig. 3), and the highest CO_2 offset (Fig. 6). Despite this material's relatively high embodied energy, only CIS has a significantly shorter EPBT (Fig. 5), Single-Si has the second highest ERF after Ribbon silicon (Fig. 5). Due to the relative complexity of the single-axis tracking systems, stationary panels were considered as the most practical installation option for all cases, including rooftops and shading structures, and a slope of tilt=latitude was chosen because of its significantly higher output (relative to tilt=0) per unit module area. The output per unit area of the system is just over 350 kWh/m^2 and it's space requirement is 5.6 m^2/MWh/yr. Installations on shading structures have the same energy pay-back times as that of building integrated PV, since the shading devices are considered to be pre-existing. However, by utilizing available areas within the kibbutz other than residential rooftops, the PV system may be sized to produce as much electricity as the entire kibbutz consumes.

The energy pay-back time for rooftop installations will be 1.9 years with an ERF of 16, and the open field installations have an EPBT of 2.2 years and an ERF of 13. Given the available areas in Kibbutz Ketura (Fig. 1), the following results were obtained:

a. Building-integrated PV: Based on a useable roof top area of approximately 11,000 m^2 and a 50% coverage ratio, the stationary panels (tilt = latitude) yield just under 2,000 MWh yr-1 of electricity. After taking into consideration 15% losses due to mutual shading, this total annual output offsets about 50% of Kibbutz Ketura's electrical demand, and approximately 37,000 tons of CO_2.
b. Locally-integrated PV: A total area of 25,000 m^2 was identified on public building rooftops and as shade for parking lots, sidewalks and open spaces, again with a 50% coverage ratio defined as usable PV area. The actual output after accounting for mutual shading is 3,250 MWh/yr, which covers 100% of the kibbutz demand and offsets 85,500 tons of CO_2.
c. Regionally-integrated PV: The designated capacity of 12,500 MWp using fixed panels (tilt-latitude) requires a land area of 140,000 m^2. The energy pay-back time in this case will be 2.2 years, and the power plant will offset 480,500 tons of CO_2 per year.

Table 2 shows a summary of the results of comparing the same technology for different scales.

Table 2. Life-cycle energy results when comparing the same technology (single-Si modules) at different scales.

Scale	EPBT (years)	ERF	tCO_2
Building	1.9	16	37,000
Local	1.9	16	85,500
Regional	2.2	13	480,500

Multiple-technology comparison

Considering the most suitable option for *each* of the different scales the following results are obtained:

a. Building integrated PV: The single-crystalline silicon PV with north-south axis tracking was determined to be the preferred system for this scale, since it is the least expensive of all tracking systems. Based on the area of residential rooftops, this option potentially gives 2,275 MWh/yr of electricity, which – considering shading losses of 15% - amounts to nearly 2,000 MWh/yr (this configuration covers 60% of the kibbutz electricity demand). The energy pay-back time in this case will be 1.7 years, and the system will offset 44,000 tones of CO_2 with a value of ERF equal to 18.

b. Locally-integrated PV: For this scale, a combination of two different installation types was selected, one for the rooftops and one for shading structures covering public areas, with the requirement that the total output should sum up to 3,250 MWh/yr to meet the annual electricity demand of Kibbutz Ketura. For rooftops, the north-south horizontal axis tracking is used, and zero tilt, single crystalline silicon panels were chosen for shading of public spaces. In total, the kibbutz-integrated PV system will offset about 61,000 tons of CO_2. By repeating the kibbutz-integrated PV scenario in different kibbutzim in the Arava, the annual demand of the region can be met easily. Such an option would use minimal land area, making efficient use of rooftops and public shaded areas. This would also reduce the transmission losses because of the point-of-use generation.

c. Regionally-integrated PV: For this scale the selected system is the SolFocus CPV, requiring 12 m^2/MWh/yr of land area. The energy pay-back time of a power plant based on this technology will be 0.8 years, with an ERF of 38. It would require 300,000 m^2 of land and offset 510,000 tons of CO_2 per year. Table 3 shows the results for the best technology for each scale.

Table 3. Results for the comparison of the "best" technology for each scale.

Scale		EPBT (years)	ERF	tCO_2
Building		**1.7**	**18**	**44,000**
Local	Shading structures	2.1	14	45,000
	Building rooftops	1.7	18	40,000
	Total (weighted average)	**1.9**	**15.7**	**85,000**
Regional		**0.8**	**38**	**510,000**

5. Conclusions

In examining the energy performance of different PV systems, this study demonstrates clearly that a wide range of variables may in fact be significant to the final comparison. Cell technology, installation type, system life span, and ground cover ratio are all factors which can substantially alter at least one of the evaluation metrics. This makes the selection of technology and installation type very sensitive to the different circumstances of the case under investigation. It was found that utilizing existing infrastructure, such as existing building roofs and shade structures, does significantly reduce the embodied energy requirements (by 20-40%) and in turn the energy payback time of PV systems due to the avoidance of energy-intensive BOS components like foundations. Considering different system scales, the study indicates that the building integrated PV and the locally integrated PV scenarios are acceptable alternatives to a centralized, large scale regional PV power plant. High-efficiency CPV systems were found to yield the shortest EPBT, the highest ERF and offset the most CO_2 – *if* land is not a limitation. Because the studied CPV systems have a very low ground cover ratio, they require large field installations which are not appropriate for local integration. On the other hand, the locally integrated model offers an alternative by which non-concentrating systems may be used locally, and while their efficiency per unit module area is lower, their life-cycle energy and carbon offset potential per unit *land* area is greater. The life-cycle energy analysis does not provide a direct assessment of the economics of PV, but does provide relevant indicators of the relative economic benefits of different systems. In particular, as energy costs rise, and a high price is put on CO_2 emissions, these metrics will become more directly relevant economically.

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