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Field installation versus local integration of photovoltaic systems and their effect on energy evaluation metrics

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HIGHLIGHTS

- We evaluate life-cycle energy impacts of PV systems at different scales.
- We calculate the energy payback time, return factor and CO_2 emissions offset.
- Utilizing existing structures significantly improves metrics of flat-plate PV.
- High-efficiency CPV installations yield best return and offset per aperture area.
- Locally-integrated flat-plate systems yield best return and offset per *land* area.

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ABSTRACT

In this study we employ Life-Cycle Assessment to evaluate the energy-related impacts of photovoltaic systems at different scales of integration, in an arid region with especially high solar irradiation. Based on the electrical output and embodied energy of a selection of fixed and tracking systems and including concentrator photovoltaic (CPV) and varying cell technology, we calculate a number of energy evaluation metrics, including the energy payback time (EPBT), energy return factor (ERF), and life-cycle CO_2 emissions offset per unit aperture and land area. Studying these metrics in the context of a regionally limited setting, 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 EPBT of flat-plate PV systems due to the avoidance of energy-intensive balance of systems (BOS) components like foundations. Still, high-efficiency CPV field installations were found to yield the shortest EPBT, the highest ERF and the largest life-cycle CO_2 offsets—under the condition that land availability is not a limitation. A greater life-cycle energy return and carbon offset per unit *land* area is yielded by locally-integrated non-concentrating systems, despite their lower efficiency per unit module area.

1. Introduction

Photovoltaic (PV) technologies have a pivotal role to play in the transition away from fossil fuel-based power generation. Solar radiation has a higher global power density than any other source of renewable energy (Smil, 2003), and PV systems in particular—because they are inherently scalable—can be integrated in a wide range of settings, from individual buildings to commercial-scale generating plants (Alsema, 1997). The considerable potential of direct solar conversion using PV is underpinned by expectations that solar energy will eventually become the most economical and sustainable solution for most energy applications, and the only viable alternative energy option throughout the world (Bradford, 2006).

At the same time, the process of PV manufacturing and installation (like any other anthropogenic activity) 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

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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 this study, we evaluate this impact via a case study of PV-supplied electricity for a region while considering different possibilities of system deployment.

The relative weight of embodied energy for the different components within a PV system's lifetime net energy yield may be quantified using Life-Cycle Energy Analysis (LCEA). The ratio of the total primary energy input to the yearly primary energy-equivalent generated by the system represents the energy payback time (EPBT) of the PV system, and a low EPBT is one measure of a PV system's appropriateness as an alternative to fossil fuel-based generation. Another measure is the Energy Return Factor (ERF) of the system, representing the ratio between the total energy generated by the PV system to the total energy consumed over its entire life cycle, and 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).

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) and considerable progress has been made in the assessment of environmental impacts from PV systems. An opportunity for reducing the energy-demand footprint of PV systems is to exploit existing infrastructure, such as suitably pitched or flat roofs of buildings, for their installation—thereby avoiding energy-intensive concrete foundations and other BOS components. It has been suggested that distributed building-integrated photovoltaics (BiPV) may offer the most cost effective application of grid connected PVs and are likely to be "the first grid feeding PV systems to reach widespread commercialization" (McNelis, 1996). Oliver and Jackson (2001) found that BiPV may allow for savings in primary energy input of over 30% due to reduced transmission and distribution losses and lower BOS requirements, despite moderate increases in the inputs for the PV modules themselves. Similarly, Boyd and Dornfeld (2005) found significant drawbacks in employing ground-based installations, including 30–50% increases in air pollutant emissions relative to BiPV.

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 as well (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. As emphasized by Vardimon (2011) in a recent case study in Israel, producing energy in large solar power stations requires vast tracts of land and may necessitate an extensive upgrade of the power grid. It was shown that high-efficiency PV rooftop installations could produce a significant portion (the equivalent of 32%) of the national electricity consumption in the long run.

PV materials that are integrated into the building envelope can in some cases replace other cladding materials, such as waterproofing roof membranes or tiles, avoiding the costs of those products and thereby providing some offset to the considerable cost of PV as an energy source alone. Alternatively, placing panels above a building's rooftop can decrease the solar heating of the building and potentially yield significant moderation of its air-conditioning loads (Sick and Erge, 1996; Wang et al., 2006). Because of such multiple potential benefits, and due to the common limitation of available roof space, it is sometimes considered judicious to combine a variety of installation options within a given populated area, including shade structures and available open land as well as buildings per se.

Since the life-cycle performance of a PV system is naturally a function of its output as well as its input energy, the EPBT and related metrics are dependent on the conversion efficiency of the PV cell, and on the level of solar collection by the system as a whole. The intensity of solar incidence per unit area of PV cell (or module) may be enhanced by optimizing the panel's fixed orientation (i.e. tilt angle) or by employing single or dual-axis tracking, and additional gains may be achieved through optical concentration using mirrors and/or lenses. Concentrating photovoltaic (CPV) systems use less cell material than flat-plate collectors and have a higher conversion efficiency, significantly reducing the required cell area and overall cost (Der Minassians et al., 2006)—but they require 2-axis tracking and relatively wide spacing between collectors, and their potential for integration with buildings is limited. It is therefore relevant to gauge the system's net energy output with respect not only to the aperture area of the collecting device, but also to the area of land that is required for its operation.

Given the numerous technological and economic constraints which must be considered, it is clear that the viability of a PV installation can ultimately hinge on its geographical location. The Negev desert of southern Israel, which includes the Arava valley stretching from the Dead Sea to the Gulf of Aqaba (Eilat), is considered a prime location for large-scale solar generation, with its average horizontal annual insolation equaling 2150 kWh m^{-2} (Faiman et al., 2006)—as compared with 1700 kWh m^{-2} per year in Southern Europe and 1300 kWh m^{-2} per year in south Germany (Fthenakis and Alsema, 2006).

In this study, the Arava region (population ca. 4000) is used as a framework for a comparative life-cycle energy analysis of a variety of PV generating systems at three different scales, from the most localized (BiPV, or 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.

2. Methodology

2.1. Evaluation process

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. Fig. 1 schematically describes the process for determining the metrics for each combination of technology and type of deployment.

Eight different PV systems were chosen for this 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 while 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 (metal frameworks are used throughout, though other options are available),

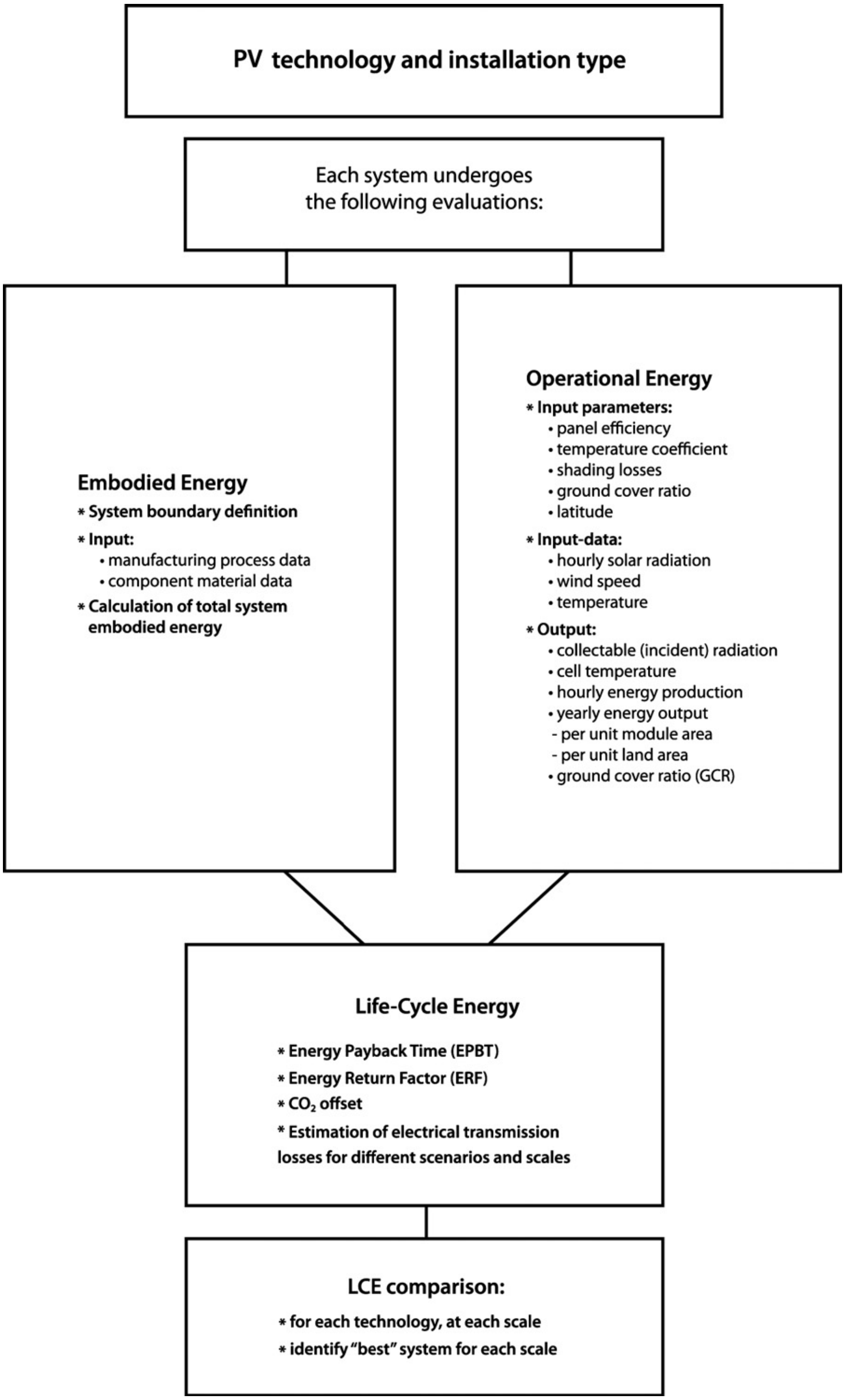

Fig. 1. Flow chart describing the process for system comparisons.

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 (EPBT), energy return factor (ERF) and CO_2 offset—are calculated for each system configuration, accounting for nominal yearly system degradation.

2.2. System energy output

The energy output per unit module area of a given technology is considered size independent. Input parameters are conversion efficiency, temperature coefficient, and panel orientation. The incidence angle modifier for flat plate collectors (the effect of reflection from the panel as function of incidence angle) is taken into account by applying the same generic formula to all flat plate systems (King et al., 1998), since specific data for the particular panels included in the study were not available; however, these functions do not change significantly from one collector to the next and therefore should not affect the results significantly.

To determine a system's energy delivery, a single-year simulation was performed using hourly meteorological input data that

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)	14.0**	−0.38
	Multi crystalline silicon (m-Si)	13.5	−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)	11.7	−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

* Values for module efficiency are taken from publications which also provide corresponding embodied energy values, and it should be noted these efficiency coefficients do not represent the highest efficiency modules available to date.

** Single-Si modules are available with up to 19–20% efficiency.

include direct and diffuse solar radiation (direct radiation only for concentrating collectors), ambient temperature and wind speed. The meteorological data for the Arava region were obtained from the local weather station at Yotvata.[1] The incidence angles for direct radiation and total irradiation on a tilted PV module surfaces were calculated via established geometric relations (Rabl 1985). The panel temperature was calculated based on a model by King et al. (1998) and the conversion efficiency was determined via the system-specific temperature coefficient. Inverter losses were taken to be constant for all installations, even though performance ratios can be slightly higher for utility-optimized systems (Fthenakis et al., 2011)—since the roof-mounted systems considered here vary significantly in size, with some being quite large.

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). The shading losses for these fixed tilt arrays could be reduced by adopting a lower ground cover ratio, but this is not considered practical in Israel due to the constraints on available land. No shading was assumed for fixed horizontal (tilt=0) collectors. The simulation results were verified against experimental output data from stationary flat plate PV panels measured over a one-year period at Keturah, which is located near the center of the region under study (see Halasah, 2010).

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) of 12.7% for FLATCON and 17.5% for SolFocus. These low GCR and accordingly small shading losses for CPV are based on systems actually installed by the two companies considered here.

2.3. Embodied energy

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 per m^2 of panel surface) were converted to primary energy units based on the UCPTE 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 21 processes, material manufacturing, and transportation, and which together are estimated to cover up to 90% of direct energy inputs (Huberman and Pearlmutter, 2008).

The manufacturing processes for PV cell materials vary for different technologies, though all silicon-based technologies, i.e., single-crystalline, multi-crystalline, ribbon cast multi-crystalline and amorphous silicon, are based on the same raw material. Thin-film technologies and silicon-based cells share many of the same processes, such as the production of the Transparent Conductive Oxide (TCO) substrate, while cells for concentrator systems are based on III-V semiconductor material. Several studies provided data for crystalline and Ribbon-Si cells (Nawaz and Tiwari, 2006; Jungbluth et al., 2008; de Wild-Scholten and Alsema, 2006; Fthenakis et al., 2009), many of which were based on the 'Ecoinvent' data base published by the Swiss Center for Life Cycle Inventories (Duebendorf, 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. In addition to these area losses, the processes of cutting and polishing result in additional weight losses, all of which have been taken into account. 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 2001b; and Knapp et al., 2000; SENSE, 2008; Fthenakis et al., 2009; Sherwani and Usmani, 2010).

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 200 kWh/m^2 was estimated for the rooftop installation, and an additional 300 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

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[1] Private Communication. The Ben-Gurion National Solar Energy Center; Meteorological data from Data Processing for the Negev Radiation Survey, 2005.

port (Ashdod) by cargo vessels with average fuel consumption of 6.7 g of oil per ton-km. An energy expense for the 268 km distance from the port to the final destination in the Arava by truck was added and converted into kWh.

2.4. Life-cycle energy metrics

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

$$EPBT = \frac{E_{input}}{E_{gen}} \tag{1}$$

where E_{input} is the primary 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[2] 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):

$$ERF = \frac{E_{gen,L}}{E_{input}} \tag{2}$$

For calculating the lifetime output, an operational lifespan 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

3.1. Energy output

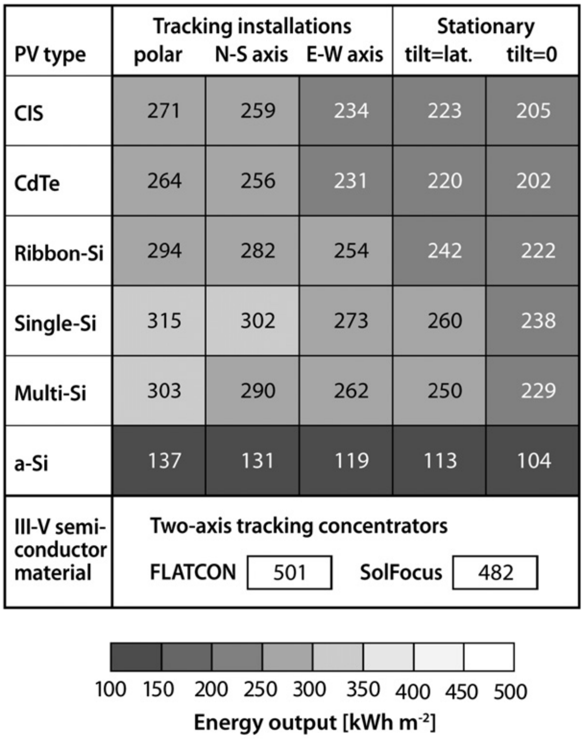
The energy output is tabulated in Fig. 2, for flat plate PV systems with a range of cell and installation types as well as for the two concentrator PV systems. These values are based on hourly simulations of collectible energy and include losses due to inverter, wiring, and cell heating.

It can be seen that 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.

3.2. Embodied energy

The embodied energy for the different PV technologies considered in this study is shown in Fig. 3. 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 FLATCON CPV technology systems has 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.



PV type	Tracking installations polar	N-S axis	E-W axis	Stationary tilt=lat.	tilt=0
CIS	271	259	234	223	205
CdTe	264	256	231	220	202
Ribbon-Si	294	282	254	242	222
Single-Si	315	302	273	260	238
Multi-Si	303	290	262	250	229
a-Si	137	131	119	113	104
III-V semi-conductor material	Two-axis tracking concentrators FLATCON 501			SolFocus 482	

Fig. 2. Total yearly energy output for individual Photovoltaic modules (without shading losses).

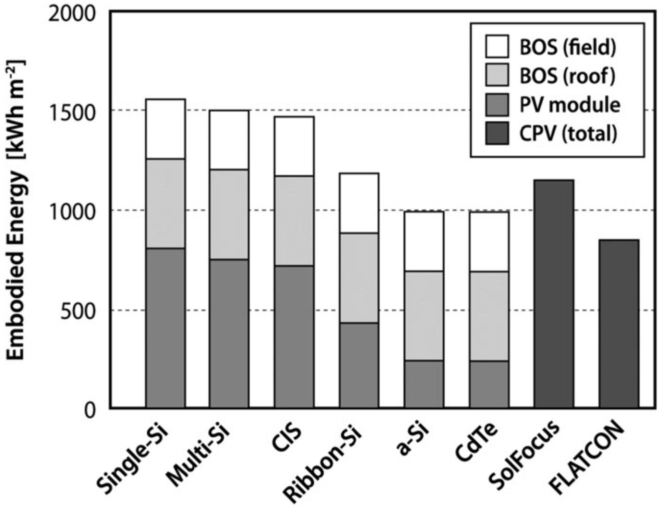


Fig. 3. Total initial embodied energy for different Photovoltaic modules. For flat-plate systems, values are broken down for PV module, BOS for rooftop installation, and additional BOS for field installation, while for CPV (FLATCON and SolFocus) systems the values are inclusive. Sources: Fthenakis et al., 2009 (single-Si, multi-Si, ribbon and CdTe); Sherwani and Usmani, 2010 (a-Si); SENSE, 2008 (CIS); Peharz and Dimroth, 2005 (FLATCON); and Der Minassians et al., 2006 (SolFocus).

The wide divergence in embodied energy values for the different flat plate technologies can be better understood through

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

a breakdown of the material components and processes contributing to the overall production energy. The main source of embodied energy consumption for the three most energy-intensive technologies (Single-Si, Multi-Si and Ribbon) is the production of the silicon for the PV cell itself. This production process includes several different stages in the conversion of raw silica to solar grade silicon cells, and for single-Si, multi-Si and ribbon silicon, it represents over 70% of the total embodied energy of the module. In contrast, the embodied energy of the remaining three technologies (a-Si, CdTe and CIS) is distributed among a large number of materials and processes.

Whereas solar cell materials have significant weight in the make-up of embodied energy, accounting of embodied energy in the balance of system—that is, support structures, foundations, tracking systems, and in the case of CPV, optical reflectors or lenses—can strongly affect the total. While rooftop installations utilize existing buildings for underlying support, panels installed in an open field require concrete foundations as well as a metal framework to resist wind loads and uplift. Thus, as seen in Table 2, the BOS is 300 kWh m^{-2} higher for the open field installations than for the rooftop installations (Nawaz and Tiwari, 2006). It should be mentioned that in cases where wind and soil conditions allow concrete foundations to be avoided, this value would be substantially lower.

In comparing the CPV and flat-plate alternatives, it is clear that for crystalline silicon based PV, the main contributor to the embodied energy is the photovoltaic cell itself, as the process of producing the silicon is a very energy-intensive process. Thus reducing the required energy depends on technological improvement. The aluminum frame is also another significant contributor whose effect can be reduced by increasing the amount of recycled aluminum used.

In the case of the thin film technology, the aluminum frame is the main contributor to the embodied energy, which makes the potential to reduce the embodied energy higher than for the crystalline silicon PV, through the use of frameless thin film panels. Glass and encapsulation are also significant contributors to the embodied energy requirement, so using other less energy-intensive materials can improve the figures for the embodied energy.

The story is different in the case of concentrator photovoltaics. The primary aim of developing the CPV technology is to reduce the required PV cell size and increase the relative aperture area. The cell here is not the main contributor to the embodied energy. In order to concentrate the sunlight, a larger amount of glass is being used, in the form of mirrors (for SolFocus) or lenses (for FLATCON); this increases the weight of the panel and the module, which in turn increases the requirements for the support structure and foundations. Steel is the main material for this, and the zinced steel pipe is on the top of the list of the energy-intensive materials used.

The CPV technology modules need to constantly track the sun, and this requires a precise dual-axis tracking system—another source for the increase in the embodied energy.

Table 2
Initial embodied energy for the BOS of flat-plate PV installations.

Item	Embodied energy (kWh m^{-2})
Inverter	125
Operating and maintenance	125
Support structure	200
Foundations (open field only)	300
Tracker	2

3.3. Evaluation

3.3.1. Energy payback time

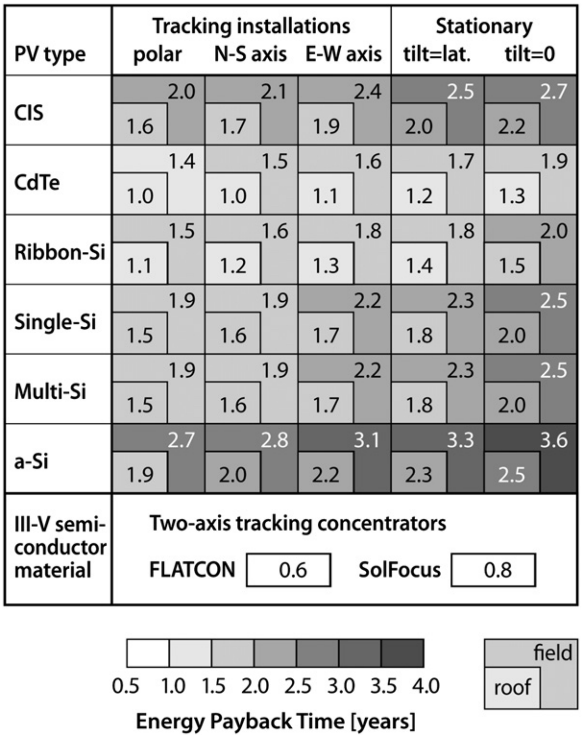
Fig. 4 shows that the energy payback time (EPBT) for flat-plate systems ranges from 1.0 to 3.6 years, with rooftop installations having a payback time which is consistently, and in some cases significantly, shorter than those in the open field. This is due to the additional balance-of-system energy that is embodied in field arrays, primarily for concrete foundations. In terms of PV cell technologies, the thin-film CdTe has the shortest payback period due to its low embodied energy (see Fig. 3) while the amorphous silicon (a-Si) thin-film has by far the highest EPBT due to its low output. The concentrator systems have a shorter EPBT—of 0.6 and 0.8 years for the Flatcon and SolFocus systems, respectively.

3.3.2. Energy return factor

The energy return factor (ERF) expresses the energy balance of the PV system over its full life time. Fig. 5 shows the results of this metric for the various systems considered, both for roof-top and field installations, with a life time of 30 years and a degradation of 1% per year assumed for all systems. For flat plate technologies, the ERF ranges from 7-8 (stationary a-Si, field installation) to over 26 (polar tracking CdTe, roof installation), while the concentrator systems show higher values (of approximately 47 for Flatcon and 33 for SolFocus) thanks to their greater output efficiency.

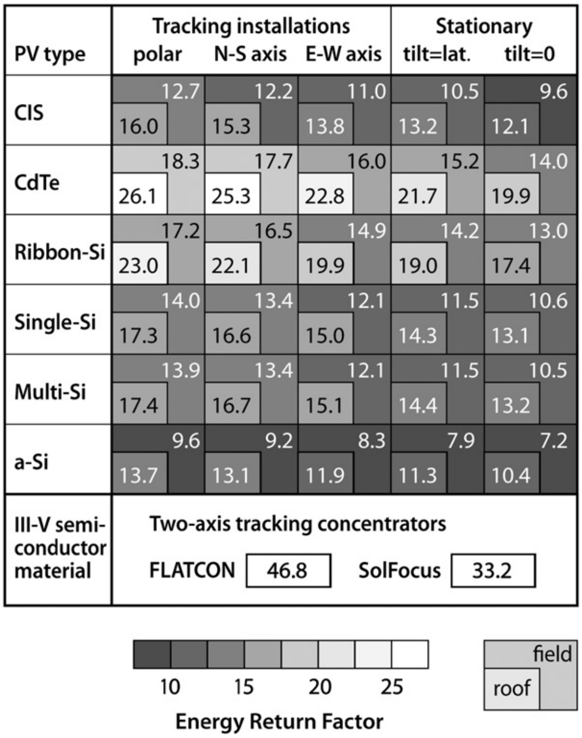
3.3.3. CO_2 offset per aperture area

Fig. 6 shows the lifetime carbon offset of each PV system, per unit aperture area. The main difference between these results and ERF is that the CO_2 offset expresses a difference, rather than a ratio, between operational and embodied energy. Thus the life-cycle advantage of the systems with the most efficient output is more pronounced for CO_2 offset than it is for ERF, which is more sensitive to embodied energy. For this reason the Single-Si technology, with



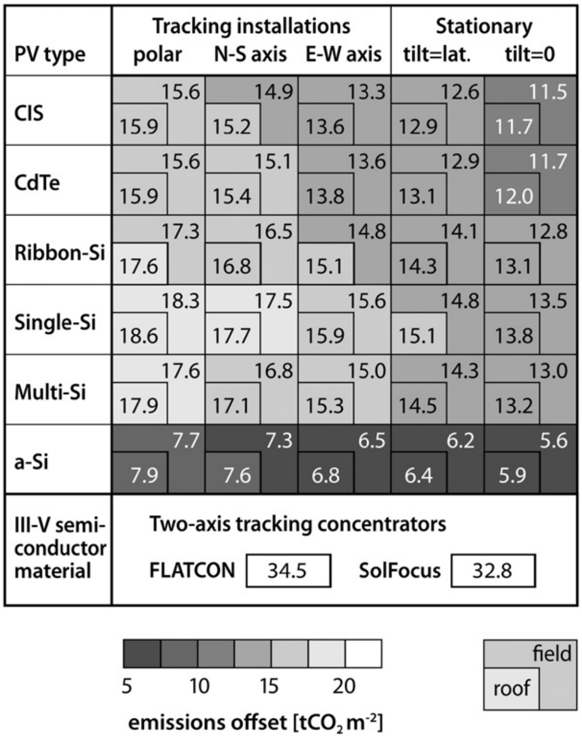
PV type	Tracking installations polar	N-S axis	E-W axis	Stationary tilt=lat.	tilt=0
CIS	2.0 1.6	2.1 1.7	2.4 1.9	2.5 2.0	2.7 2.2
CdTe	1.4 1.0	1.5 1.0	1.6 1.1	1.7 1.2	1.9 1.3
Ribbon-Si	1.5 1.1	1.6 1.2	1.8 1.3	1.8 1.4	2.0 1.5
Single-Si	1.9 1.5	1.9 1.6	2.2 1.7	2.3 1.8	2.5 2.0
Multi-Si	1.9 1.5	1.9 1.6	2.2 1.7	2.3 1.8	2.5 2.0
a-Si	2.7 1.9	2.8 2.0	3.1 2.2	3.3 2.3	3.6 2.5
III-V semi-conductor material	Two-axis tracking concentrators FLATCON 0.6		SolFocus 0.8		

Fig. 4. 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).



	Tracking installations			Stationary	
PV type	polar	N-S axis	E-W axis	tilt=lat.	tilt=0
CIS	12.7 16.0	12.2 15.3	11.0 13.8	10.5 13.2	9.6 12.1
CdTe	18.3 26.1	17.7 25.3	16.0 22.8	15.2 21.7	14.0 19.9
Ribbon-Si	17.2 23.0	16.5 22.1	14.9 19.9	14.2 19.0	13.0 17.4
Single-Si	14.0 17.3	13.4 16.6	12.1 15.0	11.5 14.3	10.6 13.1
Multi-Si	13.9 17.4	13.4 16.7	12.1 15.1	11.5 14.4	10.5 13.2
a-Si	9.6 13.7	9.2 13.1	8.3 11.9	7.9 11.3	7.2 10.4
III-V semi-conductor material	Two-axis tracking concentrators	FLATCON	46.8	SolFocus	33.2

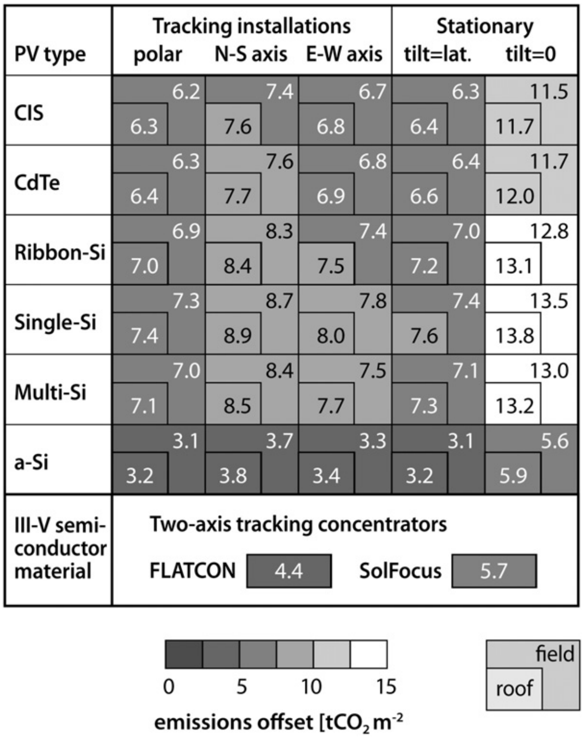
Fig. 5. Energy Return Factor (ERF) for flat-plate PV systems by type of cell and installation, on building rooftops and in open field, and concentrating PV systems with 2-axis tracking (field installation only).



	Tracking installations			Stationary	
PV type	polar	N-S axis	E-W axis	tilt=lat.	tilt=0
CIS	15.6 15.9	14.9 15.2	13.3 13.6	12.6 12.9	11.5 11.7
CdTe	15.6 15.9	15.1 15.4	13.6 13.8	12.9 13.1	11.7 12.0
Ribbon-Si	17.3 17.6	16.5 16.8	14.8 15.1	14.1 14.3	12.8 13.1
Single-Si	18.3 18.6	17.5 17.7	15.6 15.9	14.8 15.1	13.5 13.8
Multi-Si	17.6 17.9	16.8 17.1	15.0 15.3	14.3 14.5	13.0 13.2
a-Si	7.7 7.9	7.3 7.6	6.5 6.8	6.2 6.4	5.6 5.9
III-V semi-conductor material	Two-axis tracking concentrators	FLATCON	34.5	SolFocus	32.8

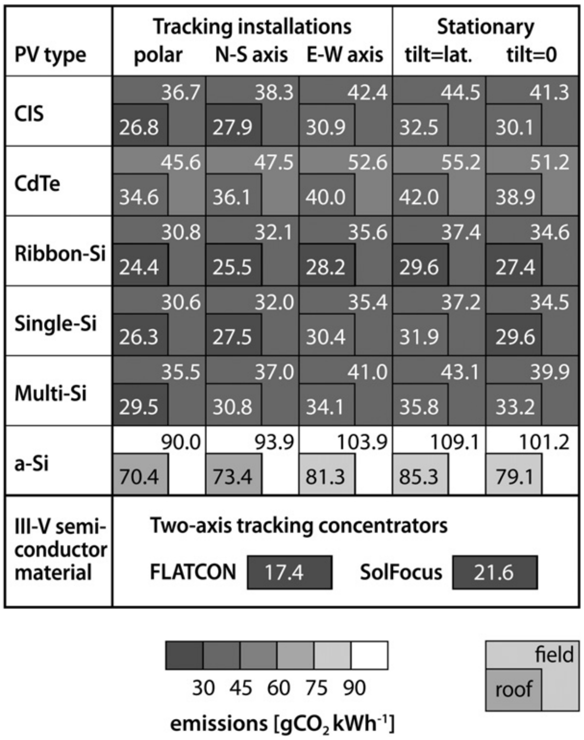
Fig. 6. CO$_2$ emissions offset by aperture area for flat-plate PV systems by type of cell and installation, on building rooftops and in open field, and concentrating PV systems with 2-axis tracking (field installation only).

its relatively high output, has the greatest lifetime CO$_2$ offset per unit aperture area (18.6 t m^{-2}) of any system except for the CPV options, which have CO$_2$ offsets over 30.



	Tracking installations			Stationary	
PV type	polar	N-S axis	E-W axis	tilt=lat.	tilt=0
CIS	6.2 6.3	7.4 7.6	6.7 6.8	6.3 6.4	11.5 11.7
CdTe	6.3 6.4	7.6 7.7	6.8 6.9	6.4 6.6	11.7 12.0
Ribbon-Si	6.9 7.0	8.3 8.4	7.4 7.5	7.0 7.2	12.8 13.1
Single-Si	7.3 7.4	8.7 8.9	7.8 8.0	7.4 7.6	13.5 13.8
Multi-Si	7.0 7.1	8.4 8.5	7.5 7.7	7.1 7.3	13.0 13.2
a-Si	3.1 3.2	3.7 3.8	3.3 3.4	3.1 3.2	5.6 5.9
III-V semi-conductor material	Two-axis tracking concentrators	FLATCON	4.4	SolFocus	5.7

Fig. 7. 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).



	Tracking installations			Stationary	
PV type	polar	N-S axis	E-W axis	tilt=lat.	tilt=0
CIS	36.7 26.8	38.3 27.9	42.4 30.9	44.5 32.5	41.3 30.1
CdTe	45.6 34.6	47.5 36.1	52.6 40.0	55.2 42.0	51.2 38.9
Ribbon-Si	30.8 24.4	32.1 25.5	35.6 28.2	37.4 29.6	34.6 27.4
Single-Si	30.6 26.3	32.0 27.5	35.4 30.4	37.2 31.9	34.5 29.6
Multi-Si	35.5 29.5	37.0 30.8	41.0 34.1	43.1 35.8	39.9 33.2
a-Si	90.0 70.4	93.9 73.4	103.9 81.3	109.1 85.3	101.2 79.1
III-V semi-conductor material	Two-axis tracking concentrators	FLATCON	17.4	SolFocus	21.6

Fig. 8. CO$_2$ emissions per unit of electrical output 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).

3.3.4. Land use

Fig. 7 shows the lifetime carbon offset per unit area of *land*, whose availability in many cases is limited. Varying from a high of 13.5–13.8 tCO$_2$ m^{-2} for stationary single crystalline Si panels with 0 tilt angle (and a ground cover ratio of unity, since overshadowing is eliminated) to only 3.1–3.2 $tCO_2\ m^{-2}$ for stationary (tilt=latitude) 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). This is especially important in the case of Israel, which has a small overall land area and where suitable terrain is limited by competing land-use pressures.

3.3.5. Carbon intensity

Fig. 8 shows the CO_2 emissions of the different systems on an electricity output basis. This ratio between embodied CO_2 and lifetime electrical output is useful when comparing each PV installation to the conventional electricity generation technologies that it is meant to replace.

4. System scaling 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 a case study *kibbutz*, or communal settlement, 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 Fig. 9, 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* settlements in the Arava region (equal to approximately 25 GWh yr^{-1}). 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^{-1}). Transmission losses were found to be negligible for transmission within the region itself (Sørensen 2007), and only the avoidance of 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 different models. The first model employs a *single* PV technology, which is judged to be adaptable to each of the different scales, and the second model 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.

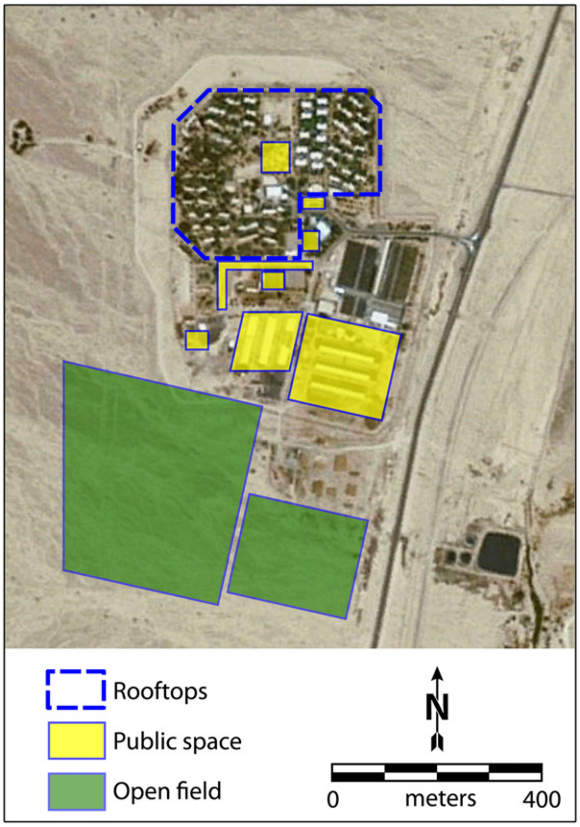


Fig. 9. Available areas for PV deployment in Kibbutz Ketura.

4.1. 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 (Fig. 2) and CO_2 offset (Figs. 6–7) of any flat-plate option. Despite this material's relatively high embodied energy (Fig. 3), only CdTe and Ribbon-Si have significantly shorter EPBT (Fig. 4) and higher ERF (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 yearly output per unit area of the system is 260 kWh m^{-2} and after considering shading losses and GCR, its space requirement is 9 m^2 MWh^{-1} yr.

Installations on shading structures have the same energy payback 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 1.8 years with an ERF of 14.3, and the open field installations have an EPBT of 2.3 years and an ERF of 11.5. Given the available areas in Kibbutz Ketura (Fig. 9), the following results were obtained:

4.1.1. Building-integrated PV

Based on a useable roof top area of approximately 11,000 m^2, 50% coverage ratio, and considering 15% shading losses, the stationary panels (tilt=latitude) yield a total annual output of 1,216 $MWh\,yr^{-1}$ which offsets about 37% of Kibbutz Ketura's electrical demand, and approximately 83,000 t of CO_2.

4.1.2. 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 2,763 $MWh\,yr^{-1}$, which covers the bulk (85%) of the kibbutz demand and offsets 188,750 t of CO_2.

4.1.3. Regionally-integrated PV

The designated capacity of 12.5 MWp using fixed panels (tilt=latitude) requires a land area of 180,000 m^2. The energy pay-back time in this case will be 2.3 years, and the power plant will offset 1,300,000 t of CO_2.

Table 3 shows a summary of the results of comparing the same technology for different scales.

4.2. Multiple-technology comparison

4.2.1. Building integrated PV

The single-crystalline silicon PV with north-south axis tracking was determined to be the preferred system for this scale, due to the favorable metrics of Single-Si (high electrical output and CO_2 offset, short EPBT and high ERF). Based on the area of residential rooftops, this option potentially gives 1,660 $MWh\,yr^{-1}$ of electricity, which—considering shading losses of 15%—amounts to 1,411 $MWh\,yr^{-1}$ (this configuration covers 43% of the kibbutz electricity demand). The energy pay-back time in this case will be 1.6 years, and the system will offset 97,900 t of CO_2 with an ERF of 16.6.

4.2.2. 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 approach 3,250 $MWh\,yr^{-1}$ to approximately 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 291,000 t of CO_2. By repeating the kibbutz-integrated PV scenario in different kibbutzim in the Arava, the annual demand of the region can be nearly matched. 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.

Table 3
Life-cycle energy results when comparing the same technology (single-Si modules, tilt=latitude) at different scales.

Scale	EPBT (years)	ERF	tCO_2
Building	1.8	14.3	83,050
Local	1.8	14.3	188,750
Regional	2.3	11.5	1,300,000

Table 4
Results for the comparison of the "best" technology for each scale. The particular cell technology and installation type for each scale is given in the text.

Scale	EPBT (years)	ERF	tCO_2
Building	1.6	16.6	97,900
Local			
Shading structures	2.0	13.1	193,200
Building rooftops	1.6	16.6	97,900
Total (weighted average)	1.9	14.2	291,100
Regional	0.8	33.2	1,710,000

4.2.3. Regionally-integrated PV

For this scale the selected system is the SolFocus CPV, requiring 12 $m^2\,MWh^{-1}\,yr$ 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 33.2. It would require 300,000 m^2 of land and offset 1,710,000 t of CO_2.

Table 4 shows a summary of the results of comparing the "best" technology for each scale.

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 and the highest ERF, and to offset the most CO_2. It should be noted, however, that this conclusion is based on the current properties of different PV technologies, and 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.

As cell parameters, embodied energy, and ground cover ratios are in constant flux, the development presented here should be seen as a methodological path that can aid in the decision-making process for choosing a PV system for a set of local conditions. Also, 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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