ENVIRONMENTAL DAMAGE AND SAVING BENEFIT OF EXTERNAL SHADING DEVICES VIA PHOTOVOLTAIC (PV) ENERGY GENERATION

Svetlana Pushkar[1]

ABSTRACT

The aim of the study is to evaluate both environmental damage and saving benefit in selecting building shading devices. The environmental damage from the production and construction (P&C) of shading devices is evaluated. The saving benefit, i.e., decreasing building operation energy (OE), due to installing shading devices is evaluated. A simple office building module is used. The external shading devices are constructed from concrete-based external shading devices and aluminum-based light shelf devices. Energy design via Life Cycle Energy Assessment (LCEA) and environmental design via Life Cycle Assessments (LCA) are applied. Environmental design is performed when PV energy generation is used. It was found that in energy design, 40% of building OE saving benefit is required to compensate energy needed for the P&C of shading devices. In environmental design, 100% of the building OE saving benefit is required to compensate for environmental damage stemming from the P&C of shading devices. It was concluded that in energy design, in addition to OE, P&C energy should be evaluated. In environmental design, due to a major reduction in the OE saving benefit, the importance of the P&C environmental damage increased. Environmental design cannot be replaced with energy design when PV energy generation is assumed for building OE needs.

KEYWORDS

external shading devices, PV, LCEA, LCA, Israel

INTRODUCTION

According to Lechner (2014), the reduction of operational energy (OE) for building heating, cooling, and lighting needs should follow a three-tiered approach. At the first tier, the possibility of including passive and low-energy architectural elements in building design should be considered. At the second tier, instead of non-renewable fossil fuel (coal and natural gas), the possibility of using a clean, renewable non-fossil fuel (hydro, wind, or solar) for OE needs should be analyzed. At the third tier, the use of mechanical and electrical equipment with a high coefficient of performance should be implemented.

1. Department of Civil Engineering, Ariel University, Israel, Tel. (+972 3 9066410), e-mail: svetlanap@ariel.ac.il.

Accordingly, shading devices are considered to be a primary first-tier strategy because they can decrease the solar heat gain of a building by 80% to 90% (Wulfinghoff 1999). Photovoltaic (PV) energy is considered to be a clean, high-grade solar energy source for OE in the second tier (Lechner 2014). This study analyzes the balance between environmental damage from the production and construction (P&C) of external shading devices and the environmental saving benefit of installing external shading devices as photovoltaic (PV) technology becomes a high-priority fuel source. This balance was analyzed using the energy design and environmental design of external shading devices.

According to an extensive and recent review by Stevanović (2013), shading devices are widely studied with respect to their OE saving benefits. However, only a few studies have considered both P&C damage and OE saving benefits resulting from shading devices (Ottelé et al. 2011; Huang et al. 2012; Ip et al. 2013; Stazi et al. 2014). Ottelé et al. (2011) performed environmental design of building façades via Life Cycle Assessments (LCAs). The authors compared the façades greened both directly and indirectly: those with living wall systems (LWS) involving planter boxes and those with LWS involving felt layers. These façades were located in Mediterranean and temperate climates. Huang et al. (2012) examined the energy design of retrofitted external overhang shading devices via Life Cycle Energy Assessments (LCEAs). The devices were installed on a university campus building located in Hong Kong. Ip et al. (2013) evaluated the energy design of external roller blinds to determine the practicality of retrofitting office buildings in the United Kingdom with these devices. Stazi et al. (2014) evaluated the environmental design of two external shading strategies (aluminum horizontal louvers and wooden persiana, or shutters) in a typical Mediterranean climate.

In energy design, Huang et al. (2012) and Ip et al. (2013) showed that it is possible to achieve a significant OE saving benefit (approximately 50%) with the use of shading devices. However, different geographical and climatic conditions require the use of special locally appropriate shading devices (Huang et al. 2012; Ip et al. 2013; Stazi et al. 2014; Babaizadeh et al. 2015). As a consequence, different shading devices produce different types of environmental damage. Ottelé et al. (2011) and Huang et al. (2012) reported that the environmental damage of shading devices should not be neglected, as approximately 50 years of OE savings are needed to offset their embodied energy. In contrast, Ip et al. (2013) reported that a much shorter period, i.e., up to three years of OE savings, is required.

In environmental design, Ip et al. (2013) converted the OE saving benefit into the environmental saving benefit using the carbon dioxide (CO_2) emission coefficient of natural gas, i.e., 0.224 kg CO_2/kWh. Huang et al. (2012) used the specific CO_2 emission coefficient for electric-power generation in Hong Kong, i.e., 0.671 kg CO_2/kWh. Ottelé et al. (2011) evaluated the OE environmental saving benefit by considering global warming, toxicity to humans, and fresh water aquatic ecotoxicity without specifying a fuel source. Thus, in these studies, the OE environmental benefit evaluations were performed using conventional fossil fuels that emit large amounts of CO_2 into the atmosphere, thereby increasing environmental damage.

However, a system can achieve better environmental performance with the use of cleaner energy sources (Shah et al. 2008). Thus, clean energy sources such as hydro, wind, and solar are already appearing as important future sustainable practices (Song et al. 2008; Li et al. 2012; Zhai et al. 2012; Milan et al. 2012; Lam et al. 2012; Li et al. 2013; Paudel and Sarper 2013). Among these sources, PV energy generation is highly subsidized and therefore highly encouraged in Israel because there is high solar radiation throughout the year (the average daily solar radiation on a horizontal surface ranges from 3.33 kWh/m^2 in winter to 7.67 kWh/m^2 in summer).

The aim of the present study is to analyze the P&C damage and OE saving benefit of concrete-based external shading devices and aluminum-based light shelf devices that are usually installed in concrete-heavy buildings in Israel. Such buildings are thermally effective in the hot and humid climate of the Mediterranean coast (Capeluto et al. 2004).

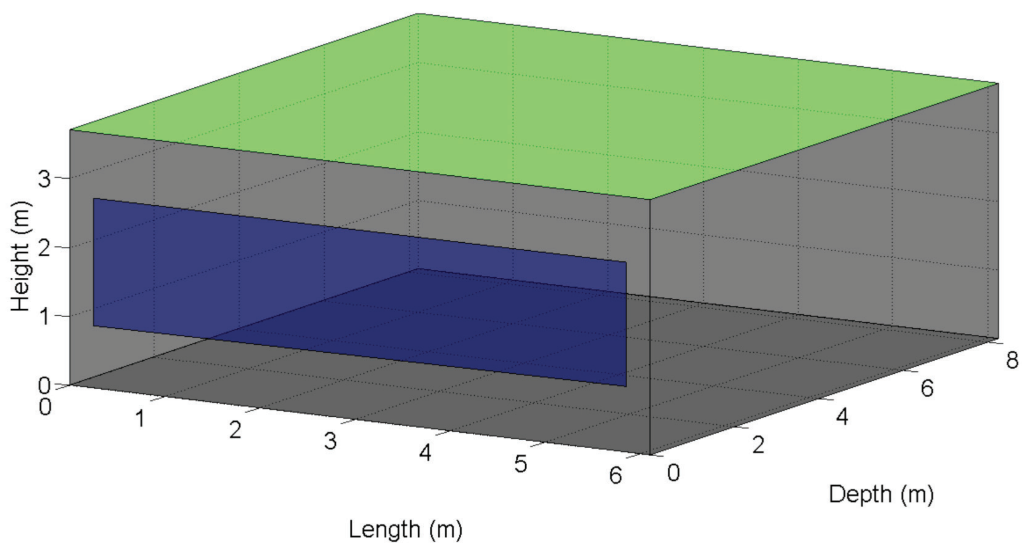
In particular, the following three questions were examined with respect to the external shading devices: (1) what OE saving benefit is needed to offset the P&C energy damage (energy design via LCEA evaluation); (2) what is the building OE environmental damage saving benefit required (through the application of PV energy generation) to offset the P&C environmental damage of shading devices (environmental design via LCA: ReCiPe evaluation); and (3) how comparable are the energy and environmental designs?

BACKGROUND: ISRAELI ENERGY CODE SI5282

A new energy code termed the "Energy Rating of Buildings: Office buildings" (SI5282) was launched in Israel in 2005. The second version of the code became available in 2011 (SI5282 2011). This code applies to the annual energy consumption of an electrically heated, cooled, and lit generic building module (50 m^2) of a typical multi-story office building.

The module examined (Figure 1) contains three internal walls (partitions) and one external wall (with one window). The module is located on a typical intermediate floor between two similar modules. The module is evaluated in each of the four cardinal directions (south, west, east, and north).

FIGURE 1. Building module. The dimensions of the module are 6.1 m in length, 3.7 m in height, and 8.2 m in depth. The dimensions of the window are 5.6 m in length and 1.8 m in height.



According to Shaviv et al. (2008), OE evaluations (performed for SI5282) were calculated with the following simulation tools: ENERGY (Shaviv and Shaviv 1978a, 1978b; Shaviv 1980), RADIANCE (Ward and Shakespeare 1998), and SHADING (Yezioro and Shaviv 1994).

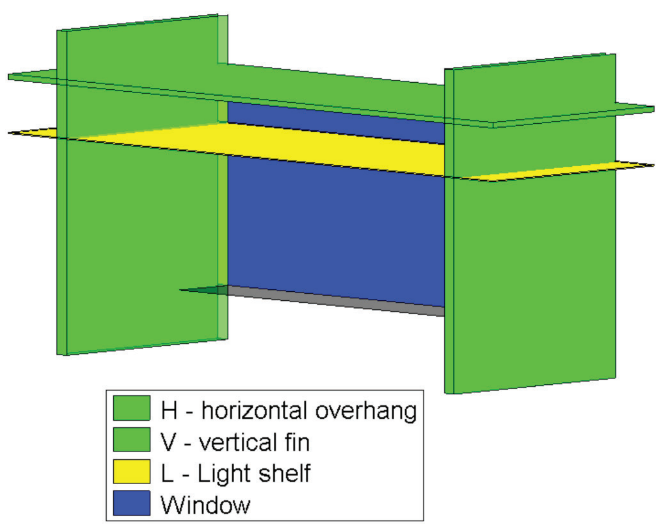
Initially, the optimal energy conscious design for building variables (wall thermal transmission (U-value); window size; thermal, solar, and visible properties of glazing; and other envelope variables) was determined, considering each of the four cardinal directions separately (Shaviv et al. 2008). As a result, SI5282 (2011) presents a number of recommended alternatives ("basic prescriptions") for each of these design variables in all four directions. For example, for south-facing modules, the basic prescription was as follows: (i) U-value of wall = 0.6 W/m^2/°C; (ii) 20% window size = % of office floor area = 50 m^2; (iii) low emissivity glazing with U = 1.8 W/m^2/°C, Shading Coefficient (SC) = 0.43, Visible Transmittance (Tv) = 68 (Shaviv et al. 2008).

Then, these optimal building variables were frozen as simulation setting parameters in evaluating building OE with the installation of each of the combinations of external shading devices. The influence of the shading devices was studied separately for each cardinal direction of the building module (SI5282 2011).

The alternatives to each of the external shading devices were separated into two energy-rating groups, "Group I" and "Group II." Installing alternatives from Group I in the building module led to 27 – 30 kWh/m^2 of yearly building OE consumption. Installing the alternatives from Group II in the building module led to 24 - 27 kWh/m^2 of yearly building OE consumption (SI5282 2011).

Shading devices consist of different combinations of a horizontal overhang (H), vertical (V) fin, and light shelf (L) (Figure 2). The combinations of shading devices suggested by SI5282 (2011) mean that (i) overhang and fins (for example, HsVl), (ii) overhang and light shelf (for example, HsLs), and (iii) fins and light shelf (for example, VsLs) can be installed in the same window area.

FIGURE 2. External shading devices.



RESEARCH METHODS

In this paper, the functional unit was "a building module with a floor area of 50 m^2 per 50-year life span." Only shading devices with the dimensions suggested by SI5282 (2011) were evaluated: (i) the depths of the component were 0.5 m for small (s) and 1.0 m for large (l) and (ii) the lengths of the component were 5 m for the horizontal overhang and light shelf and 3 m for the vertical fin (Shaviv et al. 2008; SI5282 2011). An analysis of other shading component depths (between 0.5 m and 1.0 m) was not conducted in this study.

North-facing windows require almost no shading in the northern hemisphere (Lechner 2014). Thus, the northern direction was excluded from the analysis, and only south, west, and east cardinal directions were considered.

For these three directions, the largest representative group of shades was adopted, as follows: for the south and west–facing modules, the "south" and "west" groups of shades (24 - 27 kWh/m^2 of the annual electricity consumption), and for the east–facing module, the "east" group of shades (27 - 30 kWh/m^2 of the annual electricity consumption). As a result, a different number of shades was "fitted" in each group: south - 9, west – 13, and east – 14 (Table 1). A hot and humid summer and a mild winter, represented by Tel Aviv (located on the coastal plain climate zone of Israel, 32°04'N 34°48'E), was assumed.

TABLE 1. External shading devices recommended by the Israeli energy code "Energy Rating of Buildings: Office Buildings" SI5281 (2011); south, west, and east-facing modules in Tel Aviv (the coastal plain climate zone of Israel). The depth, height and floor area of the module were 8.2 m, 3.7 m, and 50 m^2, respectively.

Module orientation	External shading devices
South	Hl, Ll, HsLs, HsLl, HlLs, HlLl, VsLs, VsLl, VlLs
West	Hl, Ll, HsVs, HsVl, HsLs, HsLl, HlVs, HlVl, HlLs, HlLl, VsLs, VsLl, VlLs
East	Hl, Ls, Ll, HsVs, HsVl, HsLs, HsLl, HlVs, HlVl, HlLs, HlLl, VsLs, VsLl, VlLs

H – horizontal overhang; V – vertical fin; L - Light shelf; s – small depth (50 cm); l – large depth (100cm)

Two calculation methods, LCEA and LCA, were used to evaluate the damage and saving benefits of the external shading devices. A 50-year lifespan was assumed for the devices. Therefore, their replacement was not relevant for this analysis. Only the P&C stage was considered for damage evaluation. Maintenance and demolition stages were excluded from the analysis due to the high uncertainty and large variability associated with their evaluation (Huberman and Pearlmutter 2008). The OE saving was considered for the benefit of evaluation.

The procedure for establishing the P&C energy and environmental burden of the shading device is composed of (1) evaluation of the quantity of the device by weight (kg) and (2) converting this weight into the energy and environmental damage using (i) the embodied energy coefficient (MJ) for the LCEA evaluation and (ii) the environmental damage score (Pt) for the LCA: ReCiPe (Goedkoop et al. 2009) evaluation.

The procedure for establishing the building OE and environmental damage saving benefit of the shading device is composed of (1) establishing the range of the OE deviation of the evaluated device from the OE of the device without any shades (denoted as "No" in SI5282 [2011], or "delta," i.e., the OE saving benefit (kWh/m^2 per year); (2) establishing the OE saving benefit per kWh per 50 m^2 per 50 years by multiplying the delta value by 50 m^2 and 50 years (for the LCEA and LCA evaluations); and (3) converting the OE saving benefit into the OE saving environmental benefit using ReCiPe (Goedkoop et al. 2009) (Pt) (for the LCA evaluation).

Analysis tools and methods: LCEA and LCA

Life cycle inventory (LCI)

Reflecting local Israeli technologies, concrete was selected as a representative building material for the horizontal overhang and vertical fin components, and aluminum was selected as an appropriate material for the light shelf (Figure 2). The density of concrete and aluminum was assumed as 2400 kg/m^3 and 2700 kg/m^3, respectively. The thickness of the horizontal overhang and vertical fin was assumed as 0.1 m, and the thickness of the light shelf was assumed as 0.01 m.

P&C stage: production. Two life cycle inventory (LCI) approaches were adopted for production of the shades: (i) LCEA: the embodied energy coefficients (i.e., 1.15 MJ/kg for concrete and 211 MJ/kg for aluminum) that were adopted from the study presented by Huberman and Pearlmutter (2008); and (ii) LCA: the LCI was presented in the Ecoinvent database (SimaPro 2011). The LCI results were simulated using the Ecoinvent (SimaPro 2011) database. In this database several options for most materials are presented. However, only commonly used processes (according to Dong and Ng 2014) were adopted. These processes were "Concrete, exacting, with de-icing salt contact, at plant/CH S" and "Aluminum, production mix, at plant/RER S." The concrete has the strength of B45/35; the aluminum mix consists of 68% primary and 32% secondary sources, reflecting global production standards.

P&C stage: transportation. Due to Israel's small total area, (20,770 km^2) there are relatively short transportation distances within the country. Therefore, a minimum transportation distance of 20 km was assumed for ready-mix concrete used for casting in place of the horizontal overhang and vertical fin components (Pushkar 2014). A relatively long transportation distance of 100 km was used for aluminum light shelf transportation because there are a limited number of aluminum light shelf manufacturers in Israel (Pushkar 2007). In the application of the embodied energy coefficient (LCEA evaluation), the commonly assumed coefficient of 1.57 MJ/tons per km (Salomonsson and Ambrose 1996) was used for the transportation of both concrete and aluminum light shelves. Applying the Ecoinvent database (SimaPro 2011), the process ("transport, combination truck, average fuel mix/tkm/RNA") was used to simulate the environmental damage resulting from transportation.

P&C stage: construction. According to Huberman and Pearlmutter (2008), the energy required for building construction can be approximated as 8% of the total embodied energy of the building. However, a negligible amount of energy is needed for the construction of the horizontal overhang and vertical fin components, e.g., for concrete placing and vibrating in place; and, the light shelf component can be installed manually (Pushkar 2007). Thus, the construction energy was disregarded.

OE stage. The operational energy for shade alternatives was calculated according to the procedure used for establishing the OE-saving environmental benefit described above. The electricity consumption of internal transportation (elevators and escalators) and electrical appliances (stove and washing and drying devices) was excluded from the analyses because these are not influenced by the external shading devices.

Life cycle impact assessment (LCIA)

The cumulative energy (MJ) saving potential of each shading device was calculated for the LCEA evaluation. In the LCA evaluation, the life cycle impact assessment (LCIA) was calculated using the ReCiPe method (Goedkoop et al. 2009). A single-score evaluation was calculated for the default hierarchical/average (h/a) methodological option. PV electricity generation was considered as a primary energy source. No detailed data were available for Israeli PV electricity generation in SimaPro (2011). Thus, the Spanish technology was used: "Electricity, production mix photovoltaic, at plant / ES S." The mixed PV electricity of Spain consists of roof-top panels that generate 1,282 kWh/kWp and façade panels that generate 813 kWh/kWp.

RESULTS

LCEA evaluations

The P&C energy offset by the OE saving benefit and "net" OE saving benefit (i.e., the difference between the OE saving benefit and the P&C energy) of external shading devices installed on the south, west, and east–facing building modules in Tel Aviv were calculated (Figures 3 – 5). The shading devices are presented in descending order of net OE saving benefit. The alternative with the largest net OE saving benefit (the best alternative) is presented in the top position (for example, Hl, Figure 3), while the alternative with the smallest net OE saving benefit (the worst alternative) is presented in the bottom position (for example, Ll, Figure 3).

The following building OE savings are needed to offset the P&C energy of the external shading devices: 2 - 30% (Hl – Ll, south group, Figure 3); 1 - 26% (Hl - Ll, HlLl, and VsLs, west group, Figure 4); 1 - 39% (Hl - HsLl and HlLl, east group, Figure 5). The difference between the highest net OE saving benefit and the lowest net OE saving benefit is as follows: 27% between Hl and Ll, south group (Figure 3); 28% between HlVs and Ll, west group (Figure 4); and 39% between Hl and HsLl, east group (Figure 5).

FIGURE 3. LCEA for the south group: P&C energy offset by OE saving benefit (MJ) and net OE saving benefit (MJ) of the external shading devices (Hl, Hs, Vl, and Vs: concrete; Ll and Ls: aluminum) in Tel Aviv. The alternatives are presented in descending order of net OE saving benefit.

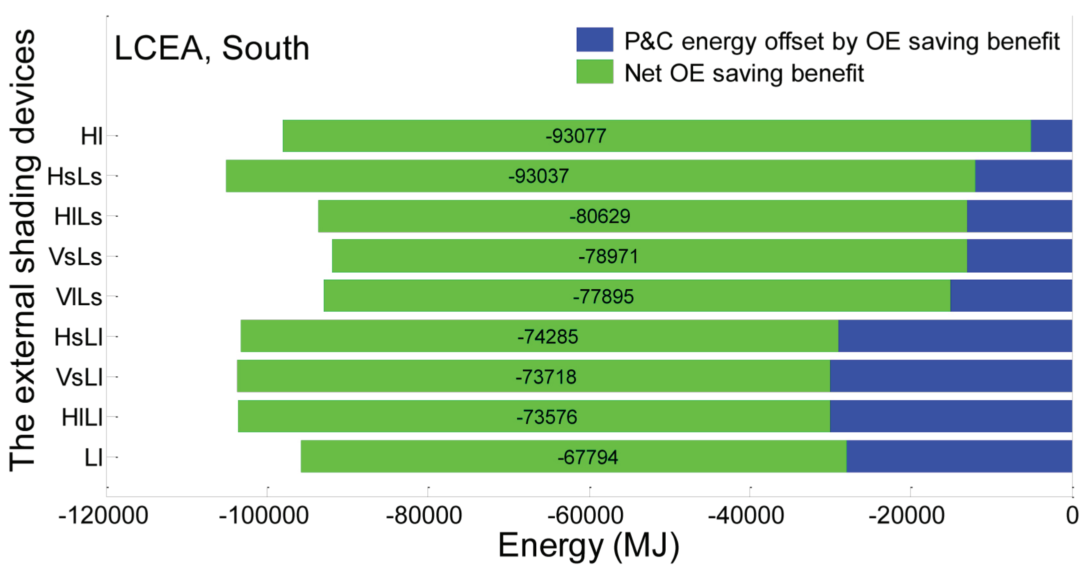


FIGURE 4. LCEA for the west group: P&C energy offset by OE saving benefit (MJ) and net OE saving benefit (MJ) of the external shading devices (Hl, Hs, Vl, and Vs: concrete; Ll and Ls: aluminum) in Tel Aviv. The alternatives are presented in descending order of net OE saving benefit.saving benefit.

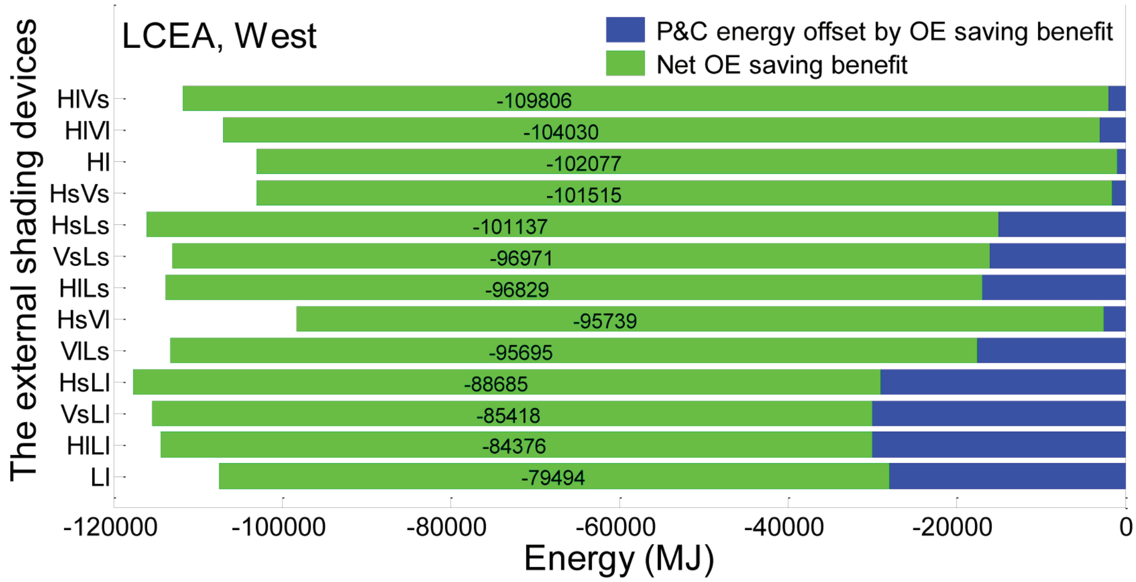
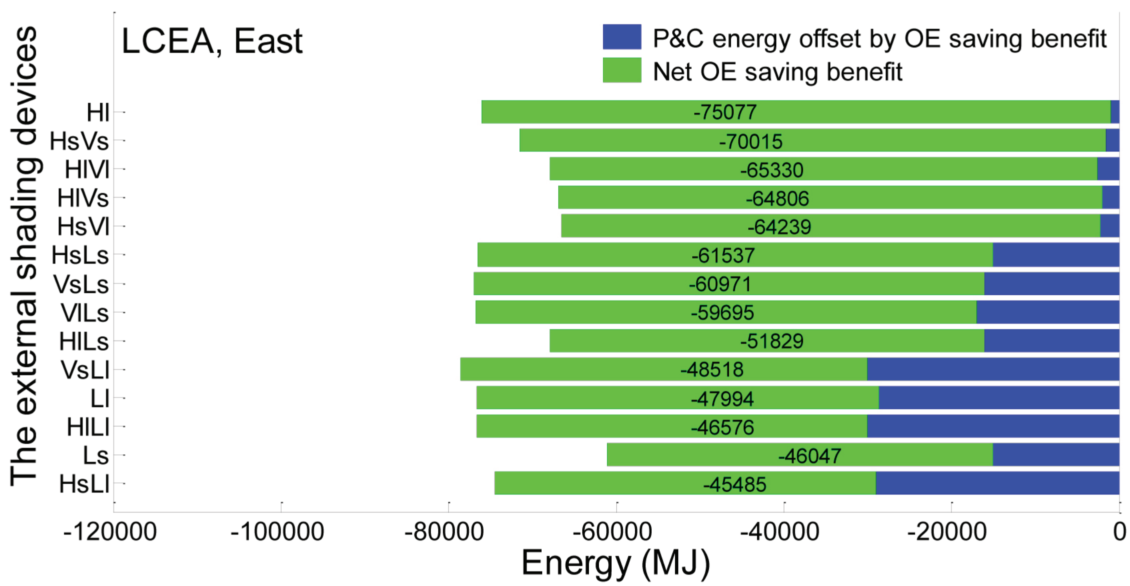


FIGURE 5. LCEA for the east group: P&C energy offset by OE saving benefit (MJ) and net OE saving benefit (MJ) of the external shading devices (Hl, Hs, Vl, and Vs: concrete; Ll and Ls: aluminum) in Tel Aviv. The alternatives are presented in descending order of net OE saving benefit.

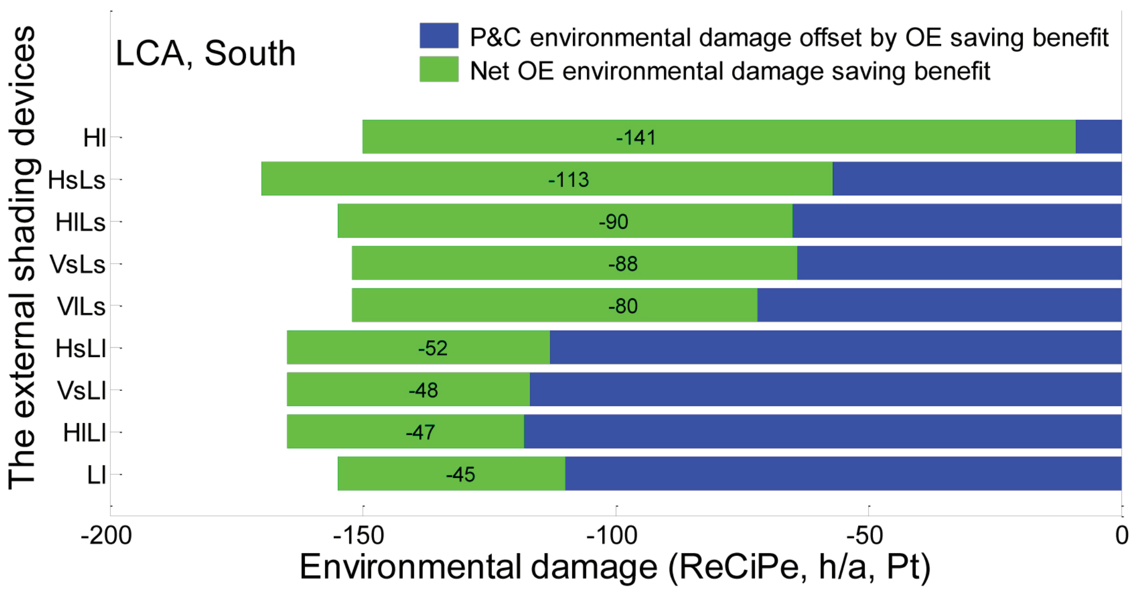


LCA evaluations

The P&C environmental damage offset by the OE saving benefit and the net OE environmental damage saving benefit of the external shading devices installed on south, west, and east–facing building modules in Tel Aviv were calculated (Figures 6 – 8). The alternatives are presented in descending order of net OE environmental damage saving benefit. The alternative with the largest net OE environmental damage saving benefit (the best alternative) is presented in the top position (for example, Hl, Figure 6), while the alternative with the smallest net OE environmental damage saving benefit (the worst alternative) is presented in the bottom position (for example, Ll, Figure 6).

The following OE savings are needed to offset the P&C environmental damage of the external shades: 6 - 72% (Hl - Ll, south group, Figure 6); 5 - 65% (HlVs - Ll, west group, Figure 7), 7 - 97% (Hl - HlLl, east group, Figure 8). The difference between the highest net OE environmental damage saving benefit and the lowest net OE environmental damage saving benefit is as follows: 68% between Hl and Ll, south group (Figure 6); 60% between HlVs and Ll, west group (Figure 7); and 96% between Hl and HlLl, east group (Figure 8).

FIGURE 6. LCA (ReCiPe) for the south group: P&C environmental damage offset by OE saving benefit (Pt) and net OE environmental damage saving benefit (Pt) of the external shading devices (Hl, Hs, Vl, and Vs: concrete; Ll and Ls: aluminum) in Tel Aviv. The alternatives are presented in descending order of net OE environmental damage saving benefit.



LCEA evaluations vs. LCA evaluations

The ranking of shading devices was performed in descending order of net OE saving benefit. According to this ranking, the alternative with the largest net OE saving benefit (the best alternative) is presented in the first position, while the alternative with the smallest net OE saving benefit (the worst alternative) is in last position.

These rankings of shading devices in south, west, and east groups are presented in Table 2. Only shading devices in the south group exhibited the same ranking based on the LCEA and LCA (ReCiPe) evaluations: Hl - 1st, HsLs - 2nd, HlLs - 3rd, VsLs - 4th, VlLs - 5th, HsLl

FIGURE 7. LCA (ReCiPe) for the west group: P&C environmental damage offset by OE saving benefit (Pt) and net OE environmental damage saving benefit (Pt) of the external shading devices (Hl, Hs, Vl, and Vs: concrete; Ll and Ls: aluminum) in Tel Aviv. The alternatives are presented in descending order of net OE environmental damage saving benefit.

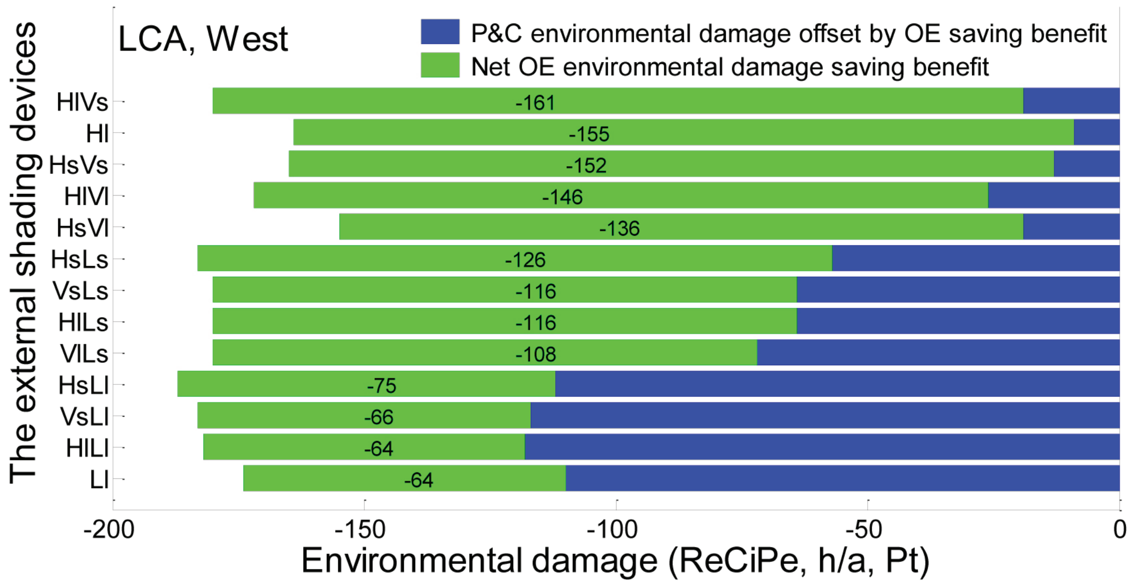
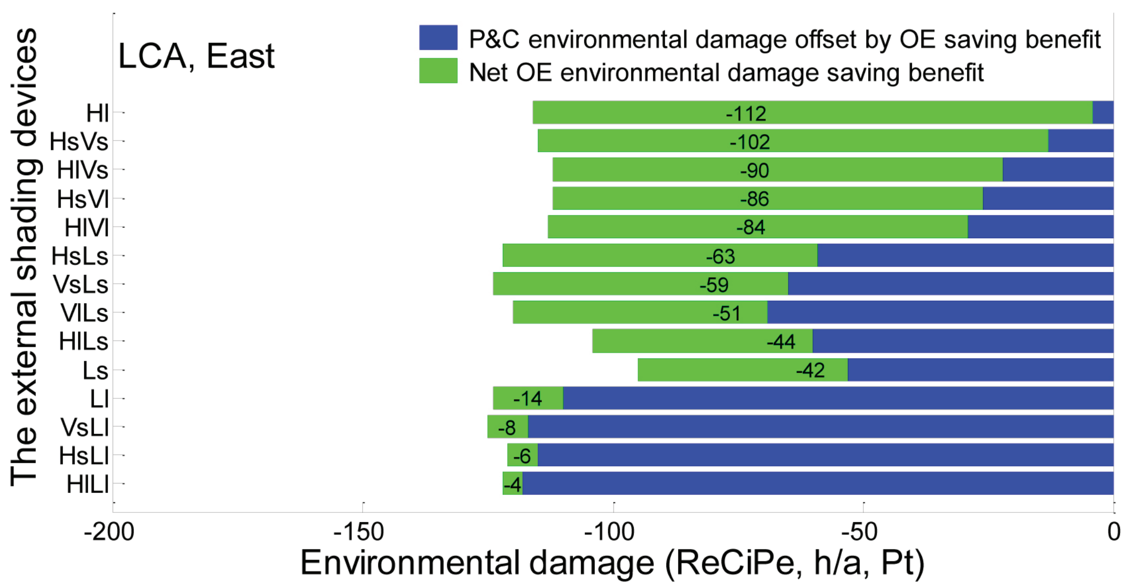


FIGURE 8. LCA (ReCiPe) for the east group: P&C environmental damage offset by OE saving benefit (Pt) and net OE environmental damage saving benefit (Pt) of the external shading devices (Hl, Hs, Vl, and Vs: concrete; Ll and Ls: aluminum) in Tel Aviv. The alternatives are presented in descending order of net OE environmental damage saving benefit.



- 6th, VsLl - 7th, HlLl - 8th, and Ll - 9th. However, in the west and east groups, the ranking of certain devices (west group: Hl, HlVl, HsVs, HsLs, VsLs, HlLs, and HsVl; east group: HlVs, HlVl, HsVl; VsLl, Ls, HlLl, and HsLl) varied based on whether the LCEA or the LCA (ReCiPe) evaluation was used. For example, for the west group, according to the LCEA evaluation, VsLs ranked in the 6th position, while according to the LCA (ReCiPe) evaluation this alternative ranked in the 7th position.

TABLE 2. Ranking of external shading devices based on: LCEA and LCA (ReCiPe) for the, south, west, and east groups. The ranking of alternatives is presented in descending order of net OE saving benefit.

South group	Ranking within south group		West group	Ranking within west group		East group	Ranking within west group	
	LCEA	LCA		LCEA	LCA		LCEA	LCA
Hl	1	1	HlVs	1	1	Hl	1	1
HsLs	2	2	HlVl	2	4	HsVs	2	2
HlLs	3	3	Hl	3	2	HlVl	3	5
VsLs	4	4	HsVs	4	3	HlVs	4	3
VlLs	5	5	HsLs	5	6	HsVl	5	4
HsLl	6	6	VsLs	6	7	HsLs	6	6
VsLl	7	7	HlLs	7	8	VsLs	7	7
HlLl	8	8	HsVl	8	5	VlLs	8	8
Ll	9	9	VlLs	9	9	HlLs	9	9
			HsLl	10	10	VsLl	10	12
			VsLl	11	11	Ll	11	11
			HlLl	12	12	HlLl	12	14
			Ll	13	13	Ls	13	10
						HsLl	14	13

H – horizontal overhang; V – vertical fin; L - Light shelf; s – small depth (50 cm); l – large depth (100 cm)

DISCUSSION

Three questions were addressed in this study: (1) what is the building OE saving benefit required to offset the P&C energy of shading devices (energy design via LCEA evaluation); (2) what is the building OE environmental damage saving benefit required to offset the P&C environmental damage of shading devices (environmental design via LCA evaluation); and (3) how do the energy and environmental designs compare?

Energy design via LCEA evaluation

The design of external shading devices (which are commonly used in Israel) currently specified by SI5282 (2011) is based only on consideration of the building OE associated with installing these devices. Two OE ranges are recommended by SI5282 (2011): 24 - 27 kWh/m^2 (11% difference; south and west groups) and 27 - 30 kWh/m^2 (11% difference; east group). However, in this study, it was demonstrated that in the case of buildings in Israel with massive concrete external shading and aluminum light shelves, the P&C damage of these shades could not be disregarded.

Approximately 25 - 40% of the OE saving was needed to offset the P&C environmental damage of the external shades (Figures 3 – 5). Thus, the net OE saving benefit must be considered instead. Moreover, it should be taken into account that the difference between the alternatives with the highest and lowest net OE saving benefit in the analyzed groups is greater (30 – 40%, Figures 3 – 5) than the difference calculated using only the OE benefit (11%, SI5282 2011).

Similar results were found in the research presented by Huang et al. (2012), who performed an LCEA of external overhanging shade devices installed on a university campus building in Hong Kong. According to Huang et al. (2012), a durable and strong structure (using a large amount of building materials) for external shading is required due to the severe climate conditions in Hong Kong (rainfall, thunderstorms, and tropical storms). Consequently, these authors noted that an extremely long energy payback period of approximately 46.3 years is needed to offset the embodied life cycle energy of external overhanging shade devices.

Environmental design via LCA evaluations

Different environmental impacts result from different sources of electricity generation. In this study, which used PV electricity generation, approximately 65 - 100% of the OE saving benefit (ReCiPe evaluation) was needed to compensate for the P&C environmental damage of the external shades (Figures 6 - 8). Huang et al. (2012) used conventional (more polluting) fossil fuels as an energy source. These authors also reported a long CO_2 emissions payback period, i.e., 63.8 years of CO_2 emissions saving, are needed to offset the embodied CO_2 emissions of external overhanging shade devices. However, the most influential factor here is the P&C of shading devices. This is because the external shading devices used in Hong Kong differ from those used in Israel. In Hong Kong, the devices are more durable and have a strong structure; therefore, their production results in greater environmental damage (Huang et al. 2012).

In this study, the two factors influencing the net OE environmental damage saving benefit must be discussed. A high net OE environmental damage saving benefit can be achieved with (i) increasing building OE saving benefit and (ii) decreasing the P&C environmental damage of the shading device. Increased building OE saving benefit can be realized with installation of an appropriate shading device for a given cardinal direction. Decreased P&C environmental damage of a shading device can be achieved with the installation of a shading device that was produced with reduced environmental damage.

(i) Different shading devices must be installed for different cardinal directions to block sun effectively. For a south-facing window, horizontal overhang is most appropriate because the sun is high in the sky in the summer. However, for east and west-facing windows, horizontal overhangs do not block sun effectively. Shading on these windows can be improved when a combination of horizontal and vertical devices is used (Lechner 2014).

(ii) Considerably less environmental damage is associated with concrete production compared with aluminum production. According to the literature, the embodied energy production coefficients for concrete are 1.0 – 1.6 MJ/kg (Alcorn and Haslam 1997), 1.15 MJ/kg (Huberman and Pearlmutter 2008), and 1.3 MJ/kg (Kofoworola et al. 2009) compared with 191 – 227 MJ/kg (Alcorn and Haslam 1997), 180 MJ/kg (Gu et al. 2006), 211 MJ/kg (Huberman and Pearlmutter 2008), and 216.5 (Kofoworola et al. 2009) for aluminum.

Therefore, despite that in the sought group (Figure 6), the highest building OE saving benefit was achieved with the HsLs shading device (concrete horizontal overhang and aluminum light shelf), the Hl shading device (concrete horizontal overhang) alternative should be preferred. However, the combination of horizontal and vertical concrete-made devices (e.g., HlVs and HsVs) were the best alternatives in the west and east groups, respectively (Figures 7 and 8).

The next-best alternatives with a lower net OE saving benefit were composed of both concrete (horizontal overhang and vertical fin) and small aluminum light shelf (for example, HsLs and VsLs, in the east group, Figure 8). There were several "neutral" (OE saving benefit being almost equal to the P&C damage) alternatives where the large aluminum light shelf was present (for example, Ll and VsLl in the east group, Figure 8).

Energy design vs. environmental design

The rankings obtained for most of the shading devices in the west and east groups (Table 2) differed between the energy and environmental designs (when PV energy generation was used for environmental design). Thus, when PV energy generation is used, it becomes difficult to correctly evaluate the environmental damage using only the LCEA. Incorrectly choosing the seemingly best alternative can result in a different level of environmental damage than would be expected, which results in distinctly different cost-effective solutions. For example, an analysis of the shading devices in the east group based only on the LCEA identified HlVl as the alternative in 3rd position according to net OE environmental damage saving benefit (Table 2). However, the LCA (ReCiPe) indicated HlVs on the 3rd position (Table 2).

CONCLUSIONS

The aim of the present study is to analyze the P&C damage and OE saving benefit of concrete-based external shading devices and aluminum-based light shelf devices that are usually installed in concrete-heavy buildings in Israel. Energy (via LCEA evaluation) and environmental (via LCA evaluation) designs were performed. In environmental design, for meeting OE needs for building cooling, heating, and lighting, PV energy generation was assumed. The following conclusions can be made:

1) Energy design. It was found that 40% of building OE saving benefit is required to offset the energy needed for the P&C of shading devices. Therefore, in the energy design of external shading devices, the OE saving benefit alone cannot serve as an appropriate measure. In addition to the OE saving benefit, the P&C energy of the shades must be evaluated.
2) Environmental design. It was found that 100% of building OE saving benefit is required to offset environmental damage stemming from the P&C of shading devices. Thus, employing PV energy generation for the environmental design of external shading devices leads to a strong reduction in the OE saving benefit. As a result, more attention must be paid to the P&C environmental performance of the shades. In this respect, the P&C of light shelves made of aluminum leads to more environmental damage than the P&C of concrete overhang and fins.
3) In ranking shading devices from the best alternative to the worst alternative, both energy and environment designs were analyzed. It was revealed that energy design rankings and environmental design rankings were different. Thus, an LCEA evaluation should not replace an LCA evaluation when PV energy generation for serving OE needs is used.

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