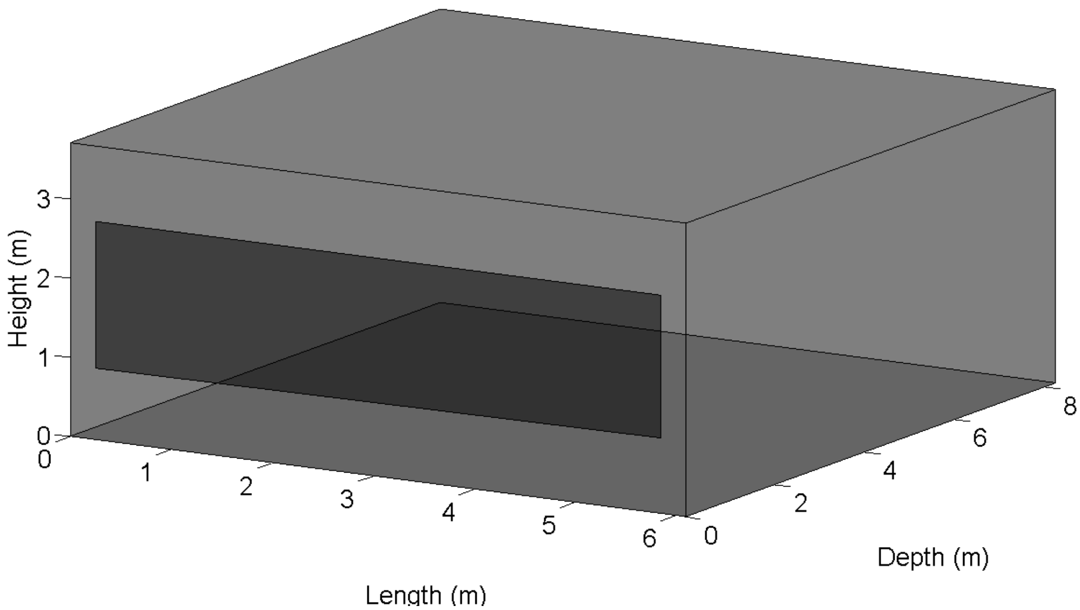

Figure 1. Building module. The dimensions of the module are 6.1 m in length, 3.7 m in height, and 8.2 m in depth. The dimensions of the window are 5.6 m in length and 1.8 m in height.

The prescriptive approach used in the energy code for office buildings SI5282 (2011) allows five levels of certification for buildings (E [the lowest], D, C, B, and A [the highest]). Following this code, five modular improvements, including changing the thermal conductivity and the thermal mass of the external wall, the type of window glazing, and the window's glazed area, as well as the use of shading (Table 1) were implemented for each of the five levels of certification.

Two life cycle stages, the P&R and OE stages, were evaluated. EnergyPlus software (EnergyPlus) was applied to evaluate the electricity needed for the OE stage. The ReCiPe (Goedkoop et al. 2009) endpoint hierarchical method (with six methodological options) was used to evaluate the environmental damage associated with both P&R and OE stages, while the electricity needed for the OE stage was evaluated for both primary energy sources, natural gas and photovoltaic (PV) energy production. A two-stage, nested ANOVA was used to evaluate the differences among the total environmental damage associated with the P&R and OE stages for the different levels of building certification.

Table 1. Modular improvements implemented for E (the lowest), D, C, B, and A (the highest) levels of certification according to SI5282 in Jerusalem, south-facing module.

Module improvements	E	D	C	B	A
Thermal conductivity of external wall Thermal mass of external wall	U≤1.2 W/m·K; TM≥250 kg/m2 (cement mortar [0.025 m], polystyrene [0.02 m], concrete [0.2 m], cement mortar [0.02 m])	*See previous column*	U≤0.9 W/m·K; TM≥250 kg/m2 (cement mortar [0.025 m], polystyrene [0.04 m], concrete [0.2 m], cement mortar [0.02 m])	*See previous column*	U≤0.6 W/m·K; TM≥250 kg/m2 (cement mortar [0.025 m], polystyrene [0.06 m], concrete [0.2 m], cement mortar [0.02 m])
Type of glass	G5 (single glazing, low-e [U-win=4.5 W/m·K, SHGC=0.8, VT=0.7])	G4 (single glazing, low-e [U-win=4.5 W/m·K, SHGC=0.7, VT=0.65])	G3 (single glazing, low-e [U-win=2.5 W/m·K, SHGC=0.6, VT=0.6])	G2 (double glazing, clear [U-win=2.5 W/m·K, SHGC=0.5, VT=0.5])	G1 (double glazing, low-e [U-win=2.05 W/m·K, SHGC=0.4, VT=0.4])
Glazed area	35% of floor area	30% of floor area	25% of floor area	*See previous column*	*See previous column*
Type of shading	-	Horizontal overhang (depth 50 cm)	See previous column	Horizontal overhang (depth 100 cm)	*See previous column*

Environmental evaluations. P&R stage. Life cycle inventories (LCIs) of building components that were required for each of the five modular improvements were performed using SimaPro software, version 7.3 (PRe´ Consultants 2011). On the material level, the Ecoinvent database (from the European countries) was used for the production and transportation of cement, water, rock, sand, limestone, glass, etc. On the component level, the masses of composite materials used in the wall, window, and shading devices were modeled in SimaPro on the basis of information obtained from relevant local Israeli building product suppliers (Pushkar 2014). For the transportation of building components, relatively short local transportation distances (such as 50–200 km) were assumed, given that Israel is a small country (Table 2) (Huberman and Pearlmutter 2008; Pushkar 2014).

Table 2. Transportation distances (from material/component suppliers to construction situ).

Building material/component	Distance (km)
Cement mortar	20
Concrete	20
Aluminum	100
Glass, polystyrene	200

OE stage. A heat pump with a coefficient of performance (COP) of 3 with set points of 20°C for heating and 24°C for cooling was used to calculate the electricity required for heating and cooling the building module using EnergyPlus v.8.3 software. Detailed weather data for a heating-dominated climate (a mild summer and cool winter) from a typical meteorological year in Jerusalem was collected from the EnergyPlus Weather Data for Israel (EnergyPlus website). A typical office occupancy schedule (07.00–18.00, Sunday to Thursday) was modeled. Air infiltration was assumed to be 0.5 ach (air changes per hour). The design levels for electric lights and electric equipment were assumed to be 360 W and 250 W respectively.

P&R and OE stages. The procedure for evaluation of the P&R environmental damage of the energy code rating is composed of (1) evaluation of the quantity of the building materials by weight (kg) and (2) converting this weight into the environmental damage using the environmental damage score (points, Pt) for the LCA: ReCiPe (Goedkoop et al. 2009) evaluation. The procedure for evaluation of the module OE associated with this energy is composed of (1) establishing the OE per kWh per 50 m^2 per 50 years by multiplying the OE (kWh per year) by 50 m^2 and 50 years and (2) converting the OE into the OE environmental damage using ReCiPe (Goedkoop et al. 2009) (points, Pt) with both energy production sources, natural gas and PV.

The ReCiPe method allows consideration of three categories of environmental damages, such as those to human health, ecosystem quality, and resources, and combines them into a single indicator (environmental points, Pt). This evaluation is made possible with three different perspectives on environmental problems: egalitarian, individualistic, and hierarchical. Each of the three perspectives considers different time frames for influencing the environment (egalitarian, long; individualistic, short; and hierarchical, intermediate). Two different weighting sets, perspective-specified and average, can be applied to each of the three perspectives. As a result, ReCiPe evaluation can be performed by applying two sets of three methodological options: egalitarian/egalitarian (e/e), hierarchist/hierarchist (h/h), and individualist/individualist (i/i); and egalitarian/average (e/a), hierarchist/average (h/a), and individualist/average (i/a), creating a hierarchical structure of environmental evaluation (Pushkar 2016a; Pushkar and Verbitsky 2016). This allowed assessment of ReCiPe environmental evaluations via a hierarchical, two-stage, nested, mixed analysis of variance (ANOVA) test.

Statistical evaluations. Pairwise comparisons of the six ReCiPe evaluations (based on the six methodological options available in ReCiPe) of the different levels of building certification were evaluated via a two-stage, nested, mixed ANOVA test (Table 3). In this way, simultaneous evaluation of the six methodological options available in ReCiPe was performed. In this comparison, NeoFisherian significance assessments were used, and a three-valued logic was applied to the P-values (Hurlbert and Lombardi 2009). The three-value logic employed included the following levels: there seems to be a difference among levels of building certification, there does not seem to be a difference among levels of building certification, and judgment is suspended with respect to the difference among levels of building certification.

Table 3. Design of study. The sampling frame contains a ReCiPe analysis of the five energy code ratings (i.e., five primary sampling units). ReCiPe contain two weighting sets (sub-units). Each of the weighting sets has three methodological options (three individual sub-units).

Primary sampling units, ReCiPe	ReCiPe top-down method				
	Sub-units, type of set		Individual sub-units, methodological options		
I	I	II	I	II	III
E	Particular weighting set		e/e	h/h	i/i
	Average weighting set		e/a	h/a	i/a
D	Particular weighting set		e/e	h/h	i/i
	Average weighting set		e/a	h/a	i/a
C	Particular weighting set		e/e	h/h	i/i
	Average weighting set		e/a	h/a	i/a
B	Particular weighting set		e/e	h/h	i/i
	Average weighting set		e/a	h/a	i/a
A	Particular weighting set		e/e	h/h	i/i
	Average weighting set		e/a	h/a	i/a

Note: E (the lowest), D, C, B, and A (the highest) levels of certification according to SI5282; Egalitarian/egalitarian (e/e), egalitarian/average (e/a), hierarchist/hierarchist (h/h), hierarchist/average (h/a), individualist/individualist (i/i), and individualist/average (i/a).

RESULTS

Preliminary events: quantities of the building materials and the effect of selected energy code ratings on the operational energy requirements for space conditioning building modules

The P&R quantities of the building materials for the five energy code ratings were evaluated, and the results are presented in Table 4.

Table 4. Production and replacement (P&R) quantities of the building materials designed for the five energy code ratings.

	Energy code ratings				
Material (kg)	E	D	C	B	A
Cement mortar	414	684	954	954	954
Concrete	2208	3648	5088	5088	5088
Polystyrene	4	6	17	17	26
Glass	135x2	113x2	90x2	180x2	180x2
Aluminum	122	101	81	162	162

Note: E (the lowest), D, C, B, and A (the highest) levels of certification according to SI5282.

The effects of the selected energy code rating on the OE stage of building modules located in Jerusalem are presented in Table 5.

Table 5. Effect of the selected energy code rating on the operational energy (OE) requirements for space conditioning building modules in Jerusalem, south-facing module.

	Energy code ratings				
	E	D	C	B	A
OE (kWh/50 m^2/50 years)	111500	109500	109250	108000	107250

Note: E (the lowest), D, C, B, and A (the highest) levels of certification according to SI5282.

Environmental impacts of the P&R and OE stages. Figure 2 shows the relationship between environmental damage as derived using ReCiPe with the h/a methodological option and different certification levels for office buildings (SI5282 2011) obtained using LCA (P&R + OE) when different primary energy sources, either natural gas or PV energy production, were used to supply the building's OE needs.

With different energy sources (either natural gas or PV), the P&R and OE stages accounted for different percentages of the total energy used: 2–4% versus 98–96% (natural gas) and 15–35% versus 65-85% (PV) (Figure 2). Thus, the primary energy source used in the OE stage was recognized as a significant factor in evaluating improvements in the level of building certification according to SI5282 (2011) for particular buildings.

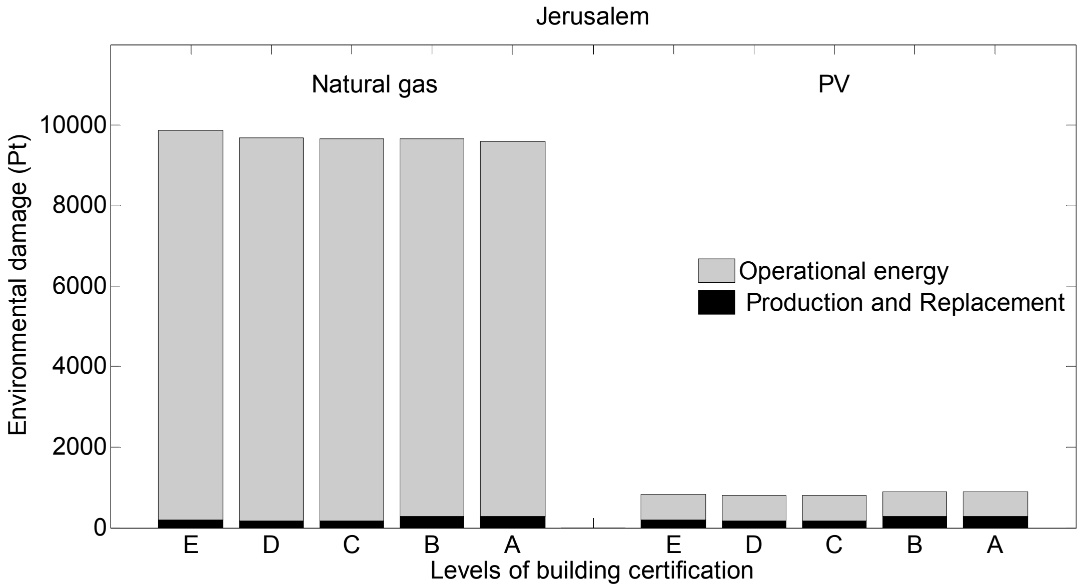

Figure 2. Environmental damage associated with the production and construction (P&R) stage and the operational energy (OE) stage in an office building in Jerusalem in which either of two energy sources, natural gas or PV, is used to supply OE needs. The five evaluated levels of building certification improvements according to SI5282 are E (the lowest), D, C, B, and A (the highest). Environmental damage (Pt) values are evaluated with the default h/a option of the ReCiPe method.

Selection of the optimal level of building certification improvement. The results of the ReCiPe method using natural gas are displayed on the left side of Figure 3. The ranking of the five levels of building certification improvements, in ascending order of total environmental damage for both the P&R and OE stages, is as follows: 1st - A, 2nd – C, 3rd - B, 4th - D, and 5th - E. However, there are some exceptions to this ranking: (i) under the e/a option, D is in the 3rd position, whereas B is in the 4th position; (ii) under the e/a option, E is in the 4th position, whereas D is in the 5th position; and under the i/i and i/a options, B is in the 2nd position, whereas C is in the 3rd position.

The results of the ReCiPe method using PV are displayed on the right side of Figure 3. Under all methodological options available in ReCiPe, the five levels of building certification improvements, listed in ascending order of total environmental damage, are as follows: 1st – C, 2nd - D, 3rd – E, 4th – A, and 5th – B.

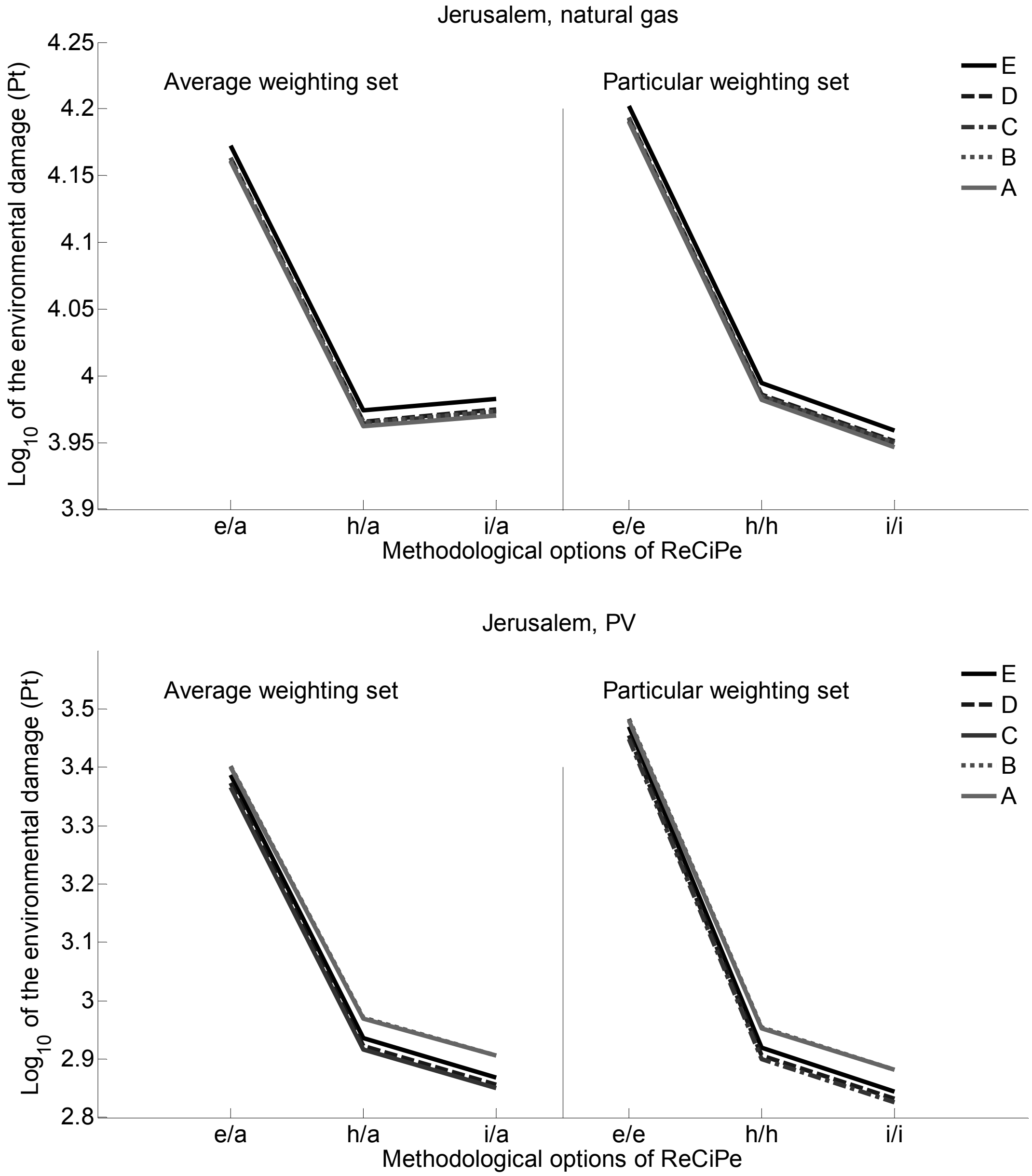

Figure 3. Life cycle environmental damage (including both the production and construction (P&R) stage and the operational energy (OE) stage) in an office building in Jerusalem in which either of two energy sources, natural gas or PV, is used to supply OE needs. The five evaluated levels of building certification improvements according to SI5282 are E (the lowest), D, C, B, and A (the highest). The life cycle environmental damage (Pt) was evaluated using two sets of methodological options, the average weighting set (e/a, h/a, and i/a) and the particular weighting set (e/e, h/h, and i/i) of the ReCiPe method.

The top of Table 6 contains the P-values using natural gas. Consistent results were obtained. The difference between each pair of the possible ten compared pairs of the levels of building certification improvements seems to be negative ($0.1886 \leq P \leq 0.9105$).

The bottom of Table 6 contains the P-values using PV. The difference between the level C and the B level of improvement, as well as between the C level of improvement and the A level of improvement seems to be positive (P=0.0365 and P=0.0380, respectively). Judgment is suspended regarding the difference between levels D and B, as well as the difference between levels D and A (P=0.0476, and P=0.0499 respectively). The differences in all other pairings seem to be negative ($0.0924 \leq P \leq 0.9121$).

Table 6. Office building with natural gas and PV options in Jerusalem. P-values assessed using two-stage, nested, mixed ANOVA of the differences within pairs of the five evaluated levels of building certification improvements according to SI5282 as a function of total life cycle environmental damage evaluated with ReCiPe. In the two-stage, nested, mixed ANOVA, the degrees of freedom (df) are df_1=1 and df_2=2. P, probability resulting from a significance test.

Fuel source	code	E	D	C	B	A
Natural gas	E	X	0.3033	0.2424	0.2712	0.1886
	D		X	0.8168	0.9105	0.6181
	C			X	0.9037	0.7782
	B				X	0.6915
	A					X
PV	E	X	0.3027	0.1771	0.0924	0.0987
	D		X	0.5727	*0.0476*	*0.0499*
	C			X	**0.0365**	**0.0380**
	B				X	0.9121
	A					X

Note: The five evaluated levels of building certification improvements according to SI5282 are E (the lowest), D, C, B, and A (the highest). Boldface text indicates values that seem to be positive, ordinary text indicates values that seem to be negative, and italicized text indicates values for which judgment is suspended.

DISCUSSION

Environmental impacts of the P&R and OE stages. There was significant influence of the primary energy source (either natural gas or PV) on the impacts of the P&R and OE stages when the levels of building certification improvement of SI5282 (2011) were compared (Figure 2). Replacing natural gas with PV resulted in a significant decrease in the OE stage. In this way, the impact of the P&R stage becomes more substantial, 15–35% of the total (P&R+OE) environmental damage. Similar results were obtained by Pushkar and Verbitsky (2016), who studied wall technologies in residential buildings located in Israel and reported that using PV for energy needs in the OE stage caused a significant increase in the P&R stage, to 40-50% of total environmental damage (P&R+OE).

Selection of the optimal level of building certification improvement. The A level of building certification resulted in the lowest environmental damage when using natural gas (Figure 3). This result can be explained in that the OE stage was primarily responsible for the environmental damage (approximately 95% of total environmental damage, P&R + OE). However, insignificant differences between the A level of building certification improvement and each of the four (either B, C, D or E) were obtained (Table 6). An increase in the level of building certification was associated with decreases in the OE stage and increases in the P&R stage, due to the additional building materials required. This resulted in almost the same total environmental damage (P&R + OE) for all five levels of building certification improvement.

Levels A and B were associated with more significant environmental damage than level C when using PV. This result can be explained in that the P&R stage made up a significant fraction of the total environmental damage (P&R + OE) (approximately 30%; Figure 2). Thus, level C is the optimal level of building certification improvement in SI5282 (2011) (Figure 3).

Contribution of this paper. In terms of the level of building certification improvement, the current operational energy code needs to be complemented by consideration of the P&R stage, in addition to the OE stage. Moreover, different results were obtained in this paper, depending on whether natural gas or PV energy sources were used. Thus, it could be suggested to devote special attention to consideration of the primary energy source used in the OE stage.

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