RESEARCH

ENVIRONMENTAL DAMAGE FROM WALL TECHNOLOGIES FOR RESIDENTIAL BUILDINGS IN ISRAEL

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ABSTRACT

Four wall technologies used for residential building in Israel (concrete, lightweight concrete block, autoclaved aerated block, and concrete block) were evaluated for their total environmental damage. The production and construction (P&C) and operational energy (OE) stages were considered. Influences of the climate (the four climate zones of Israel), building type (regular and low-energy), and primary fuel source [natural gas and photovoltaic (PV) for energy production] on the selection of the best wall technology were analyzed. EnergyPlus software was used to evaluate building heating and cooling needs for the OE stage. The ReCiPe method was used for both the P&C and OE stages to evaluate environmental damage via human health, ecosystem quality and resource depletion damage categories. It was determined that both concrete block walls and concrete walls were the best choices when natural gas was used, while the concrete block and autoclaved aerated block walls were the best choices when PV was used. The following two conclusions were reached: wall technologies with high thermal mass are environmentally preferred when natural gas is used, whereas wall technologies with reduced cement quantity are environmentally preferred when PV is used.

KEYWORDS:

life cycle assessment (LCA), PV, ReCiPe; two-stage nested ANOVA, residential building

INTRODUCTION

Both life cycle energy assessment (LCEA) and life cycle assessment (LCA) have been widely used to evaluate the environmental damage caused by different wall technologies (e.g., Karimpour et al. 2014). Both types of assessment typically consider the three main building life stages: production and construction (P&C); operational energy (OE) (for cooling, heating, supporting occupants' daily activities, dehumidification/humidification, hot water, and lighting); and maintenance to demolition (MtoD) (Ibn-Mohammed et al. 2013; Hetherington et

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al. 2016). The P&C and OE stages have the greatest influence on building-related LCA and LCEA (Ibn-Mohammed et al. 2013). The relative impacts of the P&C and OE stages on the total life cycle of a building depend significantly on climate, building type, and the primary fuel source used in energy production (Karimpour et al. 2014).

In Israel, the full influence of the above factors on the P&C and OE stages of building wall technologies has not yet been studied. In fact, only two local Israeli LCA and LCEA studies are described in the literature.

Pushkar et al. (2005) analyzed the influence of the primary fuel source used in energy production on the P&C and OE stages. The authors studied office buildings located in a mild Mediterranean climate (represented by Jerusalem) and conducted LCAs of concrete and lightweight concrete block walls under the primary fuel source factor. Coal, gas, and hydro-based fuel sources were considered for meeting OE needs. The LCA impacts of the OE stage as compared to the P&C stage were approximately 85% versus 15% for coal, 64% versus 36% for gas, and 4% versus 96% for hydro. However, neither climate nor building type factors were analyzed by Pushkar et al. (2005).

Huberman and Pearlmutter (2008) analyzed the influence of building type on both the P&C and OE stages. The authors performed LCEAs on low-energy residential buildings in a semi-arid climate (represented by Beer Sheva); they considered hollow concrete block, autoclaved aerated concrete block, stabilized soil block, and fly-ash block wall technologies. In terms of their impact on the buildings' LCEA, the ranges of the OE stage versus the ranges of the P&C stage were approximately 34–47% and 53–66%%, respectively. The authors converted the results of the LCEAs into CO_2 emissions by applying the average values of the conversion factors, which they adopted from the literature (100 kg of CO_2/GJ for the P&C stage and 50 kg of CO_2/GJ for the OE stage). However, the primary energy sources for these factors were not specified and the authors did not analyze the climate factor.

The aim of the present study was to evaluate the effects of three factors – climate (the four climate zones of Israel), building type (regular and low-energy), and primary fuel source [natural gas and photovoltaic (PV) for energy production] – on (i) the impacts of the OE and P&C stages in the total life cycle of wall technologies and (ii) the choice of the best wall technologies for residential buildings in Israel.

RESEARCH METHODS

The P&C and OE stages of four building wall technologies (concrete, lightweight concrete block, autoclaved aerated block, and concrete block) were evaluated. A building's external wall of 2500 m^2, with a 50-year life span, was examined. The walls were designed in compliance with local construction requirements (Pearlmutter et al. 2010) according to the Standard of Israel (SI) 1045 (2011) (U-value=1.25 $W/m^2 \cdot K$) and SI 5282 (2011) (U-value=0.65 $W/m^2 \cdot K$).

For the conventional building, the U-values were as follows: concrete 1.07 $W/m^2 \cdot K$, lightweight concrete block 1.09 $W/m^2 \cdot K$, autoclaved aerated block 0.94 $W/m^2 \cdot K$, and concrete block 1.16 $W/m^2 \cdot K$. For the low-energy building, the U-values were concrete 0.61 $W/m^2 \cdot K$, lightweight concrete block 0.60 $W/m^2 \cdot K$, autoclaved aerated block 0.61 $W/m^2 \cdot K$, and concrete block 0.62 $W/m^2 \cdot K$.

The building locations were selected to represent the four climatic zones of Israel: a hot Mediterranean climate (represented by Tel-Aviv), a semi-arid climate (represented by Beer Sheva), a mild Mediterranean climate (represented by Jerusalem), and a desert climate (represented by Eilat) (SI 1045 2010).

Environmental evaluations

P&C stage. The life cycle inventory (LCI) of each of the four wall technologies was modeled using SimaPro software version 7.33 (PRe´ Consultants [2011]). On the material level (e.g., raw material extraction and production of the building materials), Ecoinvent data for cement, water, rock, sand, limestone, etc. from European countries (such as Switzerland and the Federal Republic of Germany) was used.

On the component level, masses of composite materials for the walls were modeled according to the relevant local Israeli product suppliers such as Readymix Industries, Ltd. and Ytong Industries, Ltd. (Pushkar 2014). Local transportation distances were assumed (Huberman and Pearlmutter 2008; Pushkar 2014).

OE stage. Heating and cooling are achieved using a heat pump [coefficient of performance (COP), 3] with set points of 20°C for heating and 24°C for cooling. Detailed weather data for Tel-Aviv, Beer-Sheva, Jerusalem, and Eilat were collected through EnergyPlus Weather Data for Israel (EnergyPlus website). SimaPro (2011) contained no detailed data for Israeli natural gas and PV electricity generation. Thus, natural gas and PV electricity fuel sources for Spain were used.

Software and method. The U.S. Department of Energy's (DOE) building energy simulation program, EnergyPlus v.8.3 software, was used for the OE evaluation. The hierarchical ReCiPe method was used to evaluate the environmental damage of the P&C and OE stages. "ReCiPe" refers to a *recipe* for the calculation of life cycle impact category indicators. The acronym also represents the initials of the main contributors to ReCiPe's creation: RIVM (Rijksinstituut voor Volksgezondheid en Milieu) and Radboud University, CML (Centrum Milieukunde Leiden), and PRé Consultants, Netherlands (Goedkoop et al. 2009). The ReCiPe method integrates human health (disability-adjusted life-years, DALY scale), ecosystem quality (potentially affected fraction, PAF, of species scale), and resource damage (costs due to the extraction of a resource, $ scale) into a single indicator (environmental points, Pt) without compromising the overall environmental evaluation. ReCiPe achieves this by applying three different perspectives on environmental problems: egalitarian, individualistic, and hierarchical. ReCiPe contains 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) (Goedkoop et al. 2009). The hierarchical structure of ReCiPe was recently described in detail (Pushkar 2016; Pushkar and Verbitsky 2016).

Statistical evaluations

The four climate zones, the two types of buildings, and the two types of primary fuel sources for energy production create 24 unique natural combinations. Pairwise comparisons of four ReCiPes of wall technologies, within each unique natural combination, were performed. ReCiPes of wall technologies were treated as a cluster of objects. Six methodological options for ReCiPe, treated as individual objects, were subsampled from the cluster (Pushkar and Verbitsky 2016).

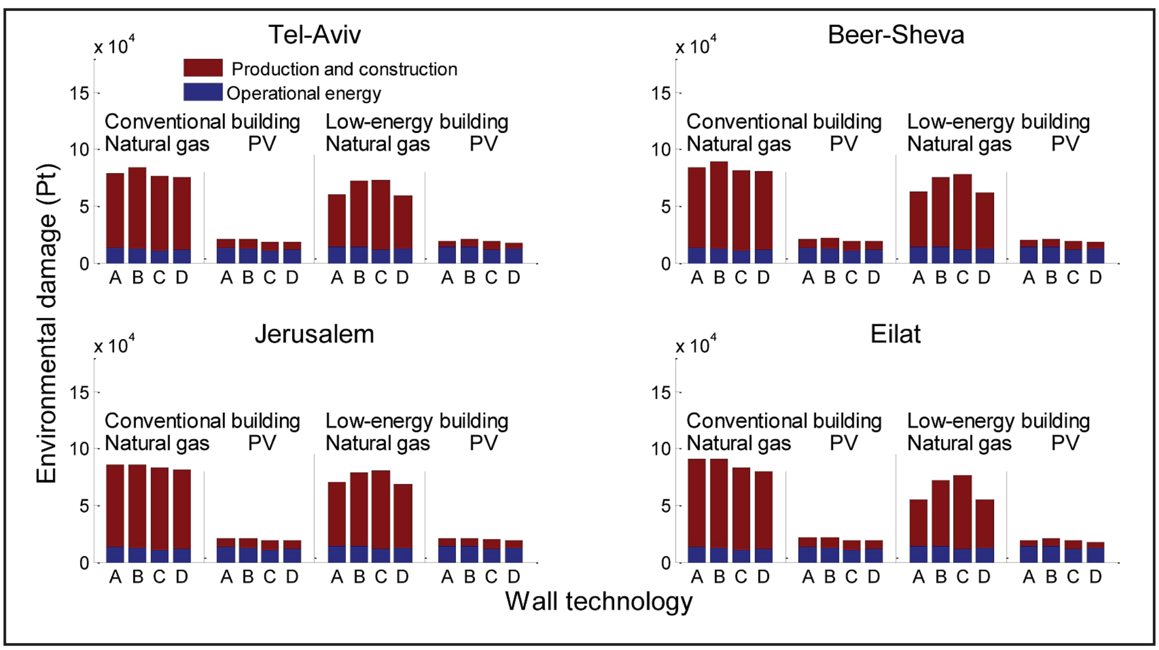
The differences among all pairings of four ReCiPe wall technologies were evaluated using two methods: a) a two-stage nested mixed analysis of variance (ANOVA) test, (i.e., simultaneous evaluation of the six methodological options of ReCiPe) and b) a percent difference in ReCiPe (h/a, default) (i.e., evaluation of a single methodological option of ReCiPe). Neo-Fisherian significance assessments and three-valued logic of the P-values were used (Hurlbert and Lombardi 2012).

RESULTS

Impacts of the P&C and OE stages

The range of the OE stage versus the range of the P&C stage was approximately 85–90% versus 15–10% for the conventional building and 75-85% versus 25–15% for the low-energy building when natural gas was used for the OE stage. In contrast, the range of the OE stage versus the range of the P&C stage was approximately 40–50% versus 60-50% for the conventional building and 30-40% versus 70-60% for the low-energy building when PV was used for the OE stage (Figure 1).

FIGURE 1: Environmental damage of the operational energy (OE) stage and the production and construction (P&C) stage in the two types of buildings, conventional and low-energy, with two energy sources, natural gas and PV, for OE needs in Tel-Aviv, Beer-Sheva, Jerusalem, and Eilat. The four evaluated wall technologies are concrete (A), lightweight concrete block (B), autoclaved aerated block (C), and concrete block (D). The environmental damage (Pt) is evaluated with the default h/a option of ReCiPe.



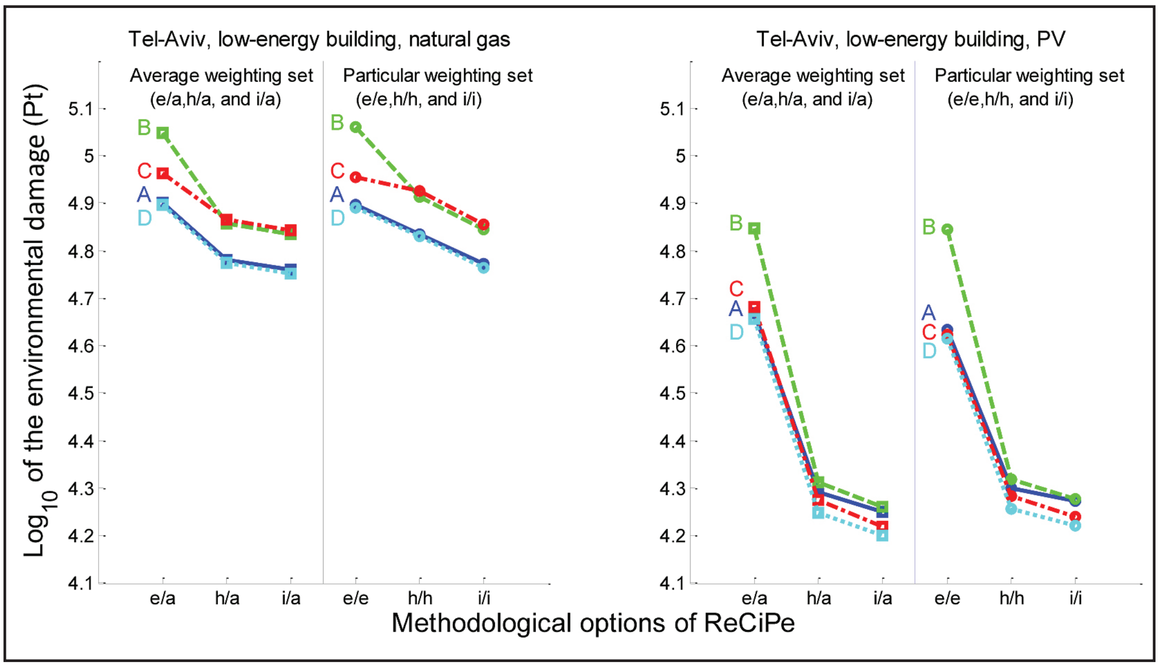
Thus, climate and building type were found to be non-significant factors, while the primary fuel source for the OE stage was recognized as a significant factor. Therefore, the selection procedure for the best wall technology is demonstrated below using the example of a low-energy building in Tel Aviv with two energy options: only natural gas and only PV.

Selection of the best wall technologies

The results of ReCiPe using natural gas are shown on the left side of Figure 2. The ranking of the four wall technologies, in ascending order of total environmental damage (P&C + OE stage) is 1st - concrete block and 2nd – concrete. The lightweight concrete block and autoclaved aerated block wall technologies alternated between 3rd and 4th place under the different methodological options (i/i, i/a, h/h, h/a: lightweight concrete block in 3rd position and autoclaved aerated block in 4th position; e/e and e/a: autoclaved aerated block in 3rd position and lightweight concrete block in 4th position).

The results of ReCiPe using PV are shown on the right side of Figure 2. Under all methodological options of ReCiPe, the wall ranking, in ascending order of total environmental damage, is as follows: 1st - concrete block, 2nd - autoclaved aerated block, 3rd - concrete and 4th - lightweight concrete block. There is only one exception to this ranking: under the e/a option, concrete is in 2nd position while autoclaved aerated block is in 3rd position.

FIGURE 2: Tel-Aviv, low-energy building: the total life cycle of the walls of a residential building using two energy sources, natural gas and PV, for OE needs. The four evaluated wall technologies are concrete (A), lightweight concrete block (B), autoclaved aerated block (C), and concrete block (D). The total life cycle environmental damage (Pt) was evaluated with the 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 ReCiPe.



The top of Table 2 contains the P-values and percent differences for ReCiPe (h/a) using natural gas. The difference between lightweight concrete block and autoclaved aerated block, and between concrete and concrete block seems to be negative (P=0.2745 and P=0.7306, respectively) and the percent change (h/a) is 2% in both pairings. Judgment is suspended regarding the differences in all other pairings (0.0242≤ P≤0.0354); the percent changes (h/a) are ≥19%.

The bottom of Table 2 contains the P-values and percent differences for (h/a) using PV. The difference between autoclaved aerated block and concrete block seems to be negative (P=0.0565) and the percent change (h/a) is 6%. Judgment is suspended regarding the difference between concrete and autoclaved aerated block (P=0.0775); the percent change (h/a) was 4%. The differences in all other pairings seem to be positive (P≤0.0050) and the percent changes (h/a) were ≤16%.

TABLE 2. Low-energy building with natural gas and PV options in Tel Aviv. P-value (P) and percent differences (%) are presented in the table as P (%) of the pairing differences in the four wall technologies as a function of total life cycle environmental damage evaluated with ReCiPe, two-stage nested mixed ANOVA, degree of freedom (df) df_1=1 df_2=2, and probability resulting from a significance test (P).

Fuel source	Wall	A	B	C	D
Natural gas	A	X	*0.0272* **(19)**	*0.0354* **(22)**	0.7306 (2)
	B		X	0.2745 (2)	*0.0242* **(21)**
	C			X	*0.0303* **(23)**
	D				X
PV	A	X	**0.0025** (5)	*0.0775* (4)	**0.0050** *(11)*
	B		X	**0.0041** (9)	**0.0014 (16)**
	C			X	0.0565 (6)
	D				X

Note: Concrete (A), lightweight concrete block (B), autoclaved aerated block (C), and concrete block (D). The P-values were evaluated according to three-valued logic: font style is bold—seems to be positive, font size is ordinal—seems to be negative, and font style is italic—judgment is suspended.

DISCUSSION

Impacts of the P&C and OE stages

The Israeli climate did not influence the impacts of the P&C and OE stages of the different wall technologies (in terms of their contributions to total environmental damage) because approximately the same OE (for heating and cooling needs) is required in all climate zones (Figure 1).

The influence of building type on the impacts of the P&C and OE stages of the different wall technologies was insignificant (Figure 1). This is because the U-values of the walls were relatively close, from 0.94 $W/m^2{\cdot}K$ for autoclaved aerated block to 1.16 $W/m^2{\cdot}K$ for concrete block (conventional building) and from 0.6 for lightweight concrete block to 0.62 for concrete block (low-energy building). To achieve lower thermal conductivity in a wall, more materials were usually needed in the initial construction stage. The difference between the conventional and low-energy buildings was in the thickness of the polystyrene layer only (in the low-energy building, the layer of polystyrene was 3 cm thicker than in the conventional building). As a result, relative to the conventional building, in the low-energy building the impact of the OE stage decreased by approximately 10% and the impact of the P&C stage increased by approximately 10%.

The influence of the primary fuel source on the impacts of the P&C and OE stages of the walls in both conventional and low-energy buildings was significant (Figure 1). Switching from natural gas to PV caused a significant decrease in OE, thereby increasing the impact of the P&C stage. In the low-energy building, the P&C stage increased to account for 60-70% of total environmental damage. Similar results were obtained by Proietti et al. (2013), who studied a low-energy building located in Perugia, Italy. They reported that using PV for energy needs in the OE stage caused a significant decrease in OE, reducing it to 10–20% of total environmental damage, thereby increasing the impact of the P&C stage to 90-80%.

Selection of the best wall technologies

Preferred walls. Under the natural gas option, the impacts of the P&C and OE stages were 20% for P&C vs 80% for OE, while under PV they were 70% for P&C vs 30% for OE.

The concrete block and concrete walls were the best technologies when using natural gas. This was due to both the concrete block and concrete wall having high mass (360 kg/ m^2 and 480 kg/m,[2] respectively) and were therefore thermally effective in Israel's climate zones (Pearlmutter et al. 2010).

The concrete block and autoclaved aerated block walls were the best technologies when using PV. This is due to the cement content of the blocks being reduced in comparison with concrete wall technology. In particular, the concrete block wall contains 88 kg of cement and the autoclaved aerated block wall contains 53 kg, while the concrete wall contains 150 kg of cement per 1000 kg of wall technology (Pushkar 2014). It is well-known that concrete production is strongly associated with high CO_2 emissions (Van den Heede and Belie 2012; Burchart-Korol 2013).

Preferred methods. It should be noted that the aforementioned results were determined using all methodological options of ReCiPe. Therefore, evaluations of the wall technologies with ReCiPe were sufficient and complementary analysis by two-stage nested mixed ANOVA was unnecessary.

However, in the case of natural gas, lightweight concrete block and autoclaved aerated block alternated between 3rd and 4th position under the different methodological options (Figure 1). This revealed the disordinal interaction between these two wall technologies' results under the different methodological options of ReCiPe. A similar interaction between the methodological options of Eco-Indicator 99 (Goedkoop and Spriensma 2001) was recently obtained in another evaluation of building technologies (Pushkar 2014). The ReCiPe method and the two-stage nested mixed ANOVA test were applied when determining the best flat roof technology from the perspective of environmental damage (Pushkar 2016).

In addition, despite the recommendation of h/a as the default methodological option (Goedkoop and Spriensma 2001), the results of the P-value analysis (a two-stage nested ANOVA) of ReCiPe were not always in agreement with the results of the percent difference when using the h/a option of ReCiPe (Table 2). For example, the significant difference between the concrete wall and the lightweight concrete block wall seems to be positive ($P=0.0025$). This means that between these two wall technologies, there was difference in effect on the environment. In contrast, the percent difference between the same two technologies, according to ReCiPe (h/a, default option), was only 5%. Thus, between these two wall technologies there was no difference in their effect on the environment.

CONCLUSIONS

Impacts of the P&C and OE stages

The following impacts were determined of total environmental damage contributed by the P&C and OE stages in the building sector in Israel:

- no difference in the impacts of the P&C and OE stages in all four climate zones;
- in the low-energy building (SI 5282 2011), the OE impact decreased and the P&C impact increased by approximately 10% relative to the conventional building (SI 1045 2011);

- the OE stage contributed 80% of the total environmental damage when natural gas was used as the primary fuel source, whereas the P&C stage contributed 70% of the total environmental damage when PV was used as the primary fuel source.

It was concluded that only the fuel source for OE production should be taken into account, while climate and building type factors can be disregarded. Using a natural gas fuel source, consideration of only the OE stage will be sufficient. Using a PV fuel source, consideration of only the OE stage is not a suitable environmental measurement because the P&C of the wall must also be evaluated.

Selection of the best wall technologies

Preferred walls. We found that when using a natural gas fuel source, both concrete block walls and concrete walls were the best choices. When using a PV fuel source, the concrete block walls and autoclaved aerated block walls were the best choices. It was concluded that when using a natural gas fuel source, wall technologies with high thermal mass are environmentally preferred; while when using a PV fuel source, wall technologies with reduced cement quantity are environmentally preferred.

Preferred methods. We found that the different methodological options of ReCiPe revealed different rankings of wall technologies for Israel's building sector. We concluded that the ReCiPe method with a two-stage nested mixed ANOVA should be used when either natural gas or PV is used as the primary fuel source.

Contribution of this paper

On the issue of wall technology, the current green building Israeli Standard (SI 5281 2011) references SI 5282 (2011) for improving the OE stage only suffices when natural gas is used as primary fuel source. However, under PV energy generation, the P&C stage can no longer be ignored. Appropriate evaluation of the environmental damage of different wall technologies requires evaluation of both the OE and P&C stages. This paper outlines the necessity of applying different evaluation approaches to the OE stage depending on whether natural gas or PV is used as the primary fuel source.

Limitation of this paper

In addition to the P&C and OE stages, the demolition and disposal stages need to be included in further research. In addition, future research should perform sensitivity analysis of wall technologies to different percent combinations of natural gas and PV fuel sources, particularly for the OE stage.

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