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Article

Life Cycle Assessment of Energy and CO_2 Emissions for Residential Buildings in Jakarta and Bandung, Indonesia

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Abstract: The objective of this study is to analyze life cycle energy and CO_2 emission profiles by employing an input–output analysis method for urban houses in major cities of Indonesia. Two surveys investigating building material inventory and household energy consumption within individual houses were conducted in Bandung in 2011 and 2012. The results show that, if reused and recycled materials were assumed to be zero, the averaged embodied energy for simple, medium and luxurious houses in Bandung was larger than that for their respective houses in Jakarta. Overall, the average annual energy consumption of all samples in Jakarta was approximately 20.6 GJ, which is 5.0 GJ larger than that in Bandung. In terms of life cycle energy, the operational energy accounted for 79%–86% and 69%–81% of the total for respective houses in Jakarta and Bandung. The profiles of life cycle CO_2 emissions are similar to those of energy. The results of the scenario analysis prove that the promotion of reusing/recycling is important to reduce building material inputs/waste and their corresponding embodied energy. It is also important to reduce the use of air-conditioning for operational energy in the future by adopting passive cooling techniques wherever possible.

Keywords: embodied energy; household energy consumption; input–output; Indonesia; life cycle assessment

1. Introduction

The ultimate purpose of this study is to propose low energy and low carbon residential buildings in major cities of Indonesia. Over the last few decades, Indonesia has been experiencing high economic growth in line with rapid urbanization and population growth. The percentage of people living in urban areas reached approximately 53% in 2014 [1]. Consequently, the need for living spaces increased rapidly, and an enormous number of residential buildings have been developed, especially in major cities. This tremendous urbanization found in the major cities sees a large increase in urban energy consumption.

In Indonesia, the household sector contributed 33.2% of the nationwide final energy consumption during the period of 2000–2013 [2]. The household energy consumption is expected to increase dramatically as the middle class in urban areas rises in the near future [3]. Energy-saving strategies are, therefore, essential to be introduced further to make the cities more sustainable.

A building consumes various natural resources, including water, materials and energy, and releases many pollutants and emissions during its life-cycle, *i.e.*, from the raw material extraction to the building's final disposal [4]. Thus, any comprehensive assessment of building energy consumption and its environmental impact must consider the entire life cycle of the building. Life cycle assessment (LCA) is a well-known analytical tool for assessing the environmental impacts of a product in its life span in order to achieve a low energy and low carbon building [4]. Several LCA methods for buildings have been developed and are commonly used in many parts of the world, particularly in developed nations [4–7]. However, there are relatively few LCA studies for buildings in developing countries to date [8–12]. This is mainly because of relatively poor data availability of building, economy and environment, which are necessary for LCA analyses.

A few LCA studies were conducted in Indonesia. For instance, Utama and Ghewala [10] evaluated the effect of building envelopes on the life cycle energy consumption of high-rise apartments in Jakarta. Furthermore, Utama and Ghewala [9] investigated the life cycle energy of single landed houses with different materials of walls in Semarang. Kurdi [11] estimated the life cycle energy and CO_2 emissions of planned houses in seven large cities in Indonesia. The above studies provide rare and useful results of LCA in residential buildings of Indonesia. However, these studies only focused on mass/planned houses and apartments. In Indonesia, individual/unplanned houses are typical of residences in major cities rather than the said mass houses, as discussed in Section 2.1.

This study, which focuses on individual houses in major cities of Indonesia, aims to assess the life cycle energy and CO_2 emissions of urban residential buildings comprising three house categories (simple, medium and luxurious houses). Two surveys were conducted in the cities of Bandung (n = 247) and Jakarta (n = 297) from September to October in 2011 and 2012 to obtain both material inventory and household energy consumption profiles of these buildings. This study consists of three parts. The first part evaluates the flow of building materials of urban residential buildings in Indonesia, focusing especially on individual houses in the cities of Jakarta and Bandung. The current status of material stock was evaluated. Furthermore, life-cycle material flows focusing on the future demolition of waste of individual houses are predicted for different scenarios using various reusing/recycling rates. The second part further analyzes the embodied energy of building materials through an input–output analysis, and operational energy. The last part assesses the life cycle energy/CO_2 emissions of those individual houses. The results of this analysis will provide useful insights for policy making in building construction, construction and demolition (C&D) waste management as well as in energy policy for achieving low-energy and low-carbon societies in Indonesia.

2. Methodology

2.1. Case Study Houses

Jakarta and Bandung were selected as the case study cities, which represent rapidly developing cities. It was assumed that Bandung and other major cities will follow the path of Jakarta city's development. Therefore, other cities will learn from its development to be more sustainable cities. Both cities are located in the same region of Java in Indonesia. Jakarta, the capital city of Indonesia, had a population of 9.99 million in 2012 [13], whereas Bandung, the capital of West Java Province, had a population of 2.45 million in 2012 [14]. Both cities are located in West Java Province and experience hot and humid tropical climates. However, the monthly average temperature in Bandung (22.9–23.9 °C) is not as high as that in Jakarta (27.1–28.9 °C) because of the former's relatively high altitude. On average, Bandung and Jakarta are situated 700–800 and 5–10 m above the sea level, respectively. Thus, comparison of the two cities would be both intriguing and needed.

In most major cities in Indonesia, individual houses, called "*Kampungs*", account for the largest proportion of the existing housing stocks. These dwellings are settled in unplanned and overcrowded urban villages without being provided with proper, basic urban infrastructure and services [15]. These individual houses accounted for approximately 74% of total housing stocks in Jakarta in 2012 [13] and approximately 89% of those in Bandung [14]. In contrast, mass/planned houses are defined as houses constructed in a proper modern urban planning. The recent mass developments comprising terraced houses are included in this type. This accounted for another 26% in Jakarta and 11% in Bandung. Moreover, these houses can be further classified into three house categories based on their construction cost and lot size, namely simple, medium, and luxurious houses (Figure 1) [16]. These houses have average technical life spans of approximately 20, 35, and 50 years, respectively [17].

We assumed that subsets of the population for respective house categories (*i.e.*, simple, medium and luxurious houses) were homogenous in Indonesia. Therefore, the disproportional stratified sampling was applied, thus a large sample size was not necessary to represent the entire population (2.2 million and 510 thousand houses in Jakarta and Bandung respectively). Several typical residential neighborhoods were selected from the cities of Jakarta (14 areas) and Bandung (6 areas), respectively. A total of 297 and 247 residential buildings were then chosen randomly in the selected neighborhoods in the two cities by considering the distance from city center and their establishment years, respectively (see Table 1). These samples were selected by considering the above-mentioned existing ratios of unplanned and planned houses in Jakarta. The whole sample consisted of mass houses of 23% and individual houses of 77%.

Since the proportion of individual houses is very large, the survey focused only on these houses in Bandung. The Ministry for Housing and Settlement of Indonesia recently set the target of proportion for balanced residential patterns for the national housing sectors [18]. They proposed the proportions of simple, medium and luxurious houses to be 3:2:1. However, the data for existing proportions of these house categories in Jakarta were not available. Therefore, this study obtained a certain number of samples from respective categories with the aim of making comparisons among these three house categories.

(**a**) (**b**) (**c**)

Figure 1. Views of sample residential buildings: (**a**) simple house; (**b**) medium house; and (**c**) luxurious house.

As shown in Table 1, the average household size was about 4–5 persons with a small variation between the three categories. The monthly average household income was also investigated by a multiple-choice question. As expected, the average income increases with house category from simple to luxurious houses. As shown, the total gross floor area also increases with house category. The largest percentage of gross floor area was less than 50 m^2 (71% in Jakarta and 51% in Bandung) for simple houses, 50 to 99 m^2 (51%) in Jakarta and 100 to 300 m^2 (58%) in Bandung for medium houses and 100 to 300 m^2 (84% in Jakarta and 64% in Bandung) for luxurious houses. These differences are due to the difference of land cost where that of Jakarta is more expensive than that of Bandung. The age distribution of the surveyed houses (actual ages) varies slightly between the two cities, although the average ages are almost the same between the cities (22 years old in Jakarta and 28 years old in Bandung). The average age of luxurious houses in Bandung is exceptionally low (10 years old). The difference between actual buildings' ages and their technical life spans, especially for simple houses occurred mainly because the occupants of the houses tend to repair and extend their houses gradually. Thus, it is very difficult to obtain the precise data of actual life spans.

Table 1. Brief profile of sample houses in Jakarta and Bandung.

	Jakarta				Bandung			
	S	**M**	**L**	**W**	**S**	**M**	**L**	**W**
Sample size (Individual/mass)	125 (125/0)	115 (75/40)	57 (29/28)	297 (229/68)	120 (120/0)	99 (99/0)	28 (28/0)	247 (247/0)
Household size (persons)	4.3	4.5	5.3	4.5	4.7	4.7	5.6	4.8
Monthly household income (%)								
<100 (USD)	4.8	1.7	1.8	3.0	10.0	0.0	0.0	4.5
100–499	76.8	59.1	19.2	58.9	75.8	58.6	7.1	61.5
500–1000	16.8	31.3	38.6	26.6	14.2	38.4	57.2	28.7
>1000	1.6	7.9	40.4	11.5	0.0	3.0	35.7	5.3
Total	100	100	100	100	100	100	100	100
Average (USD)	353.9	553.1	1047.9	572.3	330.5	550.8	1105.2	518.1
Total floor area (%)								
<50 (m^2)	71.2	9.6	0.0	33.7	50.8	6.1	0.0	25.9
50–99	20.0	51.3	0.0	28.3	39.2	34.3	3.6	32.4
100–300	8.8	36.5	84.2	34.0	10.0	58.6	64.3	37.7
>300	0.0	2.6	15.8	4.0	0.0	1.0	32.1	4.0
Total	100	100	100	100	100	100	100	100
Average (m^2)	44.2	107.2	213.6	101.1	59.6	124.3	283.1	110.9
Housing age (%)								
<10 (year)	22.4	25.2	17.5	22.6	13.3	26.3	57.1	23.5
10–20	40.0	17.4	21.0	27.6	14.2	28.3	28.6	21.5
21–30	17.6	29.6	31.6	24.9	21.7	15.1	14.3	18.2
31–40	12.8	15.6	21.1	15.5	8.3	9.1	0	7.7
>40	7.2	12.2	8.8	9.4	42.5	21.2	0	29.1
Total	100	100	100	100	100	100	100	100
Average (year(s))	19.6	24.1	24.6	22.0	34.5	23.8	10	27.5

S: simple house; M: medium house; L: luxurious house; W: whole samples.

2.2. Current Material Stock and Future Demolition Waste in Urban Residential Buildings

In Indonesia, limitations of data, such as those for population, number of households, household expenditure, and building life cycle of each type of houses, make it difficult to clarify the current material stock in individual houses and to design and implement concrete policies to address issues of C&D waste management. In this study, we first attempted to evaluate (a) the current material stock in individual houses in Jakarta and Bandung at the city level and (b) their future demolition wastes from the present (2012) to 2020 when a significant change occurs in income level (the projected income distribution in 2020 shows that the middle income class is expected to grow rapidly: 4% for high-income class, 73% for middle-income class and 23% for low income class) [3]. The change of income level will change their life-styles as well as household energy consumption rapidly. The results of these analyses would emphasize the importance of housing policy for promoting more sustainable building in whole its life-cycle.

The process used to estimate the current material stock for urban houses at the city level can be described as follows. In this analysis, it is assumed that (1) the housing stock is equal to the number of households, which is obtained by dividing the total population by the average household size; and (2) in our surveys, it was found that the average monthly income significantly increases with house category from simple to luxurious houses (see Table 1). Therefore, we assume that low-, middle- and high-income people live in simple, medium and luxurious houses, respectively. Furthermore, it is assumed that the income distribution in the surveyed residential areas of Jakarta and Bandung is the same as those throughout the entire cities. The current proportions of houses of the three house categories in the two cities are then determined based on the household income data of Jakarta [19]: simple houses (75%), medium houses (20%) and luxurious houses (5%).

The common method to analyze future demolition waste is to use building cohort analysis. Unfortunately, the demolished building data were not available. Therefore, this study designed scenarios to predict future demolition waste. Estimation of the amount of demolition waste generated by individual houses from the present (2012) to 2020 is described as follows. In this analysis, we only focus on the demolition waste generated from the current material stock. The following assumptions are made: (1) The starting year of demolition waste generation is 2012. (2) The distribution of age of houses in the surveyed residential areas of Jakarta and Bandung is the same as those throughout the entire cities (see Table 1). (3) The demolition ratios (η_j) for unplanned houses by 2020 in Jakarta and Bandung are determined by the average ages of surveyed houses as of 2012 (see Table 1) and the average technical life-spans of respective house categories (20, 35, and 50 years) as indicated by Equation (1). The resulting demolition ratios for three house categories are as follows: 64%, 38% and 7% for simple, medium and luxurious houses in Jakarta and 85%, 38% and 0% for simple, medium and luxurious houses in Bandung, respectively. (4) The reusing and recycling rates of each material are zero.

$$\eta_j = \frac{DSS_j}{SS_j} \tag{1}$$

where SS_j: total number of survey samples of house type j in 2012; DSS_j: number of survey samples of house type *j* whose ages will be older than the average life-spans of respective house categories (simple: 20, medium: 35, and luxurious: 50 years) by 2020.

However, it is unsure that the building materials used for individual houses are obtained in a formal way. It has been reported that informal private sectors play major roles in material recycling activities in Indonesia [20]. Because of the above uncertainty, we assume different sets of recycling and reusing rates and assess the effects of the policy promoting reused and recycled material use through a scenario analysis. The first scenario (Scenario 1) assumes that both recycling and reusing rates are set to be zero (minimum), and the second scenario (Scenario 2) is designed under the assumption that both recycling and reusing rates for respective building materials are increased to the maximum values (see Table 2). The effects of the promotion of reused and recycled building material use are evaluated through a comparison between the two scenarios.

In this study, a reused material is defined as one used for about the same purpose as initially intended, whereas a recycled building material is defined as one that can be remade and reused as other building materials after the building is disassembled [21]. Moreover, the recycling process can be broadly classified into two different categories: closed-loop and open-loop processes [22]. A closed-loop recycling is a process where end-of-life products are recycled as the same products, whereas the materials recycled in an open-loop process are recycled into different products (different material inputs).

The quantities of soil waste are excavated during construction work, much of which is often reused completely for construction reclamation or landscaping or disposed of in landfills. Moreover, the stone for used foundations, which has a long durability as a building material, is considered reusable for the same purpose in building construction [23]. Therefore, we assumed that soil and stone can be reused completely, as shown in Table 2.

Bricks and blocks can be separated for reuse depending on the type of mortar used. The percentage of recycled content mixed with virgin clay varies considerably according to the material being used and type of brick, but it can reach 90%, and 5% of the remains can be reused for some items such as brick fireplaces, brick gatepost and brick staircase depending on the quality of the material [23]. The rest can be reclaimed for infrastructure or disposed to landfill. In addition, clay and concrete roofs can easily be reused due to their long durability. On the other hand, the recycling ratios for closed-loop of mortar, concrete, concrete brick and roofing materials for other building's raw materials are zero [24]. Nevertheless, concrete waste can be crushed and recycled (96%) in place of virgin aggregate, which is used in a wide variety of infrastructure construction applications, such as road base, fill, and as an ingredient in concrete and asphalt pavement [25]. Moreover, the recycling of ceramic materials is almost impossible because currently these products cannot be transformed into their pure materials [23,26].

The opportunities to reuse timber in construction vary greatly according to the type of timber product employed and its intended use [27]. There are several potential applications of recycled wood, such as erosion control/groundcover, organic soil amendment, use as chipboard, and export as fuel wood. Therefore, this study assumed that timber has a maximum recycling ratio of 38% [23,26]. Metals, including steel, are easy to separate from mixed waste. The recycling ratio of steel is theoretically almost 100% [23,24]. Because reused steel for structure may lack the strength and durability of new steel, the reuse of steel is not appropriate for all steel structures. Glass is one of the easiest materials to recycle, although re-melting is an energy-intensive process [23]. Moreover, the recycling system for gypsum ensures that gypsum and plasterboard waste can be 100% recyclable [28].

Asbestos is hazardous waste that needs to be treated very carefully in sorted dismantling of construction materials. Then, it is detoxified in an intermediate treatment facility and finally fully recycled before being disposed in a controlled final landfill properly [29].

Recently, a new technology of GeoMelt was developed to recycle it into a vitreous product [30]. However, there is no such technology and no controlled final landfill in Indonesia, which should be promoted in the future. Furthermore, the recycling rate of zinc depends mainly on the collection rate of zinc-containing products at their end of life; over 90% of these collected products are recycled [31].

Since the data of recycling energy in Indonesia or in the same region are not available, in this study, the potential energy saving through recycling (closed-loop) was obtained from several references. In this analysis, we assume that 38% of all construction wood waste is recovered and used to substitute non-renewable fossil fuels in power generating plants by combustion in biomass-fired plants [32]. Therefore, the potential energy saving through recycling for wood is 100%. Recycling the steels results in energy savings of up to 60% [33]. No energy saving was considered from recycling of clay and concrete brick, only conservation of natural resources and the quantity of waste that was not sent to landfill were considered [34]. Other energy savings for recycled materials can be seen in Table 2.

Table 2. Potential reusing and recycling rates.

Materials	Potential Rate (%)		
	Reusing	Recycling	Energy Savings for Recycling
Mortar	0	100 [24]	0
Soil	100 [23]	0 [23]	0
Stone	100 [23]	0 [23]	0
Concrete	0	96 [25]	0
Clay brick	5 [23]	90 [23]	0 [34]
Concrete brick	0 [23]	96 [23]	0 [34]
Steel	0 [23]	100 [23]	60 [33]
Ceramic tile	0 [23]	0 [23]	0
Clear glass	100 [23]	100 [23]	5 [34]
Wood	50 [23]	38 [23]	100 [32]
Gypsum	0 [28]	100 [28]	10 [34]
Paint	0	0	0
Clay roof	0 [23]	100 [23]	0 [34]
Concrete roof	0 [23]	96 [23]	0 [34]
Asbestos roof	0 [29]	100 [29]	0
Zinc roof	5 [31]	90 [31]	96 [34]

2.3. Life Cycle Assessment

Generally, LCA involves six phases, namely design, material production, construction, operation, maintenance, and demolition phases. However, energy for the design, construction and demolition phases was not considered in this paper. This is due to very limited possibilities to consume energy in the above three phases since most of residential buildings in both cities are constructed and demolished by manual labor. Thus, the energy consumption used during the above phases is considered negligible.

The design records such as building drawings are required for the analysis of embodied energy of building materials. These data can normally be obtained from local authorities, developers, *etc.* [12]. Some developed countries provide the data in the literature [7]. Nevertheless, in the case of Jakarta, these data were available for mass houses and most of individual luxurious houses only. The other houses including most simple and unplanned medium houses were not constructed in the formal way in practice (they are normally constructed by non-professional neighbors), and therefore the said design records could not be obtained. Thus, actual on-site measurements by using laser distance meters and tape measures were conducted to acquire the data (Figure 2a). The survey also obtained materials used for maintenance (*i.e.*, ceramic, paint, wood, gypsum, glass and clay roof). The materials for maintenance were determined by considering the life spans of each material for building components based on survey. We assumed that when the life span of a building component is shorter than the building life-span, the component would be replaced by a new product. Meanwhile, the detailed household energy consumption data are necessary for the analysis of operational energy. However, there are few previous relevant investigations in Indonesia [10,12]. Since the energy consumption data were not available in both cities, the detailed interviews and measurement of appliance capacity by using watt checkers (MWC01, OSAKI) were conducted in order to obtain the data (Figure 2b). The material inventory data for refurbishment were also obtained during the same interviews.

(**a**) (**b**)

Figure 2. On-site measurements: (**a**) building material inventory; and (**b**) household energy consumption.

Previous studies showed that there are three main methods commonly used for the analysis of energy and environmental impacts, namely process-based, economic input–output (I-O) analysis-based, and hybrid-based methods [35]. Although it is impossible to trace all the processes unlike the process-based or the hybrid-based methods, this study adopted the I-O analysis-based method to calculate the embodied energy of households and estimate their CO_2 emissions, which consistently followed the method described by Nansai *et al.* [36]. This is because this method is considered more appropriate and effective under relatively poor data availability condition such as in Indonesia. The life cycle energy/CO_2 emissions were obtained by combining embodied energy/CO_2 emissions and operational energy/CO_2 emissions for respective house categories.

2.3.1. Embodied Energy

The procedure of the embodied energy analysis employed in this paper is as follows (see Figure 3). Firstly (Figure 3a), the combination of averaged fuel consumption in industrial and transportation sectors during 2014 based on the nationwide data [2] was calculated. Secondly (Figure 3b), the net contribution rate was determined by giving the figure 0 or 1 for each combination between the fuel type and the sectors indicated in the I-O table, in order to exclude fuel consumption that was converted into another fuel type or used as feedstock. Thirdly (Figure 3c), the Net Calorific Value (NCV) was obtained from IEA [37] and IPCC [38]. Then, fuel consumption was converted into calorific values through multiplying the gross fuel consumption by the net contribution rate and the said NCV for each fuel type in respective sectors.

The latest Indonesian nationwide I-O table published in 2005 [39] consisting of 175 by 175 sectors was used for calculating the embodied energy and CO_2 emissions. Meanwhile, the building material inventory data were investigated as described earlier. Each material was classified into domestic material and imported material respectively, based on the site observation. Then, fourthly (Figure 3d), embodied energy intensities for respective materials were calculated using the above I-O table. Embodied energy intensity is divided into two kinds. The first is imported embodied energy intensity and the second is domestic embodied energy intensity. The total embodied energy of respective houses was computed by combining all the energy consumption for respective building materials (combining initial, maintenance and recycling embodied energy).

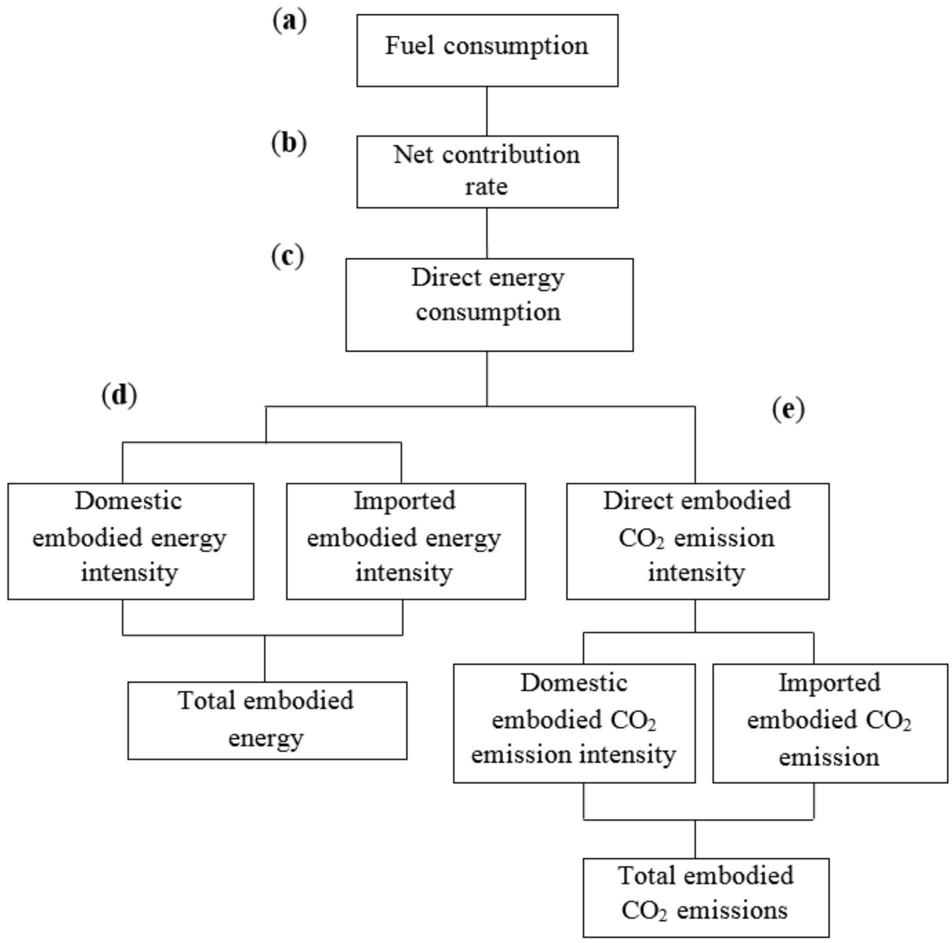


Figure 3. Flow chart of I-O analysis-based method for embodied energy. (**a**) Fuel consumption calculation, (**b**) determination of net contribution rate, (**c**) net calorific value, (**d**) embodied energy calculation and (**e**) embodied CO_2 emission calculation.

On the other hand, finally (Figure 3e), the CO_2 emissions caused by the embodied energy were estimated through multiplying the energy consumption for each fuel type by its corresponding CO_2 emission factor for Indonesia obtained from IEA [40] and IPCC [38] as shown in Table 3.

Table 3. Emission factors of energy sources for Indonesia.

Energy Sources	Emission Factor (kg/GJ)
Electricity	196.9 [40]
Coal	94.6 [38]
Oil	73.3 [38]
Natural gas	56.1 [38]
Kerosene	71.9 [38]
LPG	63.1 [38]

The CO_2 emissions released during the combustion of biomass were assumed to be balanced by the CO_2 removed from the atmosphere during growth of new biomass [41]. The total CO_2 emissions of respective houses were calculated by adding the emissions for each of the building materials.

The choice of energy resource is also important, as the type of fuel is crucial for the CO_2 emissions. This means that minimizing the final or purchased energy (secondary energy) does not automatically minimize the use of natural resource or the life cycle CO_2 emissions of a building.

2.3.2. Operational Energy

Energy consumption for respective household appliances was estimated through multiplying the number of appliances by their usage time and electric capacity, which were acquired through the interviews and measurements. The annual average household energy consumption was then calculated by combining consumption for all the appliances. As described earlier, the seasonal variation in climatic conditions is not large in Jakarta. Therefore, the usage time of appliances was assumed to be constant throughout the year. Nevertheless, the small seasonal changes of air temperature and humidity were considered in the estimation of energy consumption of air-conditioners and refrigerators, although the resultant changes were found to be negligible.

3. Results and Discussion

3.1. Embodied Energy

3.1.1. Current Material Stock and Future Demolition Waste in Urban Residential Buildings

Table 4 shows the composition of the current total building material input intensity (material input per unit gross floor area), including the materials used for maintenance, in the two cities. As shown, overall, the total material input intensity is 2.14 tons/m^2 in Jakarta and 2.06 tons/m^2 in Bandung. The average material intensity varies slightly among the different house categories in the two cities: 2.26, 2.06 and 2.05 tons/m^2 for simple, medium and luxurious houses in Jakarta, respectively, whereas the corresponding quantities are 1.88, 2.23 and 2.26 tons/m^2 for simple, medium and luxurious houses in Bandung, respectively. Overall, stone accounts for the largest percentage in Jakarta and Bandung (32% and 31%), followed by sand (31% and 30%), clay brick (19% and 19%), cement (8% and 8%), *etc*.

Table 4. Current building material inventory (unit: kg/m^2).

Materials	Density	Simple House		Medium House		Luxurious House		Whole Samples	
	(kg/m^3) [17]	J	B	J	B	J	B	J	B
1. Stone	1450	729.8	623.1	696.5	682.6	529.0	603.9	678.4	644.7
2. Sand	1400	717.5	561.0	623.1	674.4	583.8	740.2	655.3	626.8
3. Clay brick	950	494.9	371.7	309.2	414.0	413.3	451.2	407.4	397.7
4. Cement	1506	142.9	118.8	175.7	185.0	187.4	227.2	164.1	157.6
5. Wood	705	105.0	143.1	131.0	161.5	159.8	43.2	125.6	139.2
6. Ceramic tile	2500	30.8	15.5	33.9	34.2	59.5	77.4	37.5	30.0
7. Steel	7750	16.6	17.3	36.6	37.7	30.5	34.0	27.0	27.4
8. Clay roof	2300	16.6	20.7	40.9	30.2	0.0	0.0	22.8	22.2
9. Concrete roof	2500	0.0	0.0	0.0	0.0	49.9	39.2	9.6	4.4
10. Paint	700	2.0	1.6	5.4	4.4	10.0	12.4	4.9	4.0
11. Gypsum	1100	0.0	0.3	7.0	1.3	23.0	24.4	7.1	3.4

Table 4. *Cont.*

Materials	Density	Simple House		Medium House		Luxurious House		Whole Samples	
	(kg/m^3) [17]	J	B	J	B	J	B	J	B
12. Asbestos roof	2200	5.6	0.6	2.1	0.3	0.3	0.0	3.2	0.4
13. Clear glass	2579	0.8	1.2	0.8	1.3	1.3	6.2	0.9	1.8
14. Concrete brick	2300	0.0	7.5	0.0	0.0	0.0	0.0	0.0	3.6
15. Zinc roof	3330	1.2	0.8	0.1	0.1	0.0	0.0	0.5	0.4
Total		2263.7	1883.2	2062.3	2227.0	2047.8	2259.3	2144.3	2063.6

J: Jakarta; B: Bandung.

3.1.2. Scenario Analysis: Policy Effects of Promoting Reused/Recycled Material Use on Reduction of Building Waste and Embodied Energy/CO_2 Emissions

Scenario 1: Zero Reusing and Recycling Rates

Using the data of Jakarta as an example, the total flow of building materials in each type of houses is analyzed. The analysis also deals with the material flows of the current individual houses (excluding houses that will be newly constructed by 2020). As described previously, we assessed the effects of policy promoting reused and recycled material use through a scenario analysis. In this scenario (Scenario 1), the zero reusing/recycling rates were applied to all building materials used for individual houses. Figure 4a shows the results of flow analysis for the total material input and output of individual houses in Jakarta utilizing zero reuse/recycling rates for all houses (simple (75%), medium (20%), and luxurious houses (5%)). The total material inputs, including those for maintenance, for the respective house categories ("B" in the figures) are derived by using material input intensities shown in Table 2. A few materials are imported, such as ceramics (699.4 tons) in the case of luxurious houses. There are no materials reused/recycled for other buildings or other products ("E" and "F") in this scenario. Thus, all of the materials of the demolished houses until 2020 go to landfills. As described before, the demolition ratios for simple, medium and luxurious houses by 2020 were assumed to be 64%, 38% and 7%, respectively. As a consequence, the total amount of waste sent to landfills account for approximately 97.0, 29.1, 2.2 and 128.3 million tons for simple, medium and luxurious houses, and all houses, respectively ("G"), after the additions of soil derived from the surplus soil extracted in the construction phase ("C"). Overall, mortar (sand and cement) accounts for the largest proportion of material waste (24%), followed by soil (20%), stone foundation (18%), clay brick (16%) and concrete (sand, cement and gravel stone) (13%).

Scenario 2: Maximum Reusing and Recycling Rates

In this scenario (Scenario 2), we applied the maximum potential reusing/recycling rates (see Table 2). Figure 4b shows the results of the flow analysis of building material inputs and outputs for individual houses in Jakarta in Scenario 2 for the respective house categories. As shown, the total material inputs, including those for maintenance, for the respective houses in Jakarta are still the same as those in Scenario 1 ("B" in the figures). However, some materials (approximately 20.9, 5.4, 0.4 and 26.7 million tons) are reused for other buildings ("E"), whereas several materials (approximately 16.3, 4.5, 0.4 and 21.2

million tons) are recycled ("F"). The remaining reclaimed wood waste is composted/burned. As shown, overall, a total of 47.9 million tons of materials can be reused/recycled in closed-loop flows, consisting of stone (foundation and gravel stones) (49%), clay brick (39%), wood (8%), clay roof and gypsum (2.6%), *etc*. Most of the remaining materials (soil, mortar, concrete and ceramic, *etc*.) are assumed to be reclaimed for other products or infrastructure. The total amount of waste used for reclamation accounts for approximately 57.1, 18.2, 1.4 and 76.7 million tons for simple, medium and luxurious houses, and all houses, respectively ("H"). Overall, mortar accounts for the largest proportion of material waste (39%), followed by soil (34%), concrete (22%) and ceramic tile (2%). These materials cannot be reused/recycled for other building constructions due to the difficulty of separating them from mixed materials. Thus, it is observed that a closed-loop material flow is not sufficient to fully reclaim building materials and eliminate building material waste sent to landfills. Nevertheless, as explained above, these materials can be reused/recycled by crushing them and reclaimed for building infrastructure such as roads and for creating materials for building sites. In this case, the total waste sent to landfills would become very small (2.15 million tons in total) ("G"). This amount (2.15 million tons) is expected to fall within the capacity of the newly planned landfill of Jakarta (*i.e.*, Jatiwaringin and Bekasi), which is reported as 4.1 million tons in total [42].

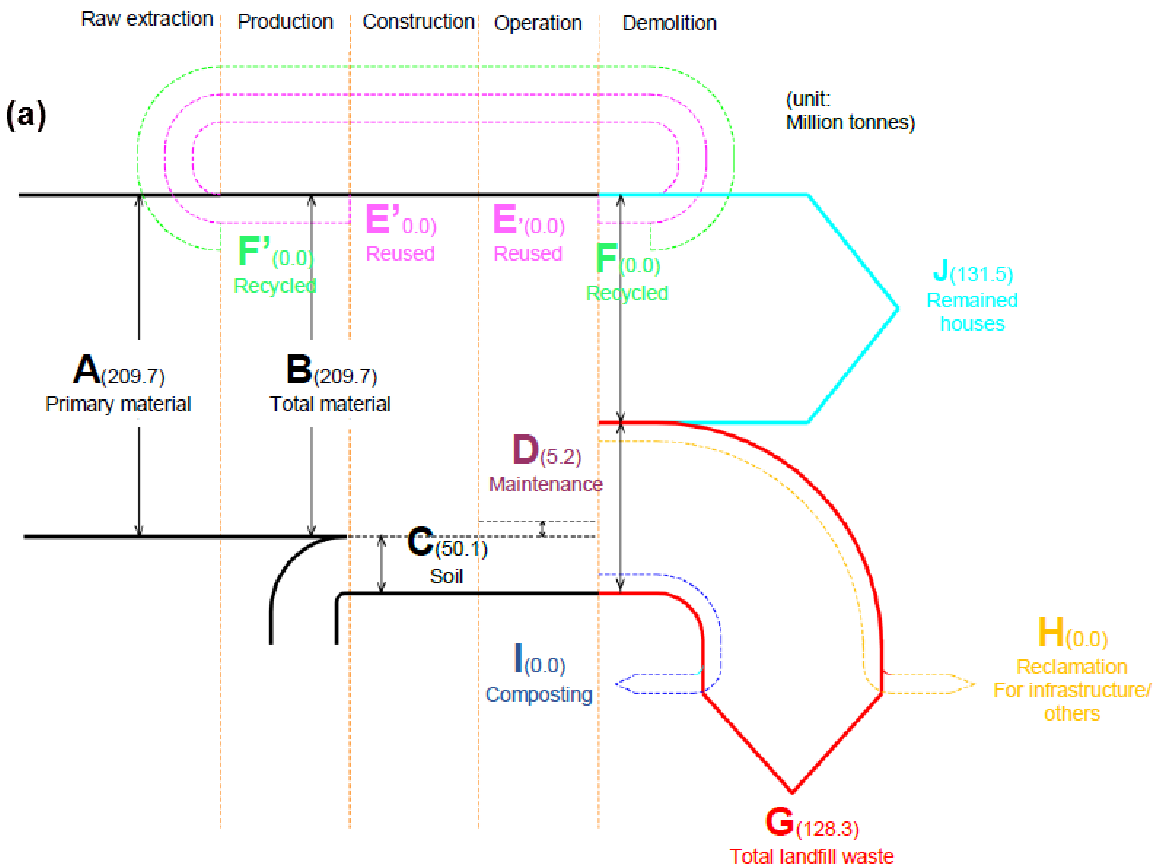


Figure 4. *Cont.*

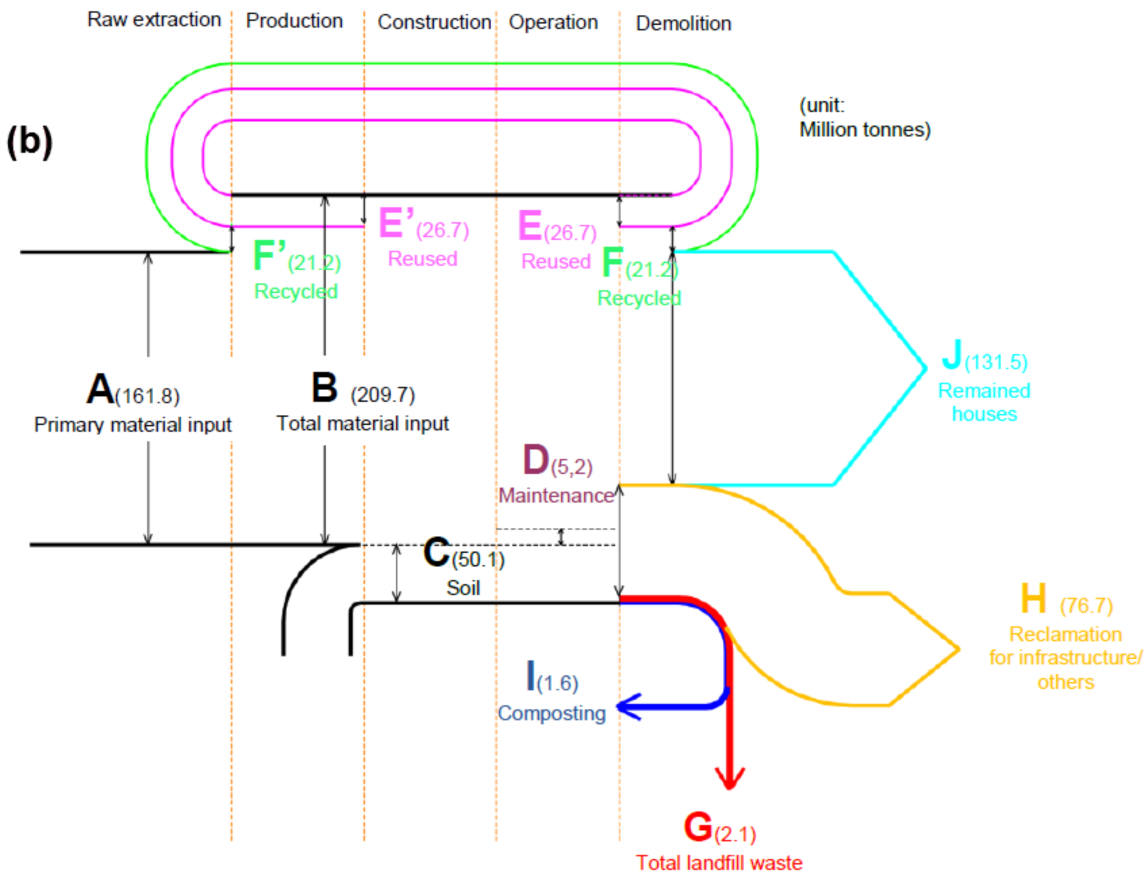


Figure 4. Flow of building materials for individual houses in Jakarta by 2020 (all houses): (**a**) Scenario 1 and (**b**) Scenario 2.

Figure 5 shows the average material waste for the respective house types for both scenarios. As shown, maximizing the reusing/recycling rates would decrease the average material waste dramatically by approximately 41% for simple house, 37% for medium house and 40% for luxurious houses.

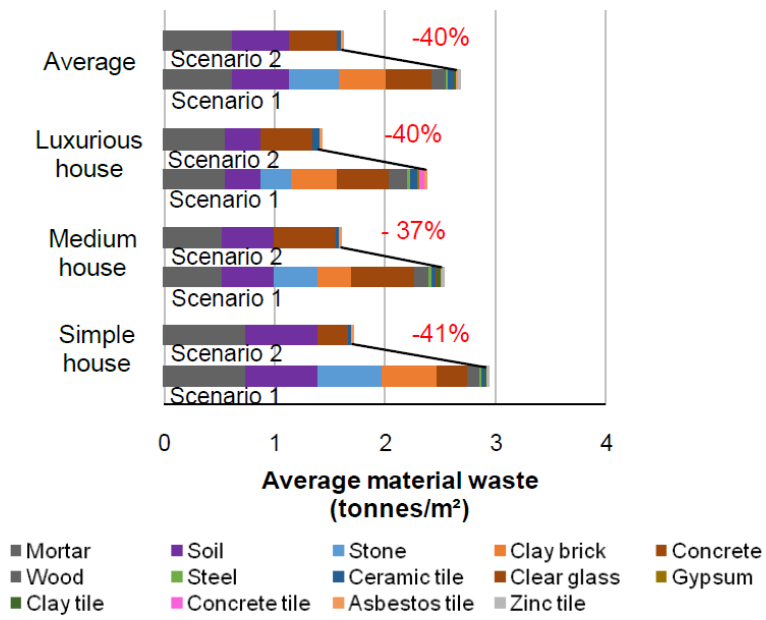


Figure 5. Average material waste.

The results of total embodied energy show that, if reusing and recycling rates was assumed to be zero, the averaged embodied energy for simple (54.5 GJ), medium (189.8 GJ) and luxurious (608.1 GJ) houses in Bandung was larger than that for houses in Jakarta (48.0, 178.3, and 438.8 GJ, respectively). Figure 6 shows the total embodied energy for the two scenarios considered (*i.e.*, zero and maximum reusing and recycling rates). The results indicate that not only do reusing and recycling materials reduce the amount of material waste generated they also diminish embodied energy. The maximum reusing/recycling rates are expected to decrease embodied energy by approximately 15.8 (33%), 47.8 (27%), 43.8 (10%) and 36.3 GJ (16%) for simple, medium and luxurious houses, and all houses, respectively (Figure 6). This scenario analysis proves that the promotion of reusing/recycling is important to reduce not only building material inputs/waste but also their corresponding embodied energy.

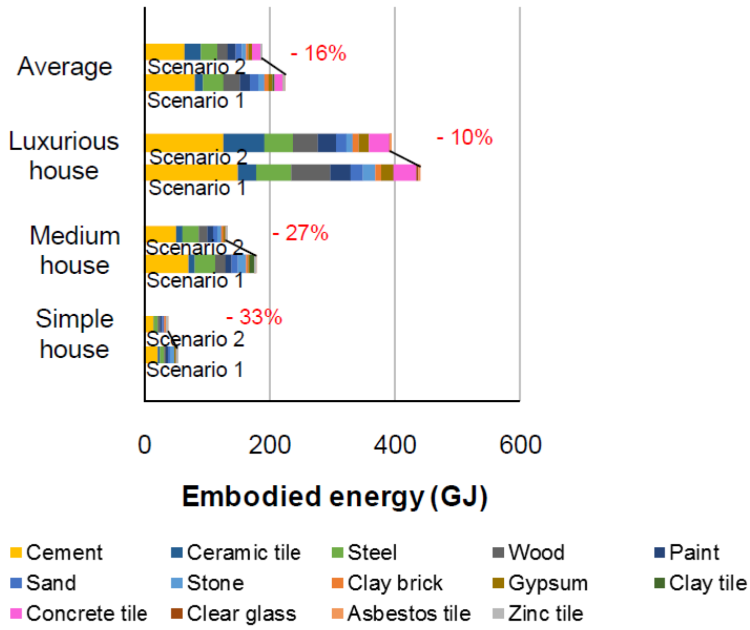


Figure 6. Embodied energy.

3.2. Operational Energy

Figure 7 presents the ownership levels of major household appliances in respective case studies. As shown, light bulbs (100%), televisions (96%–100%) and refrigerators (72%–100%) recorded high ownership levels similarly in the two cities among three house categories. In the case of Jakarta (Figure 7(1)), standing fans also recorded high ownership levels of 75%–83% reflecting the severe hot climatic condition of the city. In general, the ownership levels of other appliances increase from simple to luxurious houses, respectively. The ownership level of air-conditioners significantly differs between the two cities: it is 6%–89% in Jakarta and 0%–29% in Bandung depending on house types.

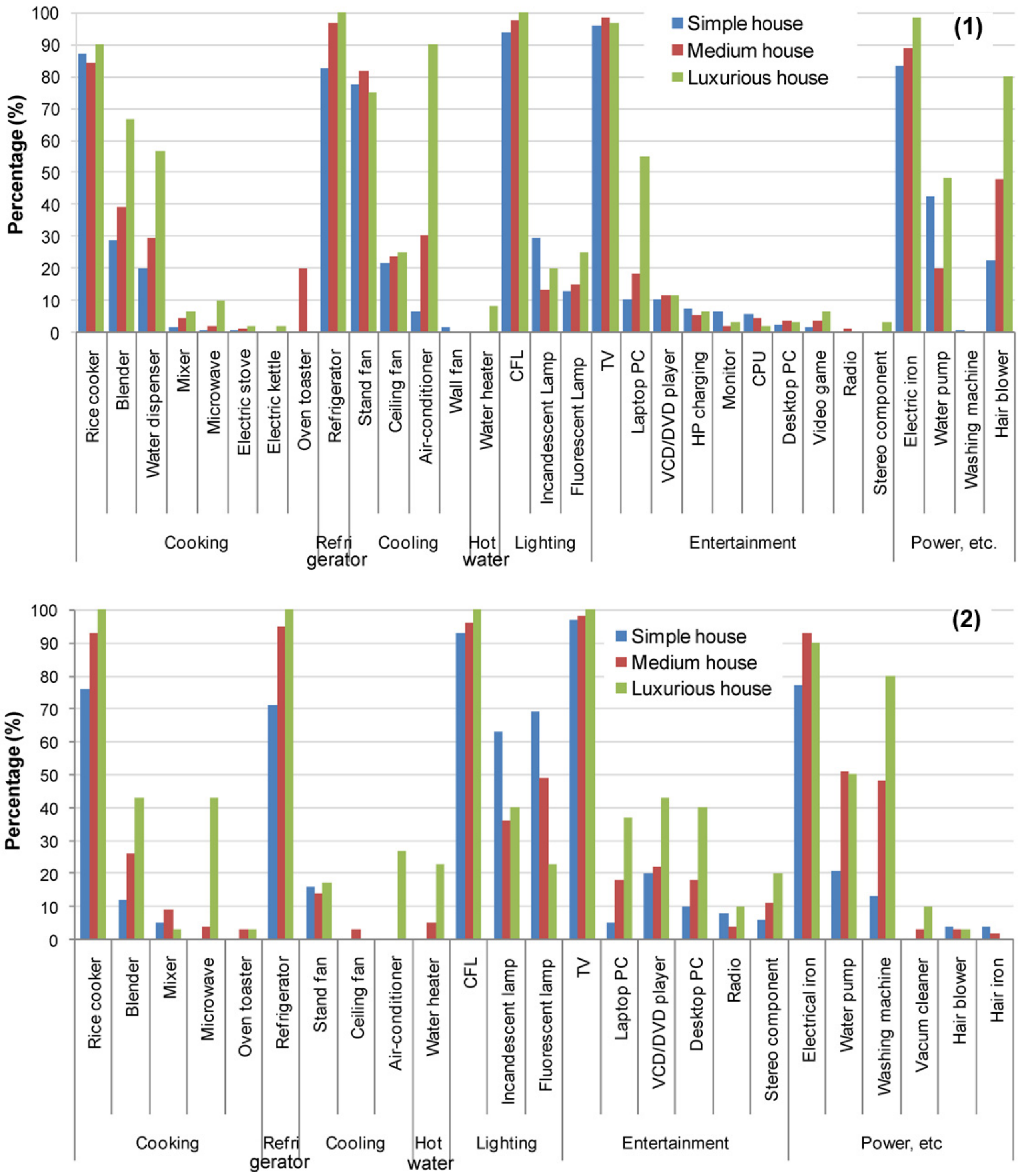


Figure 7. Ownership level of appliances in (**1**) Jakarta and (**2**) Bandung.

Figure 8 shows the annual household energy consumption averaged in respective house categories. Figure 8a indicates the energy consumption by different energy sources and Figure 8b shows those by different end-use categories. Overall, the average annual energy consumption of all samples in Jakarta is approximately 20.6 GJ, which is 5.0 GJ larger than that of Bandung (15.6 GJ). The difference is mainly attributed to the use of air-conditioning between the two cities. As shown, the energy consumption for cooling accounts for 27.8% in Jakarta on average (Figure 8(1b)), whereas the corresponding percentage is only 1.8% in Bandung (Figure 8(2b)). Hence, in the case of Jakarta, basically, the average household energy consumption of house categories increases with the increase in ownership and use of air-conditioning and the entertainment largely influences the increase in the overall energy consumption (Figure 8(2b)). Since the average household size did not vary largely among the three house categories, the above difference of ownership and usage levels of cooling appliances in Jakarta, especially air-conditioner, and those of cooking and lighting in Bandung is directly reflected in the large difference of annual energy consumption among three house categories in both cities. Energy consumption caused by electricity use is larger than by LPG: 61%–73% in Jakarta (Figure 8(1a)) and 47%–65% in Bandung (Figure 8(2a)).

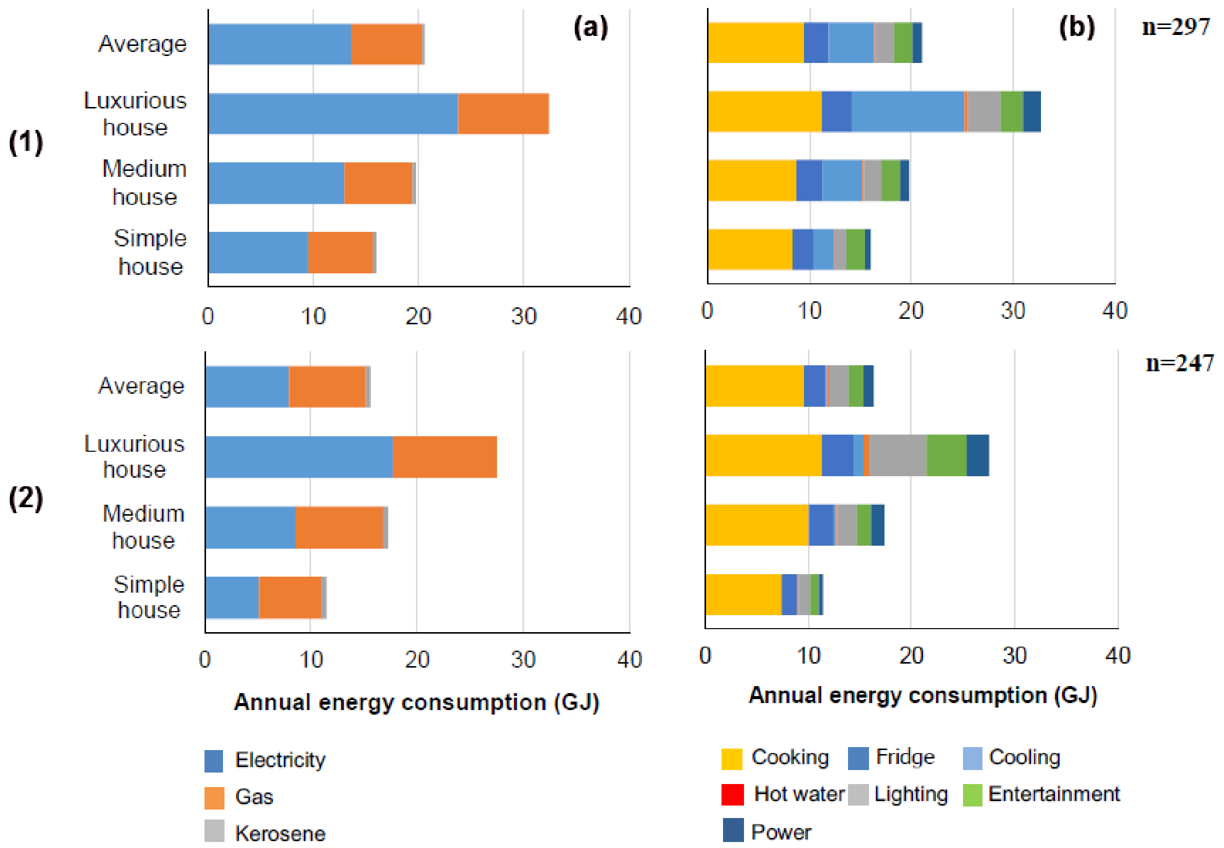


Figure 8. Annual household energy consumption by house category in (**1**) Jakarta and (**2**) Bandung, (**a**) by energy source and (**b**) end use.

3.3. Life Cycle Energy and CO_2 Emissions

As shown in Figure 9, in the Scenario 1 (zero reusing and recycling rates), the annual operational energy accounted for much larger portions of about 79%–86% than embodied energy for houses in Jakarta (Figure 9(1a)). The total annual life cycle energy was measured at 18.6, 24.9 and 41.2 GJ for simple, medium and luxurious houses, respectively. Meanwhile, in the case of Bandung (Figure 9(2a)), the proportion of annual operational energy took about 69%–81% of total life cycle energy, which was measured at 14.1, 22.6 and 39.7 GJ for simple, medium and luxurious houses, respectively. The average of annual life cycle energy for individual houses in Jakarta is larger than that of Bandung. When the maximum reused and recycling rates were (Scenario 2) applied, the total annual life cycle energy slightly decreased to 18.1, 24.0 and 39.5 GJ for simple, medium and luxurious houses in Jakarta, respectively, and to 13.7, 21.8

and 38.8 GJ for simple, medium and luxurious houses in Bandung, respectively. Overall, the proportions of annual operational energy were changed to 88%–94% and 75%–90% for houses in Jakarta and Bandung, respectively. The similar patterns are seen in the case of per-person life cycle energy (Figure 9(1b–2b)).

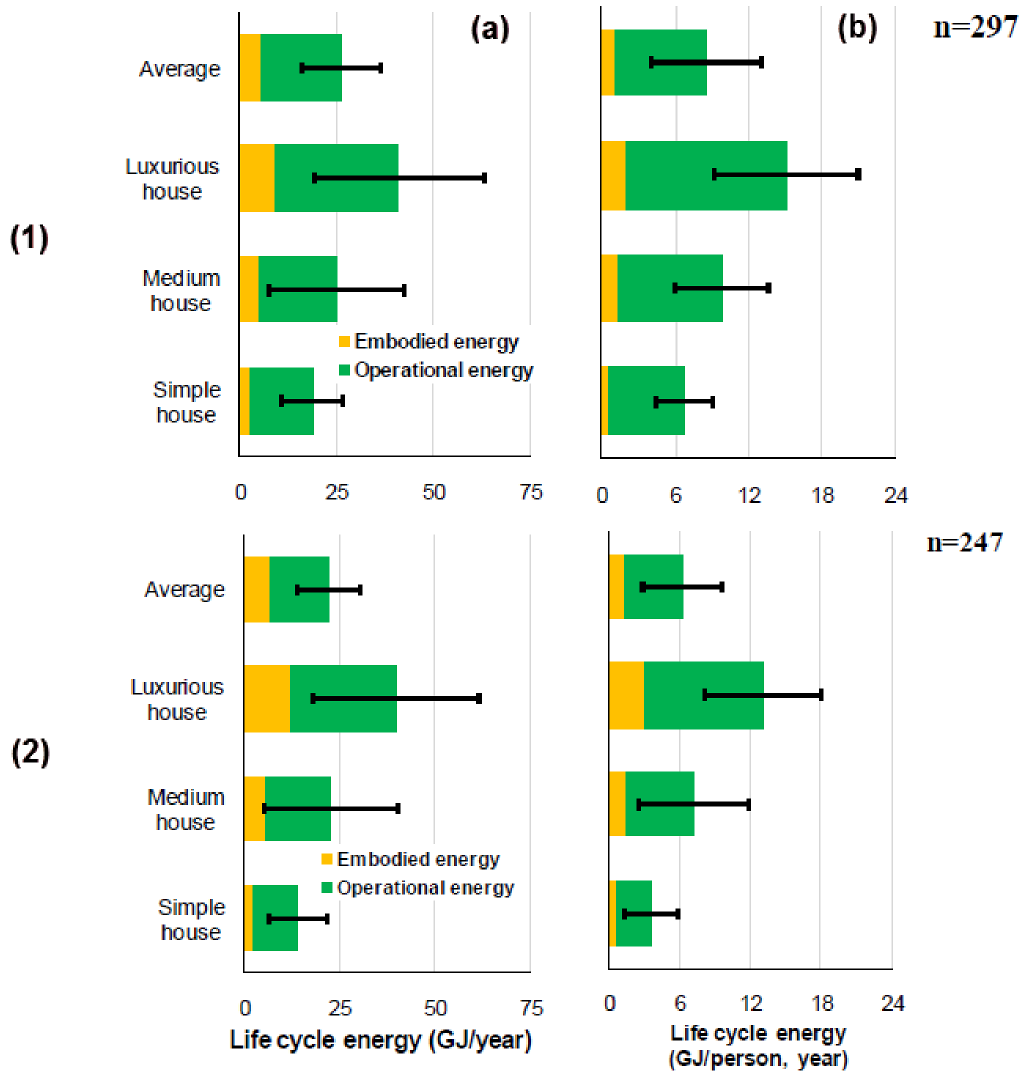


Figure 9. Average annual life cycle energy for respective house categories in (**1**) Jakarta and (**2**) Bandung for Scenario 1. (**a**) Total life cycle energy and (**b**) unit life cycle energy (per person). Note: The error bars indicate the mean values ± standard deviation.

The large differences among three house categories are due to the following two reasons. Firstly, as previously stated, the embodied energy increased with house category from simple to luxurious houses along with the increase in total floor area. Secondly, the per-person annual energy consumption increased with house category mainly due to the increase in energy consumption for cooling in the case of Jakarta and for lighting in the case of Bandung.

As shown in Figure 10, the CO_2 emissions during operation phase were larger than the embodied CO_2 emissions by six to eight times for Scenario 1 in three house categories in Jakarta. The estimated total annual life cycle CO_2 emissions were 2.6, 3.5 and 6.2 tons CO_2-eq for simple, medium, and luxurious houses, respectively. Meanwhile, in the case of Bandung, the CO_2 emissions during operation phase were larger than the embodied CO_2 emissions by four to five times for Scenario 1 in three house categories. The profiles of average life cycle CO_2 emission were similar to those of the average life cycle energy in Jakarta and Bandung, respectively.

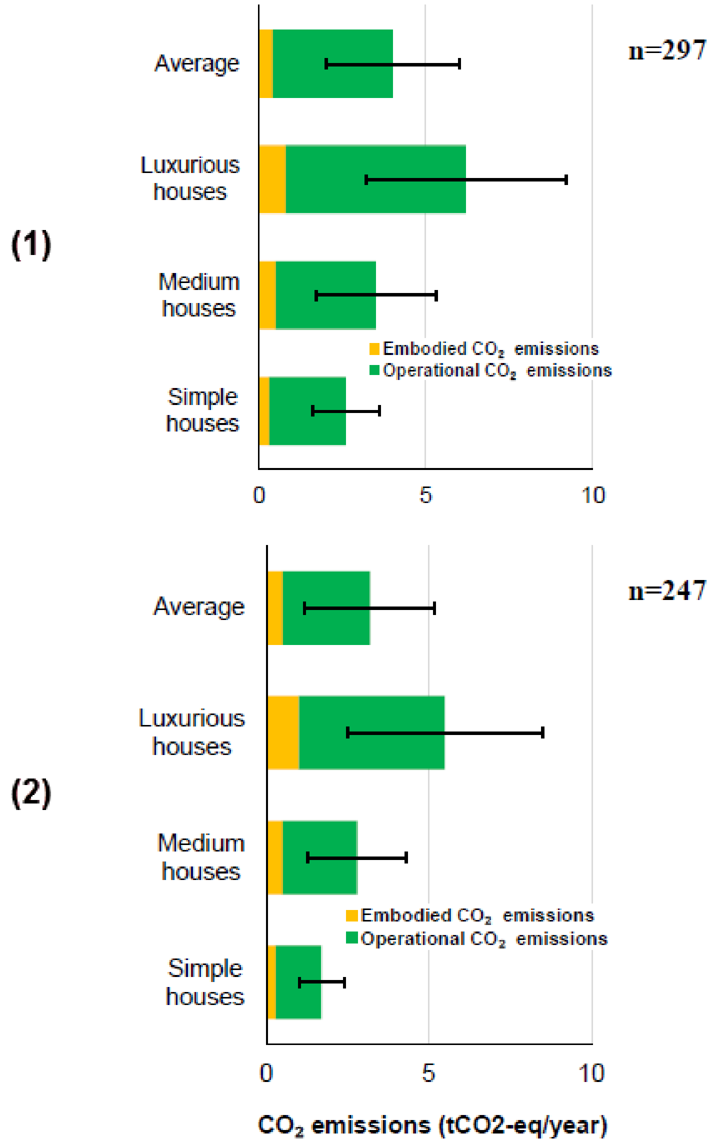
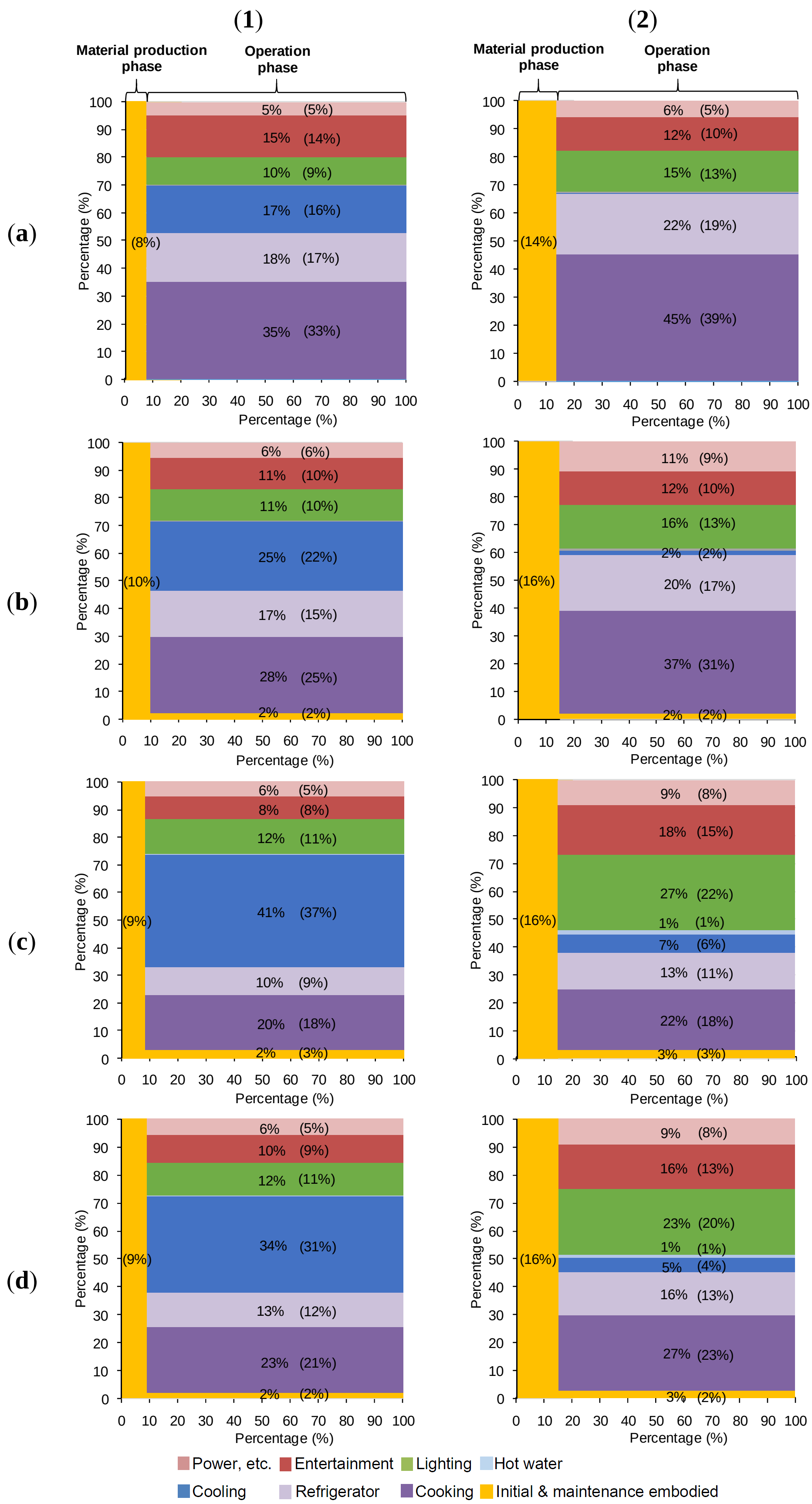


Figure 10. Average annual life cycle CO_2 emissions for respective house categories in (**1**) Jakarta and (**2**) Bandung for Scenario 1.

Figure 11 shows the contribution ratios in life cycle CO_2 emissions by respective end-uses in three house categories in Jakarta and Bandung when reusing and recycling rates are zero (Scenario 1). In the simple houses of Jakarta (Figure 11(1a)), cooking was the largest contributor to the CO_2 emissions (33% out of the whole life cycle), followed by the refrigerator (17%), cooling (16%), *etc.* Meanwhile, the percentage of CO_2 emissions caused by cooling increased with house category and became the largest contributor in the luxurious houses (37%) (Figure 11(1a–d)). Overall, cooling contributed the largest CO_2 emissions (31%), followed by cooking (21%), refrigerator (12%), *etc.* It is important to reduce the use of air-conditioning in the future despite the expected increase in household income. Passive cooling techniques should be adopted wherever possible.


(1)
(2)
Material production phase
Operation phase
(a)
(b)
(c)
(d)
Percentage (%)
5% (5%)
15% (14%)
10% (9%)
17% (16%)
(8%)
18% (17%)
35% (33%)
6% (5%)
12% (10%)
15% (13%)
(14%)
22% (19%)
45% (39%)
6% (6%)
11% (10%)
11% (10%)
25% (22%)
(10%)
17% (15%)
28% (25%)
2% (2%)
11% (9%)
12% (10%)
16% (13%)
2% (2%)
(16%)
20% (17%)
37% (31%)
2% (2%)
6% (5%)
8% (8%)
12% (11%)
41% (37%)
(9%)
10% (9%)
20% (18%)
2% (3%)
9% (8%)
18% (15%)
27% (22%)
(16%)
1% (1%)
7% (6%)
13% (11%)
22% (18%)
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6% (5%)
10% (9%)
12% (11%)
34% (31%)
(9%)
13% (12%)
23% (21%)
2% (2%)
9% (8%)
16% (13%)
23% (20%)
(16%)
1% (1%)
5% (4%)
16% (13%)
27% (23%)
3% (2%)
Power, etc.
Entertainment
Lighting
Hot water
Cooling
Refrigerator
Cooking
Initial & maintenance embodied

Figure 11. Contribution to CO_2 emissions by end-use in the whole building's lifespan for respective house categories in (**1**) Jakarta and (**2**) Bandung for Scenario 1: (**a**) simple house; (**b**) medium house; (**c**) luxurious house; and (**d**) whole sample. Note: The percentages in the parentheses show the contribution to CO_2 emissions by end-use in the whole building's lifespan.

Meanwhile, as shown in Figure 11(2a–d), in the simple houses of Bandung, cooking was the largest contributor to the CO_2 emissions (39% out of the whole life cycle), followed by the refrigerator (19%), lighting (13%), *etc.* Meanwhile, the percentage of CO_2 emissions caused by lighting increased with house category largely and became the largest contributor in the luxurious houses (22%). Therefore, further energy saving should be made for cooking by improving energy-efficiency (LPG and natural gas) for cooking appliances and for lighting by utilizing more natural lighting or shifting existing lamps (compact fluorescent and incandescent) to light emitting diode (LED). Overall, energy consumption for cooking contributed the largest proportion (23%), followed by lighting (20%), refrigerator (13%), entertainment (13%), *etc.*

Life cycle distribution of energy consumption and CO_2 emissions are concentrated in the operational phase of building. In all measurements, operation accounted for more than 80% of inventoried CO_2 emissions. The optimization of operational phase performance should still be the primary emphasis for the design, until it is evident that there is significant shift in distribution of life cycle burdens. Material selection will become a more critical factor as non-renewable resources become scarcer. However, in this country, this is still a suggestion rather than a rule, and for the time being the differential balance of burdens between operations and materials means that focus should still be put onto operation phase improvements.

A major step in the environmental impact reduction of a building would be to improve the environmental performance of the energy system that services a building such as energy generation technologies. A shift to power generation technologies, which use fossil fuels in a cleaner and more efficient manner (e.g., more natural gas and hydrogen fuel cells) or use renewable power sources, would go a long way towards reducing environmental impact. While, currently, renewable power system are still cost prohibitive in many cases, the net energy ratio (electricity generated/total fossil fuel input) for wind, photovoltaic and biomass electricity generation systems are significantly better than any contemporary utility power systems [43,44]. Further these technologies are improving rapidly, costs are dropping and market share of renewable is increasing yearly. The implementation of renewable technologies would dramatically reduce the operation phase burden of a building.

4. Conclusions

Two case studies, which investigated embodied energy and household energy consumption profiles, in Bandung and Jakarta, were analyzed in order to identify the profiles of life cycle energy and CO_2 emissions in major cities of Indonesia for respective phases of the building life cycle; *i.e.*, production and operation phases.

The total material input intensity was 2.14 tons/m^2 in Jakarta and 2.06 tons/m^2 in Bandung. The average embodied energy was estimated based on two scenario analyses. In Scenario 1 (zero reusing and recycling rates), the embodied energy for simple (54.5 GJ), medium (189.8 GJ) and luxurious (611.8 GJ) houses in Bandung was larger than that for houses in Jakarta (48.0, 178.3, and 438.8 GJ, respectively). The average embodied energy decreased by 10%–33% for respective house categories when the maximum reusing and recycling rates were applied. Several materials with high replacement rates also had high material production energy intensities. More frequent renovations during the life span of building could quickly raise the total embodied energy and shift the life cycle distribution balance. Design strategies that maximize service life of building materials should be emphasized.

The average annual energy consumption of all samples in Jakarta was approximately 20.6 GJ, which was 5.0 GJ larger than that of Bandung. The difference was mainly attributed to the use of air-conditioning between the two cities. Hence, in the case of Jakarta, basically, the average household energy consumption increased with the increase in ownership and use of air-conditioning. Meanwhile, in the case of Bandung, the energy consumption for cooking, lighting and entertainment largely influenced the increase in the overall energy consumption.

The operational energy of house categories in Jakarta and Bandung accounted for 79 to 86 % and 69% to 81% of total life cycle energy, respectively. The contribution to CO_2 emissions by end-use during each phase for respective house categories showed that cooling was the largest contributor to the CO_2 emissions in the medium (22%) and luxurious houses (37%) in Jakarta. Meanwhile, lighting was the largest contributor to the CO_2 emissions in the luxurious houses (22%) in Bandung.

In conclusion, reducing the demand for operational energy appears to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle. Embodied energy should then be addressed in second instance. As regards to this subject, there is a potential for reducing embodied energy requirements through recycling and reusing. Even though in this paper, buildings' life cycle was defined from construction to demolition, to widen the boundaries of analysis, including the recycling phase would offer a means to include that potential.

Recycling is in fact not a new issue in Indonesia. Both the formal sector and informal sector have been in this business already. However, these activities are not well-integrated yet and tend to be less sustainable. A strong political will is needed from all parties, the waste generators, waste managers, as well as the other actors involved so far with waste, to solve the problems of waste together and in integration. Meanwhile, to reduce operational energy, besides adopting passive cooling techniques, the other option could be encouraging efficiency improvement of air-conditioner usage such as using better insulation, changing setting point temperature of air-conditioner, *etc.* to reduce energy consumption/CO_2 emissions caused by air-conditioner.

Finally, this case study's inventory still has remaining data gaps, which were filled through no-specific data sources such as actual life span of building. Further research is essential to document inventories for a variety of buildings with the goal of establishing a database with sufficient specific content to enable the compiling of an LCA of this detail during the design stage. It is also possible to broaden the scope of analysis beyond pure energy and emissions accounting, in order to directly address a set of specific environmental loads caused by buildings and their operation. Future LCA studies on buildings would benefit greatly from greater data availability and more well-developed impact categories in order to provide a more comprehensive picture of environmental performance in a wider range of impacts.

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Author Contributions

As the primary author, Usep Surahman principally carried out the study, performed most of the analyses, and wrote major parts of this paper. Tetsu Kubota supervised the whole process of the study and provided advice on the research scope, methodology and analysis. Osamu Higashi contributed to the literature review and methodology improvement.

Conflicts of Interest

The authors declare no conflict of interest.

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