Embodied versus operational energy in residential and commercial buildings: where should we focus?

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Abstract. We analyze 100 case studies, which were conducted in 23 countries, and contrast their data on embodied and operational energy in residential and commercial buildings. The case studies include conventional, retrofit, low-energy, passive, and net-zero energy buildings. The buildings have different lifetimes varying from 25 to 100 years. We calculate the estimated total Life Cycle Energy (LCE) as the sum of Embodied Energy (EE) and Operational Energy (OE). The LCE in the 100 case studies ranges from 50.8 to 1840 MJ/m\textsuperscript{2} per year. Our results show that operational energy significantly dominates the life cycle energy of the buildings by an average of 419 MJ/m\textsuperscript{2} per year and an average share of 72\%. The share of embodied energy increases with decreasing operational energy. However, the overall LCE decreases significantly when the operational energy decreases. Naturally, the assumptions on the lifetime of the buildings have a great impact on the LCE. We conclude that operational energy should be primarily reduced in order to decrease greenhouse gas emissions from the existing building stock because most of the buildings are already built and changes in the embodied energy are often obtained only through new construction or deep retrofit strategies. Depending on the strategy to decrease OE, the share of EE was found to show wide fluctuations within the case studies, ranging from 4\% up to 100\%. In addition, most of the operational energy consumption has been reported by using energy simulation tools. Only about 14\% of the case studies had metered operational energy data. In order to create more accurate data, metering of buildings should be considered in future case studies.

1. Introduction
Buildings are considered a major source of greenhouse gas (GHG) emissions stemming from energy consumption during construction, operation, and demolition. Nearly 40\% of energy-related Carbon dioxide (CO\textsubscript{2}) is emitted by buildings either directly via their operational energy (OE) or indirectly via the embodied energy (EE) \cite{1}. OE refers to the energy consumed during the lifetime of a building after the building is occupied, while EE denotes the energy consumed in order to produce and transport building materials and install them in buildings. EE also incorporates the energy consumed for renovation and demolition. As GHG contributes to climate change, emissions from the building stock have to be dramatically reduced to meet climate mitigation goals. The question addressed in this paper
is whether to focus the efforts on OE or EE to decrease overall energy consumption from buildings stock. Knowing that investigating the relationship between OE and EE is challenging due to the considerable number of involved parameters, we compared 100 case studies from 32 publications to assess buildings EE, OE and LCE consumptions. Since the case studies in the corpus have been conducted by diverse groups, the way the results therein are reported varies substantially, which makes it difficult to compare them.

2. Methodology

2.1. Data gathering + Pre-processing

We conducted the literature review using Google Scholar and searching with various keywords, i.e. EE, OE, LCE, and case study. After the literature review, we grouped the publications into three categories: 1) case study, 2) theory, and 3) literature review. Overall, we found 35 publications, discussing EE and OE for a single-case study or multiple-case studies [2]-[36]. We created an initial list of 223 individual case studies without regard to exclusion criteria from these 35 publications categorized as case study papers.

In order to minimize differences among the case studies, we normalized the gathered energy results per unit of area and time (MJ/m²·a). It is important to compare the results in the same unit; therefore, only the primary results were used to include the loss of production and the actual contribution of energy production to environment. Therefore, we excluded case studies if the energy results were not stated as ‘primary’ [34], [35], [36]. We converted the results to MJ if they were given in kWh. The LCEs of the buildings were discussed by year and in consideration of its entire lifetime in order to observe the impact of lifetime assumptions. EE was divided by building lifetime to distribute the energy consumption per year and to make them comparable with OE.

In this study, we did not consider the conditioned spaces as one of the boundaries for LCE. However, if the results were expressed as ‘per MJ or kWh’, then total conditioned area was used during the normalization process of EE and OE. The majority of the case studies present energy in either MJ/m² or MJ by including the area of conditioned spaces in the study.

Some studies have discussed different versions of the same buildings. To reduce the similarities between these cases, we only included the cases with the lowest/highest EE and OE intensity. We also made an assumption that the average lifetime of three cases is 50 years [8].

Moreover, when the results were not tabulated but presented in figures and graphs, we made an educated guess by extracting results from the figures and graphs; thus, there may be slight changes in the presentation of the results of those case studies.

The given OE results show differences in terms of their usage. For example, while some of the case studies provide the results concerning heating consumption, some were found to include the data on lighting, auxiliary, service hot water, and cooking. We supposed that the given OE represents the majority of use-phase consumption; therefore, the small contribution from other consumptions can be neglected. After these exclusion and data preprocessing, we obtained a final list of 100 case studies for further analysis, published between 2000 and 2018.

2.2. Overview of case studies

Building usage is not limited to residential occupancy although 86% of the cases are stated as residential buildings. The case studies span 23 different countries; therefore, no geographical and/or climatic filters were applied. Lifetime assumptions of the case studies ranges from 25 to 100 years with 50 years being the most frequent, and 41 out of 100 case studies have a lifetime between 55 and 65 years.

We categorized the buildings into conventional, retrofit, low energy building (Low-E), passive house (PH), and net-zero energy house (NZEB). These definitions are mainly made based on the definitions provided in the case studies. In the event that they were not defined as Low-E, PH and NZEB, we classified them as a conventional building, which has no additional energy conservation measures. The retrofit cases were designed to lower OE of conventional buildings.
56 cases were reported as initial EE while 41 of 100 as initial and recurring EE and only one case study as the sum of initial, recurring and demolition EE. Two case studies were found not to state the source of EE clearly. Since the biggest portion of EE is considered initial EE and most of the studies have neglected recurring and demolition EE, we considered every given result of EE as total EE. After the normalization of embodied and operational energy to MJ/m²a, LCE was calculated summing up the normalized EE and OE. In addition, the case studies were also discussed in terms of the way they had obtained the OE results and classified into four groups: simulated, metered, simulated and metered, and others, which refer to the case studies with different approaches to get OE consumptions rather than simulating and metering. The case studies show differences by country, climate, building usage, and source of OE data.

3. Results

Results show that the lowest LCE of NZEB was half the highest LCE of conventional buildings (Table 1). The average EE and OE show that the EE of the retrofit buildings increased by 22%, but overall its LCE decreased by 32%. The passive and NZEB buildings were revealed to have the highest increase in EE as seen in Table 1. The average LCE of the passive buildings is the highest among the other buildings. The increase in EE was observed to have a substantial impact on overall LCE of passive buildings. Retrofit and Low-E buildings were found to have almost similar LCE for the whole lifetime. The highest decrease of LCE was achieved by NZEB even though they had a rise of 77% in EE.

### Table 1. Average EE, OE and LCE for each building type

| # Case Study | Average EE [MJ/m²a] | Average OE [MJ/m²a] | Average LCE [MJ/m²] | %Change in Avg. EE | %Change in Avg. OE | %Change in Avg. LCE |
|--------------|---------------------|---------------------|---------------------|-------------------|-------------------|-------------------|
| Conventional | 44                  | 139                 | 569                 | 35,269            | 0%                | 0%                |
| Retrofit     | 26                  | 169                 | 372                 | 24,102            | 22%               | -35%              |
| Passive      | 12                  | 126                 | 258                 | 22,263            | -9%               | -55%              |
| NZEB         | 4                   | 258                 | 268                 | 17,476            | 86%               | -53%              |
| All Buildings| 100                 | 163                 | 419                 | 30,524            | 17%               | -26%              |

The share of EE generally varies between 4% and 77%, except for one case study with a share of 100% [14]. Low-E building category has the lowest share of EE, while passive building category has the highest share of EE. Conventional buildings have a share of EE between 4% and 52%. In the retrofit case studies, the share of EE occurred between 9% and 50%. The share of EE for the Low-E building and passive building ranged from 19% to 60%, and from 18 to 77%, respectively. Lastly, NZEB was found to have the highest EE share, i.e., 100%, in only one case, and to range from 39% to 100% for the others (Table 2).

### Table 2. The Share of EE and OE

| # Case Study | Minimum share of EE | Maximum share of EE |
|--------------|---------------------|---------------------|
| Conventional | 44                  | 4%                  |
| Retrofit     | 26                  | 9%                  |
| Low-E building| 14                 | 19%                 |
| Passive      | 12                  | 18%                 |
| NZEB         | 4                   | 39%                 |

We also performed a linear regression of LCE on OE for each category as shown Equation 1 and give the found coefficients in Table 1.

\[
OE = \alpha \ast LCE + \beta
\]

Eq. 1
We find that LCE and OE has a linear relationship with an average $R^2 = 0.895$ (Table 3). The buildings also were evaluated in the categorized format as shown in Table 1, we find that conventional, retrofit and low-E building have higher $R^2$ between 0.87-0.95 and dominate the overall average. Due to lower $R^2$ of passive and NZEB, it is more complicated to discuss the linearity between OE and LCE for those buildings. Additionally, the relationship between OE and LCE for NZEB was not reliable because of the limited number of the case studies ($n=4$, $R^2=0.521$).

Table 3. Relationship between OE and LCE

| # Case Study         | α     | β     | $R^2$ |
|----------------------|-------|-------|-------|
| Conventional 44      | 0.8251| -14.889| 0.953 |
| Retrofit 26          | 0.9465| +9.7240| 0.946 |
| Low-E building 14    | 0.6626| +3.5356| 0.870 |
| Passive 12           | 0.3793| +68.689| 0.640 |
| NZEB 4               | 0.5746| -101.570| 0.521 |
| All Buildings 100    | 0.7833| -37.099| 0.895 |

We compared operational and embodied energy of 100 case studies as a function of LCE, building definition and result type as seen in Figure 1.

![Figure 1. OE versus EE as a function of LCE, building definition and result type](image_url)
The results, shown in Figure 1, indicate that operational energy represents the dominant pattern in most of the case studies. The lifetime LCE ranges from 5,320 MJ/m$^2$ to 107,000 MJ/m$^2$. The average OE and EE were found to be 419 MJ/m$^2 \cdot a$ and 163.3 MJ/m$^2 \cdot a$, respectively. Based on the average OE and EE, the average share of EE is 28% for the 100 case studies.

The histogram distribution of EE and OE are asymmetrical and heavy-tailed between zero and the average of OE and EE. Figure 1 also shows that the majority of the data was obtained through various simulation programs, for 8 out of 100 case studies actual metering data was available, and six of them had both simulated and metered data.

4. Conclusion
The share of EE increases with the decreasing OE for most of the case studies. However, the overall LCE decreases with decreasing OE for discussed 100 case studies. Depending on the strategy to decrease OE, the share of EE shows wide fluctuations within the case studies, ranging from 4% up to 100%. Categorization of buildings shows that Low-E buildings not only has the lowest EE but also keeps OE lower than conventional building. Based on obtained results, it can be concluded that the primary concern should be retrofitting conventional buildings and decreasing CO$_2$ contribution due to the current building stock because most of the buildings are already built and changes in the EE are often obtained only through new construction or deep retrofit strategies. If retrofitting conventional building is not an option, then new constructions should be either low-E or NZEB in order to decrease overall LCE.

Additionally, only about 14% of the case studies yielded metered OE data. In order to create more accurate data, metering of buildings should be considered in future case studies. Therefore, decreasing OE should be primary focus to decrease greenhouse gas emissions from the existing building stock.

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