Lecture 19. Building Energy Use: Life Cycle Assessment

"Nearly all the definitions of sustainability that have circulated in recent years emphasize an ecological point of view—the notion that human society and economy are intimately connected to the natural environment."

— Jeremy L. Caradonna [4]

1 Overview

Energy used in buildings accounts for about 20% of the total delivered energy in the world [8]. One of the tools which is widely used for calculating energy and environmental performance from a broad perspective is **life cycle assessment (LCA)**, which is used to evaluate the material and energy inputs and outputs in different stages through the life cycle of a given system. A building consumes energy in three phases: pre-use (production of materials to construct the building), in-use (operation, renovation and maintenance), and post-use (demolition and/ or disposal) [3]. Life cycle assessment can be used for evaluating the not only energy use associated with a building, but for its life cycle cost and CO_2 footprint.

There are several potential methods to assess the environmental performance of different products or systems. LCA is a widely accepted methodology, and one of the most popular tools for calculating the environmental performance of specific products or systems [5]. LCA measures and analyzes energy flows and the material inputs and outputs of a system. LCA studies generally consist of four phases: [9]

1. The *goal and scope definition* phase requires understanding why the study is performed, how it is helpful, and who can take advantage of the resulting information.
2. The *life cycle inventory (LCI) analysis* is performed to collect the needed input data for the system of interest. The inventory depends on the specified system boundary and the ultimate goal of the study. Inputs to the system can include land use, water, energy consumption, CO_2 footprint, and cost. All the data for the subsequent phase should be accumulated.
3. The *impact assessment* phase of LCA uses inventory analysis to calculate the system outputs. The output of the system also depends on the specified system boundary and the ultimate goal of the study. The output will be the system's final life cycle energy, cost, water, or whatever resource is of concern.
4. *Interpretation of results* means the data from the inventory analysis and results from the impact assessment are taken together and interpreted to address the ultimate goal of the study. This phase assists the readers or recipients with drawing conclusions and making decisions consistent with the aims of the study.

Buildings use energy in several different forms during different phases of the building's life cycle: **embodied energy** (similar to embodied emissions or embodied water, as in Lecture 18); operational energy (used during the lifespan of a building for functions like lighting, HVAC, domestic hot water, plug loads and appliances, and many more); demolition energy (used to remove the structure from the building site and transport the materials to recycling and/or landfill sites) [3].

2 Methods for LCA

Embodied energy has been a particular challenge in calculating the building's life cycle energy [7]. For calculating embodied energy, three primary methods have been employed in the literature:

Process analysis is a commonly used method for calculating the building's life cycle energy:

the determination of the energy required by a process, and the energy required to provide inputs to the process, and the inputs to those processes, and so forth [14]

Input-output (IO) analysis is an economically-based method for calculating system inflows and outflows:

> a top-down economic technique that uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies. The result of generalized input-output analyses are *total factor multipliers*, which describe embodiments of production factors (such as labor, energy, resources, and pollutants) per unit of final consumption of commodities. [10]

Compared with process analysis, the main advantage of the input-output approach is its complete boundary. Input-output analysis works much like control volume analysis and therefore can provide a more complete accounting of what enters or exits a system. There are several indirect energy paths which are commonly not captured through process analysis alone; by using IO tables, all sectors can be included in the study.

Hybrid analysis is a combination of the two primary methods: process and input-out analyses. Three particular combinations are discussed by Suh and Huppes [11]:

Tiered hybrid in which for operation and disposal parts process analysis is used, and for construction part, important upstream paths are accounted using IO analysis

- *Tiered hybrid analysis* in which process analysis is used for the operational and disposal phases and IO analysis is used to account for important upstream paths in the construction phase. Other data are imported from an IO-based method for significant upstream processes [11]. A sequence of approximations will be used, starting with the simplest assumption [2]. "The first approximation is at the whole- economy level: the cost of a product is multiplied by the energy intensity per unit gross domestic product GDP" [1]. The second approximation begins by identifying major energy-paths of the product."The dis-aggregated parts of the product are categorized as either typical or atypical products of the existing IO sectors. The energy requirements of typical products can be determined directly from the I-O sector and energy use factors. The atypical products require further dis-aggregations and an iterative input-output approach" [1]. The embodied energy in the remaining atypical inputs to the product is estimated using energy/GDP ratio as an average energy intensity [2].
- *IO-based hybrid analysis* which is divided into four steps as proposed by Treloar et al. [13]:

  1. "Derive an input-output LCA model;
  2. Extract the most important pathways for the construction sector;
  3. Derive case specific LCA data for the building and its components; and
  4. Substitute the case-specific LCA data into the input-output model." [13]

  This is "an excellent method, particularly when process-based data are not available for all energy sectors" [6].
- *Integrated hybrid analysis*, a matrix notation approach in which the process-based system is represented in a technology matrix where "each column of the technology matrix is occupied by a vector of inputs and outputs per unit of operation time of each process, including the use and disposal phase" [12].

3 Variation in LCA results

LCA results vary for different cases and even for a single case which is solved by different methods. This is one of the most challenging problems in using LCA for complex systems like buildings. Dixit et al. discussed the most important reasons behind the variations in results [7]:

- System boundaries

  A full description of the system's boundary is often neglected in the literature.

- Methods of embodied energy analysis

  Each potential method for quantifying embodied energy has its own limitations, uncertainties, and potential for errors. Limitations in gathering data lead to incomplete results and some of the upstream stages may be missed.

- Geographic location of study area

  Case studies are solved in different countries with diverse economic systems, weather conditions, industries, and manufacturing technologies. These characteristics, as well as differences in collecting and presenting data, can make the results vary for each country.

- Primary energy vs. delivered energy

  Primary energy is defined as "the energy required from nature (for example, coal) embodied in the energy consumed by the purchaser (for example, electricity)" [7] and delivered energy (like 'site energy') as "the energy used by the consumer" [7]. Comparing results when the type of energy in the studies differs can be misleading.

- Age of data sources

  In each country, its economy, industries, and manufacturing processes are changing throughout the years. Therefore, data taken from sources of different ages will differ.

- Technology of manufacturing processes

  Different countries use different technologies and manufacturing processes. Usually technological changes make processes more efficient and less energy consuming. Embodied energy calculations for LCA rely on technologically representative data.

4 Software tools for LCA

There are many construction-related software tools and databases that attempt to provide standardized assessment models and inventory data at multiple scales. The scales range from industry-wide and sector-wide data down to product-and even brand-specific data. These include:

- U.S. Life Cycle Inventory Database by National Renewable Energy Laboratory (free):
  `https://www.nrel.gov/lci/`
- BEES (Building for Environmental and Economic Sustainability) by National Institute of Standards and Technology (free):
  `https://www.nist.gov/services-resources/software/bees`
- OpenLCA by GreenDelta (free and open source):
  `http://www.openlca.org/`
- ecoinvent Database by ecoinvest, Switzerland (paid):
  `https://www.ecoinvent.org/database/database.html`
- Inventory of Carbon and Energy (ICE) Database, created at University of Bath, UK (free):
  `http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html`
- SimaPro LCA software by LCA Consultants, Denmark (paid):
  `https://lca-net.com/simapro/`
- GaBi software by thinkstep, Germany (paid):
  `http://www.gabi-software.com/america/index/`
- One-Click LCA by Bionava Ltd. (paid):
  `https://www.oneclicklca.com/construction/life-cycle-assessment-software/`
- Athena LCA Software by Athena Sustainable Materials Institute (free):
  `http://www.athenasmi.org/our-software-data/overview/`

5 Urban-scale LCA

There are studies that have been conducted on LCA at larger scales (district, campus, neighborhood, city, state or nation). The most common approach in performing LCA on systems larger than a single building is using economic input-output related tables. These tables may be available for countries, states, and specific cities.

One common difficulty in performing LCA for a single building is the lack of reliable, detailed, and relevant inventory data, and when dealing with multiple buildings at neighborhood or city scale, this problem can become even more complex when different building types, other land use types, roadways, and transportation come into play. Uncertainties in the analysis may grow nonlinearly as buildings are aggregated.

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