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A life-cycle energy analysis of building materials in the Negev desert

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Abstract

Environmental quality has become increasingly affected by the built environment—as ultimately, buildings are responsible for the bulk of energy consumption and resultant atmospheric emissions in many countries. In recognizing this trend, research into building energy-efficiency has focused mainly on the energy required for a building's ongoing use, while the energy ''embodied'' in its production is often overlooked. Such an approach has led in recent years to strategies which improve a building's thermal performance, but which rely on high embodied-energy (EE) materials and products. Although assessment methods and databases have developed in recent years, the actual EE intensity for a given material may be highly dependent on local technologies and transportation distances. The objective of this study is to identify building materials which may optimize a building's energy requirements over its entire life cycle, by analyzing both embodied and operational energy consumption in a climatically responsive building in the Negev desert region of southern Israel—comparing its actual material composition with a number of possible alternatives. It was found that the embodied energy of the building accounts for some 60% of the overall life-cycle energy consumption, which could be reduced significantly by using ''alternative'' wall infill materials. The cumulative energy saved over a 50-year life cycle by this material substitution is on the order of 20%. While the studied wall systems (mass, insulation and finish materials) represent a significant portion of the initial EE of the building, the concrete structure (columns, beams, floor and ceiling slabs) on average constitutes about 50% of the building's pre-use phase energy.
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1. Introduction

World energy demand is projected to increase by up to 71% between 2003 and 2030 [1]. At present the vast majority of this energy consumption is based on fossil fuels, and despite notable advances in renewable energy technology, it is questionable whether such a demand trajectory can be met in an environmentally sustainable manner [2]. It has been proposed, then, that the only way to avoid a drastic reduction in accepted standards of living is to achieve an order-of-magnitude improvement in energy-*efficiency*, defined as the ratio between energy services provided and energy consumed [3].

1.1. Energy in Israel

As in other industrialized countries, energy consumption and CO_2 emissions in Israel have increased steadily over the past decades. The country obtains nearly all of its energy from imported fossil fuels [4], though it is unique in mandating the use of solar energy for water heating in all new residential buildings. Since the 1970s Israel's electrical power generation has been based primarily on coal [5] and the country also has sizeable deposits of oil shale [4].

Rapid population growth has resulted in overcrowding in the center of the country, causing a spill-over of construction to peripheral areas such as the Negev desert. The Negev comprises 65% of Israel's land area, but accommodates less than 8% of its population. Construction in the Negev typically requires longer transportation distances from Israel's commercial and industrial centers, increasing energy requirements for physical development. The harshness of the desert climate also affects energy consumption, due to the heavy heating and cooling loads in residential and commercial buildings. By and large, planning and design follow practices that are standard in the country's more temperate regions, and particular adaptation to local conditions is the exception rather than the rule [6].

The distribution of Israel's energy use among different sectors of the economy is representative of industrialized

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countries, where buildings account for a large fraction of the overall consumption: in the U.S., the combined residential and commercial building sectors account for approximately 40% of the total [7]. These sectors, however, only include the energy consumed *in* buildings during the period of their active usage. The share of energy used *by* buildings increases significantly when the energy used in their production is included as well.

1.2. Energy-efficiency in the life cycle of buildings

Any comprehensive assessment of architectural energy consumption must in fact consider the entire life cycle of the building, which can be divided into three phases: *pre-use phase* (embodied energy, EE), *use phase* (operational energy, OE) and *post-use phase* (demolition or possible recycling and reuse).

The intensity of energy consumption in the first of these phases – for the production of buildings and their components – has increased dramatically with industrialization. In contrast to traditional building practices based on locally available raw materials and human energy, modern methods have allowed vast quantities of fuel energy to be harnessed in the manufacture of standardized, quality-controlled building products. The high-temperature processes used to produce steel, aluminum, cement, glass and expanded foam insulation are prime examples.

Industrial technologies have also led to sharp increases in operational energy consumption, most notably with the advent and proliferation of air-conditioning. Efforts in recent decades to moderate the use of non-renewable energy for heating and cooling have led to significant savings through climatically responsive design approaches, including technological innovations for improving the thermal efficiency of the building envelope [8,9]. At the same time, however, technologies yielding solutions such as super-insulated walls and windows have contributed to operational energy-efficiency through the exploitation of high embodied-energy materials.

Therefore, strategies which reduce a building's energy needs for maintaining thermal comfort do not necessarily lower energy demand in the production phase, or in the overall life cycle. While reducing operational energy consumption has been a goal of designers for many years, embodied energy has received much less attention. There are several reasons for this, among them the lack of a clear assessment methodology and the data required to implement it, as well as a common assumption that the initial energy needed for production of a building is minor compared to its long-term operational needs. Some studies have indicated that this is indeed the case, citing figures in the range of 80% running energy to 20% embodied energy [10]. It is clear, however, that as operational energy use becomes lower, the role of embodied energy in minimizing overall consumption becomes increasingly prominent [10–13].

In recent years the methodologies for embodied-energy assessment have improved, as have the reliability and availability of data. One recent report [9] indicated that the embodied energy in an office building may be as much as 67 times its annual operational energy, though most studies show more modest ratios. Depending on the expected lifetime of the building and its energy-efficiency level for operation, the embodied energy typically represents between 10% and 60% of the total energy used during the lifetime of the building [2,14,15].

The choice of a given building material can have multiple effects on a building's energy consumption over the different phases of its life cycle, and as suggested previously, these effects can be contradictory—since properties such as high insulation value may yield relative savings in operational energy together with higher embodied-energy costs. The balance of these factors is especially significant since a building's external structure and envelope (roof, floor, walls and windows) tend to account for the greatest portion of its EE [16].

Often a range of different materials can be found to fulfill the same function in a building, and since their energy-efficiency may vary significantly, savings can be achieved through substitution. In some cases these savings arise from the use of renewable energy in the production process, and in others from the reuse or recycling of existing products.

Materials which incorporate industrial and consumer wastes (such as fly-ash concrete, recycled plastic lumber, etc.) can reduce both the depletion of natural resources and the pollution generated by disposal. These ''environmentally friendly'' materials are becoming more widespread [9], though it is crucial that their benefit be gauged within the larger life-cycle context.

To obtain a comprehensive picture of a product's whole-life environmental costs, a number of guidelines and draft standards have been developed in recent years. The process whereby the component and overall environmental flows in a system are quantified and evaluated is known as life-cycle assessment (LCA) [9]. It treats the life cycle of any product as a series of stages—from ''cradle'' (raw material extraction and harvesting), through manufacturing, packaging, transportation and use, to ''grave'' (disposal). While energy-related building regulations have begun to proliferate, life-cycle environmental assessments are still voluntary in almost all countries [17].

LCA studies generally consist of four phases, as set out in ISO Standard 14040 [18]: goal and scope definition, life-cycle inventory, impact assessment and interpretation.

These four steps of the LCA methodology can be applied specifically for life-cycle *energy* analysis (LCEA), which uses energy as the only measure of environmental impact. This does not replace the broader LCA environmental assessment method, but facilitates decision-making concerning energy-efficiency as an indicator of a building's overall resource efficiency [11,19].

1.3. Previous studies

Several recent studies have attempted to evaluate the environmental impacts of buildings in an integrated fashion over the entire life cycle. Adalberth [20] suggested an organized LCEA methodology, and showed an example of its application [21] in three prefabricated single-unit dwellings in Sweden. The LCEA methodology was applied in a variety of cases for evaluating energy flows in residential buildings, such

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