Transportation Energy Analysis for Single-Family Residential Construction in California

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Abstract

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Tyler Langley

Since the oil crisis of 1973, energy use in the United States of America has been a growing area of concern. Studies have shown that the construction industry is responsible for almost half of all annual energy consumption.\(^1\) With this awareness, the analysis of energy use within the related construction fields has become an emergent subject. One facet of construction energy use that has been less studied than others is that of the energy consumed in transporting building materials from manufacturing plants to construction sites. This thesis proposes a methodology for determining the energy consumed during the transportation of building materials to a construction site and applies this methodology to estimate the transportation component of the total energy consumed in the lifecycle of a residential building in California. Comparisons are then drawn among the embodied energy of the materials used in the construction of the building, the energy used to transport the materials and the products used in the on-site assembly of the building, and the energy consumed during the occupancy of the building.

The first chapter covers the intent of the thesis, as well as a categorization and explanation of the main areas of energy usage in the construction industry. This is followed by a delineation of the methodology used to research transportation energy. Chapter 2 details the development of the framework that is discussed in Chapter 1. This includes the unique problem areas of calculating transportation energy, the resulting parameters that focus the area of study, and the general

\(^1\) [http://www.architecture2030.org/current_situation/building_sector.html](http://www.architecture2030.org/current_situation/building_sector.html)
assumptions derived from those parameters. Chapter 3 is a case study of a single-family two-story house in northern California. First, the considerations and reasons for the choice are defined, establishing this as a representative residence for the area. The material choices and structural system choices are also discussed. Then, the framework introduced in Chapter 2 is applied in the case study. This introduces more case-specific problems in the types of calculations used for estimating transportation energy. Chapter 4 contains a summary of the findings as well as a reflection on the process followed by suggestions for future research and application for the subject of transportation energy usage. In this summary, it is shown that the energy used in transportation of materials to the site of the case study house amounts to 10.5 million Btu, which is roughly 2.5% of the embodied energy, and 21% of the occupational energy usage per year.
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Chapter 1: Introduction

Energy consumption in the construction industry varies greatly depending on the stage within the continuum of raw material extraction to post-construction occupancy. There are six definable stages of energy consumption in modern construction:

1. extraction of raw materials
2. refinement to usable materials
3. fabrication of components
4. transportation of usable materials and components
5. construction of the building
6. post-construction occupancy

The first stage is the extraction of raw materials, from mining to logging. This stage only addresses the energy needed to harvest the raw materials. The second stage and third stages include the refining of these raw materials as well as the fabrication of usable components. The total energy consumed in the first three stages is most commonly referred to as the “embodied energy” of a material. Stage four, the focus of this thesis, is the calculated energy used to move materials and components from their manufacturing site to the construction site. The transportation energy component must include all trips, whether a material travels directly from the manufacturer to the site or from the manufacturer to the distribution center to the site. The fifth stage of energy use includes the fuel required to move workers to and from the site as well as physical labor and any energy used by mostly electrical equipment. The sixth and final stage
is that of occupational energy (or operational energy) use. This includes the energy (usually electricity) used to either maintain the building’s functions or accommodate the activities of its occupants.

While all of these stages are basic to the total energy consumption of a building, occupational energy and embodied energy have received the most attention from the construction community. Since the aforementioned oil crisis in the 1970s, energy usage in the United States (U.S.) as a whole has been monitored by the U.S. Department of Energy (DoE). DoE has provided comprehensive data relating to energy use in a broad sense, and occupational energy is just one small part of that. However, for more specific statistics regarding average individual residential energy consumption, private companies and independent reports have more focused studies.

With regard to embodied energy, programs like the U.S. Green Building Council’s LEED (Leadership in Energy and Environmental Design) framework have enlightened the construction community to the importance of scrutiny in this area. Embodied energy figures also vary from study to study, as the procedures used in the manufacturing process of different materials are different in various locations.

The two remaining stages of energy usage, transportation energy and construction energy, have scarcely been studied. This may be due to at least two reasons. First, their contributions to the sum of energy use appear to be nominal. Fuel energy costs are small, and only apply to such a short temporal span whilst transporting materials/workers to the site. Construction equipment, as well, is only in use for a brief time in comparison to the lifetime of a building. Second, the complexity of determining construction energy and transportation energy far exceeds that of
embodied energy and occupational energy. Though it may be difficult to obtain statistics on the latter two, the calculations for each are fairly straightforward. Embodied energy can be calculated at various factories by simply computing the total energy used for the manufacturing of a number of parts and dividing it by the number of parts produced. However, more difficult is the calculation of the energy used during the extraction of the raw materials before any manufacturing has begun. This involves factors that are typically not well defined, such as climatic conditions, type of technology available, cost of labor, and the characteristic nature of raw material deposits. Occupational energy figures are readily available from energy suppliers. On the other hand, transportation energy and construction energy have a great number of interrelated sections, all of which are dependent on the type of construction, location of the construction site, and building materials as well as a number of other, project related components. While both of these stages of energy consumption are complex enough to warrant individual study, transportation energy has been selected as the subject of the research study presented in this thesis.

Thus, the intent of this thesis is threefold. First, the development of a general framework that takes into account the principal components relevant in calculating transportation energy for a building. Second, that framework is then applied to a normative theoretical case study. Lastly, the results of this study are compared to occupational energy costs and embodied energy costs in order to determine the proportionate magnitude of these energy use components.
Chapter 2: Development of Framework

As stated in Chapter 1, the first step in calculating transportation energy is the construction of a general framework that can be applied to a building. This framework must be flexible enough to be applied to buildings of different types in different locations, and, for the purpose of comparative analysis, specific enough to derive an energy usage estimate relatable to embodied energy and operational energy estimates. This chapter delineates the factors considered in the formulation of such a framework.

2.1 Materials

For different projects, correspondingly different construction materials are required. The type of construction determines the types of materials needed, and the location of the construction is a factor in selecting how each material type is procured. A high-rise office building in Los Angeles will use mostly steel and concrete, primarily coming from within the United States but with some materials imported. A small, single-family residence in the state of Washington would likely be of timber construction with most materials from within the state. Though these two examples are different in scope, the important factor in relationships to material transportation energy usage is the amount of each material needed for each respective project.

The quantity of materials dictates two factors. First, and directly relevant to the calculation of transportation energy usage, the quantity of materials must be taken into account when determining how much fuel is used. If X units of material M are needed, and transportation type
T can only carry $\frac{1}{2}X$ units of M, then 2 shipments of $\frac{1}{2}X$ units of M must be made for the full amount of M needed. If T requires F units of fuel, then 2T requires 2F units of fuel. The second use of material quantity is the calculation of the total embodied energy in all materials combined. This use, then, is for comparison analysis after the transportation energy figure has been determined.

There are three general methods available for calculating the quantity of materials used in a building construction project. The first method is applicable only to real-world projects, and requires the careful tabulation of all materials ordered for the construction of the building. For application to a theoretical project, or a project that cannot be analyzed from start to finish, however, such calculation is not an option. The second method is a meticulous virtual simulation of the project, followed by a counting of the individual elements in that simulation. Though potentially the most accurate approach for a theoretical or already built project, this is an exceptionally tedious process, even for small-scale buildings. The last method is an approximation of materials based on the various wall, roof, and floor assemblies in the project. For example: if wall assembly A is plywood on the outside and inside surfaces with wooden studs and insulation between, then the area that is made of assembly A can be summated, and the quantity of each element in that assembly can be determined. If wall assembly A covers 1,000 square feet of the building, then that results in 2,000 square feet of plywood on the outside and inside of the wall assembly. If the insulation-to-stud ratio is 88% to 12%, then the quantity of insulation by surface area is 88% of 1,000 square feet, and the quantity of studs by surface area is 12% of 1,000 square feet. More thorough calculations are detailed in Chapter 3, including the
process by which surface area can be used to approximate assembly materials that are of a linear nature (such as 2x4 studs).

2.2 Transportation

In determining the transportation energy usage of the construction materials, the most unique aspect is that of the transportation itself. The complexity of distribution networks and infrastructures produces a web of manifold alternatives. The first step in understanding the materials distribution network is a distillation of that network into its most elemental components. When modeling distribution routes, there are three essential types of nodes among which the transportation of materials is calculated:

1. The first node is the manufacturing site for each building material component. To ensure that transportation energy estimates do not overlap embodied energy estimates, it is important to determine at what point in the manufacturing process to start counting transportation paths. For example: including the path between a redwood grove and a lumber mill might cause redundancy with assumptions made in embodied energy data for Douglas Fir lumber. While it may be possible to investigate if the energy used in that path was included in the embodied energy figure, it is a reasonable simplification to assume that it was included, or that the quantity of energy is negligible, based on the typical proximity of lumber mills to lumber sources. In this case the first node would be the lumber mill, not the grove.
2. The second node is the distribution center. This is a particularly interesting element, as there can be a single distribution center, multiple centers, or even none. An example of a single distribution center is a local lumber yard. The lumber yard receives deliveries from lumber mills, and from there those deliveries are disseminated. An example of multiple distribution centers would be that of a shipment of gypsum board from China to North America. The gypsum boards are manufactured in China (the first node of the manufacturing site), transported to a shipyard on the California West Coast (the primary distribution center node) and then divided up and transported to various hardware stores (the secondary distribution center nodes). In other cases, especially for large projects, contractors may order shipments directly from manufacturers, requiring no intermediary distribution node.

3. The final node is the construction site. At this point, the transportation component of the materials is complete, and calculations regarding the fuel use of the preceding trips can commence.

The two major components in transportation are the distance traveled, and the fuel efficiency of the transportation modes. Using the simplified notion of nodes, calculating distances traveled between nodes is a fairly straightforward matter. Fuel efficiencies must be based on the modes of transportation used between the nodes, whether powered by coal, petroleum, or electricity. For example, if a shipment travels 300 miles, and has a fuel efficiency of 15 miles per gallon (mpg) of gasoline, then dividing the distance traveled by the mpg yields a consumption of 20 gallons of gasoline.
2.3 Material Transportation Energy

In calculating a figure for the transportation energy consumed by each material, the following steps are followed:

1. Quantify each material in the building. (2.1)
2. Calculate the distance traveled by each material. (2.2)
3. Determine the transportation type for each part of each material’s trips between nodes, as well as the fuel efficiency of those modes of transportation. (2.2)
4. Analyze the loading capacity of the modes of transportation, and calculate the quantity of that portion of this loading capacity for which the construction project is responsible.

Steps 1, 2, and 3 were discussed in the preceding sections of this chapter. Step 4 is the culmination of those three steps, and results in a quantifiable, relatable energy usage figure.
Example:

An apartment building project in Los Angeles County requires 1,500 sheets of gypsum board. The gypsum board is trucked from a source 400 miles away to the local supplier, and a fully loaded truck has an estimated mpg of 12, resulting in a total fuel consumption of 33.3 gallons. Assuming that shipments to the local source are of 1,000 sheets of gypsum board due to volume and weight limitations, the building project will require 1.5 shipments. The first shipment can be fully attributed to the project, using 33.3 gallons of fuel. Of the second shipment to the distribution center, only half is required for the project, so the fuel required must be prorated to reflect that portion only. This results in a total fuel usage of roughly 50 gallons (33.3 gallons for the full trip and 16.65 gallons for half of the second trip).

The last step in analyzing material transportation energy is concerned with unit of measurement conversions. In order to make comparisons among the stages of energy usage, all estimates must be in the same units of measurement. This requires that gallons of gasoline are converted to British Thermal Units (BTUs), or Kilowatt Hours (KwH), or whatever units the embodied energy and operational energy figures are calculated in.

2.4 Embodied Energy

Calculating embodied energy estimates requires existing data for each material included in the construction project, as well as the total quantities of those materials. At this point in the analysis, it is satisfactory to use the quantities of materials calculated in section 2.1 for calculating this figure. In working with embodied energy numbers, it is important to ensure that
all units correspond with each other. Many independent groups that work with embodied energy do that work in the metric system, and most materials in the U.S. are measured in American units.

2.5 Occupancy Energy Consumption

As stated in the introductory chapter, occupational energy statistics are available for most areas through independent research groups. It is also possible to go straight to utility companies such as Pacific Gas and Electric (PG&E) on the California West Coast to obtain statistical data. However, since the focus of this research study is on transportation energy, available data applicable to the consumption of energy during the occupancy of a residential building in California derived by other researchers and government agencies will be used for comparison purposes.
Chapter 3: Case Study

To test the framework presented in Chapter 2, a case study was undertaken. As the intent of this project is the analysis of material transportation energy use in the residential construction of California, it is important to select an example that is a reasonable representative of the residences of its area. In California, the majority of residences are single-unit, detached (56% of all residences in California as of the 2000 census\(^2\)). For further accuracy, the field of selection is narrowed to one of the predominantly suburban satellite-cities of one of California's major cities, San Francisco. These satellite-cities are also known as "bedroom communities" as the many people who work in San Francisco cannot all reside within the city limits and thus must commute to work from their homes in the outlying cities. For this project, the selected construction site is in the city of Novato, north of San Francisco.

3.1 House Selection

As is the case in most localities, residence sizes can vary greatly in the suburbs of Novato. Since land in this city is relatively cheap due to its distance from San Francisco, those who work in San Francisco but commute from their homes in Novato are more likely to purchase larger homes than those who work and live nearer the big city. Therefore, single-unit residences vary in size from 700 sq. ft. to 5,000 sq. ft., and the larger sizes are not uncommon. For the purpose of this project, however, a median house size of 2,500 sq. ft. is used.

House Renderings:

First Floor:

Floor (Insulated): 1,382 ft²

Garage/concrete slab: 470 ft²
Second Floor:

Floor (Uninsulated): 665 ft²

Total Floor Area: 2,517 ft²
3.2 Construction Assemblies

As described in section 2.1, one of the methods for calculating the quantity of materials in a housing project is to use estimates from the different construction assemblies used in the building. Given that the sample residence is wooden stick-frame construction with an American Southwestern aesthetic, the construction assemblies are as follows:

Wall Assemblies:

**Exterior (Insulated)**

- Stucco
- Metal lath
- Plywood
- Fir 2x4 studs @ 12%
- Plastic membrane
- Batt insulation (R-25) @ 88%
- Gypsum board (5/8 in)

**Exterior (Uninsulated)**

- Stucco
- Metal lath
- Plywood
- Fir 2x4 studs @ 12%
- Plastic membrane
- Gypsum board (5/8 in)

**Interior (Insulated)**

- Gypsum board (5/8 in)
- Fir 2x4 studs @ 12%
- Batt insulation (R-25) @ 88%
- Gypsum board (5/8 in)
Interior (Uninsulated)

- Gypsum board (5/8 in)
- Fir 2x4 studs @ 12%
- Gypsum board (5/8 in)

Floor Assemblies:

Insulated (First floor)

- Plywood
- Fir 2x10 @ 10%
- Batt insulation (R-22) @ 90%
- Plastic membrane
- Metal mesh

Uninsulated (Second floor)

- Plywood
- Fir 2x10 @ 10%
- Gypsum board (5/8 in)

Concrete slab (Garage)

- Concrete
- Reinforcing (1/2 in)

Roof Assemblies:

Insulated (Over living areas)

- Clay tile
- Building paper
- Plywood
- Batt insulation (R-30) @ 93%
- Fir 2x6 @ 7%
- Plastic membrane
- Gypsum board (1/2 in)
3.3 Material Estimations by Assembly

After establishing the contents of each construction assembly, it is possible to make estimates of material quantities using each assembly in conjunction with the surface areas of that assembly. There are four major steps involved in this method of quantification.

3.3.1 Material Components by Assembly

The first step is a listing of the construction materials and the assemblies in which each material component is used. Since some material components may be used in more than one construction assembly, it is helpful to construct a table [Table 3.3.1.1] that contains all related components and assemblies.
Table 3.3.1.1 Material Components by Assembly

<table>
<thead>
<tr>
<th>Material</th>
<th>Wall Exterior (Insulated)</th>
<th>Wall Exterior (Uninsulated)</th>
<th>Wall Interior (Insulated)</th>
<th>Wall Interior (Uninsulated)</th>
<th>Floor Insulated</th>
<th>Floor Uninsulated</th>
<th>Floor Concrete Slab</th>
<th>Roof Insulated</th>
<th>Roof Uninsulated</th>
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<tr>
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<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2x6 Fir</td>
<td></td>
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<td>X</td>
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<tr>
<td>5/8” Plywood</td>
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<td>X</td>
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<tr>
<td>5/8” Gypsum</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
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<td>R-22 Insulation</td>
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<tr>
<td>R-25 Insulation</td>
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<td>X</td>
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<td>Metal Lath</td>
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<td>Concrete</td>
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</table>

3.3.2 Assembly Surface Area Estimations

The second step is the surface area estimations for each construction assembly. For wall assemblies, these estimations can be easily calculated by measuring the length of the wall, multiplying that length by the height of the wall, then subtracting the area of any windows or doors in that wall. Because the walls of the case study house are of various heights, it is necessary to divide the walls into sections by height. These estimations are broken down by floor level [Table 3.3.2.1 and Table 3.3.2.2] for easier tabulation.
## Table 3.3.2.1  First Floor Wall Areas

<table>
<thead>
<tr>
<th>Section</th>
<th>Color</th>
<th>Wall Type</th>
<th>Wall Length (ft)</th>
<th>Wall Height (ft)</th>
<th>Wall Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Red</td>
<td>Ext. Insulated</td>
<td>57.5</td>
<td>14</td>
<td>805</td>
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<tr>
<td>2</td>
<td>Orange</td>
<td>Ext. Insulated</td>
<td>42.5</td>
<td>17.25</td>
<td>733</td>
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<tr>
<td>3</td>
<td>Yellow</td>
<td>Ext. Insulated</td>
<td>42.75</td>
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<td>342</td>
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<tr>
<td>4</td>
<td>Green</td>
<td>Ext. Uninsulated</td>
<td>68.25</td>
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<td>546</td>
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<tr>
<td>5</td>
<td>Cyan</td>
<td>Int. Insulated</td>
<td>28.25</td>
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<td>226</td>
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<td>Blue</td>
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<td>21.5</td>
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<td>7</td>
<td>Purple</td>
<td>Int. Uninsulated</td>
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Table 3.3.2.2  Second Floor Wall Areas

<table>
<thead>
<tr>
<th>Section</th>
<th>Color</th>
<th>Wall Type</th>
<th>Wall Length (ft)</th>
<th>Wall Height (ft)</th>
<th>Wall Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Red</td>
<td>Ext. Insulated</td>
<td>89.5</td>
<td>8</td>
<td>716</td>
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<td>9</td>
<td>Blue</td>
<td>Int. Uninsulated</td>
<td>72.25</td>
<td>8</td>
<td>578</td>
</tr>
<tr>
<td>10</td>
<td>Non.</td>
<td>Int. Uninsulated</td>
<td>28</td>
<td>3.25</td>
<td>91</td>
</tr>
</tbody>
</table>

In Table 3.3.2.2, section 10 (not pictured) is a small portion of wall above section 6 on the first floor that compensates for the change in wall height between section 1 and section 2. At this point, the final step in calculating the wall areas of different construction types is the subtraction of all openings from the walls [Table 3.3.2.3].
Table 3.3.2.3 Net Wall Area

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Section</th>
<th>Area (ft²)</th>
<th>Openings (ft²)</th>
<th>Net Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Insulated</td>
<td>1</td>
<td>805</td>
<td>87</td>
<td>718</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>733</td>
<td>154</td>
<td>579</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>342</td>
<td>47</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>716</td>
<td>42</td>
<td>674</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>2,266</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior Uninsulated</td>
<td>4</td>
<td>546</td>
<td>112</td>
<td>434</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>434</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior Insulated</td>
<td>5</td>
<td>226</td>
<td>18</td>
<td>208</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>208</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior Uninsulated</td>
<td>6</td>
<td>301</td>
<td>91</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>528</td>
<td>102</td>
<td>426</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>578</td>
<td>123</td>
<td>455</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>91</td>
<td>0</td>
<td>91</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1,182</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The floor and roof assembly calculations for this project are less complex than the wall assembly calculations, but for a larger project, it may be practical to make a new set of tables for those portions.

Floor Assemblies:
- Floor (Insulated) 1,382 ft²
- Floor (Uninsulated) 665 ft²
- Concrete Slab 470 ft²

Roof Assemblies:
- Roof (Insulated) 1,908 ft²
- Roof (Uninsulated) 406 ft²
3.3.3 Quantity of Materials by Surface Area

The third step is an estimation of the quantity of each material by the surface area of each assembly. At this point in the calculations, it is helpful to use Table 3.3.1.1 to account for the values of each assembly.

**Wood Elements (stud elements)**

<table>
<thead>
<tr>
<th>Wall Area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior (Insulated)</td>
<td>2,266 ft²</td>
</tr>
<tr>
<td>Exterior (Uninsulated)</td>
<td>434 ft²</td>
</tr>
<tr>
<td>Interior (Insulated)</td>
<td>208 ft²</td>
</tr>
<tr>
<td>Interior (Uninsulated)</td>
<td>1,182 ft²</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>4,090 ft²</td>
</tr>
<tr>
<td><strong>2x4@12%</strong></td>
<td>491 ft²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Floor Area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor (Insulated)</td>
<td>1,382 ft²</td>
</tr>
<tr>
<td>Floor (Uninsulated)</td>
<td>665 ft²</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>2,047 ft²</td>
</tr>
<tr>
<td><strong>2x10@10%</strong></td>
<td>205 ft²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Roof Area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated</td>
<td>1,908 ft²</td>
</tr>
<tr>
<td>Un-Insulated</td>
<td>406 ft²</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>2,314 ft²</td>
</tr>
<tr>
<td><strong>2x6@7%</strong></td>
<td>162 ft²</td>
</tr>
</tbody>
</table>
Wood Elements (plywood)

Wall Area
- Exterior (Insulated) 2,266 ft²
- Exterior (Uninsulated) 434 ft²

Floor Area
- Floor (Insulated) 1,382 ft²
- Floor (Uninsulated) 665 ft²

Roof Area
- Insulated 1,908 ft²
- Uninsulated 406 ft²

5/8 inch Plywood Total: 7,061 ft²

Gypsum Board

Wall Area
- Exterior (Insulated) 2,266 ft²
- Exterior (Un-Insulated) 434 ft²
- Interior (Insulated) Two-Sided 416 ft²
- Interior (Un-Insulated) Two-Sided 2,364 ft²

Floor Area
- Floor (Un-Insulated) 665 ft²

5/8 inch Gypsum Total: 6,145 ft²

Roof Area
- Insulated 1,908 ft²
- Un-Insulated 406 ft²

1/2 inch Gypsum Total: 2,314 ft²
## Insulation

<table>
<thead>
<tr>
<th>Area</th>
<th>Insulation Type</th>
<th>Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior (Insulated)</td>
<td></td>
<td>2,266 ft²</td>
</tr>
<tr>
<td>R-25 @ 88%</td>
<td></td>
<td>1,994 ft²</td>
</tr>
<tr>
<td>Floor Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor (Insulated)</td>
<td></td>
<td>1,382 ft²</td>
</tr>
<tr>
<td>R-22 @ 90%</td>
<td></td>
<td>1,244 ft²</td>
</tr>
<tr>
<td>Roof Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulated</td>
<td></td>
<td>1,908 ft²</td>
</tr>
<tr>
<td>R-30 @ 93%</td>
<td></td>
<td>1,774 ft²</td>
</tr>
</tbody>
</table>

## Clay Roofing Tile

<table>
<thead>
<tr>
<th>Area</th>
<th>Insulation Type</th>
<th>Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulated</td>
<td></td>
<td>1,908 ft²</td>
</tr>
<tr>
<td>Uninsulated</td>
<td></td>
<td>406 ft²</td>
</tr>
</tbody>
</table>

Total: 2,314 ft²

## Building Paper

<table>
<thead>
<tr>
<th>Area</th>
<th>Insulation Type</th>
<th>Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulated</td>
<td></td>
<td>1,908 ft²</td>
</tr>
<tr>
<td>Uninsulated</td>
<td></td>
<td>406 ft²</td>
</tr>
</tbody>
</table>

Total: 2,314 ft²
### Plastic Waterproofing layer

<table>
<thead>
<tr>
<th>Wall Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior (Insulated)</td>
<td></td>
<td>2,266 ft²</td>
</tr>
<tr>
<td>Exterior (Uninsulated)</td>
<td></td>
<td>434 ft²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Floor Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor (Insulated)</td>
<td></td>
<td>1,382 ft²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Roof Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated</td>
<td></td>
<td>1,908 ft²</td>
</tr>
<tr>
<td>Uninsulated</td>
<td></td>
<td>406 ft²</td>
</tr>
</tbody>
</table>

Total: 6,744 ft²

### Metal Lath

<table>
<thead>
<tr>
<th>Wall Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior (Insulated)</td>
<td></td>
<td>2,266 ft²</td>
</tr>
<tr>
<td>Exterior (Uninsulated)</td>
<td></td>
<td>434 ft²</td>
</tr>
</tbody>
</table>

Total: 2,700 ft²

### Stucco

<table>
<thead>
<tr>
<th>Wall Area</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior (Insulated)</td>
<td></td>
<td>2,266 ft²</td>
</tr>
<tr>
<td>Exterior (Uninsulated)</td>
<td></td>
<td>434 ft²</td>
</tr>
</tbody>
</table>

Total: 2,700 ft²
Concrete

Stem Wall

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perimeter</td>
<td>167 ft</td>
</tr>
<tr>
<td>Width</td>
<td>8 in = 2/3 ft</td>
</tr>
<tr>
<td>Depth</td>
<td>2 ft</td>
</tr>
<tr>
<td>Volume</td>
<td>223 cu.ft.</td>
</tr>
</tbody>
</table>

Footing

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perimeter</td>
<td>167 ft</td>
</tr>
<tr>
<td>Width</td>
<td>16 in = 1+1/3 ft</td>
</tr>
<tr>
<td>Depth</td>
<td>8 in = 2/3 ft</td>
</tr>
<tr>
<td>Volume</td>
<td>149 cu.ft.</td>
</tr>
</tbody>
</table>

Total: 372 cu.ft.

Concrete Slab

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>.5 ft</td>
</tr>
<tr>
<td>Area</td>
<td>470 ft²</td>
</tr>
</tbody>
</table>

Total: 235 cu.ft.

3.3.4 Dimensions of Materials Transported

The final step in the estimation of the quantity of construction materials is a simplification of the quantities in Section 3.3.3 into the common dimensional units used in the construction industry.
Wood Elements

Wall Studs: 2x4 Nominal = 1.5”x3.5” Actual

Floor Beams: 2x10 Nominal = 1.5”x9.25” Actual

Roof Rafters: 2x6 Nominal = 1.5”x5.5” Actual

The previously calculated areas gave the studs as a percentage of total area [Figure 3.3.4.1]. The area for each type of lumber [Figure 3.3.4.2] divided by the width of the lumber (1.5 inches in all cases) gives the total in linear feet for that dimension [Figure 3.3.4.3].

Wall Studs: 491 ft²/1.5 in

\[
\frac{491 \text{ ft}^2}{.125 \text{ ft}} = 3,928 \text{ ft}
\]
Floor Beams: \( 205 \text{ ft}^2/1.5 \text{ in} \)
\[ 205 \text{ ft}^2/0.125 \text{ ft} \]
\[ = 1,640 \text{ ft} \]

Roof Rafters: \( 162 \text{ ft}^2/1.5 \text{ in} \)
\[ 162 \text{ ft}^2/0.125 \text{ ft} \]
\[ = 1,296 \text{ ft} \]

The calculations for plywood are much simpler. Since a typical sheet of plywood is 4’x9’, dividing the total area by 36 ft\(^2\) will render the number of sheets. However, given the nature of working with plywood (cutting out windows, and aligning sheets on the edges of the house) it may be necessary to increase this result by a reasonable percentage.

\[ 5/8 \text{ inch Plywood Total: } \frac{7,061 \text{ ft}^2}{36 \text{ ft}^2} = 197 \text{ sheets} \]

**Gypsum Board**

Calculations for gypsum board are similar to those for plywood. However, sheet size is 4’x8’, which results in an area of 32 ft\(^2\) per sheet.

\[ 5/8 \text{ inch Gypsum Total: } \frac{6,145 \text{ ft}^2}{32 \text{ ft}^2} = 193 \text{ sheets} \]
\[ 1/2 \text{ inch Gypsum Total: } \frac{2,314 \text{ ft}^2}{32 \text{ ft}^2} = 73 \text{ sheets} \]
Insulation

The three types of insulation are as follows:

- Walls: R-25 @ 1,994 ft²
- Floors: R-22 @ 1,244 ft²
- Roof: R-30 @ 1,774 ft²

Different spacing of elements requires different widths of batts.

- Wall member spacing is 16” o.c.
- Floor member spacing is also 16” o.c.
- Roof member spacing is 24” o.c.

Assuming that insulation is packaged and transported in rolls of varying sizes, calculations are as follows:

1,244 ft² of R-22 required

One roll of R-22 contains 49 ft² of insulation.

1,244 ft² / 49 ft² per roll = 25.4 rolls of R-22 insulation required

1,994 ft² of R-25 required

One roll of R-25 also contains 49 ft² of insulation.

1,944 ft² / 49 ft² per roll = 39.7 rolls of R-25 insulation required
1,774 ft² of R-30 required

One roll of R-30 contains 46 ft² of insulation.

\[
1,774 \text{ ft}^2 / 46 \text{ ft}^2 \text{ per roll} = 38.6 \text{ rolls of R-30 required}
\]

**Clay Roofing Tile**

Calculating the required quantity of roofing tiles needed for a project requires the use of a calculator that takes into account the overlap between tiles. One such calculator was found at: [http://www.builditsystems.com/Resources/Calculators.aspx#](http://www.builditsystems.com/Resources/Calculators.aspx#)

The result of the input was the requirement of 25.87 squares\(^3\) of material.

\[
180 \text{ pieces per square: } 25.87 \times 180 = 4,657 \text{ pieces needed}
\]

**Building Paper**

The required quantity of building paper for this house is 2,314 ft². Rolls from the selected manufacturer have dimensions of 4’x125’.

\[
2,314 \text{ ft}^2 / 500 \text{ ft}^2 \text{ per roll} = 5 \text{ rolls}
\]

---

\(^3\) One square is equal to 100 ft²
Plastic Waterproofing Layer

The required quantity of plastic waterproofing for the walls of this house is 6,744 ft². Rolls from the selected manufacturer are 9’x150’ to reduce cutting waste.

\[
6,744 \text{ ft}^2 / 1,350 \text{ ft}^2 \text{ per roll} = 5 \text{ rolls}
\]

Metal Lath

In the application of stucco, a layer of metal lath must be first applied. The required quantity for this project is 2,700 ft². It comes in 27”x96” (2.25’x8’) sheets, 10 sheets per bundle, and 50 bundles per pallet.

\[
2,700 \text{ ft}^2 / 18 \text{ ft}^2 \text{ per sheet} = 150 \text{ sheets} = 150 \text{ bundles} = 30\% \text{ pallet}
\]

Stucco

The coverage area for stucco is 2,700 ft². Each 80lb. bag covers 12 ft².

\[
2,700 \text{ ft}^2 / 12 \text{ ft}^2 \text{ per bag} = 225 \text{ bags}
\]
Concrete

As shown in section 3.3.3, the concrete poured requires a total of 607 ft³ (or 66 yd³)
3.4 Transportation Distance Calculations

For a single residence, materials are typically purchased and transported from local suppliers. However, estimating only the fuel used to transport those materials from the local supplier to the construction site is insufficient. Fuel expended also includes travel from the manufacturer to the site for each material. A typical construction material flow can be portrayed as follows:

Manufacturer → Local Supplier → Construction Site

For this project, the resulting material flow ends at 1191 Simmons Lane, Novato, CA 94945.

**Wood Elements (stud elements)**

Manufacturer: South Coast Lumber Co.  
885 Railroad Ave.  
Brookings OR 97415

Local Supplier: Golden State Lumber  
1100 Andersen Drive  
San Rafael, CA 94901

**Wood Elements (plywood)**

Manufacturer: South Coast Lumber Co.  
885 Railroad Ave.  
Brookings OR 97415

Local Supplier: Golden State Lumber  
1100 Andersen Drive  
San Rafael, CA 94901

**Gypsum Board**

Manufacturer: PABCO Gypsum  
37851 Cherry St.  
Newark, CA 94560

Local Supplier: Pacific Supply  
61 Jordan St.  
San Rafael, CA 94901

**Insulation**
Manufacturer: Knauf Insulation
3100 Ashby Road
Shasta Lake, CA 96019

Local Supplier: SDI Insulation
370 Lang Road
Burlingame, CA 94010

**Clay Roofing Tile**

Manufacturer: MCA Superior Clay Roof Tile
1985 Sampson Ave.
Corona, CA 92879

Local Supplier: Pacific Supply
61 Jordan St.
San Rafael, CA 94901

**Building Paper**

Manufacturer: Fortifiber Buildings Systems Group
300 Industrial Dr.
Fernley, NV 89408

Local Supplier: Pacific Supply
61 Jordan St.
San Rafael, CA 94901

**Plastic Waterproofing**

Manufacturer: Fortifiber Buildings Systems Group
300 Industrial Dr.
Fernley, NV 89408

Local Supplier: Pacific Supply
61 Jordan St.
San Rafael, CA 94901

**Metal Lath**

Manufacturer: CEMCO
1001-A Pittsburg Antioch Hwy.
Pittsburg, CA 94565

Local Supplier: REW Materials
135 Foley St.
Santa Rosa, CA 95401

**Stucco**

Manufacturer: Sakrete
Tracy, CA

Local Supplier: Home Depot
111 Shoreline Pkwy.
San Rafael, CA 94901

**Concrete**
Manufacturer: Various  Richmond, CA
Local Supplier: Shamrock Materials  7552 Redwood Blvd.
Novato, CA 94945

At this stage, assumptions must be made regarding the mode of transportation for each material on each path.

For the path from manufacturer to supplier, we will assume a diesel engine flatbed semi-trailer is used for each material. Common dimensions of the flatbed are 48 feet in length and 8 feet in width, with an 8 foot maximum freight height (the red block shown in Figure 3.4.1). In an interview with Tom Schmierer of Golden State Lumber, Inc., he estimated the fuel efficiency of one such diesel truck to be 8-9 mpg.

On the path from supplier to site, a smaller diesel truck (assuming a 28’ flatbed, 11 mpg) will be considered for the wood, gypsum board, insulation, and roofing tile elements. Cement is transported via mixer truck. The remaining materials are taken by sub-contractors, and for a
project of this size only require a few trips by smaller modes of transportation, such as pickup trucks (assuming 15 mpg). The resulting material paths are summarized below in Table 3.4.1.

Table 3.4.1 Material Paths

<table>
<thead>
<tr>
<th>Material</th>
<th>Path</th>
<th>Distance</th>
<th>Mode of Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (stud elements)</td>
<td>Manufacturer → Supplier</td>
<td>366 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>14 Miles</td>
<td>28 ft flatbed semi-trailer</td>
</tr>
<tr>
<td>Wood (plywood)</td>
<td>Manufacturer → Supplier</td>
<td>366 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>14 Miles</td>
<td>28 ft flatbed semi-trailer</td>
</tr>
<tr>
<td>Gypsum Board</td>
<td>Manufacturer → Supplier</td>
<td>48 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>13 Miles</td>
<td>28 ft flatbed semi-trailer</td>
</tr>
<tr>
<td>Insulation</td>
<td>Manufacturer → Supplier</td>
<td>238 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>47 Miles</td>
<td>28 ft flatbed semi-trailer</td>
</tr>
<tr>
<td>Clay Roofing Tile</td>
<td>Manufacturer → Supplier</td>
<td>439 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>13 Miles</td>
<td>28 ft flatbed semi-trailer</td>
</tr>
<tr>
<td>Building Paper</td>
<td>Manufacturer → Supplier</td>
<td>253 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>13 Miles</td>
<td>Pickup truck</td>
</tr>
<tr>
<td>Plastic Waterproofing</td>
<td>Manufacturer → Supplier</td>
<td>253 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>13 Miles</td>
<td>Pickup truck</td>
</tr>
<tr>
<td>Metal Lath</td>
<td>Manufacturer → Supplier</td>
<td>79 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>28 Miles</td>
<td>Pickup truck</td>
</tr>
<tr>
<td>Stucco</td>
<td>Manufacturer → Supplier</td>
<td>70 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>16 Miles</td>
<td>Pickup truck</td>
</tr>
<tr>
<td>Concrete</td>
<td>Manufacturer → Supplier</td>
<td>23 Miles</td>
<td>48 ft flatbed semi-trailer</td>
</tr>
<tr>
<td></td>
<td>Supplier → Site</td>
<td>2 Miles</td>
<td>Cement mixer truck</td>
</tr>
</tbody>
</table>
3.5 Material Load Calculations

After estimating the necessary quantity of each material, the following step is an estimation of the portion of the quantity that can be transported by the identified mode of transportation. It is also necessary to establish the percentage of the transportation’s maximum load that is dedicated to the project being analyzed [Table 3.5.1]. If the maximum load is 100 units, but only 40 units are needed for the project, then the project only uses 40% of the maximum load, and thus only consumes 40% of the fuel used in transportation of that load. The load for the second leg of the trip is 100% dedicated to the materials for the site. Any loads under 100% still use 100% of the gasoline for a full load, and any loads over 100% are rounded up to the nearest hundred.

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer to Supplier</th>
<th>Supplier to Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x4 Timber</td>
<td>6.6%</td>
<td>11.4%</td>
</tr>
<tr>
<td>2x6 Timber</td>
<td>3.5%</td>
<td>6%</td>
</tr>
<tr>
<td>2x10 Timber</td>
<td>7.1%</td>
<td>12.2%</td>
</tr>
<tr>
<td>5/8” Plywood</td>
<td>17.1%</td>
<td>29.5%</td>
</tr>
<tr>
<td><strong>Sum = 34.3%</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2” Gypsum</td>
<td>4.2%</td>
<td>7.2%</td>
</tr>
<tr>
<td>5/8” Gypsum</td>
<td>14%</td>
<td>24.1%</td>
</tr>
<tr>
<td><strong>Sum = 18.2%</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-22 Insulation</td>
<td>4.2%</td>
<td>7.2%</td>
</tr>
<tr>
<td>R-25 Insulation</td>
<td>6.5%</td>
<td>11.2%</td>
</tr>
<tr>
<td>R-30 Insulation</td>
<td>9.7%</td>
<td>16.7%</td>
</tr>
<tr>
<td><strong>Sum = 20.4%</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay Roofing Tiles</td>
<td>65%</td>
<td>112.1% ~ 200%</td>
</tr>
<tr>
<td>Building Paper</td>
<td>2.6%</td>
<td>100%</td>
</tr>
<tr>
<td>Plastic Waterproofing</td>
<td>6.3%</td>
<td>100%</td>
</tr>
<tr>
<td>Metal Lath</td>
<td>3%</td>
<td>100%</td>
</tr>
<tr>
<td>Stucco</td>
<td>7.1%</td>
<td>400%</td>
</tr>
<tr>
<td>Concrete</td>
<td>71.3%</td>
<td>300%</td>
</tr>
</tbody>
</table>

Table 3.5.1 Material Load Percentage
3.5.1 Manufacturer to Supplier

**Wood (stud elements)**

All 2x4, 2x6, and 2x10 members are stacked in levels. Although the maximum loading height for the 48’ trailer is 8’, these members are stacked only 6’ high to keep the weight under a common 80,000 lb. limit.

Stacked 6’ (72”) high: 72”/1.5” = 48 levels per load (single level example: Figure 3.5.1.1)

![Figure 3.5.1.1 Linear Element Loading by Level](image)

**2x4 members**

Laying these members on their broad side, side by side, lengthwise on the trailer allows for 26 lines (96”/3.5” rounded down) of 2”x4” members with 48’ in cumulative length per line.
48’ x 26 lines = 1,248 linear feet per level stacked

3,928 linear feet of 2”x4” members needed: 3,928 ft / 1,248 ft per level = 3.15 levels

3.15 levels / 48 levels per load = 6.6% maximum load

2x6 members

Laying these members on their broad side, side by side, lengthwise on the trailer allows for 16 lines (96”/5.5” rounded down) of 2”x6” members with 48’ in cumulative length per line.

48’ x 16 lines = 768 linear feet per level stacked

1,296 linear feet of 2”x6” members needed: 1,296 ft / 768 ft per level = 1.69 levels

1.69 levels / 48 levels per load = 3.5% maximum load

2x10 members

Laying these members on their broad side, side by side, lengthwise on the trailer allows for 10 lines (96”/9.25” rounded down) of 2”x10” members with 48’ in cumulative length per line.

48’ x 10 lines = 480 linear feet per level stacked

1,640 linear feet of 2”x10” members needed: 1,640 ft / 480 ft per level = 3.4 levels

3.4 levels / 48 levels per load = 7.1% maximum load
Wood (plywood)

Plywood is also stacked 6’ high to keep the weight under a common 80,000 lb. limit.

4’x9’ sheets laid flat on the 8’x48’ bed = 10 sheets per level.
197 sheets needed: 197 sheets / 10 sheets per level = 19.7 levels
72” / 5/8” = 115 levels per load
19.7 levels / 115 levels per load = 17.1% load

Gypsum Board

Gypsum board is stacked 6’ high to keep the weight under a common 80,000 lb. limit.

1/2” sheets
4’x8’ sheets laid flat on the 8’x48’ bed = 12 sheets per level.

73 sheets of 1/2” needed: 73 sheets / 12 sheets per level = 6.1 levels
72” / 1/2” = 144 levels per load
6.1 levels / 144 levels per load = 4.2% load
5/8” sheets

4’x8’ sheets laid flat on the 8’x48’ bed = 12 sheets per level.

193 sheets of 5/8” needed: 193 sheets / 12 sheets per level = 16.1 levels

72” / 5/8” = 115 levels per load

16.1 levels / 115 levels per load = 14% load

Insulation

The three types of insulation are packaged and transported in roll form [Figure 3.5.1.2].

R-22 rolls

Diameter: 21” Height: 15”

25.4 rolls needed

25.4 rolls / 608 rolls per load = 4.2% maximum load

R-25 rolls

Diameter: 22” Height: 15”

39.7 rolls needed

39.7 rolls / 608 rolls per load = 6.5% maximum load
R-30 rolls

Diameter: 23”    Height: 23”

38.6 rolls needed

38.6 rolls / 400 rolls per load = 9.7% maximum load

Clay Roofing Tile

Tile dimensions are 19”x7.25”x.5”

Pallets are 40”x48” and “double-stacked” pallets are loaded 42” high and contain 450 tiles.

16 “Double-stacked” pallets can be taken in one load.

4,657 tiles needed / 450 tiles per pallet = 10.4 pallets

10.4 pallets / 16 pallets per load = 65% load

Building Paper

5 rolls

Diameter: 2’    Length: 4’

48 rolls per level, 4 levels high = 192 rolls per load

5 rolls / 192 rolls per load = 2.6% load
Plastic Waterproofing

5 rolls
Diameter: 2’  Length: 9’
20 rolls per level, 4 levels high = 80 rolls per load
5 rolls / 80 rolls per load = 6.3% load

Metal Lath

Pallet = 4.5’x8’
10 pallets per load
.3 pallets needed / 10 pallets per load = 3% load

Stucco

Stucco comes in 80lb bags. Each bag is 5”x12”x19”.
Assuming these bags are stacked on 40” x 48” pallets, with a maximum height of 6 feet (to keep
the weight down):
8 bags per level x 14 levels per pallet = 112 bags per pallet
225 bags needed / 112 bags per pallet = 2 pallets
Assuming 28 pallets per truckload:
2 pallets / 28 pallets per load = 7.1% load
Concrete

Assuming a maximum load weight of 80,000 lb. for each component of the concrete mixture, and that the final concrete mixture has a weight of 94 lb/ft³:

\[
607 \text{ ft}^3 \times 94 \text{ lb/ft}^3 = 57,058 \text{ lb.}
\]

\[
57,058 \text{ lbs.} / 80,000 \text{ lbs. per load} = 71.3\% \text{ load}
\]
3.5.2 Supplier to Site

Loading the 8’ wide by 8’ high by 28’ long flatbed semi-trailer yields approximately 58% of the maximum space that a 48’ long trailer can accommodate.

**Wood (stud elements)**

2x4 members:
- 11.4% load of 28’ trailer

2x6 members:
- 6% load of 28’ trailer

2x10 members:
- 12.2% load of 28’ trailer

**Wood (plywood)**

4’x9’ sheets:
- 29.5% load of 28’ trailer

All wood elements: (11.4%+6%+12.2%+29.5%) < 100%

Requires 1 trip from supplier to site.
Gypsum Board

1/2” sheets:
7.2% load of 28’ trailer

5/8” sheets:
24.1% load of 28’ trailer

(7.2%+24.1%) < 100%

Requires 1 trip from supplier to site.

Insulation

R-22:
7.2% load of 28’ trailer

R-25
11.2% load of 28’ trailer

R-30
16.7% load of 28’ trailer

(7.2%+11.2%+16.7%) < 100%

Requires 1 trip from supplier to site.
Clay Roofing Tile

65% load of 28’ trailer
Requires 2 trips from supplier to site

Typical pickup truck (Ford F-150) bed dimensions of 78”x65” are used for the trips required for the building paper, plastic waterproofing, metal lath, and stucco estimations. Some estimations require more intuition than previous steps.

Building Paper

5 rolls, 4’ long by 2’ diameter
These rolls can fit lying on the floor of the truck bed.
Requires 1 trip from supplier to site.

Plastic Waterproofing

5 rolls, 9’long by 2’diameter
These rolls can be angled out of truck bed.
Requires 1 trip from supplier to site.
**Metal Lath**

Pallet = 4.5’x8’

Need .3 pallets

Since half of a pallet can easily fit in the dimensions listed above, 30% of a pallet will as well.

Requires 1 trip from supplier to site.

**Stucco**

Stucco comes in 80lb bags. Each bag is 5”x12”x19”.

225 bags required

- 20 bags can lie on the truck bed, and can be stacked 3 bags high.
- 20 x 3 = 60 bags per load
- 225 bags / 60 bags per load = 3.75 loads

Requires 4 trips from supplier to site.

**Concrete**

Concrete is transported by cement mixer with a 9 yd³ (243 ft³) capacity per load.

- 607 ft³ / 243 ft³ per load = 2.5 loads

Requires 3 trips from supplier to site.
3.6 Fuel Consumption Calculations

Table 3.6.1 contains a summary of the information taken from the calculations in Sections 3.6.1 and 3.6.2, showing the total energy used in transporting each material for each segment of the trip.

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer to Supplier</th>
<th>Supplier to Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x4 Timber</td>
<td>1,030,950 Btu</td>
<td>165,735 Btu</td>
</tr>
<tr>
<td>2x6 Timber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x10 Timber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/8” Plywood</td>
<td>1,017,900 Btu</td>
<td></td>
</tr>
<tr>
<td>1/2” Gypsum</td>
<td>142,245 Btu</td>
<td>153,990 Btu</td>
</tr>
<tr>
<td>5/8” Gypsum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-22 Insulation</td>
<td>796,050 Btu</td>
<td>557,235 Btu</td>
</tr>
<tr>
<td>R-25 Insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-30 Insulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay Roofing Tiles</td>
<td>4,658,850 Btu</td>
<td>200,100 Btu</td>
</tr>
<tr>
<td>Building Paper</td>
<td>104,400 Btu</td>
<td>100,050 Btu</td>
</tr>
<tr>
<td>Plastic Waterproofing</td>
<td>261,000 Btu</td>
<td>100,050 Btu</td>
</tr>
<tr>
<td>Metal Lath</td>
<td>39,150 Btu</td>
<td>215,050 Btu</td>
</tr>
<tr>
<td>Stucco</td>
<td>78,300 Btu</td>
<td>492,200 Btu</td>
</tr>
<tr>
<td>Concrete</td>
<td>274,050 Btu</td>
<td>113,535 Btu</td>
</tr>
<tr>
<td><strong>Sub-Total</strong></td>
<td><strong>8,402,895 Btu</strong></td>
<td><strong>2,097,945 Btu</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>10,500,840 Btu</strong></td>
</tr>
</tbody>
</table>
3.6.1 Manufacturer to Supplier

Mileage/MPG = Gallons consumed

Gallons consumed x percent of load = gallons dedicated to materials used

Each gallon of diesel = 130,500 Btu

**Wood (stud elements)**

366 miles/8 mpg = 45.75 gallons

45.75 gallons x (6.6% + 3.5% + 7.1%) = 7.9 gallons

7.9 gallons = 1,030,950 Btu

**Wood (plywood)**

366 miles/8 mpg = 45.75 gallons

45.75 gallons x 17.1% = 7.8 gallons

7.8 gallons = 1,017,900 Btu
Gypsum Board

48 miles/8 mpg = 6 gallons
6 gallons x 18.2% = 1.09 gallons
1.09 gallons = 142,245 Btu

Insulation

238 miles/8 mpg = 29.75 gallons
29.75 gallons x (4.2%+6.5%+9.7%) = 6.1 gallons
6.1 gallons = 796,050 Btu

Clay Roofing Tiles

439 miles/8 mpg = 54.88 gallons
54.88 gallons x 65% = 35.7 gallons
35.7 gallons = 4,658,850 Btu
Building Paper

253 miles/8mpg = 31.63 gallons
31.63 gallons x 2.6% = .8 gallons
.8 gallons = 104,400 Btu

Plastic Waterproofing

253 miles/8 mpg = 31.63 gallons
31.63 gallons x 6.3% = 2 gallons
2 gallons = 261,000 Btu

Metal Lath

79 miles/8 mpg = 9.88 gallons
9.88 gallons x 3% = .3 gallons
.3 gallons = 39,150 Btu
Stucco

70 miles/8 mpg = 8.75 gallons
8.75 gallons x 7.1% = 0.6 gallons
0.6 gallons = 78,300 Btu

Concrete

23 miles/8 mpg = 2.88 gallons
2.88 gallons x 71.3% = 2.1 gallons
2.1 gallons = 274,050 Btu

Total Manufacturer to Supplier Btu: 8,402,895
3.6.2 Supplier to Site

Mileage/mpg = gallons consumed

Gallons consumed x percent of load = gallons dedicated to materials used

Each gallon of diesel = 130,500 Btu

Each gallon of gasoline = 115,000 Btu

**Wood (stick elements + plywood)**

Since both the timber and plywood have the same supplier, they can both be taken on the same trip.

14 miles/11 mpg = 1.27 gallons

1.27 gallons x 1 trip = 1.27 gallons

1.27 gallons = 165,735 Btu

**Gypsum Board**

13 miles/11 mpg = 1.18 gallons

1.18 gallons x 1 trip = 1.18 gallons

1.18 gallons = 153,990 Btu
Insulation

47 miles/11 mpg = 4.27 gallons

4.27 gallons x 1 trip = 4.27 gallons

4.27 gallons = 557,235 Btu

Clay Roofing Tiles

13 miles/15 mpg = .87 gallons

.87 gallons x 2 trips = 1.74 gallons

1.74 gallons = 200,100 Btu

Building Paper

13 miles/15 mpg = .87 gallons

.87 gallons x 1 trips = .87 gallons

.87 gallons = 100,050 Btu
**Plastic Waterproofing**

13 miles/15 mpg = .87 gallons

.87 gallons x 1 trips = .87 gallons

.87 gallons = 100,050 Btu

**Metal Lath**

28 miles/15 mpg = 1.87 gallons

1.87 gallons x 1 trip = 1.87 gallons

1.87 gallons = 215,050 Btu

**Stucco**

16 miles/15 mpg = 1.07 gallons

1.07 gallons x 4 trips = 4.28 gallons

4.28 gallons = 492,200 Btu
Concrete

2 miles/7 mpg = .29 gallons

.29 gallons x 3 trips = .87 gallons

.87 gallons = 113,535 Btu

Total Supplier to Site Btu: 2,097,945
Chapter 4: Conclusion

The case study house is used in Chapter 3 to analyze the energy required to transport the building materials of the residence to its construction site. As stated in Chapter 1, the purpose of this analysis is a comparison of that transportation energy to the embodied energy and occupational energy of the case study house. This chapter contains those comparisons as well as an analysis of the process and its usefulness.

4.1 Embodied Energy

Estimating the embodied energy of a building is a two-step process. The first step is a calculation of the embodied energy for each construction assembly, and the second step uses this information in combination with the quantity of each assembly to estimate the total embodied energy of the building. Since construction assemblies were calculated by surface area in section 3.3.2, the first step in estimating embodied energy is calculated in energy per surface area units. The following step takes those units and multiplies them by the total surface area of each construction assembly for the total embodied energy for that assembly.
4.1.1 Embodied Energy Assemblies

Wall Assemblies:

Exterior (Insulated)

<table>
<thead>
<tr>
<th>Material</th>
<th>Btu/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stucco</td>
<td>18,542</td>
</tr>
<tr>
<td>Metal lath</td>
<td>5,874</td>
</tr>
<tr>
<td>Plywood</td>
<td>9,724</td>
</tr>
<tr>
<td>Fir 2x4 studs @ 12%</td>
<td>3,718</td>
</tr>
<tr>
<td>Plastic membrane</td>
<td>3,872</td>
</tr>
<tr>
<td>Batt insulation (R-25) @ 88%</td>
<td>7,140</td>
</tr>
<tr>
<td>Gypsum board (5/8 in)</td>
<td>10,419</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>59,289</td>
</tr>
</tbody>
</table>

Exterior (Un-insulated)

- Batt insulation (R-25) @ 88%     -7,140

| Total:                           | 52,149  |

Interior (Insulated)

<table>
<thead>
<tr>
<th>Material</th>
<th>Btu/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum board (5/8 in)</td>
<td>10,419</td>
</tr>
<tr>
<td>Fir 2x4 studs @ 12%</td>
<td>3,718</td>
</tr>
<tr>
<td>Batt insulation (R-25) @ 88%</td>
<td>7,140</td>
</tr>
<tr>
<td>Gypsum board (5/8 in)</td>
<td>10,419</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>31,696</td>
</tr>
</tbody>
</table>

Interior (Uninsulated)

- Batt insulation (R-25) @ 88%     -7,140

| Total:                           | 24,556  |
Floor Assemblies:

Insulated (First floor)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>9,724</td>
</tr>
<tr>
<td>Fir 2x10 @ 10%</td>
<td>4,617</td>
</tr>
<tr>
<td>Batt insulation (R-22) @ 90%</td>
<td>5,358</td>
</tr>
<tr>
<td>Plastic membrane</td>
<td>3,872</td>
</tr>
<tr>
<td>Metal mesh</td>
<td>5,522</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>29,093</strong> Btu/ ft²</td>
</tr>
</tbody>
</table>

Un-insulated (Second floor)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>9,724</td>
</tr>
<tr>
<td>Fir 2x10 @ 10%</td>
<td>4,617</td>
</tr>
<tr>
<td>Gypsum board (5/8 in)</td>
<td>10,419</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24,760</strong> Btu/ ft²</td>
</tr>
</tbody>
</table>

Concrete slab (Garage)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>63,756</td>
</tr>
<tr>
<td>Reinforcing (1/2 in)</td>
<td>125,446</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>189,202</strong> Btu/ ft²</td>
</tr>
</tbody>
</table>
Roof Assembly:

### Insulated (Over living areas)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay tile</td>
<td>11,130</td>
</tr>
<tr>
<td>Building paper</td>
<td>950</td>
</tr>
<tr>
<td>Plywood</td>
<td>9,724</td>
</tr>
<tr>
<td>Batt insulation (R-30) @ 93%</td>
<td>9,293</td>
</tr>
<tr>
<td>Fir 2x6 @ 7%</td>
<td>3,232</td>
</tr>
<tr>
<td>Plastic membrane</td>
<td>3,872</td>
</tr>
<tr>
<td>Gypsum board (1/2 in)</td>
<td>6,975</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45,176</strong> Btu/ ft²</td>
</tr>
</tbody>
</table>

### Un-insulated (Over garage)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batt insulation (R-30) @ 93%</td>
<td>9,293</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35,883</strong> Btu/ ft²</td>
</tr>
</tbody>
</table>
4.1.2 Embodied Energy Calculations

Walls:

Exterior (Insulated)
(59,289 Btu/ft²) X (2,266 ft²) = 134,348,874 Btu

Exterior (Uninsulated)
(52,149 Btu/ft²) X (434 ft²) = 22,632,666 Btu

Interior (Insulated)
(31,696 Btu/ft²) X (208 ft²) = 6,592,768 Btu

Interior (Uninsulated)
(24,556 Btu/ft²) X (1,182 ft²) = 29,025,192 Btu

Sub-total: 192,599,500 Btu

Floors:

Insulated (First floor)
(29,093 Btu/ft²) X (1,382 ft²) = 40,206,526 Btu

Uninsulated (Second floor)
(24,760 Btu/ft²) X (665 ft²) = 16,465,400 Btu

Concrete slab (Garage)
(189,202 Btu/ft²) X (470 ft²) = 88,924,940 Btu

Sub-total: 145,596,866 Btu

Roofs:

Insulated (Over living areas)
(45,176 Btu/ft²) X (406 ft²) = 18,341,456 Btu

Uninsulated (Over garage)
(35,883 Btu/ft²) X (1,908 ft²) = 68,464,764 Btu

Sub-total: 86,806,220 Btu

Total: 425,002,586 Btu
4.2 Occupational Energy

Occupational energy usage is a major concern in our currently environmentally conscientious society. As a result, it is monitored closely by various organizations, ranging from the energy providers themselves to government agencies like the National Renewable Energy Laboratory (NREL). For the purpose of this project, occupational energy calculations have been retrieved from a local Marin county organization. According to Marin Clean Energy, the average Marin county residence uses 49,443,292 Btu per year.\(^4\)

4.3 Energy Usage Summary

The calculated energy in the three main stages of energy use for this sample house is as follows:

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Energy Usage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embodied Energy</td>
<td>425,002,586 Btu</td>
<td>Section 4.1</td>
</tr>
<tr>
<td>Transportation Energy</td>
<td>10,500,840 Btu</td>
<td>Section 3.6</td>
</tr>
<tr>
<td>Occupational Energy</td>
<td>49,443,292 Btu/yr</td>
<td>Section 4.2</td>
</tr>
</tbody>
</table>

This clearly shows that transportation energy usage for this case study does not have as large of an impact as embodied or occupational energy usage. Transportation energy is only 2.5% of embodied energy, and 21% of the occupational energy usage per year.

\(^4\) http://marincleanenergy.info/pdf/background_calcs.pdf
4.4 Critique of Process

As stated before, there are two major purposes for this thesis. The first is to delineate a methodology to estimate the energy used to transport building materials to a construction site. The second purpose is the comparison and evaluation contained in Section 4.3, comparing this transportation energy to the more commonly documented energy costs of embodied and occupational energy. In order that the methodology of this thesis may be replicated for future projects, it is necessary to describe some of the choices made throughout the process which had differing levels of influence on outcomes and their subsequent evaluation.

The most significant choice made in this case study is twofold, and related to the selection of building materials. The first part of this choice is the materials themselves. The major structural element in the sample house is timber. As the location of the case study is northern California, lumber supplies are a relatively short distance to the north. However, if the house were located in southern Texas, timber would have to come from much further, thereby increasing the related fuel usage. The second part of the choice relates to the manufacturers of the materials selected. Due to the nature of the sample house in this case study, most materials were chosen from local or nearby suppliers. However, for larger projects (such as housing developments or commercial offices) or for projects not academic in nature, material costs will dictate where the construction materials come from. At the current time, it is sometimes cheaper to buy products from certain foreign countries and ship them into the United States. An example of this is gypsum board. Until recently, large quantities of gypsum board were shipped from China to the U.S., as it can be produced more cheaply there. This extra trip increases the transportation distance (and, consequently, the transportation energy used per unit) in comparison to local sources.
The second choice pertains to the loading of the chosen methods of transportation. For this project, reasonable assumptions led to the use of 48-foot and 28-foot flatbed semi-trailers for most construction materials. The loading of those trailers was governed by two things. First, there are loading dimensions for each trailer type. These dimensions limit how much material can be loaded, but are not a variable requiring extra investigation. The second governing factor, however, is that of a maximum weight limit. Due to the weight of some of the heavier materials, it may not always be possible to load a trailer to its maximum dimensions.

A third choice in the methodology is the inclusion or exclusion of waste materials in calculations. If such waste figures are available, adjusting the embodied energy total should be as simple as increasing the energy used by each material relative to its waste percentage.

4.5 Further Study

The purpose of this project is an analysis of the energy consumed in the transportation of construction materials for one single-family residence in a specific location. That nature of the project leaves room for various developments in the study of material transportation energy. Some example areas of further study are:

- Material transportation energy usage modeling for multi-unit developments (condominiums, apartments, etc.).
- Material transportation energy usage modeling for large-scale developments (skyscrapers, shopping centers, office parks, etc.).
- Grand-scale material transportation energy usage estimation (city, county, state, country).
- Monetary cost analysis for the material transportation energy usage iterations listed above.
- Material sources and distribution network mapping.
- Material transportation network efficiency assessment.
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