# RE(DE)FINING NET ZERO ENERGY: MAXIMIZING RENEWABLE RESOURCE USE THROUGH EMERGY ANALYSIS OF ENVIRONMENTAL BUILDING DESIGN

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Dedicated to my wife, Jayasubha Lakhsmanan.

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ABSTRACT

# RE(DE)FINING NET ZERO ENERGY: MAXIMIZING RENEWABLE RESOURCE USE THROUGH EMERGY ANALYSIS OF ENVIRONMENTAL BUILDING DESIGN

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The notion that raw materials for building construction are plentiful and can be extracted “at will” from Earth’s geobiosphere, and that these materials do not undergo any degradation or related deterioration in energy performance while in use is alarming and entirely inaccurate. For these reasons, a particular building, like an organism or an ecosystem must seek self-sustenance for its design to prevail in competition with other building designs in a time with limited availability of energy and materials. Self-organization of systems to maximize useful power is the key to self-sustenance. To this extent, Net Zero Energy (NZE) buildings achieve a net annual energy balance in their operations. However, approaching a NZE building goal based on current definitions is flawed for two principal reasons – they only deal with energy quantities required for operations and related emissions, and they do not establish a threshold which ensures that buildings are optimized for reduced consumption before renewable systems are integrated to obtain an energy balance. Current definitions and calculations of net energy do not include the energy flows from the sun, wind, rain, and geological cycles and so-forth from the beginning.

This dissertation develops a method to maximize renewable resource use through emergy (spelled with an “m”) analysis to close the gap between current approaches to environmental building design and the over-arching goal of creating buildings that contribute to the sustainability of the geobiosphere. The objective of this study is to assess the performance of built systems and identify the maximum potential bounds for renewable resource substitution within the building process. This study proposes using a “Renewable Emergy Balance” (REB) in environmental building design as a tool to maximize renewable resource use through disinvestment of all non-renewable resources that may be substituted with renewable resources. REB buildings preserve a high standing by optimizing buildings over their entire life-span from formation-extraction-manufacturing to maintenance and operation cycles. If such an approach were adopted, it would expand conscious decision-making and, possibly, lead to a paradigm shift in the way non-renewable resources are used in the manufacturing of building materials, which is currently of interest, but remains unchecked.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF ILLUSTRATIONS

# 1. INTRODUCTION

Buildings consume about one-third of world's energy. In the US, buildings consume 39% of the energy and 68% of the electricity; they generate 38% of the carbon dioxide, 49% of the sulfur dioxide and 25% of the nitrogen oxides found in the air. Owing to the energy crisis, increased emissions of wastes and the depletion of fossil fuels, research and development in building technologies and integrated processes has attained greater and renewed interest among stakeholders worldwide, especially governments. Such novel building technologies are the culmination of several decades of research, development and practice of building design, construction and materials technology. Such development goes beyond the boundaries of building design and construction, and utilizes scientific knowledge from other fields such as physics to examine building-related thermodynamic processes (e.g., conduction, convection and radiation across the building envelope; airflow prediction using Computational Fluid Dynamics, etc.), chemistry for developing new building material compositions (e.g., polymer technologies used for roof coatings that turn black during winter months and white in summer months, etc.), biology through bio-organism-based technologies (e.g., Living Machines™ for waste water recovery onsite, etc.).

Nevertheless, it is critical to assess a building and its sub-systems before it is put in place. One way of measuring building performance is using performance indices and definitions. While performance indices provide assessment opportunities for exploring improved building operation, performance-related definitions offer a basis for broader compliance methodologies. One of the widely used definitions is "Net Zero Energy."

Net Zero Energy definitions are still in the early development phase as new knowledge is drawn upon to revise and classify buildings. NZE can be defined based on boundaries determined by energy-flow and renewable supply options. While energy flow based NZE definitions are determined by means of segregating the boundaries of energy consumption and generation (at the site or source levels), and their quantification (energy quantity measured or energy costs), the renewable supply options based NZE definitions are established by way of demand-side location of onsite renewables. Derived from the buildings' energy consumption and generation (Torcellini et al., 2006), they can be categorized as Net Zero Site Energy (net energy consumption and generation, in kWh, within the site boundaries), Net Zero Source Energy (takes the energy source and losses associated with transmission and conversion into consideration), Net Zero Energy Costs (net energy consumption and generation, in cost terms, within the site as the boundary) and Net Zero Energy Emissions (through offsetting site emissions through sustainable purchasing from off-site; comparable to carbon-neutral technologies). On the other hand, demand-side renewable supply options based NZE definitions (Crawley et al., 2009) such as "on-site supply options," and "off-site supply options" offers definitions based on renewable site locations.

Achieving Net Zero Energy status, a global and compelling phenomenon that aims to revolutionize buildings as zero energy consumers, is one such building type. Several notable agencies/associations, cities, states and countries globally have set goals to realize NZE.

Although the definitions vary based on energy flow boundaries, the goal is being set for both new buildings and the existing building stock. While innovative processes are under development for the design-construction-operation of new buildings to take on the NZE challenge, it is the basic building design-phase process that calls for a paradigm shift.

The notion that raw materials for building construction are plentiful and can be extracted "at will" from earth's geobiosphere, and that these materials do not undergo any degradation or related deterioration in energy performance while in use is alarming and entirely inaccurate. It must be acknowledged that only a finite mass of material resource exists irrespective of the multitude of transformations needed to make a product, and that entropic degradation of such products is inevitable. For these reasons, a particular building, like an organism or an ecosystem must seek self-sustenance to prevail in competition with other building designs in a time with limited availability of energy and materials. Self-organization of systems to maximize useful power is the key to self-sustenance. To this extent, NZE buildings achieve a net annual operating energy balance. However, approaching a NZE building goal based on current definitions is flawed for the following reasons –

*(a) NZE definitions only deal with operating energy quantities and related emissions.*

NZE definitions deal with operating energy quantities and related emissions and do not include all other energy inflows required for the particular building under study such as building manufacturing, maintenance, etc., In current NZE practice, this vast quantity of energy is unaccounted for and ignored for simplification purposes. Also, current definitions and calculations for Net Zero Energy do not include the energy flows from the sun, wind, rain, geological cycles and so-forth from the beginning.

*(b) NZE definitions do not establish an "energy threshold" which ensures that buildings are optimized for reduced consumption before renewable systems are integrated to obtain an energy balance.*

Current NZE definitions are at a level that is particularly generic and does not provide information on the desired "energy threshold" to optimize building energy consumption prior to renewable system integration. For example, a building can attain NZE status by way of surplus renewable energy generation without optimizing its building energy consumption as can be noted in several of the current NZE projects. Such an approach defeats the goal of NZE and may not fulfill the larger objective of energy efficiency.

More importantly, for a building design strategy that aims to contribute to the larger goal of global sustainability, it must be acknowledged that a building relies on the geobiosphere for its very existence. Current definitions and calculations of net energy do not include the energy flows from the sun, wind, rain, geological cycles and so-forth from the beginning. Therefore, using NZE definitions without fully encompassing all related system forces and adequate scientific substantiation is misleading and, in the long run, it may be detrimental to building science, specifically when promoted by a premier organization such as the US Department of Energy.

## 1.1 Environmental Accounting and Buildings

Although buildings evolve through a rigorous decision-making process in terms of design and engineering, it is crucial to ask if an environmentally conscious approach went into the selection of building components, both for the whole building and its sub-systems. A significant component of such an approach is the proper identification of system boundaries for performing environmental accounting. For example, one may consider building energy use at the site level and work towards conserving and/or maximizing renewable resource use there. This approach, if all the energy use is "balanced" with energy generation within a certain time-frame, leads to NZE status (including site, costs, and emissions). Conversely, a different practice may be pursued with a sustainability motivation, at the scale of the global geobiosphere. This, then, approaches buildings as if they were ecosystems and, hence, requires an ecological accounting model. While the former building energy use approach requires a simplified model to determine the "balance point," the latter ecological approach requires an elaborate accounting model to support a variety of inputs and outputs that are specific to the study.

Net Zero Energy definitions are based on energy accounting principles and are entirely based on the energy used for operations at the building-scale. While energy accounting can be expanded to include energy flows of the geobiosphere that shape an environmental building design and thereby mimic an ecological accounting model, it lacks two significant components in its bookkeeping. They are (a) lack of an internal optimizing principle and (b) the ability to quantify the environment's role in absorbing and processing pollution (Herendeen, 2004). The internal optimizing principle is a distinctive characteristic of a reductionist tool. However, energy accounting may be used to implement external principles such as minimizing fossil fuel use, etc. From the perspective of the integration of renewable resource use into energy accounting, they are mere external constraints. Additionally, questions related to system boundaries in energy accounting and the merging of several types of energy are noteworthy, especially in expanding the energy accounting principles to the geobiosphere level (Hau, 2005).

On the other hand, an ecological accounting model may offer environmental decision-making solutions through elaborate bookkeeping. Such a model is supported through a variety of inputs and outputs. Inputs may include building components' embodied energy and may even extend to the material formation cycle to its life time, reiterating the notion that one may not withdraw non-renewable resources "at will" as there is only a finite quantity of those materials in this one earth for use during its life time. Outputs may include the work product of that particular building. For example, if the building function is a university or a laboratory and if the useful work has gone into the building with an environmental premise such as thermal and visual comfort, then the outputs include graduated students' knowledge, faculty, staff, research publications, inventions (as products and services), and more importantly, its energy use for operations and maintenance. Some of the methods widely used are Life Cycle Assessment (LCA), emergy analysis, etc.

Life Cycle Assessment is a tool that primarily focuses on the impact of emissions and resource consumption (Guinee et al., 1993a, b). LCA's primary objective is identifying emissions and their impact during the life cycle of a process. Through expanding the boundaries of study and suitable allocation, such environmental accounting may be pursued. However, Burgess and Brennan (2001) provide in-depth data related to LCA shortcomings. Other issues include setting the boundaries, allocation through proportionally distributing the responsibility for inputs used (resource consumption) and undesired outputs (emissions) of a process, costs of data collection as LCA strongly relies on the quality of the data, etc. The most significant inadequacy that relates to this research is that Life Cycle Assessment lacks a rigorous thermodynamic framework which is elemental for analyzing ecosystems and in certain situations it may even violate thermodynamic laws (Hau, 2005).

Nevertheless, several attempts have been made to use Life Cycle Assessment for building evaluation, the most recent and notable being the Life Cycle-based Zero Energy Building or LC-ZEB (Hernandez and Kenny, 2010). LC-ZEB is a simplified methodology to include the embodied energy of building components together with energy use in operation.

Embodied energy includes the primary energy used for the production of raw materials to complete construction. Primary energy is extracted or captured from sources such as fossil fuel, nuclear, and hydro-electric power, etc. Secondary energy is human-induced energy transformation from primary energy source. For example, electricity generated from burning coal is secondary energy. However, labor and environmental work of the geobiosphere is not included. Additionally, embodied energy does not include the energy used by the built environment's space conditioning requirements and other uses (Stein et al, 1981).

Life Cycle-based Zero Energy Building status is achieved if annualized life cycle energy ( i.e., the summation of annual energy use or the energy used in operating the building, in this case) and the annualized embodied energy, is less than or equal to zero. Annualized embodied energy refers to the initial embodied energy used in construction that is amortized over the building's life-time. For a building to achieve LC-ZEB status, the annual energy use must be significantly reduced to such an extent to compensate for the already-consumed embodied energy in the buildings. For simplicity, the authors selected primary energy (fossil fuel) as an indicator for annual energy use in operation and for determining the embodied energy. Life Cycle-based Zero Energy Building uses the Net Energy Ratio, a factor to aid building design from a life cycle perspective, to evaluate building systems. Although this research approach attempts to follow ecological modeling principles, there are shortcomings such as non-inclusion of the energy of material formation in the Life Cycle Assessment; the selection of primary energy as an indicator, in particular when renewable energies are considered; in addition, the approach does not quantify the use of progressive replacement of non-renewable by renewable resources to achieve net energy.

Emergy analysis is an environmental accounting procedure through which a consideration of the entire life-span of a building from formation-extraction-manufacturing to maintenance and operation cycles may be achieved. Solar and other energies that have been drawn upon for the formation-extraction-manufacturing of materials, the energy and material inflow necessary to resist degradation, and the resources required for operational use of the building constitute the available energy-emergy measure of what is required for the structure and function of a building. Energy Systems Theory and Emergy Analysis (Odum, 1983; Odum, 1996) through the development of integrated environmental accounting methods can offer a holistic solution for such analysis. In addition to providing a thermodynamic framework for analyzing energy transformations, emergy analysis can offer several indices for comprehensive evaluation of a building system and its sub-systems. In essence, emergy analysis uses thermodynamic principles to promote environmentally conscious decision-making. In other words, emergy analysis provides a "total environmental analysis" that goes beyond classical thermodynamics and includes all environmental energies involved in the system under investigation.

Only a handful of research efforts have focused on assessing buildings using emergy analysis: evaluation of recycling and reuse of building materials (Buranakarn, 1998); emergy associated with the operation of a Building (Meillaud et al., 2005); building manufacturing, maintenance and use – development of Em-building indices (Pulselli et al., 2007); energy and emergy based cost-benefit evaluation of building envelopes relative to geographical location and climate (Pulselli et al., 2009); and emergy evaluation of a green façade (Price and Tilley, 2010). Although these studies focused on the use of emergy as a tool to evaluate building materials and buildings as a whole, and to develop performance indices for further exploration, there is not yet a comprehensive method to maximize renewable resource use relative to a finite limit or potential as a way to optimize building design before any renewable or nonrenewable resources are expended.

## 1.2 Dissertation Statement

This dissertation focuses on the development of a method to maximize renewable resource use through emergy analysis to close the gap between current environmental building design practice and the over-arching goal of creating buildings that contribute to the overall sustainability of the geobiosphere. Challenges associated with this task are,

- Evaluation of a building through its entire life-cycle from formation-extraction-manufacturing to maintenance and operation cycles for the comprehensive optimization of the building cycle.
- Identification of non-renewable resources that have the potential to be substituted with renewable resources.
- Optimization of building envelope emergy through maximization of resource potential.
- Identification of Renewable Emergy Balance bounds based on the renewable-substitutability potential.

This dissertation undertakes these challenges with the use of emergy analysis because of its comprehensive features as discussed in the previous section.

## 1.3 Structure of Dissertation

This dissertation is comprised of chapters that are organized to deliver the body of research in a concise fashion. *Chapter 1* provided a brief introduction to NZE definitions, discussed the inherent issues with current NZE definitions and offered environmental accounting opportunities for building energy performance. Additionally, this chapter presented Emergy Analysis as one of the environmental accounting methodologies for buildings and a list of current research work in this area.

As project considerations can have a significant impact on the environment, they are assessed using structured protocols and analytical tools. Such project occurrences may be defined using metrics. Furthermore, as the dissertation focuses on the development and assessment of metrics to guide building design toward greater sustainability, at the geobiosphere-scale, *Chapter 2* starts with a detailed mapping of a variety of sustainability frameworks, analysis tools and metrics currently in use. While environmental impact assessment and strategic environmental assessment form the two types of sustainability frameworks, all sustainability evaluation tools may be identified within the larger context of whether they follow a reductionist approach or a non-reductionist approach. The reductionist tools' categorization is further expanded to map all analysis and assessment tools such as exergy, Life Cycle Assessment, embodied energy, emergy analysis, etc., (within the realm of "biophysical models and thermodynamic methods"). On the other hand, Multi Criteria Analysis which applies subjective criteria for data selection is discussed in the non-reductionist tools' section. Several environmental metrics have been developed to-date to define a project's performance at the ecosystem, the building and surroundings, or the building scales. These three metric types and their corresponding metric definitions are discussed. While the ecological footprint, surplus biocapacity measure, etc., provide metrics for the ecosystem scale, rating systems such as Leadership in Energy and Environmental Design (LEED™), etc., fit within the building and its environment level. Metrics such as net energy, zero energy, Net Zero Energy, etc., describe the building–scale. In essence, such a mapping offers clarity to modelers on the hierarchy of measurement sciences in the yet-to-be-formulated "science of building sustainability."

The core of this dissertation is the development of a Renewable Emergy Balance metric to be used in environmental building design. REB maximizes the renewable resource in building materials and operative energy use through disinvestment in all non-renewable resources that may be substituted with renewable resources. *Chapter 3* starts with the discussion of Daly's "quasi-sustainability" principle followed by Odum's "renew-non-renew" integrated system. Additionally, the terms "renewable-substitutability" and "maximum renewable emergy potential" are introduced. While an example (concrete production) is used for describing the former, an illustration is provided for the latter for the purposes of clarity. A detailed procedure to compute the maximum renewable emergy potential is discussed in this chapter.

This dissertation develops a method to assess the REB of a building project. *Chapter 4* discusses in detail the three components of the assessment method namely, the manufacturing and maintenance emergy analysis, the building operative energy use, and the maximum renewable emergy potential. The organization of a comprehensive list of building materials emergy database that includes both transformities and data related to renewable-substitutability of a non-renewable resource is a crucial portion of this dissertation. This database is available in Appendix B.

*Chapter 5* uses a case study to assess the Renewable Emergy Balance. The case study is an existing building facility. For this case study, the building structure is studied in detail and analysis is performed. As the building envelope is the interface between the interior and the exterior renewable resources, it is essential to optimize the envelope to maximize renewable resource use. A building emergy optimization component discusses a detailed procedure to compute the optimal solution that performs to its maximum potential to already used energy.  Thus, the integrated building envelope emergy optimization component is utilized to find the optimal result to balance the renewable-substitutability potential, and reach Renewable Emergy Balance status.

*Chapter 6* concludes the dissertation with detailed set of observations and recommendations. Additionally, it provides the need for future study in improving the Renewable Emergy Balance assessment method for widespread application for buildings of all sizes and shapes. The dissertation develops a method for rating a building's sustainability through evaluation of its renewable resource use. Moreover, the methodology paves the way for maximizing renewable resource use through conscious decision-making during building design (manufacturing), maintenance and operation.

## 1.4 Summary of Contributions

The following lists the major contributions made to environmental accounting of buildings.

- Development of a method to assess the Renewable Emergy Balance of a building. Renewable Emergy Balance buildings preserve a high standard in optimizing the sustainability of buildings over their entire life-span from formation-extraction-manufacturing to maintenance and operation cycles.
- Maximize renewable resource use through disinvestment of all non-renewable resources that may be substituted with renewable resources and contributing to the overall sustainability of the geobiosphere.
- Development of the maximum renewable emergy potential for buildings. This limit can be used to integrate renewable resources over the life-time of the building to achieve a Renewable Emergy Balance.
- Alleviate any ambiguity related to the limit or benchmark that is set to achieve higher levels of sustainability.
- Development of an emergy optimization to determine the optimal solution of envelope component that performs to its maximum potential to already used energy.

Such an approach could expand environmentally conscious decision-making and, possibly, lead to a paradigm shift in the way non-renewable resources are used in the manufacturing process for building materials which is currently noticed, but remains unchecked.

# 2. ASSESSING SUSTAINABILITY

*"to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." - Standard definition of sustainable development by the Brundtland Commission (WCED, 1987).*

Measurement science is vital in evaluating environmental impacts to assess sustainability. There are several types of frameworks, analytical tools and metrics that have been developed to assess the achievement of sustainability by a project under consideration. The purpose of such frameworks, tools and metrics is to evaluate impact to the environment at different scales depending on the project boundaries. When it touches projects at a larger–scale (for example, policy making at town or city–levels), sustainability frameworks play a major role. Such frameworks use structured protocols in addition to varied analytical tools for evaluation. These analytical tools are specific to the problem at-hand (magnitude and purpose).

The selection of a tool will be determined based on the objective of the problem such as a reductionist or non-reductionist approach. A reductionist tool measures the performance by compiling and then integrating measurable characteristics of the project. Examples of reductionist tools include economic and monetary tools, biophysical models and thermodynamic methods, performance evaluation tools and building energy analysis tools. On the other hand, non-reductionists tools integrate methodological choices which are subjective in nature, and may be particularly influenced by the analyst performing the analysis. Multi Criteria Analysis (MCA) is an example of such a tool.

Finally, metrics measure the achievement of a project in sustainability terms. For example, the project may perform in an energy efficient manner during its life-time. There are metrics available specific to the efficient use of energy in building operations and those may be applied to the project to measure and describe the project's level of achievement in energy efficiency. This chapter provides an in-depth mapping of a variety of sustainability frameworks, analysis tools and metrics currently in use.

While the Environmental Impact Assessment and Strategic Environmental Assessment form the two types of sustainability frameworks, all sustainability evaluation tools may be identified within the larger context of whether they follow a reductionist or a non-reductionist approach. The reductionist and non-reductionist tools' categorization is further expanded to map all analyses and assessments. Furthermore, several environmental metrics have been developed to-date to define a project's performance at an ecosystem, building-environmental, or building scale. In essence, such a mapping offers clarity to modelers on the hierarchy of measurement sciences in the yet-to-be-formulated "science of sustainability."

## 2.1 Ecosystems and Sustainability

An ecosystem is a complex interconnected setting where both living and non-living networks operate together. Such networks exchange materials and energy, and through feedback systems, self-organize connectivity in space, time (Ulgiati and Brown, 2009). Owing to excessive human exploitation and interventions, this fabric of self-sustenance is stretched and conceivably to irreparable order if unchecked. Harvesting beyond biological limits has caused significant decline to natural ecosystems such as depletion of fish stocks, forest cover, grasslands, wetlands, etc. (WRI, 2000).

Sustainability, in its broadest scope, through balanced development and through promoting environmental health and societal equity seeks to offer a solution to the ruin of ecosystems. An "ideal metric" should aid such a balancing act. Currently, there are no universally accepted metrics that characterize the natural environment and its interactions with social, economic and technical environments (Giannetti et al., 2010). This may be in part due to lack of a unified accepted definition of sustainable development (Parris and Kates, 2003) and opposing approaches to quantitative analysis in the field of sustainability (Giampietro et al., 2006). However, renewed interests in environment and sustainability have provided increasing momentum to the field, specifically in data gathering and characterization, for the development of sustainability metrics.

Several research efforts in the field of sustainability, particularly in environmental decision-making, performance monitoring, policy evaluation and benchmarking comparisons, are evolving within the scientific community.

## 2.2 "Science of Sustainability" and its Lack Thereof

Sustainability is an emerging field. However, the urgency of the dire state of the world has boosted research efforts in the field of sustainability through the emergence of distinct research branches – not yet unified. Although natural science, social science, humanities and engineering fields have focused research efforts towards sustainability, a unified framework assessing economic, environmental and social issues and equity is yet to become a standard and / or a legal requirement worldwide (Giannetti et al., 2010). Ness et al (2007) attempted "Sustainability Science" through appropriate discussions including categorization of sustainability assessment tools. This is due to the unique nature of assessing the economic, environmental, and social considerations simultaneously that calls for a "science of sustainability" which develops the scientific basis for dealing with this relatively new concept (Giannetti et al., 2009).

Lack of a "science of sustainability" has led to debate at philosophical and ethical levels of sustainability; for example, substitutability between the economy and the environment, or "natural capital" and "manufactured capital" or between "weak" and "strong" sustainability (Ayres et al., 1998). Debate about the economy and the environment, or "natural capital" and "manufactured capital" lie in the difference between eco-centric or anthropocentric viewpoints respectively. On the other hand, while "weak" sustainability is attained through the substitutability of economic, natural and social capital for natural capital, "strong" sustainability conserves natural capital such as natural resources and environmental quality (Brekke, 1997; Daly and Cobb 1989). In other words, strong sustainability rejects substitutability of natural capital.

Further to this concept, a “very strong” sustainability implies that every subsystem of the natural environment is preserved (Pearce and Atkinson, 1995). However, the quantification of natural capital and its contribution to economic activity is critical for environmental sustainability (Hau, 2005).

## 2.3 Sustainability Assessment Frameworks, Evaluation Tools and Metrics

Environmental considerations have gained significant importance for assessing a project’s impact, both positive and negative, on the environment. The framework for sustainability assessment tools may contain the following – temporal characteristics for evaluation of past and / or future outcomes; focus areas such as a product or a proposed change in policy; and integration of nature-society systems. Based on the above, Ness et al (2007), categorized three major areas – (a) indicators and indices, (b) product-related assessment tools, and (c) integrated assessment. The proposed assessment tool framework is based on the temporal and object focus of the tool. Under this umbrella of sustainability assessment tools, indicators are simple measures which then can be aggregated to an index. Examples include Ecological Footprint, Wellbeing Index, Environmental Sustainability Index, Human Development Index, etc. The product-related assessment tools focus on production and consumption of goods and services. Examples include Life Cycle Analysis, Life Cycle Costing (LCC), product material flow analysis, etc. Integrated assessment tools are used for supporting decisions related to a project or a policy. Examples include Multi Criteria Analysis, Cost Benefit Analysis, etc.

However, as noted by Ness et al (2007) categorizing the tools may pose significant problems such as whether the objectives of sustainability assessment are fulfilled, whether established guidelines are available for tool practitioners, etc. More importantly is the selection of assessment approaches based on the sustainability requirements (or interpretations of those requirements). As research progresses in the field of sustainability owing to demand for this knowledge, new tools emerge and become accessible. The challenge is whether all of the fundamental sustainability objectives mentioned above were integrated into the method and easily employed by modelers over a diverse set of problems.

For the purposes of this dissertation, sustainability assessment approaches are categorized based on the hierarchical structure in their application, e.g., frameworks, analytical tools and metrics, Figure 1. However, these approaches can be assessed using frameworks or structured protocols to study several options within the framework using analytical tools, and to define such project occurrences using metrics.

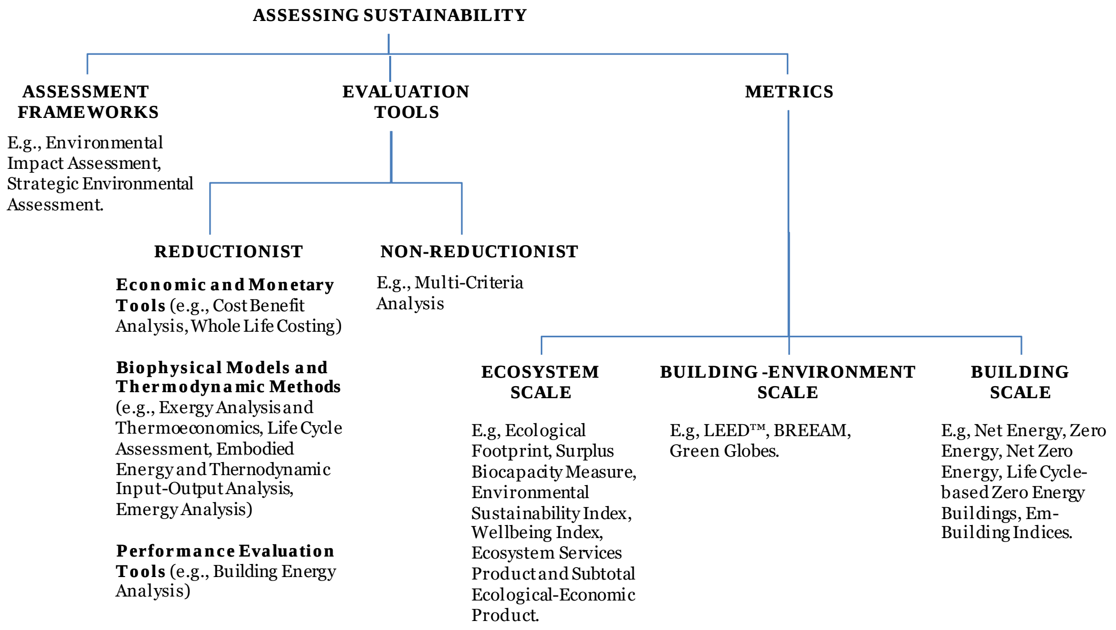

**Figure 1. Sustainability assessment approaches.**

The first level category includes the Assessment Frameworks. These are integrated and structured assessment models that aid in the comparison of various alternatives for projects and policies. Examples include Environmental Impact Assessment and Strategic Environmental Accounting.

The second first level category is comprised of analytical evaluation tools that assist in decision-making or in finding potential solutions to specific problems within the framework (Gasparatos et al., 2010). However, to preserve the generic nature of the framework, it does not identify the analytical tools that may be used; rather it provides the protocols for assessment. These tools are discussed under two second level sub-categories - reductionist and non-reductionist tools. While a reductionist tool measures performance by analyzing and integrating measurable characteristics of the project, non-reductionists tools integrate methodological choices which are subjective in nature and may be particularly influenced by the analyst performing the analysis. All of these sub-categories include specific analysis tools that perform a particular function. For example, the biophysical models possess the advantage of nature-society integration. Similarly, the building energy analysis tools specifically monitor and / or evaluate building energy use as a sustainability objective. Multi Criteria Analysis forms part of the non-reductionist tool sub-category.

The third first level category of sustainability measurement science includes environmental metrics. Three second level sub-categories are used to categorize the metrics at varied scales or measurement boundaries. They are the ecosystem, building - environment, and building scales. Examples of ecosystem scale metrics include Ecological Footprint, Surplus Biocapacity Measure, Environmental Sustainability Index, Wellbeing Index, etc. Examples of building - environment metrics include rating systems such as Green Globes, LEED™, BREEAM, etc. Finally, the building scale metrics include net energy, zero energy, LC-ZEB, NZE, etc. This section does not include all possible frameworks, tools and metrics that are currently in use. Only those with established methodologies, adequately tested and applied are included in this chapter.

The following sub-sections map the various sustainability frameworks, analytical tools, and metrics and offer tool users clarity on the hierarchy of measurement sciences in the yet-to-be-formulated "science of sustainability." Additionally, it makes a case for the use of a particular type of analysis tool for the purposes of this dissertation which is discussed at the end of this chapter.

### 2.3.1 Sustainability Assessment Frameworks

In most cases, prior to proceeding with major projects, environmental impact studies are conducted by specialists. Such studies are part of the larger sustainability framework to assess project impact on the environment. Sustainability frameworks are integrated and structured procedures that meet a pre-determined objective. Such approaches should be well structured, integrated, and organized to respond to three inquiries (Ness et al., 2007) namely – (are the tools capable of integrating nature-society systems?; is the tool capable of assessing different scales or spatial levels?; and, are the tools able to address both the short and long-term perspectives?) One significant and noticeable characteristic of frameworks is that they do not explicitly specify the different analytical tools that may be used for such analysis. However, selection of a tool is of utmost importance, because if it is not properly identified for the stated purpose, it may provide a distorted sustainability evaluation (Gasparatos, 2010).

Among others, two major frameworks that have gained traction are the Environmental Impact Assessment and Strategic Environmental Assessment and they are part of the legal requirements for evaluating many projects and policies (Gasparatos et al., 2010). The Directives 97/11/EC (EC, 1997) and 2001/41/EC (EC, 2001) have rendered both EIA and SEA as legal requirements in the European Union. Through comparison of different project alternatives' environmental impact, these frameworks evaluate and assist in the decision-making process.

### Environmental Impact Assessment

The Directive 85/337/EEC on "the assessment of the effects of certain public and private projects on the environment" by the Council of Environment Ministers of the European Communities is referred to as the Environmental Impact Assessment. The Environmental Impact Assessment is expected to conform to four basic principles (Robert, 1988) – (a) identification of the proposed and induced activities; (b) identification of environmental elements affected; (c) evaluation of initial and subsequent impacts; and (d) management of the beneficial and adverse impacts which are generated. EIA outcomes are presented on an objective basis which then is used for decision-making. At the end of the assessment, an audit is conducted to compare actual impacts with those that were predicted during the assessment. Additionally, the success of mitigation measures is validated.

Environmental Impact Assessment is undertaken for larger global projects and primarily focuses on the environmental elements affected. However, it is to be noted that the "scale" at which the EIA study is conducted is vital for the study outcome. Scale as *spatial extent* and scale as *geographical detail or granularity* affect project analysis. Scale issues are discussed in Joao (2002). Several EIA study examples at varied scales can be found in academic literature such as water quality (Osterkamp, 1995), landscape studies (Meentemeyer and Box, 1987), ecology (Fernandes et al., 1999), etc.

#### Strategic Environmental Assessment

In a Strategic Environmental Assessment framework, the strategic decision-making takes into account the environmental considerations in support of environmentally sound and sustainable development (UNECE, 2007). The framework uses a step-by-step, methodological approach through mapping plan / policy or program / project making them relevant to sustainability assessment. The steps include definition of objectives; formulation of alternatives; scenario analysis; environmental analysis; valuation and conclusions (Nilsson et al., 2001).

However, it does not recommend the "best" analytical tool to be used for the analysis. Needless to say, the quality of the analysis through the use of the analytical tools is critical because it is the vehicle that provides necessary information to decision-makers. Gasparatos (2007) discussed the Strategic Environmental Assessment as an example to show differences between evaluation tools and frameworks. Such assessments have been effective for evaluating several applications including energy policies (Nilsson et al., 2001).

Both Environmental Impact Assessment and Strategic Environmental Assessment frameworks may be used to evaluate impact to the environment particularly at a larger scale. Depending on the project to be evaluated, evaluation tools and metrics may be selected to be part of the framework. The selection must coincide with project objectives and specific outcomes that are required to enable environmental decision-making. The following sub-sections discuss a set of evaluation tools and metrics specific to buildings.

### 2.3.2 Sustainability Evaluation Tools

Sustainability evaluation tools have been developed to support conscious environmental decision-making. Such tools may be broadly classified as reductionists and non-reductionists tools. While a reductionist tool measures the performance by reducing to a fewer set of variables and integrating measurable characteristics of the project, non-reductionist tools incorporate methodological choices that are subjective. However, the selection of the evaluation tool lies with the analyst's particular worldview (or subject of expertise), which is ultimately projected upon a particular project. In this case, the tool becomes the yardstick to evaluate the sustainability of the project at hand (Gasparatos, 2010). Since the dissertation focuses on environmental building design, only tools related to buildings are discussed below.

#### 2.3.2.1 Reductionists Tools

A reductionist tool uses a single measureable indicator, a single dimension, a single objective, a single scale of analysis and a single time horizon (Munda, 2006). For example, Cost benefit Analysis is a type of reductionist tool where "cost" is the single indicator used for evaluation. In other words, it can be stated that a "common denominator" approach is taken to deduce diverse aspects to a set of numbers for analysis. There are several types of reductionists tools namely economic and monetary tools; biophysical models and thermodynamic methods; performance evaluation tools; and building energy analysis.

Economic and monetary tools use cost as an indicator for evaluation. Examples include Cost Benefit Analysis and Whole Life Costing. Biophysical models and thermodynamic methods use some physical quantity as the indicator to determine what was required for the production of goods / services. Examples include exergy analysis, thermo-economics, LCA, embodied energy, thermodynamic input-output analysis, and emergy analysis.

The economic and biophysical tools, although they use a reductionist approach, have dissimilar perspectives in their evaluations. While the former uses currencies, the latter uses physical units. In other words, economic models use an "anthropocentric perspective" approach to valuation while the biophysical tools use an "eco-centric perspective" (Gasparatos, 2010).

Performance analysis tools use energy (use) as an indicator for evaluation. Such tools can be either of prescriptive or performance type. While the prescriptive approach confirms within energy standards, the performance option goes beyond minimum energy standards. Building energy analysis tools are a type of performance analysis tools. These tools enable whole-building energy analysis for in-depth assessment of building energy.

## Economic and Monetary Tools

Economic and monetary tools use "currencies" as a common denominator. Thus, by measuring performance of projects using a common denominator, the project is evaluated. Since these use a single measurable indicator, they are examples of reductionist tools. Cost Benefit Analysis and Whole Life Costing are types of economic and monetary tools.

### *Cost Benefit Analysis and Whole Life Costing*

Cost Benefit Analysis and Whole Life Costing are approaches to economic decision-making. Cost Benefit Analysis is evaluated based on the public's willingness to pay (to benefit from) or to accept a compensation (to avoid) consumption of the commodity. The relevant costs and benefits are computed at present value. Therefore, in order to determine future costs and benefits, a discount rate is introduced. Typically the discount rate (interest) applied is drawn from financial markets which may, at times, prove contentious as they may not adequately correspond to future environmental impacts. In other words, it is primarily focused on efficiency in the allocation of resources. Similarly, the objective of Whole Life Costing is to minimize costs throughout the life of the asset. This tool uses both initial and operational costs. This is comparable to Life Cycle Cost which refers to the total cost of ownership. However, it oversimplifies environmental problems by collapsing them into a monetary dimension.

For environmental building design that focuses on sustainability at a geobiosphere level, biophysical models and thermodynamic methods may be apt when compared to Cost Benefit Analysis and Whole Life Costing.

## Biophysical Models and Thermodynamic Methods

Biophysical models and thermodynamic methods for analysis of a good/service provide an acceptable measurable method to evaluate resources used in the production of the same. The common denominator in this case is a physical measure of the "natural capital" (or resources) invested for the production of the good/service. Most biophysical models allow substitution within the same form of natural capital or resource and not between different forms of capital, emergy being the exception, since the normalization of quality between different resource types is performed when converting any quantity into emergy. Several tools such as exergy analysis, Life Cycle Assessment, embodied energy and thermodynamic input-output analysis, emergy analysis, etc., are examples of biophysical models.

### *Exergy Analysis and Thermoeconomics*

Exergy, like energy and entropy, is a thermodynamic concept . The concept of energy does not show the quality and consumption aspects as it focuses entirely on quantity (of use). Exergy provides some data related to the quality of inputs and offers information on efficiencies. For each energy transfer, there is a corresponding exergy and entropy transfer. Exergy analysis is another thermodynamic-based framework that may be adopted as an evaluation tool for environmental building design. Exergy heat transfer depends on both the system and the (temperature of) the reference environment. In other words, it depends on the temperature at which an action happens relative to the background temperature of the external environment. Several exergy-based research studies have been made to investigate building components such as heating system evaluation (Balta et al., 2008); residential buildings (Saidur et al., 2007; Zmeureanu and Wu, 2007); heating and cooling systems (Schmidt et al., 2004); daylighting, electric lighting and space cooling systems (Taufiq et al., 2006), etc. However, as this dissertation focuses on a geobiosphere scale for accounting all energies for an environmental building design, exergy analysis was not employed.

### *Life Cycle Assessment*

Life Cycle Assessment is a tool to assess the environmental impacts and resources during a product's life-time. Its primary objective is identifying emissions and their impact during the life cycle of a process. Life Cycle Assessment is comprised of four phases namely goal and scope definition; inventory analysis; Life Cycle Impact Assessment and interpretation. The Life Cycle Impact Assessment evaluates the potential environmental impacts of a product. It involves selection of impact categories, assignment of the inventory data to impact categories for appropriate classification and quantification of the contributions from the product to the chosen impact categories.

Through expanding the boundaries of the study and with suitable information on allocation, environmental accounting may be pursued. However, Burgess and Brennan (2001) provide in-depth data related to the shortcomings of LCA. Other issues include setting the boundaries, allocation through proportionally distributing the responsibility for inputs used (resource consumption) and undesired outputs (emissions) of a process, costs of data collection as LCA strongly relies on the quality of the data, etc.

Nevertheless, several attempts were made to use Life Cycle Assessment for building evaluation, the most recent and notable being the Life Cycle-based Zero Energy Building or LC-ZEB (Hernandez and Kenny, 2010). LC-ZEB is a simplified methodology to include embodied energy of building components together with energy use in operation. Embodied energy includes the primary energy use such as fuel, nuclear, hydro-electric, etc., for the production of raw materials to construction completion.

For a building to achieve LC-ZEB status, the annual energy use must be negative to such an extent to compensate for the already-consumed embodied energy in buildings. Although the research approach attempts to follow ecological modeling principles, there are shortcomings such as non-inclusion of material formation in Life Cycle Assessment; the selection of primary energy as an indicator, in particular when renewable energies are considered; and the approach does not quantify progressive replacement of non-renewable by renewable resources to achieve net energy.

The most significant inadequacy that relates to this research is that Life Cycle Assessment lacks a rigorous thermodynamic framework which is elemental for analyzing ecosystems and in certain situations may even violate thermodynamic laws (Hau, 2005).

### *Embodied Energy and Thermodynamic Input-Output Analysis*

Embodied energy, sometimes referred to as thermodynamic input-output analysis, includes the primary energy use such as fuel, nuclear, hydro-electric, etc., for the production of raw materials to construction completion. However, labor and environmental work of the geobiosphere is not included. Additionally, the embodied energy does not include the energy used by the built environment's space conditioning requirements and other uses (Stein et al, 1981). Such limitations do not offer a solution for in-depth analysis of a given product / service over its entire life-time and is disadvantageous for the purposes of this dissertation.

### *Emergy Analysis*

Emergy is an environmental accounting quantity that is based on the summation of all the available energy of one kind required directly and indirectly for the production of a product or service. Emergy analysis or emergy synthesis is a methodology that applies the principles of Energy Systems Theory to understand the holistic structure and function of all kinds of systems. Emergy methods apply thermodynamic principles governing equilibrium and non-equilibrium systems for environmentally conscious decision-making. In addition to providing a thermodynamic framework for the analysis of energy transformations, emergy analysis offers several indices for comprehensive evaluation of systems and sub-systems. In essence, emergy analysis uses thermodynamic principles for environmentally conscious decision-making. In other words, emergy analysis provides a "total environmental analysis" that goes beyond typical thermodynamics and includes all environmental and human energies involved in the system under investigation.

Emergy is the available solar energy previously used, both directly and indirectly, in order to make a service or a product (Odum 1996; Odum, 1971; Odum 1983). Solar energy is used as a common denominator for all resources, services and goods. Thus, any product or service uses a common unit, "solar emergy joule" (sej), as the unit of emergy.

## TRANSFORMITIES AND BUILDING MATERIALS

There are three main types of unit emergy intensity values namely, "transformity," "specific emergy," and "emergy per unit money." Transformity is the solar emergy required to make 1 energy unit of a quantity (e.g., a Joule) of a product or service. Specific emergy is the emergy value per unit mass of material (kg). In other words, specific emergy provides the energy that is required to concentrate materials. Emergy per unit money is used to convert monetary benefits into emergy values.

The emergy of a product can be calculated by multiplying energy quantities (J) by its transformity. Solar transformity of a product is its solar emergy divided by its available energy,

$$M = \tau B \tag{2.1}$$

M is energy (J), $\tau$ is transformity (sej/J) and B is available energy.

The solar transformity of the sunlight absorbed by the earth is 1.0 by definition. Transformities are calculated based on the production process. This leads to changes in transformities of the same product by different production processes. For example, the transformities of concrete varies by production process and location (U.S., Italy, etc.). Transformity measures the position of any energy flow or storage in the universal energy hierarchy (Odum, 1998). Using transformities, the emergy values of materials can be computed, see tables C-1 to C-10. Emergy is the product of available energy and transformity.

Additionally, transformities are measured relative to a baseline. The baseline is developed using the three primary energy source such as solar radiation, heat generated from deep earth, and the gravitational attraction of the sun and moon (Odum, 1996; Campbell, 2000). Transformities used in this dissertation use $9.44 \times 10^{24}$ sej/yr baseline.

Several research projects have been conducted to develop transformity values, most notably Buranakarn (1998) for building materials. Transformities related to building materials are listed in Appendix A.

## EMERGY DIAGRAMMING AND TABLE

A general methodology for emergy evaluations is discussed in Odum (1996); Brown and Ulgiati (1997); and Ulgiati and Brown (2001). The Energy Systems Language and symbols are used to describe ecological and socio-economic interactions (Odum 1994). The first step of the emergy evaluation is the diagramming of the system and sub-systems, figure 2. This diagram provides relationships between components and pathways of resource flow. The diagrammatic representation shows the system boundary using a rectangular frame. A hierarchical order of quality is used to locate the systems from left to right.

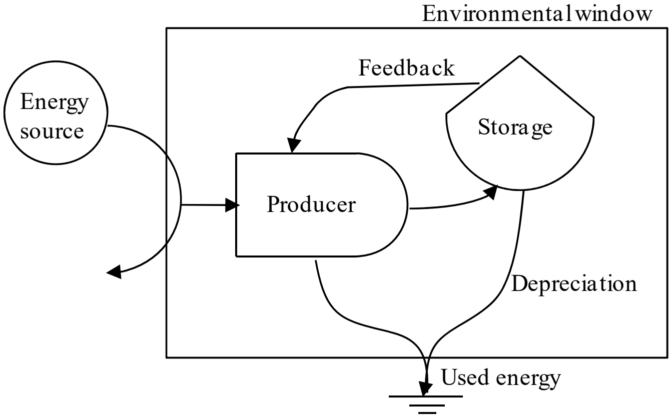

**Figure 2. Emergy diagram.**

In addition to the diagram, an emergy table is also constructed using the format suggested by Odum (1996) with six columns, from left to right in the following order: "footnote," "item," "input resource (J,g,$)," "Solar Emergy per unit (sej/J, sej/g, sej/$)," "Solar Emergy," and "Emdollar (Em$/yr.)," table 1.

**Table 1. Emergy table.**

| Footnote | Item | Input Resource (J, g, $) | Solar Emergy per unit (sej/J, sej/g, sej/$) | Solar Emergy | Emdollar (Em$/yr) |
|---|---|---|---|---|---|
| | | | | | |

EMERGY INDICES

Among others, four emergy indices are used predominantly in the literature. They are Emergy Investment Ratio (EIR), Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR) and the Emergy Sustainability Index (ESI). EIR is the ratio of purchased emergy feedback from the economy (services and other resources) to the free emergy inflow from the environment. EIR measures the intensity of the economic development and the resulting loading of the environment (Odum, 1996). The Emergy Sustainability Index is the ratio of the Emergy Yield Ratio to the Environmental Loading Ratio.

Emergy Yield Ratio is the ratio of the emergy of yield from a system to the emergy of the purchased inputs from the economy. In other words, EYR can be stated as the ratio of emergy yield to emergy of all the feedbacks from the economy including fuels, fertilizers, and services. Thus, EYR is a measure of its net contribution to the economy beyond its own operation,

$$EYR = M_P/M_F \qquad (2.2)$$

$M_P$ is emergy of the product $P$ and $M_F$ is the emergy of economic resources in the feedback from the larger system.

The Environmental Loading Ratio is the sum of the feedback emergy from the economy and emergy from non-renewable resource use divided by the emergy from the renewable resources. It indicates the potential stress on the local environment,

$$ELR = (M_F + M_{NR}) / M_{RR} \tag{2.3}$$

$M_{NR}$ and $M_{RR}$ represent non-renewable and renewable emergy inputs respectively.

The Emergy Sustainability Index is the ratio of the Emergy Yield Ratio to the Environmental Loading Ratio. This index evaluates the integrated ecological-economic performance of the activity,

$$ESI = EYR/ELR \tag{2.4}$$

Emergy analysis uses thermodynamic principles for environmentally conscious decision-making. In other words, emergy analysis provides a "total environmental analysis" that goes beyond typical thermodynamics and includes all environmental energies involved in the system under investigation. Based on the above, emergy analysis tool is chosen for evaluating environmental building design.

## Performance Evaluation Tools

Building energy performance evaluation aids designers in analyzing various components of buildings in relation to the environment, both internal and external. Several modes of evaluating energy performance of a building exist namely, standards, performance tools, and performance indices and definitions. By complying with the prescriptive path of an energy standard, the building may secure a rating. On the other hand, performance tools use computer-based simulations and related protocols to assess building performance. Moreover, building performance indices and definitions characterize buildings based on their overall energy consumption over a period of time (for example, Net Zero Energy buildings).

Standards are technical documents that provide instructions for designers and are recognized as a model of authority. However, there are several energy standards that have been developed over the past few decades to offer solutions in both simple prescriptive format (for easy implementation), as well as performance-based (for enhanced energy savings). While the prescriptive conforms within "energy standards," the performance option utilizes "performance tools" to demonstrate compliance. One such standard is the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) 90.1-2007 standard for the energy-efficient design of buildings except low-rise residential buildings (ASHRAE, 2007). Several states have adopted codes incorporating this Standard; these codes provide requirements for the building's envelope (insulation for walls, roofs, windows, floors, etc.), mechanical (equipment efficiency requirements, etc.) and lighting (wattage requirements, etc.), at a minimum.

ASHRAE's Advanced Energy Design Guides (AEDG) for small office buildings, small retail buildings, K-12 school buildings, small warehouses and self-storage buildings, highway lodging, small hospitals and healthcare facilities provide prescriptive paths for reducing energy consumption over 30% as compared to ASHRAE 90.1-1999 (ASHRAE, 1999). In addition, ASHRAE 189-2010 for the design of high-performance green buildings except low-rise residential buildings is the latest standard that offers prescriptive performance (ASHRAE, 2010).

The State of California's Title 24 is one of the most stringent energy efficiency codes practiced globally (CA Title 24, 2010). The International Energy Conservation Code (IECC) is the energy code adopted by several states (IECC, 2010). The International Residential Code (IRC) is also used for residential application (IRC, 2010). One of the most commonly adopted rating systems is the US Green Building Council's Leadership in Energy & Environmental Design or LEED (USGBC, 2010). LEED™ exploits existing standards and rates buildings. Among others, energy consumption through prescriptive approaches is allowed within the LEED™ framework.

Performance tools employ computer-based simulations to evaluate buildings. These buildings are rated based on their energy consumption,. For example, ASHRAE 90.1-2007 Appendix G, also referred as the "Performance Rating Method" provides a method for evaluating the performance of all proposed designs, including alterations and additions to existing buildings, except designs with no mechanical systems.

ASHRAE's new tool-based rating methodology for building energy consumption is the Building Energy Quotient Program (BEQP), which is another tool for performance evaluation (ASHRAE, 2009). This program relies on several standards, and measures both the energy the building is designed to use and the energy actually being consumed. US Environmental Protection Agency's (EPA) EnergyStar offers a performance rating system for existing buildings through identifying site and source Energy Use Intensities; commercial buildings are rated on a scale of 1-100 (EPA, 2010).

### *Building Energy Analysis Tools*

Energy analysis tools may be broadly classified into System Sizing Tools and System Performance Evaluation Tools (Axley, 2004). While System Sizing Tools help in sizing individual components, System Performance Evaluation Tools simulate a system to specified excitations. Tools may be differentiated into Macroscopic Analysis Tools – those that utilize fundamental conservation principles providing a whole-system analysis rather than room-specific data, and Microscopic Analysis Tools – those that utilize Partial Differential Equations (PDEs) to evaluate spaces.

The US Department of Energy's DOE-2 engine and US Department of Defense's BLAST engine aided the development of building energy analysis tools. ENERGYPLUS engine is the convergence of DOE-2 and BLAST and is currently updated regularly by Lawrence Berkeley National Laboratory. Currently, building energy analysis tools include the software tools for building energy and renewable performance simulation. Although most of these tools have undergone mandatory validation per US Department of Energy's requirements, they still do not comprise all possible design strategies implemented (Crawley et al., 2005).

In some cases, only a few tools have integrated new strategies and developments in building technologies. For example, Variable Refrigerant Flow systems have been deployed for cooling/heating for more than a decade, but currently only a handful of software tools can simulate such a system (e.g., Trane Trace™ 700, EnergyPro, etc.). The software tools use variants of the energy simulation engine; for example, eQuest™ and VisualDOE™ use different versions of DOE-2 engine, while DesignBuilder™ uses the ENERGYPLUS engine, and Trane Trace™ 700 uses its proprietary engine. Therefore, given the same geometrical design data and strategies, the results may vary if two software tools are used to implement the same design. For building energy analysis, envelope thermal performance calculation is a critical component that calls for further development for the reasons stated below.

Heat transfer through the building envelope is due to the temperature difference and may occur through one, two or all of the three heat transfer modes – conduction, convection and radiation. While conduction is based on the thermal property (thermal conductivity) of the envelope material and the temperature difference between the outside and the inside surfaces, convection occurs at the junction where the fluid (in motion) is in contact with the envelope surface. On the other hand, radiation arises when envelope bodies emit photons or radiant energy. In a whole building energy model, the building envelope characteristics such as the U-factor is input in the software for energy consumption estimation.

Thermal envelope calculation methodologies can be largely classified based on envelope material composition and heat transfer (spatial) dimensionality. In the material composition type, a mass wall and metal- or wood- framed wall may be categorized into separate groups. While a mass wall can be accurately computed using a "one-dimensional heat flow" method, the metal- or wood- framed wall will require a "two-dimensional heat flow" method (ASHRAE, 2009). The metal- framed envelope can be computed using the "isothermal-planes method" as the conductivities differ moderately from those of the adjacent materials in particular. The wood- framed envelope can be analyzed using the "parallel-path method" as the thermal conductivity of the dissimilar materials in the layer is rather close in value, within the same order of magnitude. Additionally, if the envelope includes materials with very high difference in conductivities (two orders of magnitude or more), a "zone method" or "modified zone method" are appropriate. Experiments carried out to evaluate multi-dimensional heat transfer show up to 44% errors in R-value calculations for metal-framed envelopes, using a one-dimensional approach (Kosny and Kossecka, 2002).

On the other hand, heat flow phenomena occur in all three-dimensions concurrently and spatially. All of the heat transfer methods discussed above are, in spatial terms, "uni-directional." In other words, these methods are simplifications of complex envelope assemblies in one-dimensional space, i.e., considering heat flows from the surface with higher temperature to a surface with lower temperature, in one particular direction. In reality, heat flow is three-dimensional, and may not be simplified to one-dimensional investigation. Several studies confirm the inaccuracies in one-dimensional approach over two-, and three-dimensional analysis in the actual testing of envelope assemblies (Kosny and Kossecka, 2000). Two-dimensional heat flow analysis solves issues related to thermal bridging in walls, windows and other envelope components unlike one-dimensional analysis. Needless to say, thermal bridges significantly affect energy performance of the envelope, and thereby, overall building energy consumption.

Currently, the hourly building energy programs used for energy consumption calculation cannot accurately represent the transient and multi-dimensional effects of envelope heat transfer. Each of the hourly building energy modeling software uses a different method to calculate heat flow transfer for envelope assemblies. It is possible to generate a series of response factors or transfer functions for the envelope, however complex it may be, and modify the existing hourly energy programs' source codes for accurate results. "Equivalent wall" concept, a simple one-dimensional multi-layer structure that replicates the thermal properties of an actual wall, including the dynamic thermal behavior, provides a step forward in envelope heat transfer modeling (Kosny and Kossecka, 2002).

Oak Ridge National Laboratory (ORNL) has developed an Interactive Internet-based Envelope Material Database for the whole-Building Energy Simulation Program. A hotbox test is used to calibrate the R-value situated in the envelope material database. The database provides a direct link to hotbox testing results, advanced three-dimensional heat transfer simulations, and whole-building energy analysis (ORNL, 2009). However, the database possesses a fewer number of envelope configurations for use by designers. However, ENERGYPLUS™ has improved ground heat transfer modeling through links to three-dimensional finite difference ground models. Until such programs with in-built multi-dimensional heat flow analysis exist, it is crucial to develop U-factors using other auxiliary programs, and input the relevant and more accurate data in existing hourly building energy programs to determine whole building energy consumption. Considering that almost all of building energy consumption studies are computed using such hourly energy programs, it is evident that the building energy consumption data is either over- or under-estimated. Currently, computing heat flow for two- or three-dimensions spatially is achieved by using auxiliary programs.

One of the tools used for such two-dimensional analysis is THERM. THERM is a finite-element heat transfer analysis tool using a steady-state conduction algorithm, CONRAD (Curcija et al., 1995). THERM's calculation routine evaluates conduction and radiation from first principles (Huizenga et al., 1999). Furthermore, three-dimensional heat transfer analysis using PDE-solvers can accurately address thermal bridge problems (Bloomberg, 1996; Posey and Dalgliesh, 2005).

Nevertheless, building energy analysis is an integral component of building sustainability. However, building energy analysis provides and aids in optimization of operative energy only. This dissertation expands the study to energy used in the formation-extraction-manufacturing and maintenance of the building.

#### 2.3.2.2 Non-Reductionists Tools

Non-reductionists tools integrate methodological choices which are subjective in nature that is they are particularly influenced by the analyst performing the analysis. MCA is an example of such a tool. In the case of MCA, subjective criteria are applied to data selection, criteria definition, aggregation and weighting (Messner et al., 2006). It is a family of indicator based techniques similar to composite indicators (Gasparatos, 2010). A type of MCA was used for renewable energy assessment (Gamboa and Munda, 2007; Madlener and Stagl, 2005). Since the aggregation of individual indicators does not take place, MCA is closer to the concept of strong sustainability (Gasparatos, 2010).

### 2.3.3 Sustainability Metrics

The third aspect of sustainability measurement science is metrics. Sustainability metrics rate the sustainability of a system. Since the measurement boundaries vary for systems, they can be categorized into three types namely ecosystem scale, building-environment scale, and building scale.

## Ecosystem Scale

Ecosystem-scale metrics enable the measurement and evaluation at a larger neighborhood or even at a regional aggregation. Examples of ecosystem–scale metrics include Ecological Footprint Analysis, Surplus Biocapacity Measure, Environmental Sustainability Index, Wellbeing Index, etc.

### *Ecological Footprint Analysis*

The human demand on Earth's ecosystems is measured in terms of Ecological Footprint Analysis or EFA (Rees and Wackernagel, 1996). In other words, it represents the natural resources of the earth that are required to sustain human populations. For example, a specific lifestyle may require a greater demand of Earth's resources. This demand can be plotted and compared against others for judging relative sustainability. Ecological footprints for several countries were developed as a measure of sustainability. Measurement boundaries vary depending on the stakeholder's requirements. The calculation procedures are standardized for widespread implementation and available at the Global Footprint Network.

### *Surplus Biocapacity Measure*

The Surplus Biocapacity Measure (SBM) assesses the sustainability of consumption patterns. In short, SBM is the difference between the country's ecological footprint and domestic productive area. Thus, it can be stated that the SBM of a country is a combination of its consumption, ecological space and population.

### *Environmental Sustainability Index*

The Environmental Sustainability Index (ESI) uses several indicators that assess the environmental, socio-economic, and institutional aspects of sustainability. It was developed by the World Economic Forum's Global Leaders for Tomorrow Environment Task Force, the Yale Center for Environmental Law and Policy, and the Columbia University Center for International Earth Science Information Network (WEF, 2010).

### *Wellbeing Index*

The Wellbeing Index (WI) assesses the wellbeing of humanity and ecosystems, equally weighed. While the Human Wellbeing Index (HWI) uses the health, population, household and national wealth, knowledge and culture, community, and equity, the Ecosystem Wellbeing Index (EWI) consists of land, water, air, species and genes, and resource use (Prescott-Allen, 2001).

### *Ecosystem Services Product and Subtotal Ecological-Economic Product*

While the Ecosystem Services Product (ESP) is the economic value of ecosystem services, the Subtotal Ecological-Economic Product is the sum of Gross Domestic Product (GDP) and ESP. These two sustainability metrics enable the evaluation of countries regarding their sustainability.

## Building-Environment Scale

Examples of Building-Environment scale include rating systems such as Green Globes, LEED™, BREEAM, etc.

### *Green Globes, LEED™ and BREEAM*

Green Globes is a building environmental design and management tool. The online tool provides assessment to new and existing buildings. LEED™ was developed by the US Green Building Council and this rating system uses a point-based system to evaluate the building and its environment in sustainability terms. Recently, the system has been revised with new weighting methodology and represented as points for tallying. Based on the points, the building is certified. On the other hand, BREEAM is a UK-based building rating system akin to LEED™. These rating systems assess the building and its environment.

## Building Scale

The building scale metrics include net energy, zero energy, LC-ZEB, NZE, etc.

### *Net Energy*

Net Energy is a technique for evaluation which compares the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form (Cleveland et al., 2006). Thus, Net Energy is the true value of energy to society (Odum, 1973). The difficulty with Net Energy is the definition of the boundary, similar to LCA methodologies such as non-inclusion of energy related to material formation. However, several terms have been developed to capture the essence of the larger Net Energy concept such as energy payback, energy return on investment (Hall, 2008), energy yield ratio, etc.

### *Zero Energy*

The Zero Energy metric is applied to balancing the energy delivered to a grid and energy used. This balance is maintained on an annual basis and specifically includes the life cycle energy associated with delivering the building and its components in addition to building operation. This is the significant difference with the Net Zero Energy metric.

### *Net Zero Energy*

Owing to the energy crisis, increased emissions and the depletion of fossil fuels, research and development in NZE technologies and integrated processes have attained greater and renewed interests among stakeholders, especially governments worldwide. NZE buildings achieve net annual operative energy balance. NZE is the culmination of several decades of research, development and practice in building design, construction and materials technology. NZE development goes beyond the boundaries of building design and construction, and utilizes scientific knowledge from other sciences such as physics for building-related thermodynamic processes (e.g., conduction, convection and radiation in the building envelope; airflow prediction using Computational Fluid

Dynamics, etc.), chemistry for building material compositions (e.g., polymer technologies used for roof coatings that turn black during winter months and white in summer months, etc.), biology through bio-organism-based technologies (e.g., Living Machines™ for waste water recovery onsite, etc.).

However, NZE definitions are still in the early development phase as new knowledge is drawn upon to revise and classify buildings. Currently, NZE can be identified based on boundaries determined by energy-flow and renewable supply options. While energy flow based NZE definitions are determined by means of segregating the boundaries of energy consumption and generation (site or source levels), and their quantification (energy quantity measured or energy costs), the renewable supply options based NZE definitions are established by way of demand-side location of site renewables. Derived from the buildings' energy consumption and generation (Torcellini et al., 2006), they can be categorized as Net Zero Site Energy (net energy consumption and generation, in kWh terms, with the site as the boundary), Net Zero Source Energy (takes energy source and losses associated with transmission and conversion into consideration), NZE Costs (net energy consumption and generation, in cost terms, within the site as the boundary) and NZE Emissions (through offsetting site emissions through sustainable purchasing from off-site sources; comparable to carbon-neutral strategies).

Net Zero Site Energy: A site Zero Energy Building (ZEB) produces at least as much energy as it uses in a year, when accounted for at the site.

Net Zero Source Energy: A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.

Net Zero Energy Costs: In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.

Net Zero Energy Emissions: A net zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

On the other hand, demand-side renewable supply options based Net Zero Energy definitions (Crawley et al., 2009) such as "on-site supply options," and "off-site supply options" offer definitions based on renewable site locations.

However, approaching a NZE building goal based on current definitions is flawed for two principal reasons – current NZE definitions deal with operative energy quantities and related emissions, and they do not establish a threshold which ensures that buildings are optimized for reduced consumption before renewable systems are integrated to obtain an energy balance. More importantly, for a building design strategy that aims to contribute to the larger goal of global sustainability, it must acknowledge that a building relies on the geobiosphere for its very existence right from its start. This dissertation develops a method to maximize renewable resource use through emergy analysis to close the gap between current environmental building design and the over-arching goal of creating buildings that contribute to the overall sustainability of geobiosphere. The following chapters discuss in detail the methodology to assess buildings to achieve a Renewable Emergy Balance status.

### *Life Cycle-based Zero Energy Buildings*

Life Cycle-based Zero Energy Buildings is a simplified methodology to include embodied energy of building components together with energy use in operation over a defined life-time (Hernandez and Kenny, 2010). LC-ZEB status is achieved if annualized life cycle energy, the summation of annual energy use (operative energy, in this case) and the annualized embodied energy, is less than or equal to zero. For a building to achieve LC-ZEB status, the annual energy use must be negative to such an extent to compensate for the already-consumed embodied energy in buildings. For simplicity, the authors selected primary energy as an indicator for annual energy use in operation and for embodied energy. LC-ZEB uses the Net Energy Ratio, a factor to aid building design with a life cycle perspective, to evaluate building systems. Although the research approach attempts to follow ecological modeling principles, there are shortcomings such as non-inclusion of material formation in LCA; the selection of primary energy as an indicator, in particular when renewable energies are considered; the approach does not quantify progressive replacement of non-renewable by renewable resources to achieve “net energy.”

### *Em-Building Indices*

Yet another way of measuring building performance is using performance indices and definitions. While performance indices provide assessment opportunities for improved performance exploration, performance-related definitions offer broader compliance methodology. For example, “Em-building indices” were formed through a comprehensive evaluation of building materials, technologies and structural elements (Pulselli et al., 2007). Additionally, indices such as building emergy per person (“em-building per person”), building emergy/money ratio (“em-building money ratio”), building emergy per volume (“em-building volume”), etc., were developed for emergy assessment of a building.

Among the tools discussed above, for the purposes of this dissertation, emergy analysis was selected for assessing the building. The Emergy approach is well structured, integrated, and organized. The tool is capable of integrating nature-society systems. It is capable of assessing different scales or spatial levels – in this case, the building envelope optimization. More importantly, emergy analysis provides a “total environmental analysis” that goes beyond typical thermodynamics and includes all environmental energies involved in the system under investigation.

# 3. RENEWABLE EMERGY BALANCE IN ENVIRONMENTAL BUILDING DESIGN

Building materials may be broadly classified into renewable and non-renewable resources. From the initial formation over its life-time, each resource may be categorized by these two resource types. While renewable resources are beneficial for sustainability, a portion of the non-renewable resources may be exploited to develop renewable resources (Daly 1990; Odum and Odum, 2001).

Holling (1986) and Odum (1983; 1994) discussed the longer-range sustainable oscillation that includes four phases. This is a complete pulsing cycle of a system namely "growth stage," "climax (maturity)," "descent," and "low energy restoration." During the "growth stage," the competition that maximizes growth performance inhibits diversity and drains resources. This is followed by "climax (maturity)" during which the performance switches from being the most rapid exploiter of resources to being efficient. During "descent," will less energy, systems can only be sustained if diminished; this decline can be gradual or catastrophic. Finally, during the "low energy restoration", stage the production of net storages of resources through environmental processes is accomplished. Such a model can be represented as a pulsing model with two oscillating components, one that accumulates resources and one that consumes them (Odum 1999).

However, in the one-source model of a society operating on renewable energy alone, the potential exploitation of non-renewable resources for renewable assets in time makes the narrow renewable resource potential less competitive. Bastianoni et al (2009) have shown the theoretical possibilities of Odum's renew-non-renew model, figure 3. It is to be noted that renewable storage does not converge with non-renewable resources.

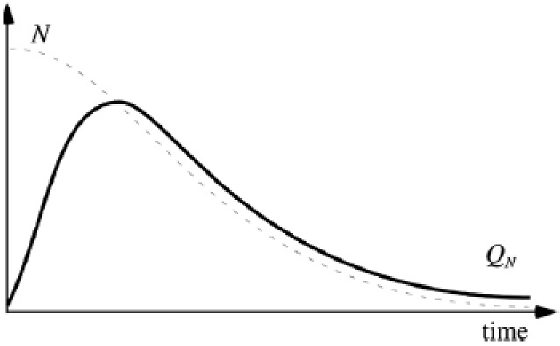

**Figure 3. Adapted from Bastianoni et al. (2009), "potential exploitation of non-renewable resources in time." $Q_N$ is the storage that can be supported by renewable resource after exploitation of non-renewable stock *N*.**

Odum's renew-non-renew model, also referred to as "two-source model," showed a progressive depletion of non-renewable resources - the third phase of "descent" - which once depleted cannot be replaced and they recognized as the final phase of "low energy restoration" (Odum and Odum 2001), figure 4. The pattern of this model is that non-renewable resources will be progressively replaced by the renewable ones.

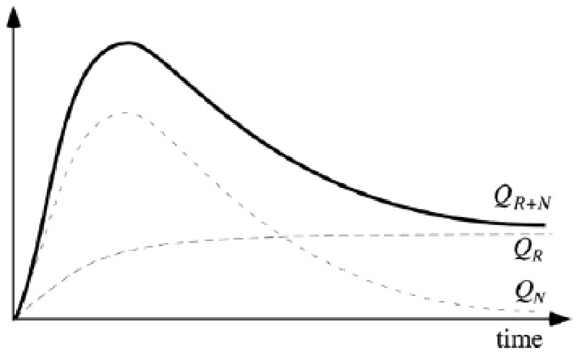

**Figure 4. Odum's "renew-non-renew model." Adapted from Bastianoni et al. (2009), "potential combined exploitation of renewable and non-renewable resources in time. Scenario: business as usual (current trend) implying a progressive exhaustion of non-renewables without improving the use of renewables." $Q_{R+N}$ represents the storage that is built using non-renewable resources ($Q_N$). While $Q_N$ depletes, renewable resource stock ($Q_R$) progressively improves.**

As the non-renewable resources are depleted, it is crucial that they be replaced with renewable ones. In other words, in the renew-non-renew model, the integrated system that uses different technologies to obtain energy to grow and power itself will be replaced by renewable ones. Daly (1990) proposed a pathway wherein non-renewable resources are substituted to generate renewable in line with a "quasi-sustainability" principle. Bastianoni et al (2009) have shown the theoretical possibility of using non-renewable resources to take advantage of renewable resources, figure 5.

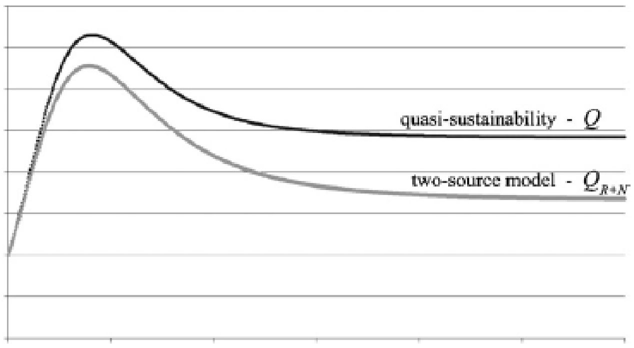

**Figure 5. Daly's quasi-sustainability model. Adapted from Bastianoni et al. (2009), "potential combined exploitation of renewable and non-renewable resources in time. The quasi-sustainability scenario compared to the two-source model." In this model, the permanent investment of non-renewables to further enhance renewable using the quasi-sustainability model ($Q$) proved rewarding as compare to two-source model ($Q_{R+N}$).**

The quasi-sustainability principle can be extended to buildings to develop metrics related to renew-non-renew substitution. In other words, as emergy accounting advances for a particular system, renew-non-renew of materials are appropriately identified. This requires identification and listing of non-renewable resources that have the potential to be substituted by renewable resources. For example, the electric energy from coal used in a cement manufacturing unit might be replaced with electricity generated from renewable resources such as solar, kinetic energy of wind, water or geothermal heat. Thus, the use of non-renewable resources to improve system capacity to exploit renewable resources permanently will aid a quasi-sustainable solution. Such resources that may be replaced with renewable resources possess the property "renewable-substitutability."

To give an example from Pulselli et al (2008), the specific emergy of concrete production is 1.81E9 sej/g, figure 6. The production has utilized materials (water, 1.89E6g; cement, 3.77E6g; sand, 6.79E6g; gravel, 1.06E7); transport, 2.11E7g; plant and machinery and human work. A detailed assessment of cement production shows energy inputs (electric energy, 2.93E14J; petroleum coke, 2.31E15; oil, 6.23E13); materials; special materials for quarrying; packing materials (paper bag, 1.51E9; polyethylene, 6.65E7; pallets, 1.31E3); water input, 3.18E11 and human work.

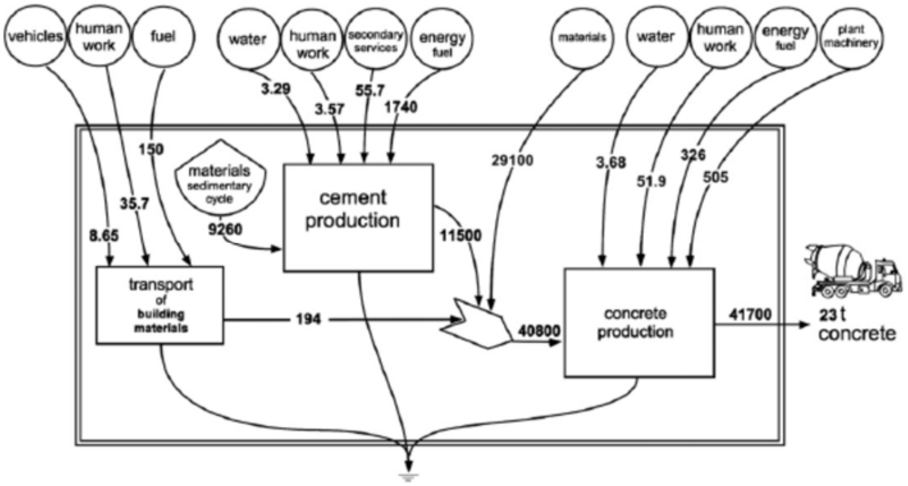

**Figure 6. Emergy diagram of concrete production. Values are in sej x $10^{12}$ (adapted from Pulselli et al., 2008).**

Considering only cement – a raw material for concrete – the renewable resources include water and paper bags. All others fall under the non-renewable resources category. Within the non-renewable resources category, all energy and water inputs have the potential to be replaced with renewable resources, hence hold some of the renewable-substitutability property. This then is extended to concrete; the non-renewable resource, transport, has renewable-substitutability. Transport is unique – the proximity of raw material from source to site reduces the non-renewable resource use, thus promoting sustainability. Alternatively, fuel with higher renewable resource content may be a solution to alter the renew-non-renew measure.

For buildings, the novelty of investing non-renewable resources to boost renewable resources permanently will shift towards self-sustenance in renewable emergy terms or a REB. Thermodynamically, a REB building preserves a balanced renewable-substitutability through investment (or progressive improvement) of all non-renewable resources with renewable-substitutability to develop renewable resources. For example, a particular building in a highly dense setting such as Manhattan, New York, can maximize renewable resource use under existing conditions, yet continue to connect, over its life-time, to on-site or off-site supply of renewable resources to compensate for all of the non-renewable resources with renewable-substitutability potential, thereby rendering the building an REB building.

The central aspect of Renewable Emergy Balance is the computation of an explicit quantity of renewable resources integrated over the building life-time, also referred to as the maximum renewable emergy potential of the building, after maximization of renewable resource use during the design phase of the building. This limit is a moving target and improves as the technology improves to integrate and/or generate more renewable resources. The significance of this limit is that it alleviates any ambiguity related to a benchmark that is required to achieve a higher level of sustainability.

Figure 7 illustrates the cumulative emergy use of a typical building. The duration (in yrs) between phases A and B represents the emergy content of the building materials through formation, extraction and manufacturing. The duration between phases B and C represents the building life-time during which the building uses energy for its day-to-day operations (operative energy) and for maintenance. Phases B1 and B2 represent building component replacement according to maintenance schedule during the building life-time.

Using emergy analysis and through the identification of renewable-substitutability of all non-renewables, the emergy content may be split into Renewable Substitutability potential and non-renewables. This identification of Renewable Substitutability is a significant component of the Renewable Emergy Balance. Appendix B lists the Renewable Substitutability and non-renewable portions of building materials. Table B-1 will be expanded to include all building materials.

This notion underscores the reality that non-renewable resources without renewable-substitutability may not be altered back to their original structure without expending resources. In other words, such resources may not be replenished to native form unlike the renewable resources particularly after diverse transformations that are required to make a product.

However, for those non-renewable resources with renewable-substitutability, there is a potential to be replaced by renewable resources and this should be exploited. Through emergy analysis, this definite quantity (maximum potential) to achieve Renewable Emergy Balance can be calculated. Moreover, as conscious decision-making over material selection prevails (as indicated in phases B1 and B2), the Renewable Substitutability potential and non-renewable split changes, thereby changing the maximum renewable emergy potential. This is evident in the lower portion of the graph showing the decrease in the maximum Renewable Substitutability potential over building's life-time.

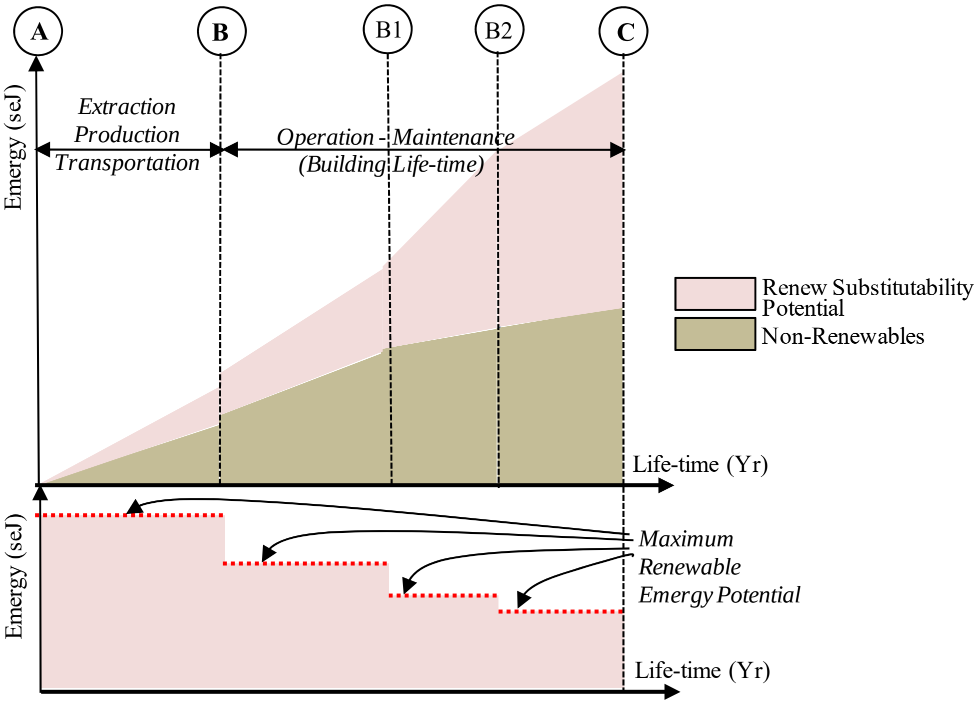

**Figure 7. Identification of maximum renewable emergy potential for Renewable Emergy Balance.**

The maximum potential is a moving target that improves based on improvements in renewable resources technology. Thus, the Renewable Emergy Balance over life-time of building is achieved by attaining the maximum renewable emergy potential.

Figures 8 and 9 represent typical scenarios based on renewable substitution. While the trend line (represented in dashed line-type) shows significant improvement leading to REB status in figure 8, the maximum renewable emergy potential increases over the building's life-time in figure 9. The latter may be due to inadequate measures undertaken during building operation and maintenance. Conscious decision-making is the key to achieving REB status. The advantage of this method is that the trend may be projected for the entire life-time. Based on actual realization of the building operation and maintenance, errors, if any, may be corrected for the remainder of the time period thus adjusting the accuracy of the maximum renewable emergy potential curve. Additionally, various alternatives may be simulated before they are implemented for the building project.

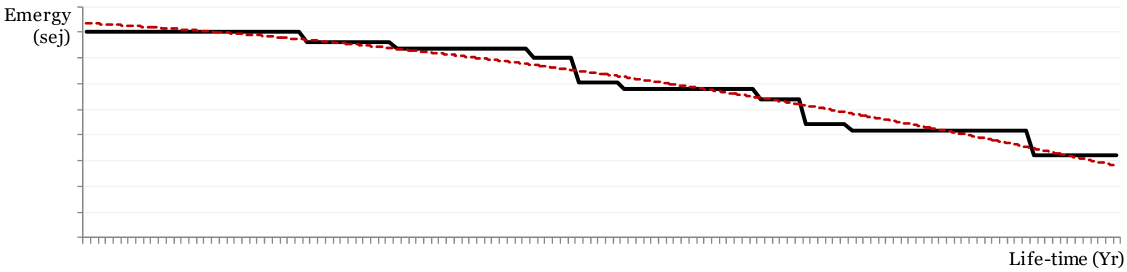

**Figure 8. Trend line of maximum renewable emergy potential showing improvement over building life-time and eventually leading to REB status with further renewable integration.**

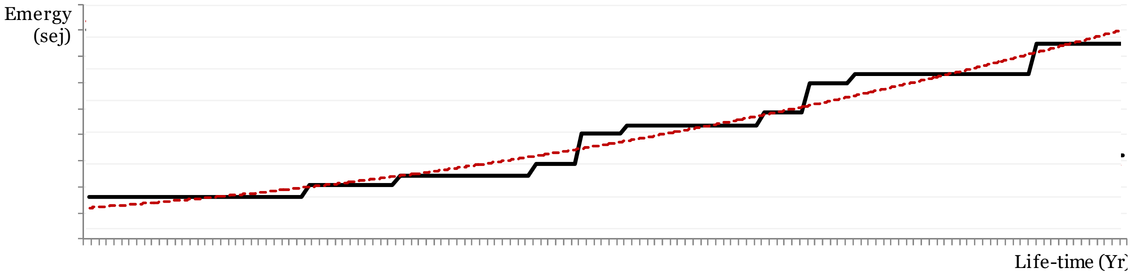

**Figure 9. Trend line shows that the building may not achieve REB status owing to decrease in renewable substitution over building life-time.**

Such an approach would expand conscious decision-making and, possibly, produce a paradigm shift in the way non-renewable energy is used in the manufacturing process of building materials. Thus, by progressive improvement, over the life time of the building, if all non-renewable resources with renewable-substitutability are replaced by renewable resources, the building achieves a Renewable Emergy Balance status. Such an order fits well within the quasi-sustainability principle of "a prosperous way down" Odum and Odum 2001).

This dissertation develops a method to maximize renewable resource use through emergy analysis to close the gap between current environmental building design and the over-arching goal of creating buildings that contribute to the overall sustainability of the geobiosphere. For the purposes of this dissertation, the system boundary includes the built environment, its components specifically that enable conditioning the thermal environment; however, it does not include building occupants. The objective of this study is to develop a maximum limit for renewable resource substitution, assess the performance of systems and maximize renewable resource use. The study proposes a Renewable Emergy Balance in environmental building design that maximizes renewable resource use through disinvestment in non-renewable resources that may be substituted with renewable resources. In order to achieve Renewable Emergy Balance status, a structured assessment method is followed as discussed in the next section.

# 4. RENEWABLE EMERGY BALANCE ASSESSMENT

Renewable Emergy Balance in environmental building design maximizes renewable resource use through disinvestment of non-renewable resources through renewable resource substitution. The building environmental system boundary includes the building structure, its components specifically that enable conditioning the thermal environment. However, the system does not include building occupants. In addition to the building structure, the building components comprise of the Heating, Ventilation and Air-Conditioning systems, electrical, lighting systems, the appliances and furniture that occupy the spaces.

The systems diagram of a typical building is presented in figure 10. The boundary of the system is defined as the building. The components are organized in a hierarchical order based on emergy quality from left to right such as the materials used in manufacturing and maintenance, building HVAC system, building structure, appliances, furniture, electrical systems including lighting, energy use (i.e., electricity, natural gas, etc.), material content of appliances, etc., and services.

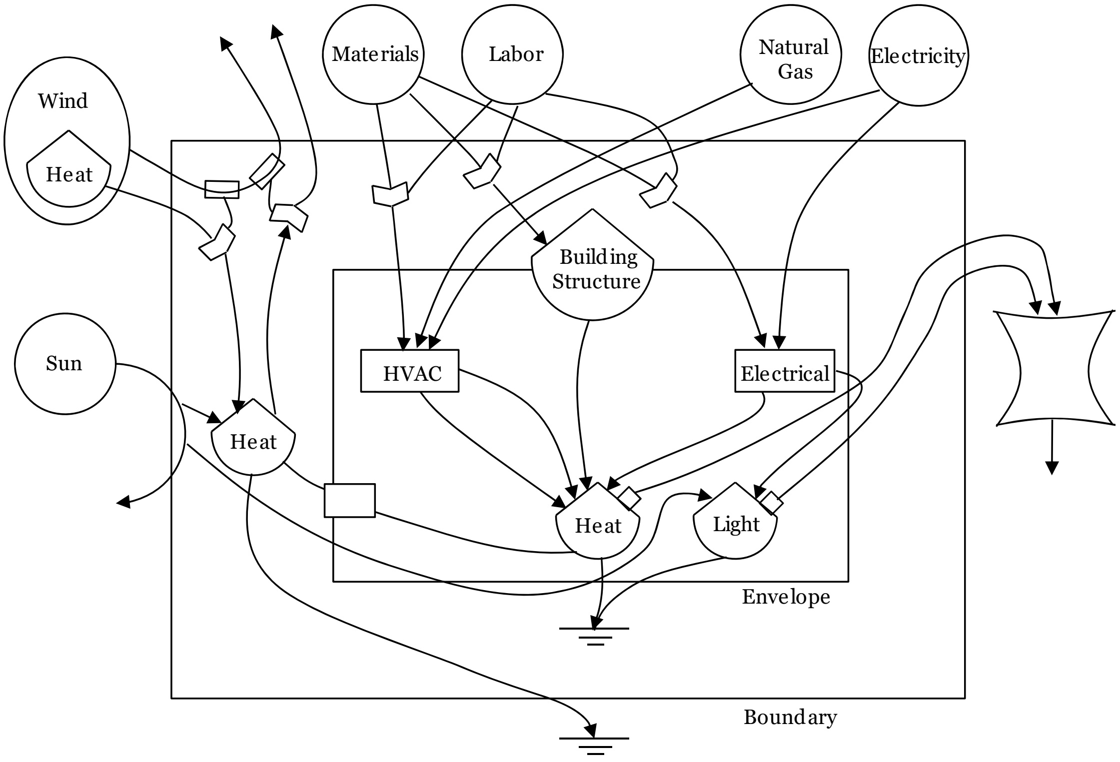

**Figure 10. Systems diagram of building environmental design showing energy pathways.**

The building structure is an important component of the system. The rectangular box represents the building envelope structure. Envelope structure enables heat transfer between the outdoor environmental conditions and building indoors. Based on the thermal conditioning requirements, heating or cooling may be necessary. Envelope structure is comprised of opaque and transparent surfaces. For opaque systems, heat is added to the interior spaces using conduction of heat through the structure. For transparent systems such as glazing, heat is added by conduction, convection and radiation. In addition to external renewable source using sun's solar radiation, any additional heating requirement is supplemented by HVAC systems. Heat is also generated by electrical systems. During the operation of electrical systems, heat is generated.

Transparent envelope systems enable heat transfer and daylight penetration. Daylighting, a renewable resource, using outdoor diffused lighting can provide a significant source of interior lighting. Additional lighting requirements may be satisfied using electrical lighting systems.

The objective of this study is to develop a maximum limit for renewable resource substitution, assess the performance of systems and maximize renewable resource use. The study proposes a Renewable Emergy Balance in environmental building design that maximizes renewable resource use through disinvestment of non-renewable resources that can be substituted with renewable resources. In order to achieve REB status, a structured assessment method is followed as discussed in the next section.

## 4.1 Methodology

Renewable Emergy Balance assessment is comprised of three components namely, the manufacturing and maintenance emergy analysis, the building operation emergy and the maximum renewable emergy potential, figure 11.

The manufacturing and maintenance emergy analysis component enables the calculation of emergy values split into renewable resources, Renewable Substitutability and non-renewable resources. Appendix B, specifically table B-1 provides the specific emergy values of building materials with Renewable Substitutability and non-renewable split. Tables B-2 to B-15 show emergy evaluation of building materials. Eventually, Table B-1 will be expanded to include all building materials. Appendix A, table A-1 shows the transformities of building materials without Renewable Substitutability and non-renewable split and may be used for those materials not found in table B-1.

This is followed by the building operation emergy component. In this component, building emergy use during operation is split into the three independent emergy portions (renewable resources, Renewable Substitutability and non-renewable resources). If the building is an existing facility, the operative energy use is obtained from historical data. If the building is a new facility and the evaluation is conducted during the design phase, a detailed energy model is developed to determine operative energy use.

Operative emergy use data is calculated by multiplying transformities of different energy source (i.e., electricity, natural gas, etc.) with corresponding usage values. Using the results obtained from the above two components, the maximum renewable emergy potential is computed.

The maximum potential is a moving target that changes based on improvements in renewable resource use during maintenance and other technological advancements in material manufacturing processes. Thus, by balancing the Renewable Substitutability values using renewable resources during the building life-time, Renewable Emergy Balance is achieved.

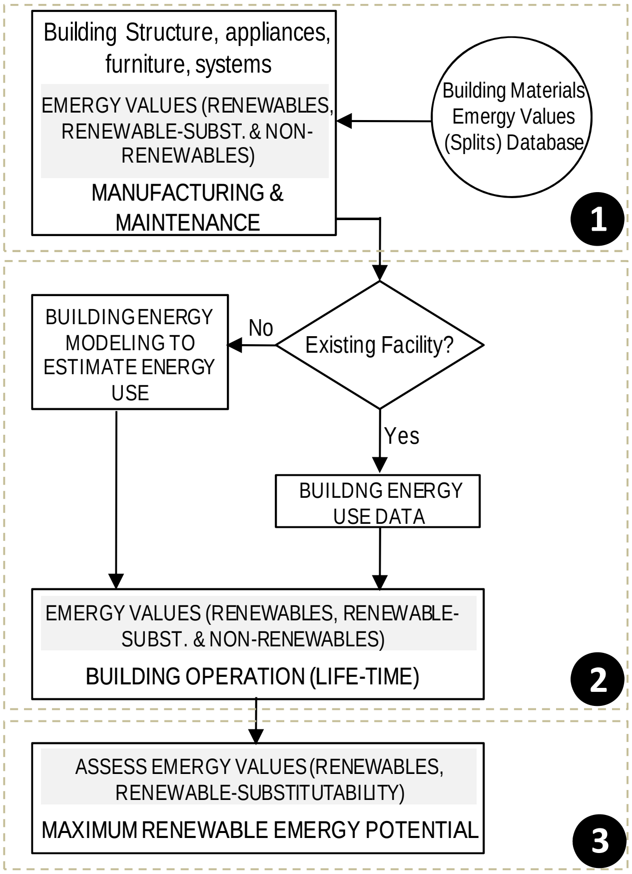

**Figure 11. Renewable Emergy Balance assessment structure.**

## Manufacturing and Maintenance Emergy Analysis

For every building component, the formation-extraction-manufacturing emergy quantity is assessed.

*STEP 1: Emergy analysis in "Formation-Extraction-Manufacturing"*

For each building component emergy data for formation-extraction-manufacturing is calculated. The emergy values are split into three portions namely renewable resources, Renewable Substitutability and non-renewable resources used. These values are available in the building materials emergy database. This database encompasses the most recent emergy data available for building materials. Odum and several other researchers have published material transformities. Such transformities are fundamental to this assessment. Therefore, the crucial task involves identifying and organizing all available emergy data for building materials with suitable references for easy access. The database corresponds to the formation-extraction-manufacture phase. As a building is studied in detail, the building material information is listed. These building materials are then matched to the transformities data to derive the emergy content. However, the existing literature does not include information related to renewable resources used and renewable-substitutability of the material composition.

Using the earlier example, portions of electricity and water drawn for cement production, in addition to oil use may be substituted using renewable resource. This quantity is tracked for all building materials. Thus, to measure renewable-substitutability of concrete, individual renewable-substitutability of raw materials for concrete such as cement, sand and water are used. The building materials emergy database is provided in Appendix A. Thus, the manufacturing emergy quantity of all building components is represented as,

$$\sum_{i=1}^{x} R_{manufacturing} = \sum_{i=1}^{x} (R_{mi} + RS_{mi} + NR_{mi}) \tag{4.1}$$

where $R_m$, $RS_m$ and $NR_m$ represents renewable, Renewable Substitutability and non-renewable emergy values of building materials manufacturing respectively.

The total emergy content is computed by evaluating every building component (represented as $x$).

*<u>STEP 2</u>: Emergy analysis in "Maintenance"*

Maintenance restores the depreciation of energy associated with building components. For example, building fenestration (glazing) is replaced in 30 years (Buranakarn, 1998). The building component replacement schedule is used to determine the emergy associated with replacement components.

Since new components replace old, worn out components, it is crucial to count only the difference in emergy values as opposed to adding the new replacement emergy values to the existing structure. It is important to select the replacement component based on its environmental performance and its renewable resource content.

The emergy values are split into three portions as discussed in *STEP 1*. Thus, the maintenance emergy quantity of all building components during its life-time is represented as,

$$\sum_{i=1}^{y} R_{maintenance} = \sum_{i=1}^{y} (R_{ni} + RS_{ni} + NR_{ni}) \tag{4.2}$$

where $R_n$, $RS_n$ and $NR_n$ represents renewable, Renewable Substitutability and non-renewable emergy values of building materials maintenance respectively.

The total emergy value is computed by including the difference in emergy values due to replacement of building component and this is conducted based on the maintenance schedule (represented as $y$).

## Building operative energy use

If the building is an existing facility, the operative emergy use is obtained from historical data. If the building is a new facility and the evaluation is conducted during design phase, a detailed energy model is developed to determine operative energy use.

*<u>STEP 3</u>: Operative energy use*

Operative energy use data is calculated by multiplying transformities of different energy source (i.e., electricity, natural gas, etc.) with corresponding usage values.

Similar to STEP 1, the emergy values are split based on their renewable, Renewable Substitutability and non-renewable content. Thus, the emergy quantity of all energy sources used during operation of the building during its life-time is represented as,

$$\sum_{i=1}^{z} R_{operation} = \sum_{i=1}^{z} (R_{pi} + RS_{pi} + NR_{pi}) \tag{4.3}$$

where $R_p$, $RS_p$ and $NR_p$ represents renewable, Renewable Substitutability and non-renewable emergy values of operative energy sources respectively.

The total emergy value is computed by adding emergy values due to building operation during its life-time (represented as $z$).

## Maximum renewable emergy potential

In order to maximize renewable resource use, the maximum renewable emergy potential is calculated for the building.

### <u>STEP 4</u>: *Maximum renewable emergy potential*

The maximum renewable emergy potential of the building is the addition of all Renewable Substitutability potentials during manufacturing, maintenance and operative phase of the building. Thus, it can be represented as,

$$\{\sum_{i=1}^{x} RS_{ni} + \sum_{i=1}^{y} RS_{ni} + \sum_{i=1}^{z} RS_{pi}\} \tag{4.4}$$

This emergy value when divided by the building life-time provides the annual maximum renewable emergy potential (see figure 7.2). Decision-making during design (selecting building materials during manufacturing), maintenance and operative energy use during life-time should aim at maximizing renewable resources used. The total renewable resource use is represented as,

$$\{\sum_{i=1}^{x} R_{mi} + \sum_{i=1}^{y} R_{ni} + \sum_{i=1}^{z} R_{pi}\} \tag{4.5}$$

In order to achieve Renewable Emergy Balance status, the renewable resource use should approach or be equal to the Renewable Substitutability of the building. This is represented below,

$$\{\sum_{i=1}^{x} R_{mi} + \sum_{i=1}^{y} R_{ni} + \sum_{i=1}^{z} R_{pi}\} = \{\sum_{i=1}^{x} RS_{mi} + \sum_{i=1}^{y} RS_{ni} + \sum_{i=1}^{z} RS_{pi}\} \tag{4.6}$$

During the building design (if the building is a new facility), conscious decision-making toward improving renewable resource use is important. Similarly, during replacement of building components for maintenance, it is important to identify materials that possess greater renewable resource content in addition to materials' environmental performance. Additionally, by virtue of reducing operative energy use during the building's life-time, the Renewable Substitutability associated with this phase can be significantly reduced. Again, this involves appropriate selection of energy source that maximizes overall renewable resource use to achieve Renewable Emergy Balance status.

# 5. RENEWABLE EMERGY BALANCE ASSESSMENT – CASE STUDY OF AN EXISTING FACILITY

The USEPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division at Narragansett, RI conducts sediment, water quality and ecosystem research in a variety of environments ranging from freshwater to marsh and estuarine to near shore marine environments along the Atlantic coast of the United States from Florida to Maine.

The property on which the laboratory is located is bounded by a residential neighborhood to the north, the University of Rhode Island's Bay Campus to the south, Narragansett Bay to the east, and the Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce to the west as well as open land belonging to the University of Rhode Island. The building includes wet laboratories and a greenhouse to provide areas for clean culture as well as for holding and performing research on marine and estuarine plants and animals. Tanks and wet tables are supplied with seawater that is unfiltered to maintain a natural food source or filtered to allow control of the food source with the addition of cultured algae or shrimp. Flexible systems allow for research using small aquaria for studying populations of small organisms to large tanks for holding and doing experiments with larger animals.

The building also contains chemistry laboratories that provide areas for analysis of water, sediment, and tissue samples for inorganic and organic contaminants, and acid-volatile sulfides in sediments as well as sediment grain-size analysis. In order to examine ecological effects on marine organisms, examples of special analyses that can be conducted include isotope ratio mass spectrometry for measuring stable isotopes of carbon and nitrogen in fish to identify connections in the food web and reconstructing historical conditions and cellular and sub-cellular structure studies. This laboratory also carries out a broad spectrum of research related to understanding the effects of anthropogenic actions on ecosystems oriented toward protecting human health and the environment.

## Existing facility description

The Main Office building, Wet Lab and Wet Lab Addition (Buildings #1 - #3 respectively) comprise the main facility buildings at the center of the site, figure 12. The Wet Lab Addition was constructed in 1975 as an add-on to the Main Office and Wet Lab buildings constructed in 1963. An Office Addition (Building #4) is an expansion constructed in 1999.

The Main Office building contains EPA administrative support functions as well as computer facilities. The old Wet Lab is a three story building and continues to house some laboratory functions; however, its current purpose is for the location of lab systems equipment, such as power generators and air pressure pumps for the Wet Lab Addition. The three story new wet lab addition houses chemistry labs and offices on the upper floor and houses a salt water experimental facility on the mezzanine and lower levels. The lab supports basic research functions and contains sample preparation areas, constant temperature and humidity chambers, test chambers, office support and storage rooms.

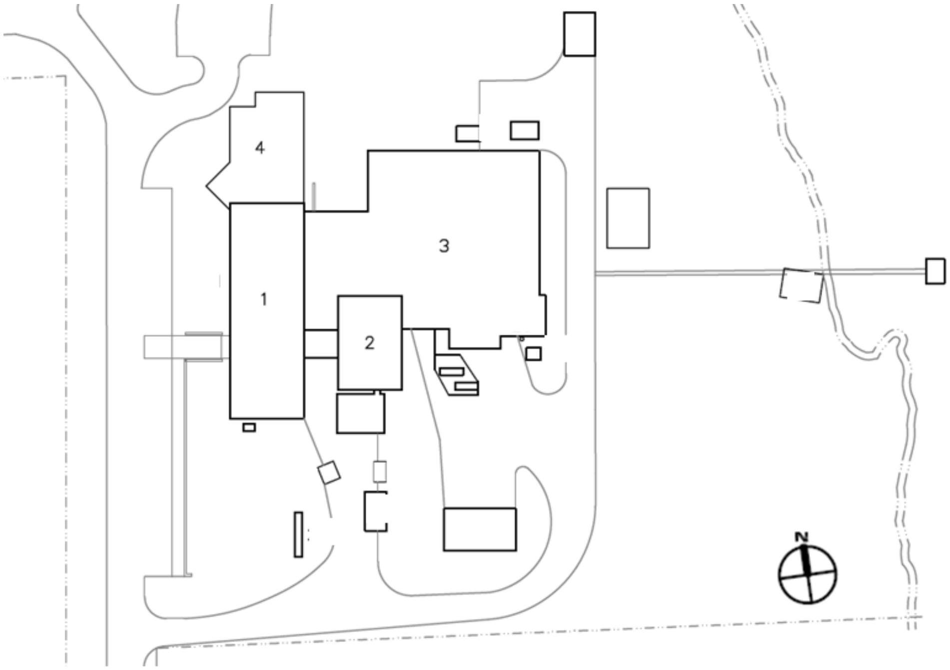

**Figure 12. Site plan showing NHEERL Atlantic Ecology Division buildings. (Building #1 – Main office; Building #2 – old wet lab; Building #3 – new wet lab; Building #4 – new office).**

The Chiller Plant located at the ground floor level consists of 3, 150 ton, water-cooled centrifugal chillers with associated cooling towers and pumps. It produces 42° - 54° F chilled water delivered to air handling units and sea water heat exchangers. The existing 50 ton air-cooled outdoor chiller is utilized for winter operation of sea water heat exchangers and for cooling the 1999 office addition.

The Boiler Plant is located at the ground floor level and consists of 2, 10.4 MBH (million BTUs per hour), low pressure fire tube steam boilers. Most of the steam is utilized by the original steam-to-hot water shell and tube heat exchangers. The hot water is delivered to reheat coils, preheat coils, perimeter radiation, and sea water heat exchangers.

The majority of the existing Main Building's electrical service and electrical distribution equipment was installed in 1963. This facility is currently being renovated as part of the Master Plan.

## 5.1 Building Structure Emergy Evaluation Methodology

The evaluation follows the *STEPS 1 to 4* discussed in Section 4. The manufacturing and maintenance emergy analysis component enables the calculation of emergy values split into renewable resources, renewable-substitutable and non-renewable resources. This is followed by the building operation emergy component. In the case of the NHEERL's AED building, as it is an existing facility, the historical energy use data is used. Using the results obtained from the above two components, the maximum renewable emergy potential is computed.

To illustrate the method proposed in this dissertation, the structures of Buildings #1 - #4 are studied. As building envelope structure is an enabler of energy-emergy flow, this case study focuses on the envelope structure only. In addition to developing the maximum renewable emergy potential possible for the building, the next section discusses a method to optimize the emergy quantities related to the envelope for better environmental performance.

### 5.1.1 Results

#### Systems Diagram

The building environmental system boundary includes the building structure, figure 13. The system does not include building occupants. The boundary of the system is defined as the building envelope (represented as a rectangular box). The components are organized in a hierarchical order based on emergy quality from left to right, for example, heating cooling, building structure, and lighting, also forcing functions are ordered from sun through fuels and electricity to the materials used in manufacturing and maintenance. The building structure enables heat transfer between the outdoor environmental conditions and building indoors. Based on the thermal conditioning requirements, heating or cooling may be necessary; these are represented as storages.

Building structure is comprised of both opaque and transparent surfaces. For opaque systems, heat is added to the interior spaces using conduction of heat through the structure. Transparent envelope systems enable both heat transfer and daylight penetration through the envelope. Daylighting using outdoor diffuse lighting can provide a significant source of interior lighting. Additional lighting requirements may be satisfied using electrical lighting systems. Thus, a pathway leads from sun to lighting to account for daylighting. Similarly, a pathway leads from sun to heating of the building structure. Additional lighting, heating and cooling can be achieved through electric energy sources.

In order to determine the maximum renewable emergy potential, all emergy quantities derived are split into three portions namely renewable, renewable substitutable and non-renewable resources.

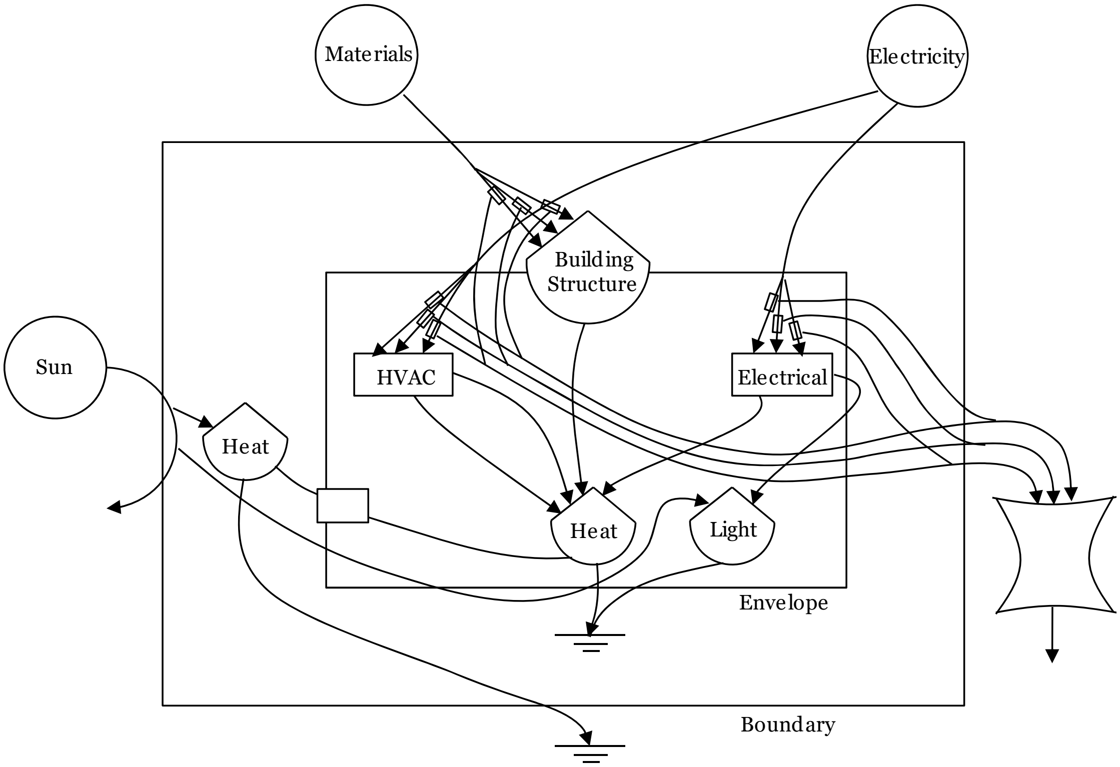

**Figure 13. NHEERL's AED building structure systems diagram showing emergy pathways.**

## Emergy Evaluation

The logic program symbol shown to the right of the system boundary receives information on the overall emergy splits due to building manufacturing, maintenance and operation. This symbol contains the related equations (4.1) to (4.6) from which the maximum renewable emergy potential and Renewable Emergy Balance status can be evaluated. Emergy analysis in building structure manufacturing shows 23% Renewable Substitutability for all buildings, table C-11. Building #4 shows the highest Renewable Substitutability, at 53%, due to large window-to-wall ratio as compared to the other buildings.

The emergy quantities due to building manufacturing are plotted over the buildings' life-times in figure 14. The horizontal axis tracks the buildings' life-times (typical building life-time considered for this study is 100 years after which it ceases to perform for the intended purposes). Since Buildings #1 to #4 were constructed during different time periods, the cumulative emergy quantities peak when all buildings were entirely built and operational. Phase A represents Buildings #1 and #2; phase B represents Building #3; and phase C represents Building #4. After the buildings' useful end-of-life periods, their emergy is deducted (refer phases C, D and E). Using the emergy splits, the Renewable Substitutability and non-renewable content is plotted. A total of 23% Renewable Substitutability is show in dashed line-type. The emergy values split into Renewable Substitutability and non-renewable quantities are available in Appendix C.

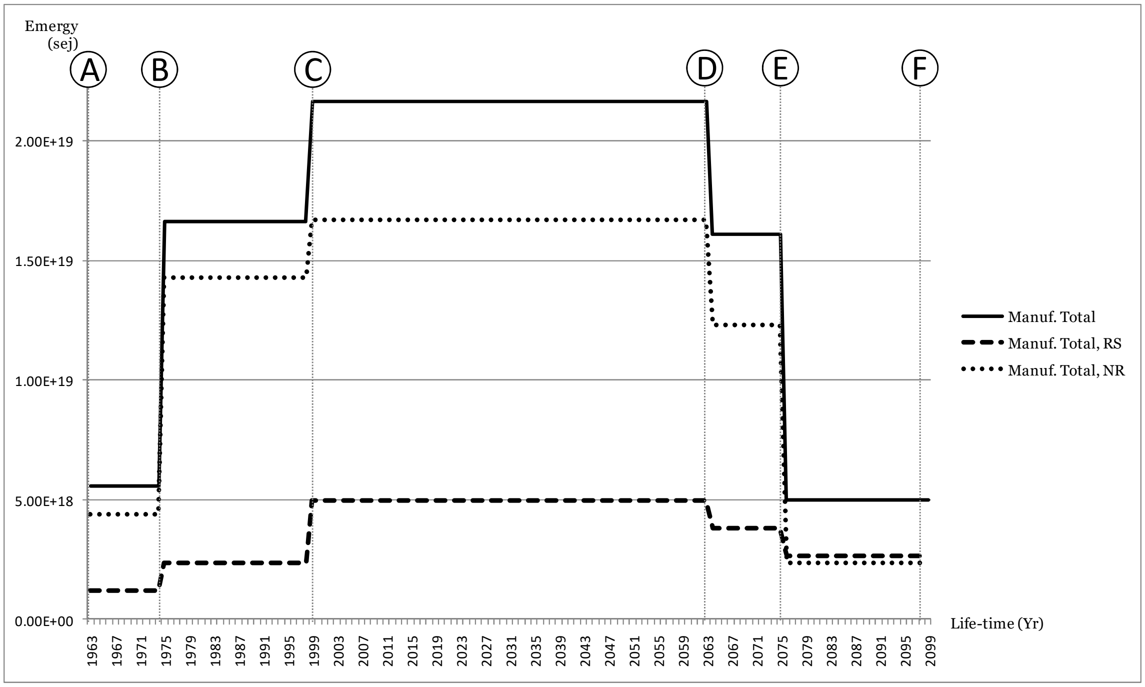

**Figure 14. Emergy values from building manufacturing (in sej). The emergy values shown above are cumulative. For example, when Building #3 is built (represented as Phase B), the cumulative value of Buildings #1 to #3 is reported.**

Using the maintenance schedule, the replacement of glazing is simulated. Glazing replacement is performed every 30 years (Buranakarn, 1998). The conventional float glass is replaced with in-house traditional recycling float glass product, table 2. The Renewable Substitutability of the replacement glass is high as compared to conventional float glass. Therefore, after replacement, the Renewable Substitutability of building emergy quantities will increase. Since new components replace old, worn out components, it is crucial to account only the difference in emergy values as opposed to adding the new replacement emergy values to the existing structure. It is important to select the replacement component based on its environmental performance and its renewable resource content.

**Table 2. Glass products used in the case study.**

| | | Specific Emergy (sej/kg) | |
|---|---|---|---|
| Item | Description | Renew-Substitutability | Non-Renewables |
| Glass | Conventional float glass | 6.22047E+12 | 1.65354E+12 |
| | In-house traditional recycling float glass product | 6.65031E+12 | 1.04008E+12 |

Figure 15 shows the emergy values from building maintenance. These schedules are represented as phases 1 though 9. First maintenance schedule for Buildings #1 and #2 is represented as phase 1. The stepped formation as noted in the illustration below is due to the cumulative emergy values due to maintenance of the buildings.

Since a glass product with higher Renewable Substitutability is used as a replacement, the total emergy quantity due to maintenance is negative. In other words, the Renewable Substitutability of overall emergy quantity is greater than one-half of the total.

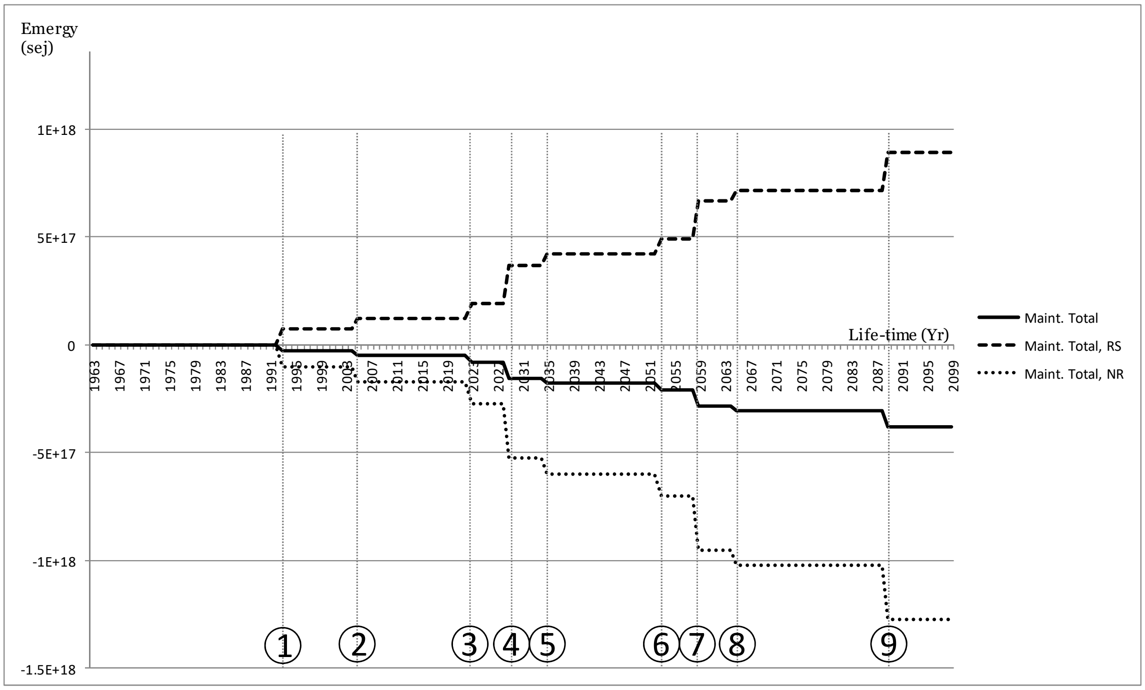

**Figure 15. Emergy values from building maintenance (in sej). Replacement of glazing per maintenance schedule is simulated. The emergy values shown above are cumulative. For example, when Building #3 undergoes maintenance (represented as Phase 2), the cumulative value of Buildings #1 to #3 is reported.**

Figure 16 shows the cumulative emergy quantities that combine both manufacturing and maintenance. It is to be noted that there is an increase in Renewable Substitutability quantities (shown in dashed line-type) owing to increased Renewable Substitutability potential from the replacement glass. Due to increased Renewable Substitutability potential of the replacement glass product, the Renewable Substitutability curve improves over the life-time of the building. A decrease in the non-renewable portion is noticed as the percentage of non-renewables decreases during maintenance.

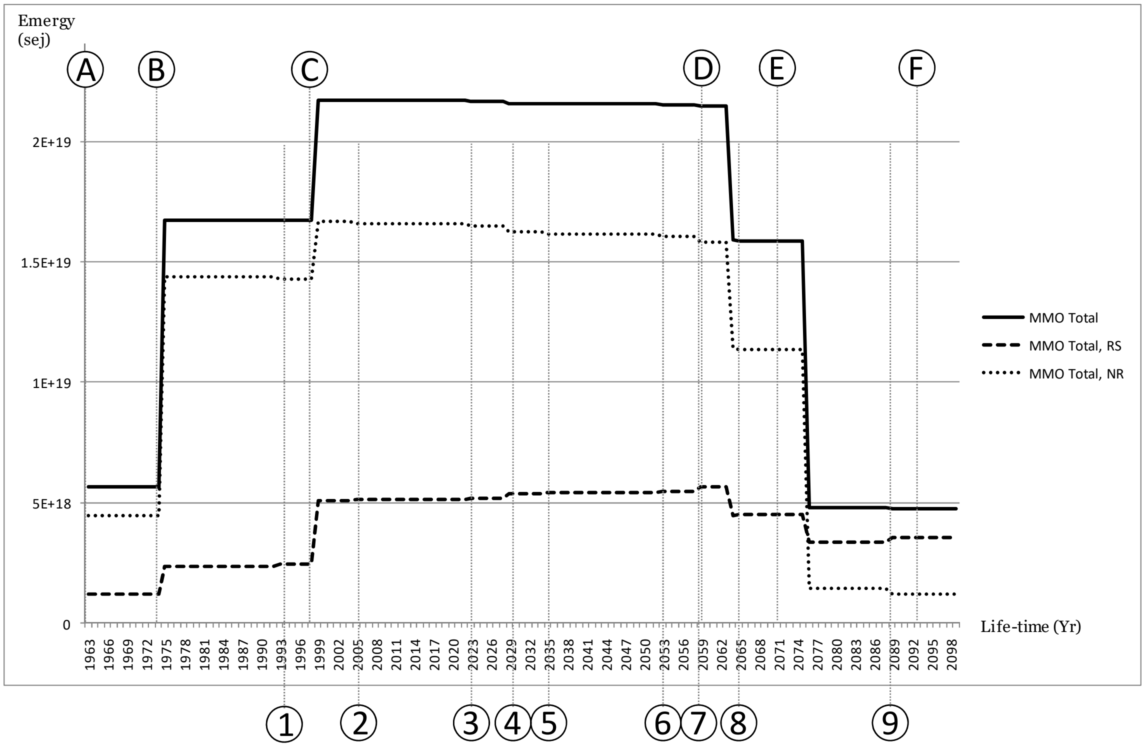

**Figure 16. Emergy values after combining building manufacturing and maintenance (in sej).**

As this study focuses on building structure, the effect of building envelope load is simulated using DOE-2 engine. Integrated daylighting algorithm was activated to include the effect of transparent surfaces to internal lighting loads. Since the building envelope comprised of varied type of envelope configurations such as spandrel glazed surfaces, masonry structure, etc., THERM is used to evaluate the U-factors of these individual envelope types. This then is used to develop a weighted-average U-factor for improved accuracy, refer Appendix D. Based on the location, building orientation and annual weather influence, the envelope and internal lighting loads equaled 2.19E+09 BTUs. This is the operational energy use of the building structure to maintain ASHRAE 55 interior condition. In 2009, total electricity generation in the U.S. was made up of 10.6% renewable generation (DOE, 2010). For this case study, a 10% Renewable Substitutability is assumed for operational energy source.

Figure 17 shows the cumulative effect of building manufacturing, maintenance and operational energy use. The maximum renewable emergy potential is the total Renewable Substitutability amortized over the buildings' life-time (as shown in vertical bars). In this scenario, as renewable resource is not included, the maximum renewable emergy potential does not converge to zero in order to balance the Renewable Substitutability. Thus, there is no improvement over time to balance the Renewable Substitutability.

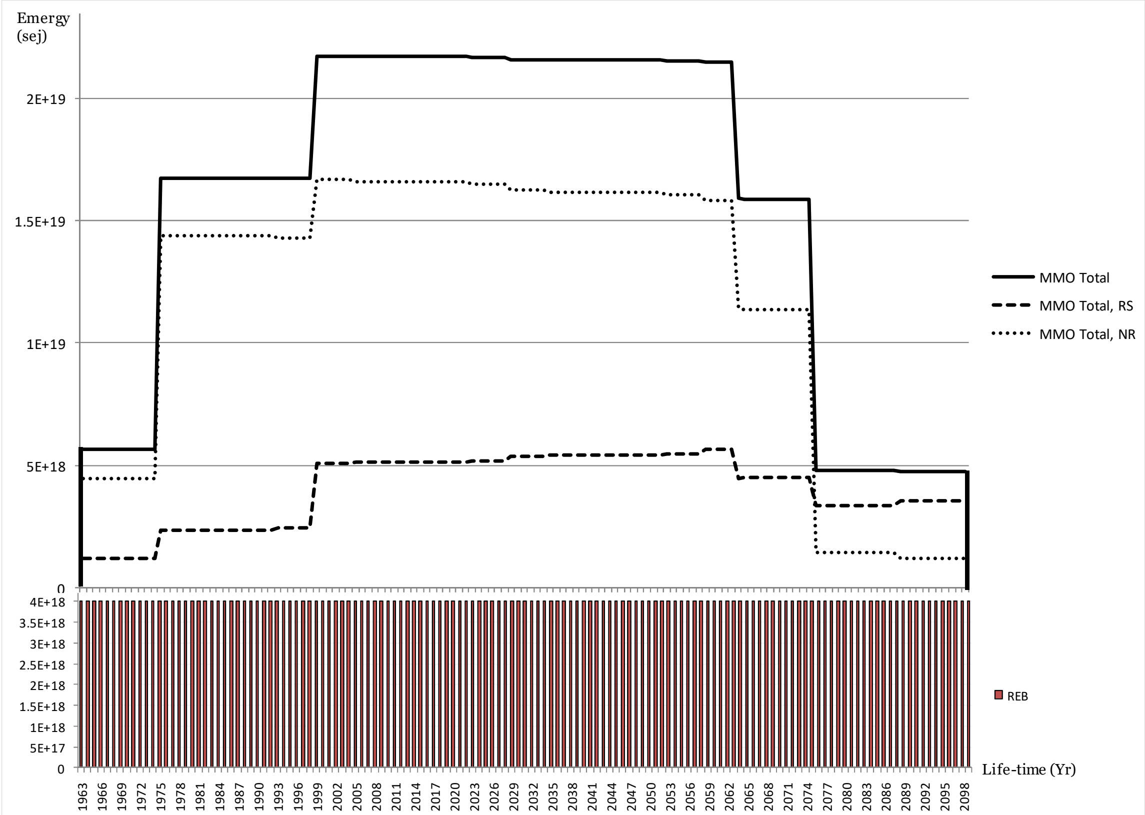

**Figure 17. Emergy values after combining building manufacturing, maintenance and operational energy use (in sej). Dashed line-type represents the maximum renewable emergy potential over buildings' life-time.**

To understand the influence of maximizing renewable resource use, a new scenario is developed. In this scenario, it is assumed that the replacement glass product includes a 15% (of total emergy quantity) renewable resource. The cumulative effect of this scenario is shown in figure 18. Through inclusion of renewable resource use in building maintenance, as an example, the maximum renewable emergy potential approaches zero (represented as vertical bars), thereby, attempting to balance the Renewable Substitutability. For any given year during the building lifetime, this illustration can be used to determine the renewable energy substitution that is required to balance the Renewable Substitutability. Thus, by introducing 15% renewable resource in the replacement glass product, a significant improvement is noticed to balance the Renewable Substitutability. The computation of emergy quantities and development of graphs follow equations (4.1) to (4.6).

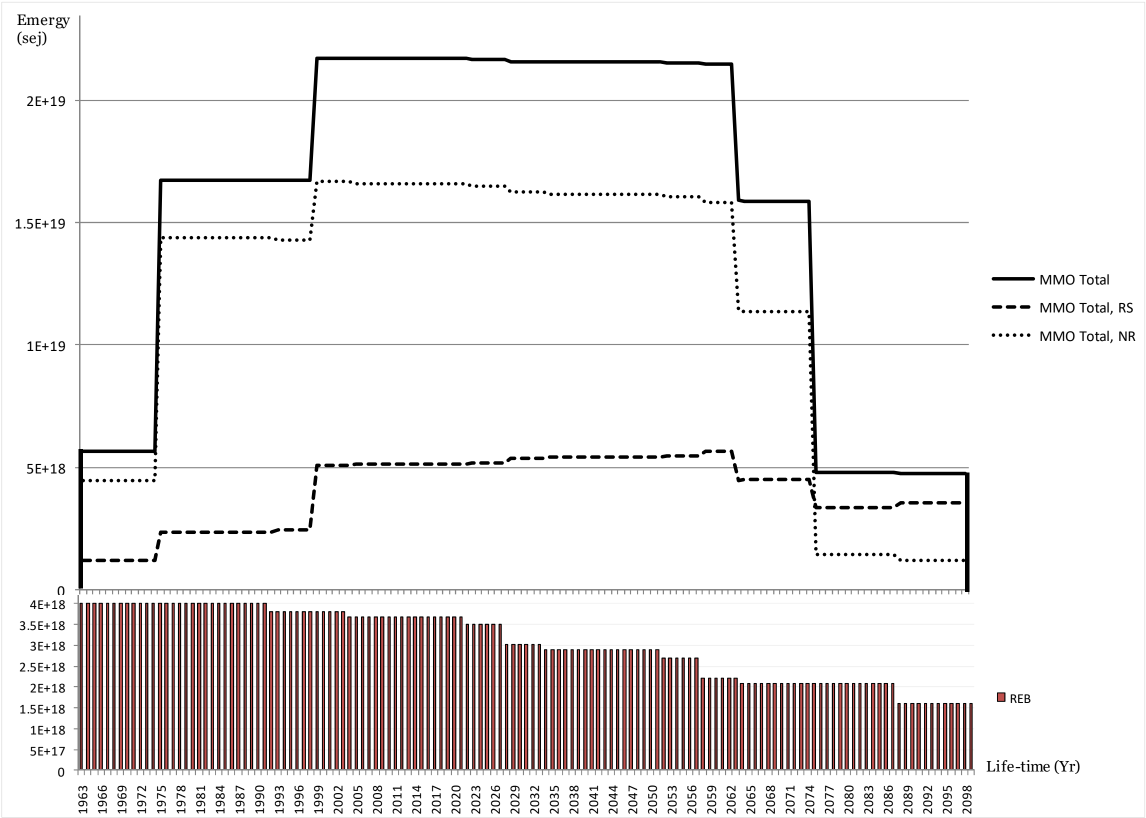

**Figure 18. Emergy values after combining building manufacturing, maintenance and operational energy use (in sej). In this scenario, a 15% renewable resource content is simulated during maintenance (replacement of glazing per maintenance schedule). Dashed line-type represents the maximum renewable emergy potential over buildings' life-time which approaches to zero to balance the Renewable Substitutability quantities.**

Thus, during environmental building design and maintenance, conscious decision-making through selection of appropriate building materials is fundamental to maximize renewable resource use. For building structure, such decisions can be effectively made using the following emergy optimization method.

## 5.2 Building envelope emergy optimization Methodology

The Building Envelope Emergy optimization consists of four modules namely, figure 19, Sub-System Identification (SSI), Energy-Emergy Evaluation (EEE) , Thermodynamic Minimum Computation (TMC), and System Performance Evaluation (SPA).

Building systems are split into sub-systems in the SSI module. This is followed by net emergy analysis of the building that involves in-depth assessment of materials and energy-emergy inflow from material manufacturing to maintenance and operational of a building, in the EEE Module. For the largest contributor to overall system performance, a thermodynamic minimum transformity is identified in the TMC module. Using building energy-emergy performance indices, system performances are assessed in the SPA module.

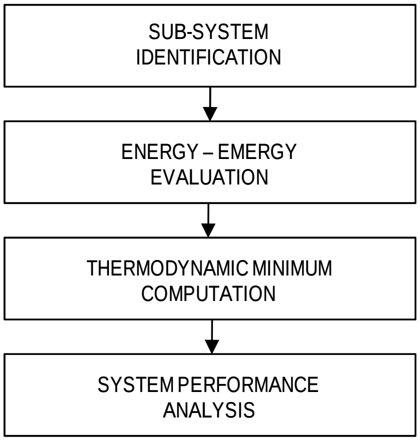

**Figure 19. Four-layer Building Envelope Emergy Optimization structure.**

The core of this optimization component is the recognition of the occurrence of a thermodynamic minimum transformity that exists for the generation of any product or service dependent on a building system and/or its sub-systems. This thermodynamic minimum for generation of the desired product or service is used to evaluate current building performance. As the performance allows the desired product to approach a thermodynamic minimum transformity, systems and sub-systems attain the most efficient formation possible for maximum empower and advance the building towards self-sustenance.

The Sub-System Identification module identifies the sub-systems that comprise the building envelope system. This is followed by Energy-Emergy Evaluation analysis that determines energy-emergy data for all three phases of a system namely manufacture, maintenance, and operation. For the sub-system that contributes the largest to the operational energy-emergy quantity, thermodynamic minimum transformity is identified. Using the already computed emergy values and the minimum transformity, system performance, in emergy terms, is analyzed for further improvement. Figure 20 shows the envelope emergy analysis to maximize renewable resource use.

Building envelope heat and light transport includes surface conductance measurements for opaque and transparent surfaces, surface radiation modeling for transparent surfaces, condensation effects, sol-air characteristics for detailed envelope heat flow analysis, and related light penetration for transparent surfaces.

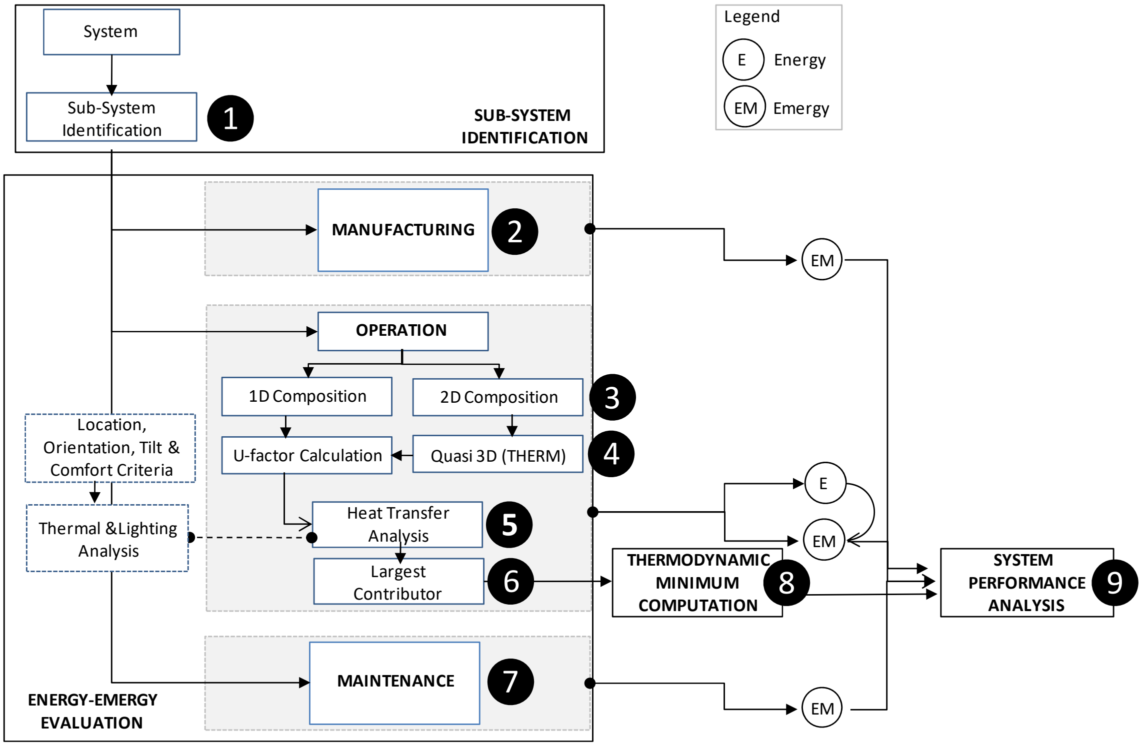

**Figure 20. Building envelope emergy optimization flowchart.**

## Sub-system identification module

The building envelope is an enabler of energy-emergy flow. An envelope system may be comprised of several sub-systems (or layers). In depth assessment at the sub-system level provides opportunities to improve energy performance. Such an approach aids in improving holistic system performance through identifying sub-systems based on their individual and collective emergy-energy impact. In this module, the various sub-systems that constitute the envelope system are identified (*STEP 1*).

*<u>STEP 1</u>: Energy-emergy analysis in "Identification of Sub-Systems"*

- In this step, sub-systems of the envelope are identified.

## Energy-emergy evaluation module

For every sub-system, the manufacturing emergy quantity (*STEP 2*), the operative energy consumption emergy (*STEPS 3 to 5*), and related maintenance data (*STEP 7*) is computed in this module. This is performed in the course of several steps and the process uses an iterative approach until all sub-system energy-emergy data are obtained (energy data are converted to related emergy quantities using appropriate translations).

The initial step (*STEP 3*) involves the determination of sub-system material composition in terms of dimensionality: "one-dimensional," if the sub-system uses a single material type such as wall cladding, etc. On the other hand, the sub-system material composition may be "two-dimensional" if the sub-system is comprised of two or more materials such as envelopes with cavity zones filled with insulation. This is followed by determination of sub-system U-factors (*STEP 4*). Once U-factors are established, sub-system operational energy consumption is computed (*STEP 5*) using whole building simulation. Thus, for each envelope sub-system, energy-emergy accounting is performed for three stages, formation-extraction-manufacturing, maintenance and operation.

### *STEP 2: Energy-emergy analysis in "Manufacturing"*

- For each envelope sub-system, emergy data for formation-extraction-manufacturing are calculated.

### *STEP 3: Energy-emergy analysis in "Operation: Identification of Material Composition"*

- In this step, the operative energy data related to envelope sub-system is computed.

### *STEP 4: Energy-emergy analysis in "Operation: Determination of U-factors"*

- In this step, the sub-system U-factor is calculated. If the composition is one-dimensional, the U-factor computation is determined (reciprocal of thermal resistance, if available, or thermal conductivity supplied by the manufacturer is adequate). On the other hand, if the composition is two-dimensional (for example, a wood- or steel-framed envelope structure that includes cavity zones with multiple material configurations such as the frame and insulation material), then a quasi 3D U-factor computation methodology is used. The quasi-3D method uses the modeling of a detailed section of the sub-system in a 2D Finite-Element-Method (FEM) environment to closely replicate 3D heat transfer spatially to determine the U-factor of an "equivalent wall."
- This step employs THERM software for computing U-factors of a two-dimensional sub-system.

### *STEP 5: Energy-emergy analysis in "Operation: Heat Transfer Analysis"*

- In this step, the sub-system is then analyzed for heat transfer using a whole building energy analysis. Annual envelope (sub-system) heat transfer is computed. While exterior conditions are location specific (using weather data), interior conditions are maintained at thermal comfort conditions complying with ASHRAE 55 thermal criteria, particularly temperature.

- While the heat portion of the radiation spectrum is taken into consideration during the heat transfer computation for both opaque and transparent surfaces, the contribution of the visible portion (380~780nm) is determined by introducing necessary daylight sensors which are integrated as part of the whole building energy simulation engine, for evaluation of the additional energy consumption required.

- This step utilizes DOE-2 engine for computing the annual envelope heat transfer (includes the additional energy requirement for supporting light levels for task illumination).

<u>STEP 6</u>*: Energy-emergy analysis during "Operation: Largest Contributor"*

- For each envelope sub-system, the "largest contributor" to system performance, in terms of energy-emergy quantity, is identified in this step.

<u>STEP 7</u>*: Energy-emergy analysis in "Maintenance"*

- For each envelope sub-system, emergy required for maintenance is calculated.

### Thermodynamic minimum computation module

As the performance approaches a thermodynamic minimum transformity, sub-systems attain the most efficient product formation possible for maximum empower. Using parametric analysis, the "largest contributor" sub-system is evaluated for maximum empower (or minimum transformity).

<u>STEP 8</u>*: Energy-emergy analysis in "Thermodynamic Minimum Computation"*

For the "largest contributor," the emergy/energy ratio provides its transformity. In order to identify the minimum (thermodynamic minimum transformity) to attain maximum empower, a parametric assessment (e.g., changing the thickness of the insulation) is performed until a thermodynamic minimum is realized.

- Using parametric analysis, the minimum transformity associated with the "largest contributor" to the emergy is identified.

Material transformity is the ratio of emergy to available energy or the potential to do work. While the emergy of the material can be calculated using all direct and indirect energy forms to make the product, the available energy is the internal kinetic energy, in this case made up of envelope heat transfer through one or more modes – conduction, convection and radiation.

Every system and sub-system configuration attains the most efficient formation possible for maximum empower. Thus, for the largest contributor material, the transformity reaches a minimum following either of these two conditions – (a) material life-time is longer (consistent with the goals of sustainability as frequent replacements of a material cumulatively may possess larger emergy value) and (b) higher potential energy of the material (again, in line with sustainability objectives as the system and/or subsystem is less active in transporting heat based on the exterior-interior conditions).

All energy-emergy calculations are carried out for one life-time period of the building and, therefore, the transformity reaches a minimum as the potential energy maximizes.

### System performance analysis module

In this module, the sub-system minimum transformity is used to evaluate current sub-system performance.

*STEP 9: Energy-emergy analysis in "System Performance Analysis"*

- The current sub-system performance is evaluated (as a potential for improvement) to the thermodynamic minimum derived from *STEP 8*.

For each sub-system evaluated for a location and orientation (tilt included), only one thermodynamic minimum exists. This data can be used to develop "Building Emergy Spectrum of Envelope Systems" which is unique for a particular envelope system (or sub-system). By virtue of generalizing the location characteristics, the envelope systems' performance can be mapped for climatic zones and orientations.

Thus, the emergy optimization method for envelope design offers a procedure for mapping envelope systems and their performances. Through understanding sub-system level (layer) flows, this method aids in the maximizing renewable resource use by employing the minimum transformity concept.

### 5.2.1 Results

The NHEERL's AED building structure was used as a case study to optimize envelope using emergy analysis. The envelope system is comprised of spandrel glazing, masonry wall and windows. As part of the opaque wall system, the spandrel glazing and the masonry wall were analyzed in detail. The performance evaluation follows the four-step process – Sub-System Identification, Energy-Emergy Evaluation, Thermodynamic Minimum Computation and System Performance Analysis.

Among all the sub-systems that constitute the envelope, the insulation used in the masonry wall was identified as the largest contributor to building energy flow. In order to iteratively seek the best performing insulation using emergy analysis, a set of insulation values were identified. They range from R-11 to R-35 in increments of R-3 (approximately 1" thickness).

In the Energy-Emergy Evaluation module, an emergy calculation is performed for the envelope system. This corresponds to the formation-extraction-manufacturing portions of the envelope system. Tables C-1 to C-5 list the building structure (Buildings #1 to #4). Data from this table are used for computing emergy values specific to the envelope system only. This includes the opaque and transparent systems. However, for this analysis, the transformity data provided in table A-1 are used in lieu of Renewable Substitutability and non-renewable splits.

In the Thermodynamic Minimum Computation module, the envelope structure is analyzed using THERM. The masonry wall with new insulation (R-value) was simulated using THERM to determine U-factor of the envelope configuration. Additionally, the spandrel glazing portion is analyzed to compute the U-factor using THERM, see figure 21. This is performed for all R-value options for the masonry wall. Using both the masonry and spandrel glazing units' U-factors, the weighted U-factor data are obtained. The purpose of this exercise is to determine the weighted average U-factors to input in an energy model for thermal analysis.

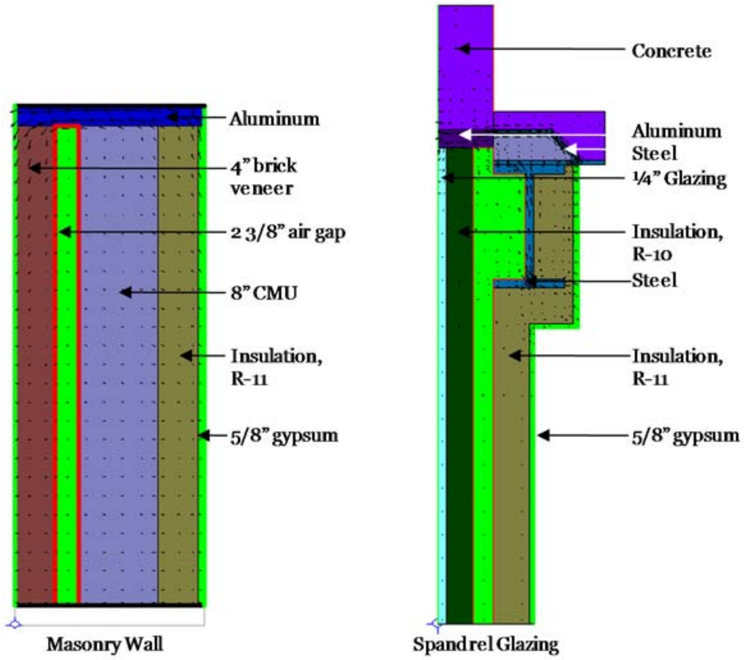

**Figure 21. Building envelope system model using THERM.**

Table 3 lists the weighted average U-factor that corresponds to R-value of the material. A THERM simulation was performed after removing the insulation. This represents the wall with R-0 type which will be used as a baseline to compute energy savings due to insulation.

**Table 3. Insulation values and U-factors of masonry wall and weighted average for entire opaque wall assembly.**

| Insulation R-value | U-factor | | |
|---|---|---|---|
| | Masonry Wall | Spandrel Glazing | Overall Envelope |
| 0 | 0.2881 | 0.3033 | 0.2914 |
| 11 | 0.1856 | 0.3033 | 0.2111 |
| 14 | 0.1612 | 0.3033 | 0.1920 |
| 17 | 0.1509 | 0.3033 | 0.1839 |
| 20 | 0.1355 | 0.3033 | 0.1718 |
| 23 | 0.1238 | 0.3033 | 0.1626 |
| 26 | 0.1158 | 0.3033 | 0.1564 |
| 29 | 0.1097 | 0.3033 | 0.1516 |
| 32 | 0.1050 | 0.3033 | 0.1479 |
| 35 | 0.1017 | 0.3033 | 0.1453 |

Three scenarios were considered for evaluation – (1) performance of the opaque envelope system, using electricity for cooling and natural gas for heating, (2) performance of opaque envelope system, using electricity for cooling and heating, and (3) opaque and transparent (windows) envelope system, using electricity for cooling and lighting, and natural gas for heating. While scenario #1 and #2 focus on the opaque envelope system only (maintaining window specifications as a constant), they use different fuel types. In addition to evaluation opaque systems, the purpose of these scenarios is to determine performance changes due to change in fuel types. In scenario #3, the envelope configuration is maintained as a constant and the window specifications are changed to determine the performance, in emergy terms. Thus, in scenario #3, effect (savings) of daylighting is also studied.

In order to conduct integrated thermal and daylighting analyses, the existing facility was modeled using the DOE-2 program. Once developed, this building energy simulation model may be used to simulate various scenarios such as changes to U-factors of envelope systems to evaluate the changes to loads (BTUs), energy use (kWh), etc.

## Model Setup and Assumptions

The NHEERL's AED building structure that is comprised of all four buildings was modeled in a DOE-2 program, figure 22. The model used several assumptions and these were maintained as a constant for all variations of the base-model. The lighting power was introduced in spaces based on electrical drawings. The equipment power for spaces was input based on ASHRAE 90.1-2007 User Manual requirements (ASHRAE-UM, 2007). The value used for equipment power for spaces is 0.75 w/ft$^2$. For occupancy, a value (275 ft$^2$/person) consistent with the User Manual was used. The indoor temperature was maintained per ASHRAE 55-2005 Standard (ASHRAE, 2005). The building operation schedule is based on actual operating hours. All other equipment efficiencies were maintained as a constant.

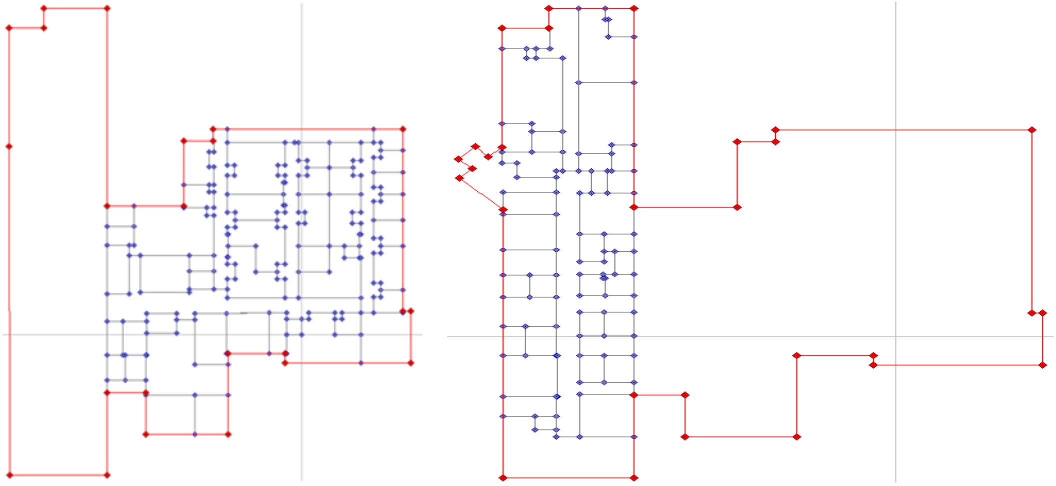

**Figure 22. Geometric representation of floors in DOE-2 program.**

### *Scenario #1: Opaque envelope structure – using electricity for cooling and natural gas for heating.*

For this scenario, lighting energy savings owing to daylighting sensors was not included. Thus, for change in R-value (or weighted average U-factor of the opaque envelope assembly), the corresponding envelope heating and cooling loads (BTUs), and heating and cooling energy use (kWh) were determined, see table D-1. Using the transformity of the fuels (electricity and natural gas), the emergy content of fuels was computed. Similarly, from tables C-1 to C-5, the emergy content of the envelope system was computed. It is critical to extend these values to the life-time of the buildings. For example, energy analysis provides annual consumption data. This, then, is extended to the entire life-time of the building as the emergy content pertains to the useful life of the system. Wherever the systems' useful life-time is shorter than the life-time of the building, replacement of the system is undertaken. Similarly the heating and cooling envelope loads were extended to the life-time of the building. For the purposes of this case-study, a 2.5 factor has been used for material emergy. The factor takes into consideration the glazing (replacement time is 20 years), brick (replacement time is 30 years), etc., (Buranakarn, 1998).

In order to determine the transformities of each envelope configuration, the ratio of the total emergy content (material and fuel usage) to total energy savings from the baseline configuration with no insulation is calculated. These are then evaluated to determine the option that attains the minimum transformity.

From figure 23, it is to be noted that the rate of energy saved (represented in continuous line-type) is significantly higher than the rate of energy-use (represented in dashed line-type) saved by improving insulation, figure 23. Energy saved represents the additional BTUs saved from a baseline. This rate-of-change in savings is a critical factor for determining the optimal insulation criteria for the envelope system, in emergy terms.

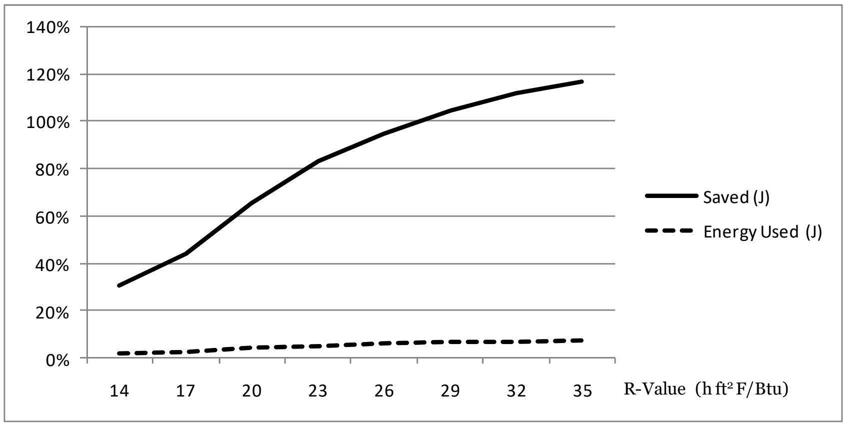

**Figure 23. Rate of energy saved and rate of energy used plotted for insulation R-values.**

Figure 24 shows the relationships of a change in insulation for the opaque envelope system, the material emergy content and the emergy use (fuel consumption). Although the material emergy and the fuel use emergy were in the same magnitude, their behavior change due to increase in insulation is significant.

While the fuel use emergy content (represented in continuous line-type) decreased at a slower pace (to increases in insulation), the material emergy increased at a rapid pace (represented in dotted line-type). For example, when the insulation value is R-11, the structure's fuel use emergy content is higher than material emergy value. It is to be noted that these values correspond to the entire useful life-time of the buildings. However, these two quantities intersect near insulation option R-23. Beyond this insulation value, the emergy content of material surpasses the fuel use emergy values.

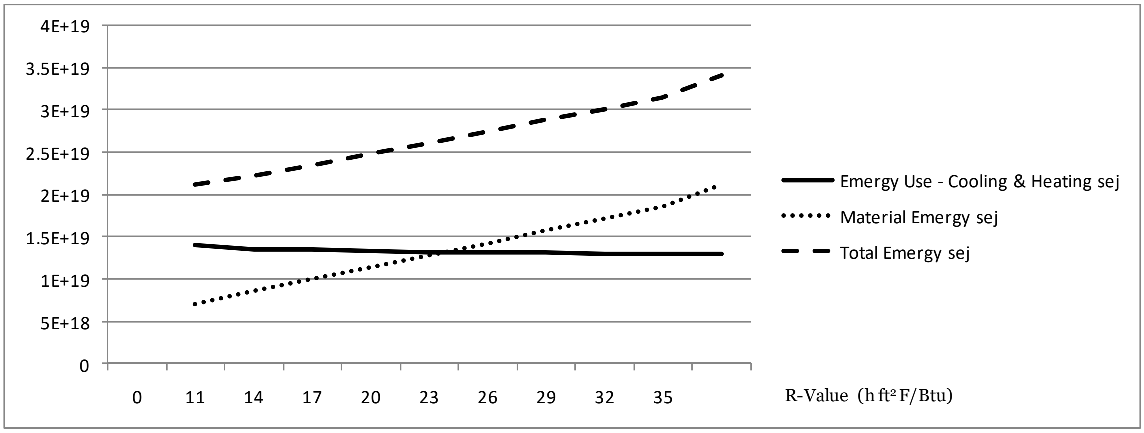

**Figure 24. Material and fuel use emergy plotted for insulation R-values, scenario #1.**

Using table D-1, the transformities are plotted against insulation R-values, see figure 25. The thermodynamic minimum transformity occurs at insulation R-23 (transformity is 9.95E+05 sej/J). As noted in figure 24, this is the point of intersection between material emergy content and fuel use emergy. However, further research may be needed to confirm the behavior of material and fuel use emergy, and the occurrence of minimum transformity. Thus, at an insulation R-23 for the opaque envelope system, the best performance in emergy terms is exhibited through maximizing its potential (empower).

With an energy framework, a different insulation option may be selected (based on the lowest fuel use in kWh). However, for a total environmental assessment approach, the insulation selected may vary as discussed in this experiment.

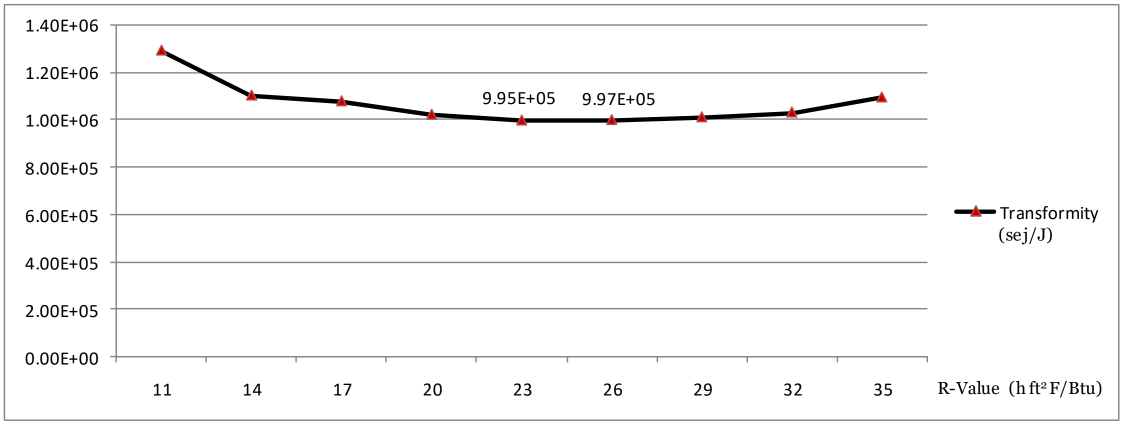

**Figure 25. Transformity values calculated for insulation R-values, scenario #1.**

Figure 26 shows the three-arm emergy diagram for the insulation option R-23 that attained the most efficient formation possible.

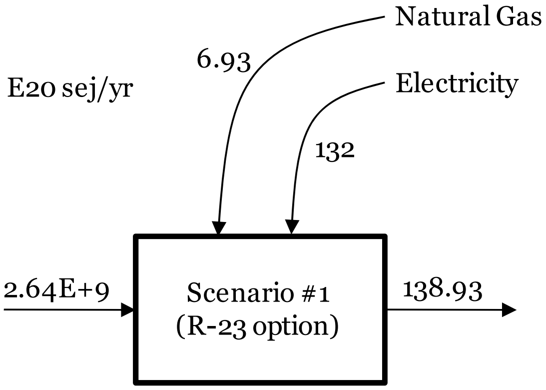

**Figure 26. Three-arm diagram for insulation option R-23 selected, scenario #1.**

*Scenario #2: Opaque envelope structure – using electricity for cooling and heating.*

For this scenario, the fuel type for both heating and cooling is maintained as electricity. The objective of this exercise is to find the correlation of fuel type (and its emergy content) to transformity. Table D-2 lists the emergy quantities and transformities for various insulation options. Figures 27 and 28 correspond to scenario #2. Since only electricity is used for this scenario, the material emergy content increased from scenario #2. This is due to the fact that the transformity of electricity used for this experiment is 1.60E+05 sej/J (Odum, 1996) as compared to natural gas which posses a lower transformity, 4.39E+04 sej/J (Odum, 1996; Campbell, 2009). The minimum transformity occurs at insulation value R-26 (transformity 1.03E+06 sej/J). Figure 29 shows the three-arm emergy diagram for the insulation option R-26 that attained the most efficient formation possible.

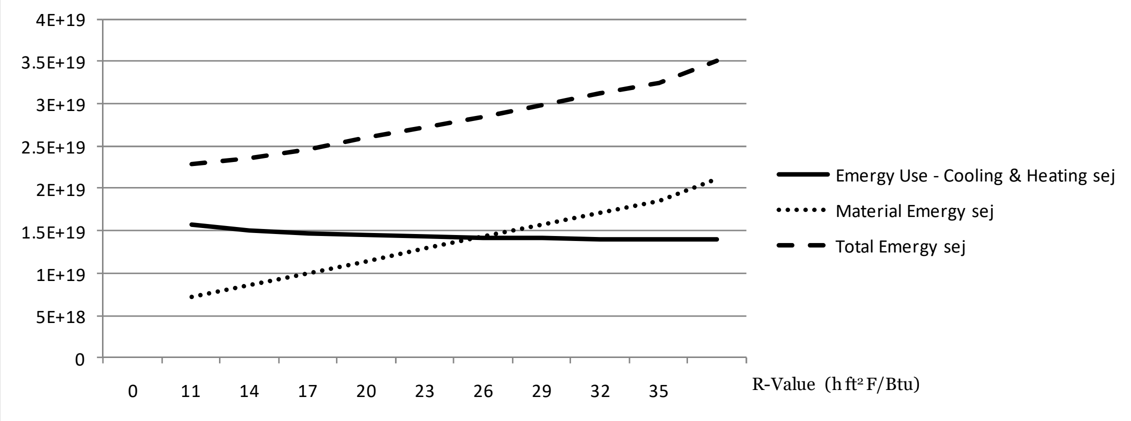

**Figure 27. Material and fuel use emergy plotted for insulation R-values, scenario #2.**

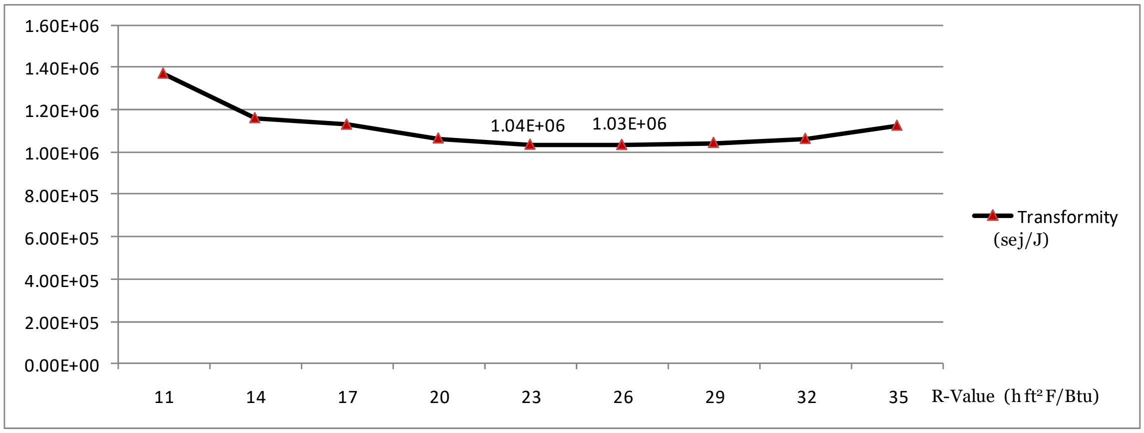

**Figure 28. Transformity values calculated for insulation R-values, scenario #2.**

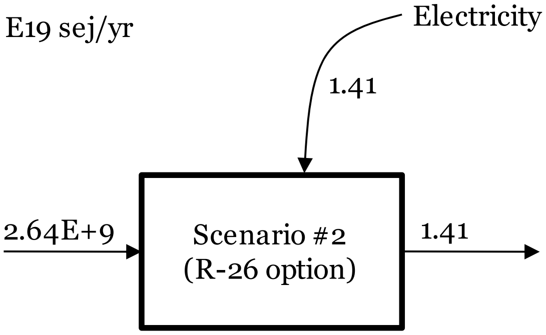

**Figure 29. Three-arm diagram for insulation option R-26 selected, scenario #2.**

*Scenario #3: Opaque and transparent envelope structure – using electricity for cooling and lighting, and natural gas for heating.*

For scenario #3, the opaque envelope systems are maintained as a constant and the window specifications are changed to determine the performance, in emergy terms. Thus, in scenario #3, effect (savings) of daylighting is also studied. Currently, there is lack of transformity data related to glazing data such as low-e coated glazing, etc. Table A-1 lists the glazing options for which transformity data is available. Thus, for this experiment, the glazing specification change will include the number of glazing panels, i.e., single, double and triple-glazed systems. These three systems will be evaluated for their transformities when integrated to the building under investigation. To determine electrical energy savings due to daylighting, glazing type #1 (single glazed) will be used. However, no daylight sensors will be activated in perimeter spaces with windows. The other glazing types are double glazed (glazing type #2) and triple glazed (glazing type #3), see table 4. For this scenario, the effect of daylighting will be studied by introducing daylight sensors in perimeter spaces with windows. Thus, reduction in lighting energy can be studied for glazing options.

**Table 4. Glazing types used for scenario #3.**

| Glazing Type | Specifications | | |
|---|---|---|---|
| | U-value | SHGC | VT |
| Single Glazed | 1.04 | 0.86 | 0.90 |
| Double Glazed | 0.55 | 0.76 | 0.89 |
| Triple Glazed | 0.38 | 0.68 | 0.74 |

Figure 30 shows the three glazing types mapped based on their material emergy and fuel use emergy values. The single glazed option serves as a baseline for this scenario. With increased panes for glazing option, the material emergy values significantly increase as compared to emergy use for cooling, heating and lighting purposes. However, as seen in figure 31, the thermodynamic minimum transformity occurs with triple glazing as the savings due to heat and cool loads (BTUs) and lighting savings (kWh) is greater when compared with single glazed option (used as a baseline for this exercise), refer table D-3. A cost-benefit analysis would benefit to evaluate between a double and triple glazing. Figure 32 shows the three-arm emergy diagram for triple glazed option.

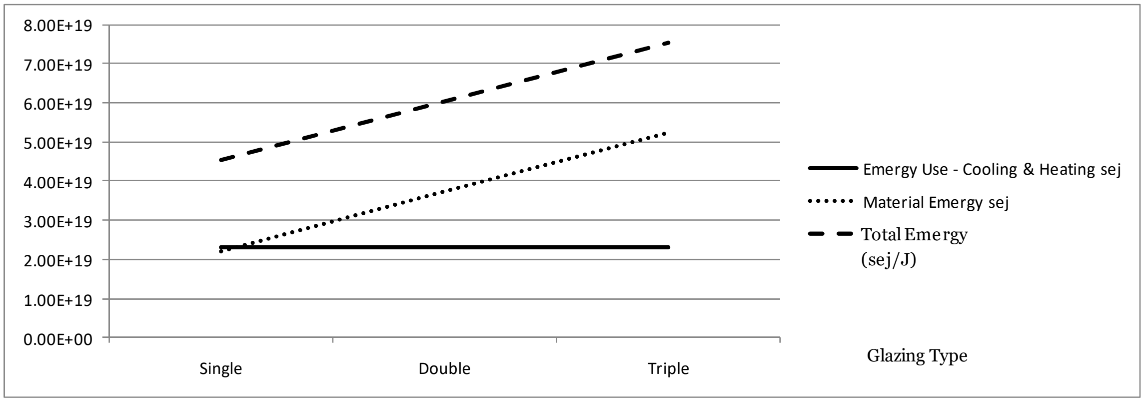

**Figure 30. Material and fuel use emergy plotted for insulation R-values, scenario #3.**

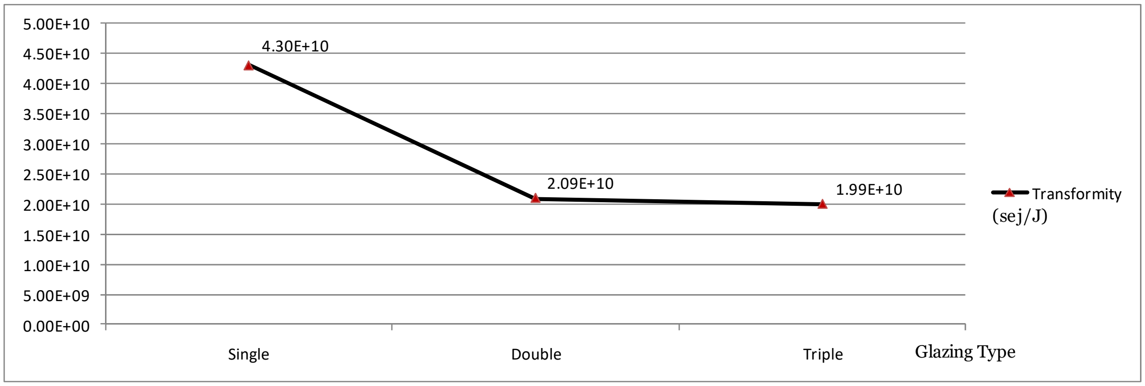

**Figure 31. Transformity values calculated for insulation R-values, scenario #3.**

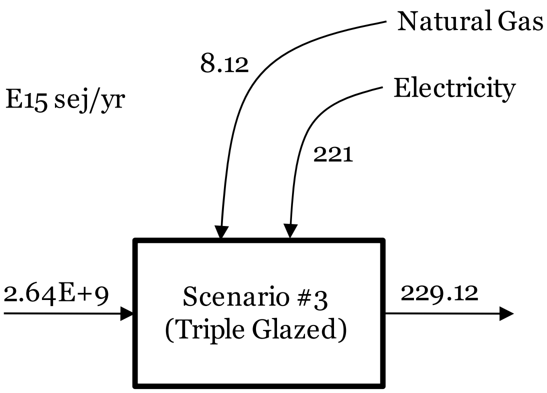

**Figure 32. Three-arm diagram for triple glazed option selected, scenario #3.**

Thus, using this methodology, optimization of envelope emergy quantities is attained. Using energy quantities aid building operational energy use and does not constitute the much needed total environmental analysis. On the other hand, evaluating building components using emergy terms enables optimization at the highest level of sustainability which takes into account of all environmental aspects.

# 6. CONCLUSIONS

This dissertation developed a method to maximize renewable resource use through emergy analysis to close the gap between current approaches to environmental building design and the over-arching goal of creating buildings that contribute to the sustainability of the geobiosphere. The objective of this study was to assess the performance of built systems and identify the maximum potential bounds for renewable resource substitution within the building process. This study proposed using a Renewable Emergy Balance in environmental building design as a tool to maximize renewable resource use through disinvestment of all non-renewable resources that may be substituted with renewable resources.

In addition, the dissertation provided an assessment method for buildings to achieve REB status. The assessment method comprised of three components namely, the manufacturing and maintenance emergy analysis, the building operative energy use, and the maximum renewable emergy potential. Using the building materials emergy database and building envelope emergy optimization components an estimate of renewable-substitutability potential over all the phases of the building cycle is derived. This, then, was used to compute the maximum renewable emergy potential of the building. For a building to achieve REB status, the renewable resource use gained through the disinvestment of non-renewable resources must be equivalent to or approach the maximum renewable emergy potential. In addition to identifying the maximum potential for renewable resource substitution, the method also assessed the performance of systems and maximized renewable resource use. The proposed study will aid environmental building design using emergy analysis, thereby, guiding the way toward maximizing renewable resource use and non-renewable resource substitution, thereby contributing to the overall sustainability of the geobiosphere. For the purposes of this dissertation, the system boundary included the built environment, and its components, specifically those that enabled thermal conditioning of the environment; however, it did not include the building occupants. This study identified the maximum renewable emergy potential for buildings. This limit may be used to integrate renewable resources over the life-time of the building to achieve a Renewable Emergy Balance. It overcame the challenges associated with the evaluation of the building through its entire life-cycle through maximizing renewable resource use for environmental building design. More importantly, the dissertation alleviated any ambiguity related to the limit or benchmark that is set to achieve higher levels of sustainability.

REB buildings preserve a high standing by optimizing buildings over their entire life-span from formation-extraction-manufacturing to maintenance and operation cycles. In addition, REB alleviates any ambiguity related to a maximum limit or benchmark that is set to achieve higher levels of sustainability. If such an approach were adopted, it would expand conscious decision-making and, possibly, lead to a paradigm shift in the way non-renewable resources are used in the manufacturing of building materials, which is currently of interest, but remains unchecked.

## 6.1 Concluding remarks

A particular building, like an organism or an ecosystem must seek self-sustenance to prevail in competition with other building designs in a time with limited availability of energy and materials. Self-organization of systems to maximize useful power is the key to self-sustenance.

During the building design (if the building is a new facility), conscious decision-making toward improving renewable resource use is important. Similarly, during replacement of building components for maintenance, it is important to identify materials that possess greater renewable resource content in addition to the materials' environmental performance. Additionally, by virtue of reducing operative energy use during the building's life-time, the Renewable Substitutability associated with this phase can be significantly reduced. Again, this involves appropriate selection of energy source that maximizes overall renewable resource use to achieve Renewable Emergy Balance status. The following sections summarize the main objectives achieved in this dissertation.

### Evaluation of building through its entire life-cycle

For a building design strategy that aims at contributing to the larger goal of global sustainability, it must be acknowledged that a building relies on the geobiosphere for its very existence right from its start. Current definitions and calculations of net energy do not include the energy flows from the sun, wind, rain, and geological cycles and so-forth from the beginning.

This dissertation used emergy analysis to promote environmentally conscious decision-making. Emergy analysis provided a "total environmental analysis" that goes beyond classical thermodynamics and included all environmental energies involved in the system under investigation.

### Identification of Renewable Substitutability in building materials

This dissertation developed the Renewable Substitutability of building materials. For each building component, emergy data for formation-extraction-manufacturing is calculated. The emergy values are split into three portions namely renewable resources, Renewable Substitutability and non-renewable resources used. This database encompasses the most recent emergy data available for building materials.

Thus, to measure renewable-substitutability of a building material, for example, concrete, individual renewable-substitutability of raw materials for concrete such as cement, sand and water are computed first.

### Identification of maximum renewable resource potential

This dissertation developed a method to maximize renewable resource use through emergy analysis to close the gap between current approaches to environmental building design and the over-arching goal of creating buildings that contribute to the sustainability of the geobiosphere. The central aspect is the computation of an explicit quantity of renewable resources integrated over the building life-time, also referred to as the maximum renewable emergy potential of the building, after maximization of renewable resource use during the design phase of the building.

This limit is a moving target and improves as the technology improves to integrate and/or generate more renewable resources. The significance of this limit is that it alleviates any ambiguity related to a benchmark that is required to achieve a higher level of sustainability.

### Renewable Emergy Balance assessment

Renewable Emergy Balanced buildings preserve a high standing by optimizing buildings over their entire life-span from formation-extraction-manufacturing to maintenance and operation cycles. In addition, REB alleviates any ambiguity related to a maximum limit or benchmark that is set to achieve higher levels of sustainability.

For buildings, the novelty of disinvesting in non-renewable resources and replacing them with renewable resources permanently will shift towards self-sustenance in renewable emergy terms or achieve a Renewable Emergy Balance.

### Building envelope emergy optimization

This dissertation developed a method to optimize the building envelope in emergy terms. Thus, during environmental building design and maintenance, conscious decision-making through selection of appropriate building materials is fundamental to maximize renewable resource use. For building structure, such decisions can be effectively made using the building envelope emergy optimization method.

## 6.2 Future Work

The following recommendations are presented as future work, which will enhance the methods developed in this dissertation. More importantly, for widespread use as a metric for evaluating building environmental design, it is important to maintain simplicity in adopting the methodology, yet preserve rigor.

- A comprehensive building materials' emergy database with renewable resource use, Renewable Substitutability and non-renewable contents is crucial for applying this method to a wide variety of built environments. Currently, for the same material, several transformities exist. This is due to the inclusion of location aspect and the manufacturing process. Further study is required to assimilate all the available transformities available for building materials and develop a method for a novel "adjustment" factor for location and manufacturing process. Such an approach can be pursued until a real-time transformities database is developed.

- Renewable Substitutability of energy sources requires additional effort to provide location-specific values. For example, a project in Narragansett, RI uses energy from a local plant. The configuration of raw materials, both renewable and non-renewable portions will differ as compared to the national data. This may pose issues when calculating operational energy use quantities and associated renewable resource.

- For new facility, since operational energy use requires the use of an energy simulation algorithm, the Renewable Emergy Balance methodology can be integrated with the algorithm. For example, a module that accesses ENERGYPLUS routines and the building materials' emergy database can provide results in real-time. Once developed, this module can be integrated with ENERGYPLUS routines for widespread application by building designers and engineers for evaluating environmental building design using the "total environmental analysis" approach. Additionally, this module may be integrated with Building Information Modeling (BIM) software for effective decision-making.

- Using a web-based approach, a tool may be developed for building material manufacturers to provide information related to the renewable resources used in the process. Currently, this is not a requirement by any industry standard or rating authority. The adoption of Renewable Emergy Balance will require the manufacturers to explicitly provide such data and more importantly, as the market drives towards total sustainability, it will force the manufacturers to maximize renewable resources for their production processes.

# APPENDIX A

Table A-1. Transformity or specific emergy values of building materials, fuel and energy.

| Item | Unit | Transformity or Specific Emergy (sej/unit) | Reference | Dissertation Reference Notation |
|---|---|---|---|---|
| Building Materials | | | | |
| Aggregate | kg | 1.00E+12 | Odum et al., 1995 | a |
| Aluminum Frame | kg | 2.13E+13 | Brown and Buranakarn, 2003 | b |
| Bauxite | kg | 8.55E+11 | Odum, 1996 | c |
| Binder | kg | 3.31E+12 | Brown and Buranakarn, 2003 | b |
| Brick | kg | 3.68E+12 | Brown and Buranakarn, 2003 | b |
| Brick, Fired | kg | 4.80E+12 | Brown and Buranakarn, 2003 | b |
| Cement Plaster | kg | 3.29E+12 | Meillaud et al., 2005 | d |
| Clay | kg | 2.00E+12 | Odum, 1996 | c |
| Concrete | kg | 1.81E+12 | Simoncini, 2006 | e |
| Concrete block | kg | 1.35E+12 | Odum et al., 1983 | f |
| Copper | kg | 1.04E+14 | Brown and Arding, 1991 | g |
| Coral | kg | 1.00E+12 | Brown and McClanahan, 1992 | h |
| Fiberboard Production (1972) | kg | 1.84E+12 | Haukoos, 1995 | i |
| Glass, Float | kg | 4.74E+12 | Haukoos, 1995 | i |
| Glass, MSW | kg | 8.44E+11 | Odum et al., 1987 | j |
| Gypsum | kg | 1.00E+12 | Odum et al., 1995 | a |
| Hardboard Production (Split Production) | kg | 1.92E+12 | Haukoos, 1995 | i |
| Insulation, PVC | kg | 9.86E+12 | Brown and Buranakarn, 2003 | b |
| Insulation, HDPE | kg | 8.85E+12 | Brown and Buranakarn, 2003 | b |
| Limestone | kg | 6.70E+09 | Odum, 1996 | c |
| Paint | kg | 2.55E+13 | Brown and Buranakarn, 2003 | b |
| Particleboard Production (1972) | kg | 1.57E+12 | Haukoos, 1995 | i |
| Rubber (MSW) | kg | 2.10E+07 | Odum et al., 1983 | f |
| Sand | kg | 1.00E+12 | Odum, 1996 | c |
| Shale | kg | 1.00E+12 | Odum, 1996 | c |
| Softwood plywood and others (split products) | kg | 1.63E+12 | Haukoos, 1995 | i |
| Steel | kg | 6.97E+12 | Brown and Buranakarn, 2003 | b |
| Vapour barrier | kg | 9.86E+12 | Brown and Buranakarn, 2003 | b |
| Water | J | 1.00E+09 | Odum, 1996 | c |
| Wood | kg | 2.40E+12 | Odum, 1996 | c |
| Wood, Rainforest | kg | 4.40E+07 | Odum, 1996 | c |
| Zinc | kg | 6.80E+09 | Brown et al., 1992 | k |
| Fuel and Energy | | | | |
| Coal | J | 4.00E+04 | Odum, 1996 | c |
| Crude Oil | J | 5.30E+04 | Odum, 1996 | c |
| Electricity | J | 1.74E+05 | Odum, 1996 | c |
| Human work | J | 1.24E+07 | Ulgiati et al., 1993 | l |
| LP Gas | J | 7.00E+04 | Odum et al., 1983 | f |
| Natural Gas | J | 4.39E+04 | Odum, 1996; Campbell, 2009 | m |
| Natural Gas, Petroleum Gas | J | 4.80E+04 | Odum, 1996 | c |
| Oils, gasoline, fuels | J | 6.60E+04 | Odum, 1996 | c |

# APPENDIX B

Table B-1. Specific Emergy values of building materials showing Renewable Substitutability and non-renewable split. Refer tables A-2 to A-15 for details related to calculations.

| Note Item | Description | Specific Emergy (sej/kg) | |
|---|---|---|---|
| | | Renew-Substitutability | Non-Renewables |
| Cement | Conventional cement | 1.95E+11 | 1.79E+12 |
| | Byproduct use cement | 1.92E+11 | 2.01E+12 |
| Concrete | Conventional ready-mix concrete | 3.47E+10 | 1.41E+12 |
| | Byproduct use ready-mix concrete | 2.84E+10 | 1.53E+12 |
| | Material recycling ready-mix concrete | 3.47E+10 | 1.56E+12 |
| Fired clay brick | Conventional fired clay brick | 1.89E+11 | 2.03E+12 |
| | Byproduct use (sawdust) fired clay brick | 1.02E+11 | 2.17E+12 |
| | Byproduct use (oil-contaminated soil) fired clay brick | 2.93E+11 | 1.64E+12 |
| Steel | Conventional steel product - pig iron | 4.52E+11 | 3.71E+12 |
| | Material recycling steel - post consumer steel | 3.57E+12 | 8.48E+11 |
| | Material recycling and byproduct use steel - steel scrap & post consumer | 3.39E+12 | 8.52E+11 |
| | Conventional steel product | 1.17E+12 | 4.18E+12 |
| | In-house material recycling steel - steel scrap | 1.89E+12 | 3.47E+12 |
| Aluminum | Conventional aluminum sheet - ingot | 4.70E+10 | 1.27E+13 |
| | Material recycling aluminum sheet - used aluminum can | 1.22E+13 | 8.06E+11 |
| | Material recycling and byproduct use aluminum sheet - scrap & used | 8.58E+12 | 4.38E+12 |
| Plywood, lumber | Softwood plywood product | 9.99E+11 | 2.07E+11 |
| | Laminated plywood using shaved wood byproduct | 1.16E+12 | 4.76E+11 |
| | Lumber product | 7.98E+11 | 8.70E+10 |
| | Recycled lumber - used lumber | 1.32E+12 | 5.43E+12 |
| | Plastic lumber (HDPE) product | 1.54E+11 | 5.60E+12 |
| | Adaptive reuse plastic lumber (HDPE) product | 4.95E+12 | 1.39E+12 |
| Floor - vinyl | Vinyl floor production using byproduct PVC | 5.29E+09 | 6.32E+12 |
| Floor - ceramic | Ceramic tile product | 1.03E+12 | 2.03E+12 |
| | Adaptive reuse ceramic tile with windshield glass | 2.01E+12 | 1.41E+12 |
| | Adaptive reuse ceramic tile with post-consumer glass bottles | 2.01E+12 | 1.41E+12 |
| Glass | Conventional float glass | 6.22E+12 | 1.65E+12 |
| | In-house traditional recycling float glass product | 6.65E+12 | 1.04E+12 |

Table B-2. Emergy evaluation of cement production with coal fly ash.
Emergy values adapted from Buranakarn (1998), Table 3-1.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (Sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| A. Conventional cement product | | | | | | | |
| 1 | Limestone | g | 8.01E+13 | 1.00E+09 | 801.42 | | 801.42 |
| 2 | Cement rock | g | 2.42E+13 | 1.00E+09 | 241.64 | | 241.64 |
| 3 | Coral | g | 6.80E+11 | 1.00E+09 | 6.8 | | 6.8 |
| 4 | Clay | g | 4.29E+12 | 2.00E+09 | 85.88 | | 85.88 |
| 5 | Shale | g | 4.38E+12 | 1.00E+09 | 43.78 | | 43.78 |
| 6 | Bauxite | g | 9.61E+11 | 8.50E+08 | 8.27 | | 8.27 |
| 7 | Sand and sand stone | g | 2.95E+12 | 1.00E+09 | 29.51 | | 29.51 |
| 8 | Iron ore | g | 1.52E+12 | 1.32E+09 | 20.1 | | 20.1 |
| 9 | Gypsum | g | 4.00E+12 | 1.00E+09 | 39.97 | | 39.97 |
| 10 | Coal | j | 2.98E+17 | 4.00E+04 | 119.21 | 119.21 | |
| 11 | Natural gas | j | 4.06E+16 | 4.80E+04 | 19.5 | 19.5 | |
| 12 | Oil | j | 1.65E+15 | 6.60E+04 | 1.09 | 1.09 | |
| 13 | Liquid fuel. Waste | j | 2.30E+13 | 6.60E+04 | 0.02 | 0.02 | |
| 14 | Tires, waste | j | 3.61E+15 | 2.10E+04 | 0.77 | 0.77 | |
| 15 | Electricity | j | 3.91E+16 | 1.74E+05 | 69.15 | 6.915 | 62.235 |
| 16 | Transport (Boat) | ton-mile | 2.61E+08 | 1.11E+11 | 0.31 | | 0.31 |
| 17 | Transport (Railroad) | ton-mile | 3.44E+08 | 5.01E+10 | 0.17 | | 0.17 |
| 18 | Transport (Truck) | ton-mile | 1.40E+08 | 9.65E+11 | 0.88 | | 0.88 |
| 19 | Labor | $ | 6.16E+08 | 1.25E+12 | 7.71 | | 7.71 |
| 20 | Annual Yield (y) | g | 7.55E+13 | 1.98E+09 | 1496.2 | 147.51 | 1348.67 |
| | | | | | Specific Emergy (sej/kg) | 1.95E+11 | 1.79E+12 |
| B. Byproduct use cement product | | | | | | | |
| 21 | Limestone | g | 8.01E+13 | 1.00E+09 | 801.42 | | 801.42 |
| 22 | Cement rock | g | 2.42E+13 | 1.00E+09 | 241.64 | | 241.64 |
| 23 | Coral | g | 6.80E+11 | 1.00E+09 | 6.8 | | 6.8 |
| 24 | Clay | g | 4.29E+12 | 2.00E+09 | 85.88 | | 85.88 |
| 25 | Shale | g | 4.38E+12 | 1.00E+09 | 43.78 | | 43.78 |
| 26 | Bauxite | g | 9.61E+11 | 8.55E+08 | 8.27 | | 8.27 |
| 27 | Sand and sand stone | g | 2.95E+12 | 1.00E+09 | 29.51 | | 29.51 |
| 28 | Iron | g | 1.52E+12 | 1.32E+09 | 20.1 | | 20.1 |
| 29 | Gypsum | g | 4.00E+12 | 1.00E+09 | 39.97 | | 39.97 |
| 30 | Flyash | g | 1.40E+12 | 1.40E+10 | 195.44 | | 195.44 |
| 31 | Coal | j | 2.98E+17 | 4.00E+04 | 119.21 | 119.21 | |
| 32 | Natural gas | j | 4.06E+16 | 4.80E+04 | 19.5 | 19.5 | |
| 33 | Oil | j | 1.65E+15 | 6.60E+04 | 1.09 | 1.09 | |
| 34 | Liquid fuel. Waste | j | 2.30E+13 | 6.60E+04 | 0.02 | 0.02 | |
| 35 | Tires, waste | j | 3.61E+15 | 2.10E+04 | 0.77 | 0.77 | |
| 36 | Electricity | j | 3.91E+16 | 1.74E+05 | 69.15 | 6.915 | 62.235 |
| 37 | Transport (Boat) | ton-mile | 2.61E+08 | 1.11E+11 | 0.31 | | 0.31 |
| 38 | Transport (Railroad) | ton-mile | 3.44E+08 | 5.01E+10 | 0.17 | | 0.17 |
| 39 | Transport (Truck) | ton-mile | 9.14E+07 | 9.65E+11 | 0.88 | | 0.88 |
| 40 | Labor | $ | 6.16E+08 | 1.25E+12 | 7.71 | | 7.71 |
| 41 | Annual Yield (y) | g | 7.69E+13 | 2.20E+09 | 1691.6 | 147.51 | 1544.11 |
| | | | | | Specific Emergy (sej/kg) | 1.92E+11 | 2.01E+12 |

Table B-3. Emergy evaluation of concrete production with coal fly ash and recycled concrete aggregate. Emergy values adapted from Buranakarn (1998), Table 3-2.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (Sej/Unit) | Emergy (sej) 1.00E+18 | Renew Substitutability (sej) 1.00E+18 | Non-Renewables (sej) 1.00E+18 |
|---|---|---|---|---|---|---|---|
| A. Conventional ready-mixed concrete product | | | | | | | |
| 1 | Sand | g | 3.36E+10 | 1.00E+09 | 33.59 | | 33.59 |
| 2 | Aggregates | g | 4.29E+10 | 1.00E+09 | 42.9 | | 42.9 |
| 3 | Cement | g | 1.32E+10 | 2.31E+09 | 30.6 | 0.00 | 30.60 |
| 4 | Water | J | 3.63E+10 | 4.80E+04 | 0.0017 | 0.0017 | |
| 5 | Electricity | J | 1.20E+12 | 1.74E+05 | 0.21 | 0.02 | 0.19 |
| 6 | Transport (Truck) | ton-mile | 3.46E+07 | 9.65E+11 | 33.42 | | 33.42 |
| 7 | Machinery | g | 5.80E+06 | 6.70E+09 | 0.04 | | 0.04 |
| 8 | Labor | S | 9.45E+04 | 1.20E+12 | 0.11 | | 0.11 |
| 9 | Annual Yield (y) | g | 9.71E+10 | 1.44E+09 | 140.65 | 0.02 | 140.63 |
| | | | | | Specific Emergy (sej/kg) | 2.34E+08 | 1.45E+12 |
| B. Byproduct use ready-mixed concrete product | | | | | | | |
| 10 | Sand | g | 3.36E+10 | 1.00E+09 | 33.59 | | 33.59 |
| 11 | Aggregates | g | 4.29E+10 | 1.00E+09 | 42.9 | | 42.9 |
| 12 | Cement | g | 1.24E+10 | 2.31E+09 | 28.6 | 0.00 | 28.60 |
| 13 | Fly ash | g | 8.58E+08 | 1.40E+10 | 12.01 | | 12.01 |
| 14 | Water | J | 3.63E+10 | 4.80E+04 | 0.0017 | 0.0017 | |
| 15 | Electricity | J | 1.20E+12 | 1.74E+05 | 0.21 | 0.02 | 0.19 |
| 16 | Transport (Truck) | ton-mile | 3.46E+07 | 9.65E+11 | 33.42 | | 33.42 |
| 17 | Machinery | g | 5.80E+06 | 6.70E+09 | 0.04 | | 0.04 |
| 18 | Labor | $ | 9.45E+04 | 1.20E+12 | 0.11 | | 0.11 |
| 19 | Annual Yield (y) | g | 9.71E+10 | 1.55E+09 | 150.89 | 0.02 | 150.87 |
| | | | | | Specific Emergy (sej/kg) | 2.34E+08 | 1.55E+12 |
| C. Material recycling ready-mixed concrete product | | | | | | | |
| 20 | Sand | g | 3.36E+10 | 1.00E+09 | 33.59 | | 33.59 |
| 21 | Cement | g | 1.32E+10 | 2.31E+09 | 30.6 | 0.00 | 30.60 |
| 22 | Crushed concrete | g | 4.29E+10 | 1.26E+09 | 54.1 | | 54.1 |
| 23 | Demolition | g | 4.29E+10 | 4.81E+07 | 2.07 | | 2.07 |
| 24 | Crushing | g | 4.29E+10 | 1.66E+07 | 0.71 | | 0.71 |
| 25 | Water | J | 3.63E+10 | 4.80E+04 | 0.0017 | 0.0017 | |
| 26 | Electricity | J | 1.20E+12 | 1.74E+05 | 0.21 | 0.02 | 0.19 |
| 27 | Transport (Truck) | ton-mile | 3.46E+07 | 9.65E+11 | 33.42 | | 33.42 |
| 28 | Machinery | g | 5.80E+06 | 6.70E+09 | 0.04 | | 0.04 |
| 29 | Labor | $ | 9.45E+04 | 1.20E+12 | 0.11 | | 0.11 |
| 30 | Annual Yield (y) | g | 9.71E+10 | 1.59E+09 | 154.79 | 0.02 | 154.77 |
| | | | | | Specific Emergy (sej/kg) | 2.34E+08 | 1.59E+12 |

Table B-4. Emergy evaluation of fired clay brick with oil-contaminated soil, natural gas and sawdust fuel. Emergy values adapted from Buranakarn (1998), Table 3-3.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (Sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| A. Conventional fire brick product | | | | | | | |
| 1 | Clay | g | 6.77E+11 | 2.00E+09 | 13.5 | | 13.5 |
| 2 | Water | J | 8.97E+11 | 4.80E+04 | 0.0004 | 0.0004 | |
| 3 | Natural gas | J | 2.67E+15 | 4.80E+04 | 1.28 | 1.28 | |
| 4 | Machinery | g | 8.00E+07 | 6.70E+09 | 0.0054 | | 0.0054 |
| 5 | Labor | $ | 1.71E+07 | 1.15E+12 | 0.2 | | 0.2 |
| 6 | Annual Yield (y) | g | 6.77E+11 | 2.22E+09 | 15.01 | 1.28 | 13.73 |
| | | | | | Specific Emergy (sej/kg) | 1.89E+11 | 2.03E+12 |
| B. Byproduct use (sawdust) fired clay brick product | | | | | | | |
| 7 | Clay | g | 6.77E+11 | 2.00E+09 | 13.5 | | 13.5 |
| 8 | Water | J | 8.97E+11 | 4.80E+04 | 0.0004 | 0.0004 | |
| 9 | Natural gas | J | 6.68E+14 | 4.80E+04 | 0.32 | 0.32 | |
| 10 | Sawdust fuel | J | 2.01E+15 | 1.56E+04 | 0.31 | 0.31 | |
| 11 | Machinery | g | 8.00E+07 | 6.70E+09 | 0.0054 | | 0.0054 |
| 12 | Labor | $ | 1.71E+07 | 1.15E+12 | 0.2 | | 0.2 |
| 13 | Annual Yield (y) | g | 6.17E+11 | 2.12E+09 | 14.03 | 0.63 | 13.40 |
| | | | | | Specific Emergy (sej/kg) | 1.02E+11 | 2.17E+12 |
| C. Byproduct use (oiI-contaminated soil) fired clay brick product | | | | | | | |
| 14 | Clay | g | 5.42E+11 | 2.00E+09 | 10.84 | | 10.84 |
| 15 | Oil-contaminated soil | g | 1.35E+11 | 1.00E+09 | 1.35 | 1.35 | |
| 16 | Water | J | 8.97E+11 | 4.80E+04 | 0.0004 | 0.0004 | |
| 17 | Natural gas | J | 6.68E+14 | 4.80E+04 | 0.32 | 0.32 | |
| 18 | Sawdust fuel | J | 2.01E+15 | 1.56E+04 | 0.31 | 0.31 | |
| 19 | Transport (Railroad) | ton-mile | 2.24E+06 | 5.07E+10 | 0.0011 | | 0.0011 |
| 20 | Transport (Truck) | ton-mile | 2.24E+06 | 9.65E+11 | 0.02 | | 0.02 |
| 21 | Machinery | g | 8.00E+07 | 6.70E+09 | 0.0054 | | 0.0054 |
| 22 | Labor | $ | 1.71E+07 | 1.15E+12 | 0.2 | | 0.2 |
| 23 | Annual Yield (y) | g | 6.77E+11 | 1.93E+09 | 13.05 | 1.98 | 11.07 |
| | | | | | Specific Emergy (sej/kg) | 2.93E+11 | 1.64E+12 |

Table B-5. Emergy evaluation of steel and steel recycling alternatives using electric arc furnace process. Emergy values adapted from Buranakarn (1998), Table 3-4.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| A. Conventional steel product | | | | | | | |
| 1 | Pig iron | g | 4.53E+13 | 2.83E+09 | 1283 | | 1283 |
| 2 | Natural gas | J | 3.11E+17 | 4.80E+04 | 152.38 | 152.38 | |
| 3 | Other fuels | J | 2.80E+16 | 6.60E+04 | 18.51 | 18.51 | |
| 4 | Electricity | J | 1.84E+17 | 1.74E+05 | 319.45 | 31.945 | 287.51 |
| 5 | Transport (Railroad) | ton-mile | 7.50E+09 | 5.07E+10 | 3.8 | | 3.8 |
| 6 | Transport (Truck) | ton-mile | 7.50E+09 | 9.65E+11 | 72.34 | | 72.34 |
| 7 | Labor | $ | 1.58E+09 | 1.20E+12 | 18.98 | | 18.98 |
| 8 | Annual Yield (y) | g | 4.49E+13 | 4.15E+09 | 1867.6 | 202.84 | 1664.77 |
| | | | | | Specific Emergy (sej/kg) | 4.52E+11 | 3.71E+12 |
| B. Material recycling steel product | | | | | | | |
| 9 | Post-consumer steels | g | 4.53E+13 | 2.83E+09 | 1283 | 1283 | |
| 10 | Post-consumer steel collection | g | 4.53E+13 | 2.51E+08 | 113 | 113 | |
| 11 | Post-consumer steel separation | g | 4.53E+13 | 8.24E+06 | 3.7 | 3.7 | |
| 12 | Natural gas | J | 3.11E+17 | 4.80E+04 | 152.38 | 152.38 | |
| 13 | Other fuels | J | 2.80E+16 | 6.60E+04 | 18.51 | 18.51 | |
| 14 | Electricity | J | 1.84E+17 | 1.74E+05 | 319.45 | 31.945 | 287.51 |
| 15 | Transport (Railroad) | ton-mile | 7.50E+09 | 5.01E+10 | 3.8 | | 3.8 |
| 16 | Transport (Truck) | ton-mile | 7.50E+09 | 9.65E+11 | 72.34 | | 72.34 |
| 17 | Labor | $ | 1.58E+09 | 1.20E+12 | 18.98 | | 18.98 |
| 18 | Annual Yield (y) | g | 4.49E+13 | 4.41E+09 | 1983.3 | 1602.54 | 380.77 |
| | | | | | Specific Emergy (sej/kg) | 3.57E+12 | 8.48E+11 |
| C. Material recycling and byproduct use steel product | | | | | | | |
| 19 | Post-consumer steels | g | 1.36E+13 | 2.83E+09 | 385.01 | 385.01 | |
| 20 | Steel scrap or slag | g | 3.11E+13 | 2.83E+09 | 898.36 | 898.36 | |
| 21 | Post-consumer steel collection | g | 1.36E+13 | 2.51E+08 | 34.13 | 34.13 | |
| 22 | Post-consumer steel separation | g | 1.36E+13 | 8.24E+06 | 1.12 | 1.12 | |
| 23 | Natural gas | J | 3.11E+17 | 4.80E+04 | 152.38 | 152.38 | |
| 24 | Other fuels | J | 2.80E+16 | 6.60E+04 | 18.51 | 18.51 | |
| 25 | Electricity | J | 1.84E+17 | 1.74E+05 | 319.45 | 31.945 | 287.51 |
| 26 | Transport (Railroad) | ton-mile | 7.50E+09 | 5.07E+10 | 3.8 | | 3.8 |
| 27 | Transport (Truck) | ton-mile | 7.50E+09 | 9.65E+11 | 72.34 | | 72.34 |
| 28 | Labor | $ | 1.58E+09 | 1.20E+12 | 18.98 | | 18.98 |
| 29 | Annual Yield (y) | g | 4.49E+13 | 4.24E+09 | 1904.1 | 1521.46 | 382.64 |
| | | | | | Specific Emergy (sej/kg) | 3.39E+12 | 8.52E+11 |

Table B-6. Emergy evaluation of in-house recycling of steel production using basic Oxygen furnace process. Emergy values adapted from Buranakarn (1998), Table 3-5.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| A. Conventional steel product | | | | | | | |
| 1 | Pig iron | g | 6.11E+13 | 2.83E+09 | 1730 | | 1730 |
| 2 | Water | J | 4.06E+15 | 4.80E+04 | 1.95 | 1.95 | |
| 3 | Coal/Coke | J | 8.22E+17 | 4.00E+04 | 328.77 | 328.77 | |
| 4 | Natural gas | J | 2.82E+17 | 4.80E+04 | 135.36 | 135.36 | |
| 5 | Other fuels | J | 2.31E+17 | 6.60E+04 | 156.19 | 156.19 | |
| 6 | Electricity | J | 4.92E+17 | 1.74E+05 | 855.62 | 85.56 | 770.06 |
| 7 | Labor | $ | 2.43E+09 | 1.20E+12 | 29.11 | | 29.11 |
| 8 | Annual Yield (y) | g | 6.04E+13 | 5.35E+09 | 3233.4 | 707.83 | 2525.59 |
| | | | | | Specific Emergy (sej/kg) | 1.17E+12 | 4.18E+12 |
| B. In-house material recycling steel product | | | | | | | |
| 9 | In-house steel scrap | g | 1.53E+13 | 2.83E+09 | 431.6 | 431.6 | |
| 10 | Pig iron | g | 4.58E+13 | 2.83E+09 | 1294.8 | | 1294.81 |
| 11 | Water | J | 4.06E+15 | 4.80E+04 | 1.95 | 1.95 | |
| 12 | Coal/Coke | J | 8.22E+17 | 4.00E+04 | 328.77 | 328.77 | |
| 13 | Natural gas | J | 2.82E+17 | 4.80E+04 | 135.36 | 135.36 | |
| 14 | Other fuels | J | 2.31E+17 | 6.60E+04 | 156.19 | 156.19 | |
| 15 | Electricity | J | 4.92E+17 | 1.74E+05 | 855.62 | 85.56 | 770.06 |
| 16 | Labor | $ | 2.43E+09 | 1.20E+12 | 29.11 | | 29.11 |
| 17 | Annual Yield (y) | g | 6.04E+13 | 5.35E+09 | 3233.4 | 1139.43 | 2093.99 |
| | | | | | Specific Emergy (sej/kg) | 1.89E+12 | 3.47E+12 |

Table B-7. Emergy evaluation of aluminum sheet production using electrolytic process. Emergy values adapted from Buranakarn (1998), Table 3-6.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| A. Conventional aluminum sheet product | | | | | | | |
| 1 | Primary aluminum (ingot) | g | 4.17E+11 | 1.11E+10 | 48.8 | | 48.8 |
| 2 | Electricity | J | 1.08E+15 | 1.74E+05 | 1.88 | 0.19 | 1.69 |
| 3 | Labor | $ | 2.90E+09 | 1.15E+12 | 0.33 | | 0.33 |
| 4 | Annual Yield (y) | g | 4.00E+11 | 1.27E+10 | 51.01 | 0.19 | 50.82 |
| | | | | | Specific Emergy (sej/kg) | 4.70E+10 | 1.27E+13 |
| B. Material recycling aluminum sheet product | | | | | | | |
| 5 | Used aluminum can | g | 4.17E+11 | 1.11E+10 | 48.8 | 48.8 | |
| 6 | Used AL can connection | g | 4.17E+11 | 2.51E+08 | 1.04 | | 1.04 |
| 7 | Used AL can separation | g | 4.17E+11 | 8.24E+06 | 0.03 | | 0.03 |
| 8 | Electricity | J | 1.08E+15 | 1.74E+05 | 1.88 | 0.19 | 1.69 |
| 9 | Transport (Truck) | ton-mile | 1.38E+07 | 9.65E+11 | 0.13 | | 0.13 |
| 10 | Labor | $ | 2.90E+07 | 1.15E+12 | 0.33 | | 0.33 |
| 11 | Annual Yield (y) | g | 4.00E+11 | 1.30E+10 | 52.21 | 48.99 | 3.22 |
| | | | | | Specific Emergy (sej/kg) | 1.22E+13 | 8.06E+11 |
| C. Material recycling and byproduct use aluminum sheet product | | | | | | | |
| 12 | Used aluminum can | g | 2.29E+11 | 1.11E+10 | 26.81 | 26.81 | |
| 13 | Primary aluminum (ingot) | g | 1.25E+11 | 1.11E+10 | 14.63 | | 14.63 |
| 14 | Aluminum scrap | g | 6.25E+10 | 1.11E+10 | 7.31 | 7.31 | |
| 15 | Used AL can connection | g | 2.29E+11 | 2.51E+08 | 0.57 | | 0.57 |
| 16 | Used AL can separation | g | 2.29E+11 | 8.24E+06 | 0.02 | | 0.02 |
| 17 | Electricity | J | 1.08E+15 | 1.74E+05 | 1.88 | 0.19 | 1.69 |
| 18 | Transport (Truck) | ton-mile | 2.82E+09 | 9.65E+11 | 0.27 | | 0.27 |
| 19 | Labor | $ | 2.90E+07 | 1.15E+12 | 0.33 | | 0.33 |
| 20 | Annual Yield (y) | g | 4.00E+11 | 1.29E+10 | 51.82 | 34.31 | 17.51 |
| | | | | | Specific Emergy (sej/kg) | 8.58E+12 | 4.38E+12 |

Table B-8. Emergy evaluation of softwood plywood production.
Emergy values adapted from Buranakarn (1998), Table 3-7.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| 1 | Hardwood logs | J | 4.28E+16 | 8.01E+03 | 3.43 | 3.43 | |
| 2 | Softwood logs | J | 1.51E+18 | 8.01E+03 | 120.82 | 120.82 | |
| 3 | Lumber | J | 2.71E+14 | 4.40E+04 | 0.12 | 0.12 | |
| 4 | Hardwood veneer | J | 6.39E+14 | 4.40E+04 | 0.28 | 0.28 | |
| 5 | Softwood plywood | J | 5.76E+14 | 4.40E+04 | 0.25 | 0.25 | |
| 6 | Hardboard | J | 1.14E+13 | 1.21E+05 | 0.01 | 0.01 | |
| 7 | Oil (fuel) | J | 4.96E+15 | 6.60E+04 | 3.27 | 3.27 | |
| 8 | Electricity | J | 9.61E+15 | 1.74E+05 | 16.72 | 1.67 | 15.05 |
| 9 | Labor | $ | 8.21E+10 | 1.43E+12 | 11.83 | | 11.83 |
| 10 | Annual Yield (y) | g | 1.30E+13 | 1.21E+09 | 156.74 | 129.852 | 26.888 |
| | | | | | Specific Emergy (sej/kg) | 9.99E+11 | 2.07E+11 |

Table B-9. Emergy evaluation of laminated plywood production using shaved wood product. Emergy values adapted from Buranakarn (1998), Table 3-8.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+18 | Renew Substitutability (sej) 1.00E+18 | Non-Renewables (sej) 1.00E+18 |
|---|---|---|---|---|---|---|---|
| 1 | Shaved lumber | g | 7.25E+09 | 8.79E+08 | 6.37 | 6.37 | |
| 2 | Veneer | g | 5.80E+09 | 1.21E+09 | 7.01 | 7.01 | |
| 3 | Plastics resin | g | 1.45E+09 | 3.28E+09 | 4.75 | | 4.75 |
| 4 | Water | J | 4.30E+09 | 4.80E+04 | 0.0002 | 0.0002 | |
| 5 | Natural gas | J | 3.04E+13 | 4.80E+04 | 1.46 | 1.46 | |
| 6 | Oil (fuel) | J | 3.04E+13 | 6.60E+04 | 2 | 2 | |
| 7 | Electricity | J | 1.73E+11 | 1.70E+05 | 0.03 | 0.003 | 0.027 |
| 8 | Labor | $ | 1.85E+06 | 1.15E+12 | 2.12 | | 2.12 |
| 9 | Annual Yield (y) | g | 1.45E+10 | 1.64E+09 | 23.75 | 16.84 | 6.91 |
| | | | | | Specific Emergy (sej/kg) | 1.16E+12 | 4.76E+11 |

Table B-10. Emergy evaluation of lumber production.
Emergy values adapted from Buranakarn (1998), Table 3-9.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+20 | Renew Substitutability (sej) 1.00E+20 | Non-Renewables (sej) 1.00E+20 |
|---|---|---|---|---|---|---|---|
| 1 | Hardwood logs | J | 1.72E+18 | 8.01E+03 | 137.63 | 137.63 | |
| 2 | Softwood logs | J | 6.91E+18 | 8.01E+03 | 554.39 | 554.39 | |
| 3 | Hardwood lumber | J | 2.64E+16 | 4.40E+04 | 11.64 | 11.64 | |
| 4 | Softwood lumber | J | 7.70E+16 | 4.40E+04 | 33.9 | 33.9 | |
| 5 | Glue and Adhesives | g | 5.20E+10 | 3.80E+08 | 0.2 | | 0.2 |
| 6 | Oil (fuel) | J | 1.39E+16 | 6.60E+04 | 9.19 | 9.19 | |
| 7 | Electricity | J | 2.43E+16 | 1.74E+05 | 42.36 | 4.24 | 38.12 |
| 8 | Labor | $ | 3.05E+09 | 1.43E+12 | 43.55 | | 43.55 |
| 9 | Annual Yield (y) lumber | g | 9.41E+13 | 8.79E+08 | 832.86 | 750.99 | 81.87 |
| | | | | | Specific Emergy (sej/kg) | 7.98E+11 | 8.70E+10 |

Table B-11. Emergy evaluation of recycled lumber.
Emergy values adapted from Buranakarn (1998), Table 3-10.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+16 | Renew Substitutability (sej) 1.00E+16 | Non-Renewables (sej) 1.00E+16 |
|---|---|---|---|---|---|---|---|
| 1 | Used lumber | g | 2.94E+08 | 8.79E+08 | 26 | 26 | |
| 2 | Propane gas | J | 2.31E+10 | 4.80E+04 | 0.11 | 0.11 | |
| 3 | Oil (fuel) | J | 2.64E+10 | 6.60E+04 | 0.17 | 0.17 | |
| 4 | Transport (Truck) | ton-mile | 9.72E+04 | 9.65E+11 | 9 | | 9 |
| 5 | Labor (demolition) | $ | 8.58E+05 | 1.15E+12 | 99 | | 99 |
| 6 | Annual Yield (y) | g | 1.99E+08 | 6.74E+09 | 134.28 | 26.28 | 108 |
| | | | | | Specific Emergy (sej/kg) | 1.32E+12 | 5.43E+12 |

Table B-12. Emergy evaluation of vinyl floor production using byproduct PVC.
Emergy values adapted from Buranakarn (1998), Table 3-11.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+18 | Renew Substitutability (sej) 1.00E+18 | Non-Renewables (sej) 1.00E+18 |
|---|---|---|---|---|---|---|---|
| 1 | Plastics (PVC) | g | 5.61E+09 | 5.87E+09 | 33.26 | | 33.26 |
| 2 | Electricity | J | 1.73E+12 | 1.74E+05 | 0.3 | 0.03 | 0.27 |
| 3 | Transport (Truck) | ton-mile | 6.24E+05 | 9.65E+11 | 0.6 | | 0.6 |
| 4 | Machinery | g | 9.08E+05 | 6.70E+09 | 0.0061 | | 0.0061 |
| 5 | Labor | $ | 1.45E+06 | 1.15E+12 | 1.67 | | 1.67 |
| 6 | Annual Yield (y) | g | 5.67E+09 | 6.32E+09 | 35.84 | 0.03 | 35.81 |
| | | | | | Specific Emergy (sej/kg) | 5.29E+09 | 6.32E+12 |

Table B-13. Emergy evaluation of plastic lumber (HDPE) production.
Emergy values adapted from Buranakarn (1998), Table 3-12.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+16 | Renew Substitutability (sej) 1.00E+16 | Non-Renewables (sej) 1.00E+16 |
|---|---|---|---|---|---|---|---|
| A. Conventional plastic lumber (HDPE) product | | | | | | | |
| 1 | Wood fiber | j | 2.67E+12 | 4.20E+04 | 11.2 | 11.2 | |
| 2 | Plastic resin | g | 7.22E+08 | 5.27E+09 | 380.71 | | 380.71 |
| 3 | Electricity | j | 1.08E+12 | 1.74E+05 | 18.79 | 1.879 | 16.911 |
| 4 | Transport (Truck) | ton-mile | 1.87E+05 | 9.65E+11 | 18.04 | | 18.04 |
| 5 | Machinery | g | 4.84E+05 | 6.70E+09 | 0.32 | | 0.32 |
| 6 | Labor | $ | 5.27E+05 | 1.15E+12 | 60.64 | | 60.64 |
| 7 | Annual Yield (y) | g | 8.50E+08 | 5.75E+09 | 489.47 | 13.079 | 476.391 |
| | | | | | Specific Emergy (sej/kg) | 1.54E+11 | 5.60E+12 |
| B. Adaptive reuse plastic lumber (HDPE) product | | | | | | | |
| 8 | Post-consumer paper | j | 2.67E+12 | 1.42E+05 | 37.89 | 37.89 | |
| 9 | Post-consumer plastic | g | 7.22E+08 | 5.21E+09 | 380.71 | 380.71 | |
| 10 | Collection | g | 8.49E+08 | 2.51E+08 | 21.33 | | 21.33 |
| 11 | Separation | g | 8.49E+08 | 8.24E+06 | 0.7 | | 0.7 |
| 12 | Electricity | j | 1.08E+12 | 1.74E+05 | 18.79 | 1.88 | 16.91 |
| 13 | Transport (Truck) | ton-mile | 1.87E+05 | 9.65E+11 | 18.04 | | 18.04 |
| 14 | Machinery | g | 4.84E+05 | 6.70E+09 | 0.32 | | 0.32 |
| 15 | Labor | $ | 5.21E+05 | 1.15E+12 | 60.64 | | 60.64 |
| 16 | Annual Yield (y) | g | 8.50E+08 | 6.33E+09 | 538.41 | 420.48 | 117.93 |
| | | | | | Specific Emergy (sej/kg) | 4.95E+12 | 1.39E+12 |

Table B-14. Emergy evaluation of ceramic tile production.
Emergy values adapted from Buranakarn (1998), Table 3-13.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+18 | Renew Substitutability (sej) 1.00E+18 | Non-Renewables (sej) 1.00E+18 |
|---|---|---|---|---|---|---|---|
| A. Conventional ceramic tile product | | | | | | | |
| 1 | Silica sand | g | 3.38E+09 | 1.00E+09 | 3.38 | | 3.38 |
| 2 | Sand | g | 1.31E+08 | 1.00E+09 | 0.13 | | 0.13 |
| 3 | Clay | g | 1.09E+09 | 2.00E+09 | 2.18 | | 2.18 |
| 4 | Others | g | 2.18E+08 | 1.00E+09 | 0.22 | | 0.22 |
| 5 | Water | J | 1.08E+09 | 4.80E+04 | 5E-05 | 0.000052 | |
| 6 | Natural gas | J | 8.85E+13 | 4.80E+04 | 4.25 | 4.25 | |
| 7 | Electricity | J | 1.61E+12 | 1.74E+05 | 0.28 | 0.03 | 0.25 |
| 8 | Transport (Truck) | ton-mile | 1.19E+06 | 9.95E+11 | 1.14 | | 1.14 |
| 9 | Machinery | g | 4.08E+07 | 6.70E+09 | 0.27 | | 0.27 |
| 10 | Labor | $ | 6.85E+05 | 1.20E+12 | 0.82 | | 0.82 |
| 11 | Annual Yield (y) ceramic tile | g | 4.14E+09 | 3.06E+09 | 12.69 | 4.28 | 8.41 |
| | | | | | Specific Emergy (sej/kg) | 1.03E+12 | 2.03E+12 |
| B. Adaptive reuse ceramic tile product with windshield glass | | | | | | | |
| 12 | Sand | g | 1.31E+08 | 1.00E+09 | 0.13 | | 0.13 |
| 13 | Clay | g | 1.09E+09 | 2.00E+09 | 2.18 | | 2.18 |
| 14 | Post-consumer windshield glass | g | 2.70E+09 | 1.90E+09 | 5.13 | 5.13 | |
| 18 | Others | g | 2.18E+08 | 1.00E+09 | 0.22 | | 0.22 |
| 16 | Used windshield glass (collection) | g | 2.70E+09 | 9.65E+11 | 0.86 | | 0.86 |
| 17 | Used windshield glass (separation) | g | 2.70E+09 | 8.24E+06 | 0.02 | | 0.02 |
| 18 | Water | J | 1.08E+09 | 4.80E+04 | 5E-05 | 0.000052 | |
| 19 | Natural gas | J | 6.65E+13 | 4.80E+04 | 3.19 | 3.19 | |
| 20 | Electricity | J | 1.21E+12 | 1.74E+05 | 0.21 | 0.02 | 0.19 |
| 21 | Transport (Truck) | ton-mile | 1.19E+06 | 9.65E+11 | 1.14 | | 1.14 |
| 22 | Machinery | g | 4.08E+07 | 6.70E+09 | 0.27 | | 0.27 |
| 23 | Labor | $ | 6.85E+05 | 1.20E+12 | 0.82 | | 0.82 |
| 24 | Annual Yield (y) ceramic tile | g | 4.14E+09 | 3.42E+09 | 14.16 | 8.34 | 5.82 |
| | | | | | Specific Emergy (sej/kg) | 2.01E+12 | 1.41E+12 |
| C. Adaptive reuse ceramic tile product with post-consumer glass bottles | | | | | | | |
| 25 | Sand | g | 1.31E+08 | 1.00E+09 | 0.13 | | 0.13 |
| 26 | Clay | g | 1.09E+09 | 2.00E+09 | 2.18 | | 2.18 |
| 27 | Post-consumer windshield glass | g | 2.70E+09 | 1.90E+09 | 5.13 | 5.13 | |
| 28 | Others | g | 2.18E+08 | 1.00E+09 | 0.22 | | 0.22 |
| 29 | Used windshield glass (collection) | g | 2.70E+09 | 2.51E+08 | 0.86 | | 0.86 |
| 30 | Used windshield glass (separation) | g | 2.70E+09 | 1.32E+07 | 0.02 | | 0.02 |
| 31 | Water | J | 1.08E+09 | 4.80E+04 | 5E-05 | 0.000052 | |
| 32 | Natural gas | J | 6.65E+13 | 4.80E+04 | 3.19 | 3.19 | |
| 33 | Electricity | J | 1.21E+12 | 1.74E+05 | 0.21 | 0.02 | 0.19 |
| 34 | Transport (Truck) | ton-mile | 1.19E+06 | 9.65E+11 | 1.14 | | 1.14 |
| 35 | Machinery | g | 4.08E+07 | 6.70E+09 | 0.27 | | 0.27 |
| 36 | Labor | $ | 6.85E+05 | 1.20E+12 | 0.82 | | 0.82 |
| 37 | Annual Yield (y) ceramic tile | g | 4.14E+09 | 3.42E+09 | 14.16 | 8.34 | 5.82 |
| | | | | | Specific Emergy (sej/kg) | 2.01E+12 | 1.41E+12 |

Table B-15. Emergy evaluation of float glass production.
Emergy values adapted from Buranakarn (1998), Table 3-14.

| Sr No | Note Item | Unit | Input Resource | Solar Emergy per Unit (sej/Unit) | Emergy (sej) 1.00E+18 | Renew Substitutability (sej) 1.00E+18 | Non-Renewables (sej) 1.00E+18 |
|---|---|---|---|---|---|---|---|
| A. Conventional float glass product | | | | | | | |
| 1 | Silica (SiO2) | g | 1.72E+11 | 1.00E+09 | 172 | | 172 |
| 2 | Soda ash (Na2O) | g | 1.91E+10 | 3.80E+08 | 7.27 | | 7.27 |
| 3 | Lime (CaO) | g | 1.27E+10 | 6.70E+06 | 0.09 | | 0.09 |
| 4 | Magnesium oxide (MgO) | g | 3.82E+09 | 3.80E+08 | 1.45 | | 1.45 |
| 5 | Others | g | 2.55E+09 | 3.80E+08 | 0.97 | | 0.97 |
| 6 | Oil | J | 1.20E+16 | 6.60E+04 | 790 | 790 | |
| 7 | Transport (Railroad) | ton-mile | 6.37E+07 | 5.07E+10 | 3.23 | | 3.23 |
| 8 | Transport (Truck) | ton-mile | 2.39E+06 | 9.65E+11 | 2.31 | | 2.31 |
| 9 | Labor | $ | 2.18E+07 | 1.15E+12 | 25.01 | | 25.01 |
| 10 | Annual Yield (y) | g | 1.27E+11 | 7.87E+09 | 1000 | 790 | 210 |
| | | | | | Specific Emergy (sej/kg) | 6.22E+12 | 1.65E+12 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| B. In-house traditional recycling float glass product | | | | | | | |
| 11 | Silica (SiO2) | g | 9.18E+10 | 1.00E+09 | 91.77 | | 91.77 |
| 12 | Soda ash (Na2O) | g | 1.91E+10 | 3.80E+08 | 7.27 | | 7.27 |
| 13 | Lime (CaO) | g | 1.27E+10 | 6.70E+06 | 0.09 | | 0.09 |
| 14 | Magnesium oxide (MgO) | g | 3.82E+09 | 3.80E+08 | 1.45 | | 1.45 |
| 15 | Others | g | 2.55E+09 | 3.80E+08 | 0.97 | | 0.97 |
| 16 | Glass Scrap | g | 5.46E+10 | 1.90E+09 | 103.79 | 103.79 | |
| 17 | Oil | J | 1.12E+16 | 6.60E+04 | 740.8 | 740.8 | |
| 18 | Transport (Railroad) | ton-mile | 6.37E+07 | 5.07E+10 | 3.23 | | 3.23 |
| 19 | Transport (Truck) | ton-mile | 2.39E+06 | 9.65E+11 | 2.31 | | 2.31 |
| 20 | Labor | $ | 2.18E+07 | 1.15E+12 | 25.01 | | 25.01 |
| 21 | Annual Yield (y) | g | 1.27E+11 | 7.66E+09 | 976.68 | 844.59 | 132.09 |
| | | | | | Specific Emergy (sej/kg) | 6.65E+12 | 1.04E+12 |

# APPENDIX C

Table C-1. Quantity estimation of Building #1, specific emergy and transformities.

| Item | Vol (m3) | Density (kg/m3) | Raw Data | Unit | Specific Emergy (sej/unit) | | Transformity (sej/unit) | Ref |
|---|---|---|---|---|---|---|---|---|
| | | | | | RS | NR | | |
| GROUND WORK | | | | | | | | |
| Basement foundation | 131.39 | 2400 | 315336 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Basement foundation | | 7850 | 39417 | kg | 4.52E+11 | 3.71E+12 | | Self |
| STRUCTURAL FRAME | | | | | | | | |
| Columns, beams | 53.77 | 2400 | 129039 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Columns, beams | | 7850 | 16130 | kg | 4.52E+11 | 3.71E+12 | | Self |
| GROUND FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 22.26 | 1045 | 23259 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 50.13 | 1000 | 50129 | kg | | | 1.35E+09 | f |
| Insulation | 9.49 | 1380 | 13098 | kg | | | 9.61E+12 | d |
| Interior finish | 41.77 | 1000 | 41774 | kg | | | 1.84E+09 | i |
| Interior finish | 0.17 | 1450 | 240 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 22.95 | 2500 | 57386 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls (lightened) | 94.57 | 667 | 63077 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 5.92 | 1300 | 7691 | kg | | | 3.31E+12 | b |
| Plaster | 22.36 | 1450 | 32424 | kg | | | 3.29E+12 | d |
| Paint | 0.04 | 1450 | 58 | kg | | | 2.55E+13 | b |
| FIRST FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 31.97 | 1045 | 33412 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 72.01 | 1000 | 72012 | kg | | | 1.35E+09 | f |
| Thermal Insulation | 13.63 | 1380 | 18815 | kg | | | 9.61E+12 | d |
| Interior finish | 60.01 | 1000 | 60010 | kg | | | 1.84E+09 | i |
| Interior finish | 0.24 | 1450 | 344 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 31.84 | 2500 | 79588 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls (lightened) | 94.57 | 667 | 63077 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 5.92 | 1300 | 7691 | kg | | | 3.31E+12 | b |
| Plaster | 22.36 | 1450 | 32424 | kg | | | 3.29E+12 | d |
| Paint | 0.04 | 1450 | 58 | kg | | | 2.55E+13 | b |
| Floor | | | | | | | | |
| Floor Slab | 90.13 | 2400 | 216314 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Floor Slab | | 7850 | 27039 | kg | 4.52E+11 | 3.71E+12 | | Self |
| Roof Slab | | | | | | | | |
| Roof | 90.13 | 2400 | 216314 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Roof | | 7850 | 27039 | kg | 4.52E+11 | 3.71E+12 | | Self |

Table C-2. Quantity estimation of Building #2, specific emergy and transformities.

| Item | Vol (m3) | Density (kg/m3) | Raw Data | Unit | Specific Emergy (sej/unit) | | Transformity (sej/unit) | Ref |
|---|---|---|---|---|---|---|---|---|
| | | | | | RS | NR | | |
| GROUND WORK | | | | | | | | |
| Basement foundation | 41.27 | 2400 | 99052 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Basement foundation | | 7850 | 12382 | kg | 4.52E+11 | 3.71E+12 | | Self |
| STRUCTURAL FRAME | | | | | | | | |
| Columns, beams | 10.58 | 2400 | 25395 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Columns, beams | | 7850 | 3174 | kg | 4.52E+11 | 3.71E+12 | | Self |
| GROUND FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 11.46 | 1045 | 11977 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 25.81 | 1000 | 25814 | kg | | | 1.35E+09 | f |
| Thermal Insulation | 4.89 | 1380 | 6745 | kg | | | 9.61E+12 | d |
| Interior finish | 21.51 | 1000 | 21512 | kg | | | 1.84E+09 | i |
| Interior finish | 0.09 | 1450 | 123 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 3.55 | 2500 | 8884 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls (lightened) | 15.45 | 667 | 10302 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 0.97 | 1300 | 1256 | kg | | | 3.31E+12 | b |
| Plaster | 3.65 | 1450 | 5296 | kg | | | 3.29E+12 | c |
| Paint | 0.01 | 1450 | 9 | kg | | | 2.55E+13 | c |
| FIRST FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 11.42 | 1045 | 11929 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 25.71 | 1000 | 25710 | kg | | | 1.35E+09 | f |
| Thermal Insulation | 4.87 | 1380 | 6718 | kg | | | 9.61E+12 | d |
| Interior finish | 21.43 | 1000 | 21425 | kg | | | 1.84E+09 | i |
| Interior finish | 0.08 | 1450 | 123 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 8.22 | 2500 | 20558 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls (lightened) | 15.45 | 667 | 10302 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 0.97 | 1300 | 1256 | kg | | | 3.31E+12 | b |
| Plaster | 3.65 | 1450 | 5296 | kg | | | 3.29E+12 | d |
| Paint | 0.01 | 1450 | 9 | kg | | | 2.55E+13 | b |
| Floor | | | | | | | | |
| Floor Slab | 45.55 | 2400 | 109331 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Floor Slab | | 7850 | 13666 | kg | 4.52E+11 | 3.71E+12 | | Self |
| Roof Slab | | | | | | | | |
| Roof | 45.55 | 2400 | 109331 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Roof | | 7850 | 13666 | kg | 4.52E+11 | 3.71E+12 | | Self |

Table C-3. Quantity estimation of Building #3 (except first floor), specific emergy and transformities.

| Item | Vol (m3) | Density (kg/m3) | Raw Data | Unit | Specific Emergy (sej/unit) | | Transformity (sej/unit) | Ref |
|---|---|---|---|---|---|---|---|---|
| | | | | | RS | NR | | |
| GROUND WORK | | | | | | | | |
| Basement foundation | 239.66 | 2400 | 575183 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Basement foundation | | 7850 | 71898 | kg | 4.52E+11 | 3.71E+12 | | Self |
| STRUCTURAL FRAME | | | | | | | | |
| Columns, beams | 188.53 | 2400 | 452464 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Columns, beams | | 7850 | 56558 | kg | 4.52E+11 | 3.71E+12 | | Self |
| Retention wall | 3.72 | 2400 | 452464 | kg | 3.47E+10 | 1.41E+12 | | Self |
| GROUND FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 48.26 | 1045 | 50432 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 108.69 | 1000 | 108694 | kg | | | 1.35E+09 | f |
| Insulation | 20.58 | 1380 | 28400 | kg | | | 9.61E+12 | d |
| Interior finish | 90.58 | 1000 | 90579 | kg | | | 1.84E+09 | i |
| Interior finish | 0.36 | 1450 | 519 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 4.59 | 2500 | 11468 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls | 355.01 | 667 | 236791 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 20.96 | 1300 | 27252 | kg | | | 3.31E+12 | b |
| Plaster | 0.02 | 1450 | 35 | kg | | | 3.29E+12 | d |
| Paint | 0.04 | 1450 | 54 | kg | | | 2.55E+13 | b |
| Walls (lightened) | 31.03 | 667 | 20699 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 1.94 | 1300 | 2524 | kg | | | 3.31E+12 | j |
| Plaster | 7.34 | 1450 | 10640 | kg | | | 3.29E+12 | d |
| Paint | 0.01 | 1450 | 19 | kg | | | 2.55E+13 | b |
| MEZZANINE FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 48.26 | 1045 | 50432 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 108.69 | 1000 | 108694 | kg | | | 1.35E+09 | f |
| Insulation | 48.26 | 1380 | 66599 | kg | | | 9.61E+12 | d |
| Interior finish | 90.58 | 1000 | 90579 | kg | | | 1.84E+09 | i |
| Interior finish | 0.36 | 1450 | 519 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 4.59 | 2500 | 11468 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls | 355.01 | 667 | 236791 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 20.96 | 1300 | 27252 | kg | | | 3.31E+12 | b |
| Plaster | 0.02 | 1450 | 35 | kg | | | 3.29E+12 | d |
| Paint | 0.04 | 1450 | 54 | kg | | | 2.55E+13 | b |
| Walls (lightened) | 31.03 | 667 | 20699 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 1.94 | 1300 | 2524 | kg | | | 3.31E+12 | b |
| Plaster | 7.34 | 1450 | 10640 | kg | | | 3.29E+12 | d |
| Paint | 0.01 | 1450 | 19 | kg | | | 2.55E+13 | b |
| Floor | | | | | | | | |
| Floor Slab | 228.99 | 2400 | 549572 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Floor Slab | | 7850 | 68697 | kg | 4.52E+11 | 3.71E+12 | | Self |

Table C-4. Quantity estimation of Building #3 (first floor), specific emergy and transformities.

| Item | Vol (m3) | Density (kg/m3) | Raw Data | Unit | Specific Emergy (sej/unit) | | Transformity (sej/unit) | Ref |
|---|---|---|---|---|---|---|---|---|
| | | | | | RS | NR | | |
| FIRST FLOOR | | | | | | | | |
| External Wall | | | | | | | | |
| Façade brick | 37.19 | 1045 | 38859 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Structural Wall | 83.75 | 1000 | 83751 | kg | | | 1.35E+09 | f |
| Insulation | 15.86 | 1380 | 21882 | kg | | | 9.61E+12 | d |
| Interior finish | 69.79 | 1000 | 69792 | kg | | | 1.84E+09 | i |
| Interior finish | 0.28 | 1450 | 400 | kg | | | 2.55E+13 | b |
| External Windows | | | | | | | | |
| Glazing | 37.85 | 2500 | 94614 | kg | 6.22E+12 | 1.65E+12 | | Self |
| Internal Walls | | | | | | | | |
| Walls | 201.81 | 667 | 134608 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 6.31 | 1300 | 8207 | kg | | | 3.31E+12 | b |
| Plaster | 23.86 | 1450 | 34597 | kg | | | 3.29E+12 | d |
| Paint | 0.04 | 1450 | 62 | kg | | | 2.55E+13 | b |
| Walls (lightened) | 19.97 | 667 | 13321 | kg | 1.89E+11 | 2.03E+12 | | Self |
| Binder | 1.25 | 1300 | 1624 | kg | | | 3.31E+12 | b |
| Plaster | 4.72 | 1450 | 6848 | kg | | | 3.29E+12 | d |
| Paint | 0.01 | 1450 | 12 | kg | | | 2.55E+13 | b |
| Floor | | | | | | | | |
| Floor Slab | 257.11 | 2400 | 617057 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Floor Slab | | 7850 | 77132 | kg | 4.52E+11 | 3.71E+12 | | Self |
| Roof Slab | | | | | | | | |
| Roof | 257.11 | 2400 | 617057 | kg | 3.47E+10 | 1.41E+12 | | Self |
| Roof | | 7850 | 77132 | kg | 4.52E+11 | 3.71E+12 | | Self |

Table C-5. Quantity estimation of Building #4, specific emergy and transformities.

| Item | Vol (m3) | Density (kg/m3) | Raw Data | Unit | Specific Emergy (sej/unit) |  | Transformity (sej/unit) | Ref |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | RS | NR |  |  |
| GROUND WORK |  |  |  |  |  |  |  |  |
| Basement foundation | 72.31 | 2400 | 173537 | kg | 3.47E+10 | 1.41E+12 |  | Self |
| Basement foundation |  | 7850 | 21692 | kg | 4.52E+11 | 3.71E+12 |  | Self |
| STRUCTURAL FRAME |  |  |  |  |  |  |  |  |
| Columns, beams | 70.42 | 7850 | 56558 | kg | 4.52E+11 | 3.71E+12 |  | Self |
| GROUND FLOOR |  |  |  |  |  |  |  |  |
| External Wall |  |  |  |  |  |  |  |  |
| Façade brick | 4.72 | 1045 | 4937 | kg | 1.89E+11 | 2.03E+12 |  | Self |
| Structural Wall | 10.64 | 1000 | 10640 | kg |  |  | 1.35E+09 | f |
| Insulation | 2.01 | 1380 | 2780 | kg |  |  | 9.61E+12 | d |
| Interior finish | 8.87 | 1000 | 8867 | kg |  |  | 1.84E+09 | i |
| Interior finish | 0.04 | 1450 | 51 | kg |  |  | 2.55E+13 | b |
| External Windows |  |  |  |  |  |  |  |  |
| Glazing | 81.72 | 2500 | 204306 | kg | 6.22E+12 | 1.65E+12 |  | Self |
| Internal Walls |  |  |  |  |  |  |  |  |
| Walls | 12.79 | 667 | 8529 | kg | 1.89E+11 | 2.03E+12 |  | Self |
| Binder | 0.40 | 1300 | 520 | kg |  |  | 3.68E+12 | o |
| Plaster | 1.51 | 1450 | 2192 | kg |  |  | 3.31E+12 | o |
| Paint | 0.00 | 1450 | 4 | kg |  |  | 0.00E+00 | o |
| Walls (lightened) | 34.03 | 667 | 22699 | kg | 1.89E+11 | 2.03E+12 |  | Self |
| Binder | 2.13 | 1300 | 2768 | kg |  |  | 3.31E+12 | o |
| Plaster | 8.05 | 1450 | 11668 | kg |  |  | 3.29E+12 | o |
| Paint | 0.01 | 1450 | 21 | kg |  |  | 2.55E+13 | o |
| FIRST FLOOR |  |  |  |  |  |  |  |  |
| External Wall |  |  |  |  |  |  |  |  |
| Façade brick | 4.72 | 1045 | 4937 | kg | 1.89E+11 | 2.03E+12 |  | Self |
| Structural Wall | 10.64 | 1000 | 10640 | kg |  |  | 1.35E+09 | f |
| Insulation | 4.72 | 1380 | 6519 | kg |  |  | 9.61E+12 | d |
| Interior finish | 8.87 | 1000 | 8867 | kg |  |  | 1.84E+09 | i |
| Interior finish | 0.04 | 1450 | 51 | kg |  |  | 2.55E+13 | b |
| External Windows |  |  |  |  |  |  |  |  |
| Glazing | 81.72 | 2500 | 204306 | kg | 6.22E+12 | 1.65E+12 |  | Self |
| Internal Walls |  |  |  |  |  |  |  |  |
| Walls | 12.79 | 667 | 8529 | kg | 1.89E+11 | 2.03E+12 |  | Self |
| Binder | 0.40 | 1300 | 520 | kg |  |  | 3.68E+12 | b |
| Plaster | 1.51 | 1450 | 2192 | kg |  |  | 3.31E+12 | b |
| Paint | 0.00 | 1450 | 4 | kg |  |  | 0.00E+00 | b |
| Walls (lightened) | 34.03 | 667 | 22699 | kg | 1.89E+11 | 2.03E+12 |  | Self |
| Binder | 2.13 | 1300 | 2768 | kg |  |  | 3.31E+12 | b |
| Plaster | 8.05 | 1450 | 11668 | kg |  |  | 3.29E+12 | d |
| Paint | 0.01 | 1450 | 21 | kg |  |  | 2.55E+13 | b |
| Floor |  |  |  |  |  |  |  |  |
| Floor Slab | 86.18 | 2400 | 206832 | kg | 3.47E+10 | 1.41E+12 |  | Self |
| Floor Slab |  | 7850 | 25854 | kg | 4.52E+11 | 3.71E+12 |  | Self |
| Roof Slab |  |  |  |  |  |  |  |  |
| Roof | 86.18 | 2400 | 206832 | kg | 3.47E+10 | 1.41E+12 |  | Self |
| Roof |  | 7850 | 25854 | kg | 4.52E+11 | 3.71E+12 |  | Self |

Table C-6. Manufacturing emergy estimation of Building #1, specific emergy of Renewable Substitutability (RS) and non renewables (NR).

| Item | Emergy (sej) | | | (%) | | |
|---|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR | Total |
| GROUND WORK | 2.8749E+16 | 5.91972E+17 | 6.20721E+17 | 5% | 95% | 16% |
| Basement foundation | 1.09425E+16 | 4.45824E+17 | 4.56767E+17 | 2% | 98% | |
| Basement foundation | 1.78066E+16 | 1.46147E+17 | 1.63954E+17 | 11% | 89% | |
| STRUCTURAL FRAME | 1.17644E+16 | 2.4224E+17 | 2.54005E+17 | 5% | 95% | 7% |
| Columns, beams | 4.47775E+15 | 1.82435E+17 | 1.86913E+17 | 2% | 98% | |
| Columns, beams | 7.28662E+15 | 5.98048E+16 | 6.70914E+16 | 11% | 89% | |
| GROUND FLOOR | 3.73296E+17 | 5.35706E+17 | 9.09001E+17 | 41% | 59% | 24% |
| External Wall | 4.39889E+15 | 1.79291E+17 | 1.8369E+17 | 9% | 91% | |
| Façade brick | 4.39889E+15 | 4.71689E+16 | 5.15678E+16 | 9% | 91% | |
| Structural Wall | | | 6.76739E+13 | | | |
| Thermal Insulation | | | 1.25868E+17 | | | |
| Interior finish | | | 7.68641E+13 | | | |
| Interior finish | | | 6.10924E+15 | | | |
| External Windows | 3.56967E+17 | 9.489E+16 | 4.51857E+17 | 79% | 21% | |
| Glazing | 3.56967E+17 | 9.489E+16 | 4.51857E+17 | 79% | 21% | |
| Internal Walls | 1.19297E+16 | 2.61525E+17 | 2.73454E+17 | 9% | 91% | |
| Walls (lightened) | 1.19297E+16 | 1.27921E+17 | 1.39851E+17 | 9% | 91% | |
| Binder | | | 2.54585E+16 | | | |
| Plaster | | | 1.06675E+17 | | | |
| Paint | | | 1.47007E+15 | | | |
| FIRST FLOOR | 5.52766E+17 | 1.46284E+18 | 2.01561E+18 | 27% | 73% | 53% |
| External Wall | 6.31914E+15 | 2.57557E+17 | 2.63876E+17 | 9% | 91% | |
| Façade brick | 6.31914E+15 | 6.77595E+16 | 7.40787E+16 | 9% | 91% | |
| Structural Wall | | | 9.72155E+13 | | | |
| Thermal Insulation | | | 1.80814E+17 | | | |
| Interior finish | | | 1.10418E+14 | | | |
| Interior finish | | | 8.77611E+15 | | | |
| External Windows | 4.95075E+17 | 1.31602E+17 | 6.26677E+17 | 79% | 21% | |
| Glazing | 4.95075E+17 | 1.31602E+17 | 6.26677E+17 | 79% | 21% | |
| Internal Walls | 1.19297E+16 | 2.61525E+17 | 2.73454E+17 | 9% | 91% | |
| Walls (lightened) | 1.19297E+16 | 1.27921E+17 | 1.39851E+17 | 9% | 91% | |
| Binder | | | 2.54585E+16 | | | |
| Plaster | | | 1.06675E+17 | | | |
| Paint | | | 1.47007E+15 | | | |
| Floor | 1.97212E+16 | 4.0608E+17 | 4.25801E+17 | 5% | 95% | |
| Floor Slab | 7.50629E+15 | 3.05826E+17 | 3.13332E+17 | 2% | 98% | |
| Floor Slab | 1.22149E+16 | 1.00254E+17 | 1.12469E+17 | 11% | 89% | |
| Roof Slab | 1.97212E+16 | 4.0608E+17 | 4.25801E+17 | 5% | 95% | |
| Roof | 7.50629E+15 | 3.05826E+17 | 3.13332E+17 | 2% | 98% | |
| Roof | 1.22149E+16 | 1.00254E+17 | 1.12469E+17 | 11% | 89% | |
| | 9.66576E+17 | 2.83276E+18 | 3.79934E+18 | 34% | 75% | 100% |

Table C-7. Manufacturing emergy estimation of Building #2, specific emergy of Renewable Substitutability (RS) and non—renewables (NR).

| Item | Emergy (sej) | | | (%) | | |
|---|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR | Total |
| GROUND WORK | 9.03054E+15 | 1.85948E+17 | 1.94979E+17 | 5% | 95% | 16% |
| Basement foundation | 3.4372E+15 | 1.40041E+17 | 1.43478E+17 | 2% | 98% | |
| Basement foundation | 5.59334E+15 | 4.59073E+16 | 5.15006E+16 | 11% | 89% | |
| | | | | | | |
| STRUCTURAL FRAME | 2.31529E+15 | 4.76741E+16 | 4.99894E+16 | 5% | 95% | 4% |
| Columns, beams | 8.81245E+14 | 3.59042E+16 | 3.67855E+16 | 2% | 98% | |
| Columns, beams | 1.43404E+15 | 1.17699E+16 | 1.32039E+16 | 11% | 89% | |
| | | | | | | |
| GROUND FLOOR | 5.94789E+16 | 1.49732E+17 | 2.09211E+17 | 28% | 72% | 18% |
| External Wall | 2.26526E+15 | 9.23278E+16 | 9.45931E+16 | 2% | 98% | |
| Façade brick | 2.26526E+15 | 2.42901E+16 | 2.65554E+16 | | | |
| Structural Wall | | | 3.48494E+13 | | | |
| Thermal Insulation | | | 6.48173E+16 | | | |
| Interior finish | | | 3.9582E+13 | | | |
| Interior finish | | | 3.14602E+15 | | | |
| | | | | | | |
| External Windows | 5.52652E+16 | 1.46908E+16 | 6.9956E+16 | 79% | 21% | |
| Glazing | 5.52652E+16 | 1.46908E+16 | 6.9956E+16 | 79% | 21% | |
| | | | | | | |
| Internal Walls | 1.94843E+15 | 4.27139E+16 | 4.46623E+16 | 4% | 96% | |
| Walls (lightened) | 1.94843E+15 | 2.08929E+16 | 2.28413E+16 | 9% | 91% | |
| Binder | | | 4.15804E+15 | | | |
| Plaster | | | 1.74228E+16 | | | |
| Paint | | | 2.40102E+14 | | | |
| | | | | | | |
| FIRST FLOOR | 1.52021E+17 | 5.79152E+17 | 7.31173E+17 | 21% | 79% | 62% |
| External Wall | 2.25612E+15 | 9.19556E+16 | 9.42118E+16 | 2% | 98% | |
| Façade brick | 2.25612E+15 | 2.41922E+16 | 2.64483E+16 | 9% | 91% | |
| Structural Wall | | | 3.47089E+13 | | | |
| Thermal Insulation | | | 6.4556E+16 | | | |
| Interior finish | | | 3.94224E+13 | | | |
| Interior finish | | | 3.13334E+15 | | | |
| | | | | | | |
| External Windows | 1.27881E+17 | 3.39936E+16 | 1.61874E+17 | 79% | 21% | |
| Glazing | 1.27881E+17 | 3.39936E+16 | 1.61874E+17 | 79% | 21% | |
| | | | | | | |
| Internal Walls | 1.94843E+15 | 4.27139E+16 | 4.46623E+16 | 4% | 96% | |
| Walls (lightened) | 1.94843E+15 | 2.08929E+16 | 2.28413E+16 | 9% | 91% | |
| Binder | | | 4.15804E+15 | | | |
| Plaster | | | 1.74228E+16 | | | |
| Paint | | | 2.40102E+14 | | | |
| | | | | | | |
| Floor | 9.96768E+15 | 2.05245E+17 | 2.15212E+17 | 5% | 95% | |
| Floor Slab | 3.79389E+15 | 1.54573E+17 | 1.58367E+17 | 2% | 98% | |
| Floor Slab | 6.17378E+15 | 5.06712E+16 | 5.6845E+16 | 11% | 89% | |
| | | | | | | |
| Roof Slab | 9.96768E+15 | 2.05245E+17 | 2.15212E+17 | 5% | 95% | |
| Roof | 3.79389E+15 | 1.54573E+17 | 1.58367E+17 | 2% | 98% | |
| Roof | 6.17378E+15 | 5.06712E+16 | 5.6845E+16 | 11% | 89% | |
| | | | | | | |
| | 2.22845E+17 | 9.62507E+17 | 1.18535E+18 | 19% | 81% | 100% |

Table C-8. Manufacturing emergy estimation of Building #3 (except first floor), specific emergy of Renewable Substitutability (RS) and non—renewables (NR).

| Item | Emergy<br>(sej) | | | (%) | | |
|---|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR | Total |
| GROUND WORK | 5.24391E+16 | 1.07977E+18 | 1.13221E+18 | 5% | 95% | 11% |
| Basement foundation | 1.99594E+16 | 8.13197E+17 | 8.33157E+17 | 2% | 98% | |
| Basement foundation | 3.24798E+16 | 2.66577E+17 | 2.99057E+17 | 11% | 89% | |
| STRUCTURAL FRAME | 5.69517E+16 | 1.48909E+18 | 1.54604E+18 | 4% | 96% | 15% |
| Columns, beams | 1.57009E+16 | 6.39696E+17 | 6.55397E+17 | 2% | 98% | |
| Columns, beams | 2.555E+16 | 2.09701E+17 | 2.35251E+17 | 11% | 89% | |
| Retention wall | 1.57009E+16 | 6.39696E+17 | 6.55397E+17 | 2% | 98% | |
| GROUND FLOOR | 1.29575E+17 | 1.06545E+18 | 1.19503E+18 | 11% | 89% | 11% |
| External Wall | 9.53812E+15 | 3.88757E+17 | 3.98295E+17 | 2% | 98% | |
| Façade brick | 9.53812E+15 | 1.02276E+17 | 1.11814E+17 | 9% | 91% | |
| Structural Wall | | | 1.46737E+14 | | | |
| Thermal Insulation | | | 2.7292E+17 | | | |
| Interior finish | | | 1.66664E+14 | | | |
| Interior finish | | | 1.32467E+16 | | | |
| External Windows | 7.13384E+16 | 1.89634E+16 | 9.03018E+16 | 79% | 21% | |
| Glazing | 7.13384E+16 | 1.89634E+16 | 9.03018E+16 | 79% | 21% | |
| Internal Walls | 4.86986E+16 | 6.57731E+17 | 7.06429E+17 | 7% | 93% | |
| Walls | 4.47838E+16 | 4.80213E+17 | 5.24996E+17 | 9% | 91% | |
| Binder | | | 9.02054E+16 | | | |
| Plaster | | | 1.15741E+14 | | | |
| Paint | | | 1.37817E+15 | | | |
| Walls (lightened) | 3.91471E+15 | 4.19771E+16 | 4.58918E+16 | 9% | 91% | |
| Binder | | | 8.35416E+15 | | | |
| Plaster | | | 3.50052E+16 | | | |
| Paint | | | 4.82402E+14 | | | |
| MEZZANINE FLOOR | 1.79679E+17 | 2.46424E+18 | 2.64392E+18 | 7% | 93% | 25% |
| External Wall | 9.53812E+15 | 7.55854E+17 | 7.65392E+17 | 1% | 99% | |
| Façade brick | 9.53812E+15 | 1.02276E+17 | 1.11814E+17 | 9% | 91% | |
| Structural Wall | | | 1.46737E+14 | | | |
| Thermal Insulation | | | 6.40018E+17 | | | |
| Interior finish | | | 1.66664E+14 | | | |
| Interior finish | | | 1.32467E+16 | | | |
| External Windows | 7.13384E+16 | 1.89634E+16 | 9.03018E+16 | 79% | 21% | |
| Glazing | 7.13384E+16 | 1.89634E+16 | 9.03018E+16 | 79% | 21% | |
| Internal Walls | 4.86986E+16 | 6.57731E+17 | 7.06429E+17 | 7% | 93% | |
| Walls | 4.47838E+16 | 4.80213E+17 | 5.24996E+17 | 9% | 91% | |
| Binder | | | 9.02054E+16 | | | |
| Plaster | | | 1.15741E+14 | | | |
| Paint | | | 1.37817E+15 | | | |
| Walls (lightened) | 3.91471E+15 | 4.19771E+16 | 4.58918E+16 | 9% | 91% | |
| Binder | | | 8.35416E+15 | | | |
| Plaster | | | 3.50052E+16 | | | |
| Paint | | | 4.82402E+14 | | | |
| Floor | 5.01042E+16 | 1.0317E+18 | 1.0818E+18 | 5% | 95% | |
| Floor Slab | 1.90706E+16 | 7.76988E+17 | 7.96059E+17 | 2% | 98% | |
| Floor Slab | 3.10335E+16 | 2.54707E+17 | 2.85741E+17 | 11% | 89% | |

Table C-9. Manufacturing emergy estimation of Building #3 (first floor), specific emergy of Renewable Substitutability (RS) and non—renewables (NR).

| Item | Emergy (sej) | | | (%) | | |
|---|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR | Total |
| FIRST FLOOR | 7.36382E+17 | 3.16161E+18 | 3.898E+18 | 19% | 81% | 37% |
| External Wall | 7.34927E+15 | 2.99543E+17 | 3.06892E+17 | 2% | 98% | |
| Façade brick | 7.34927E+15 | 7.88055E+16 | 8.61548E+16 | 9% | 91% | |
| Structural Wall | | | 1.13063E+14 | | | |
| Thermal Insulation | | | 2.10289E+17 | | | |
| Interior finish | | | 1.28418E+14 | | | |
| Interior finish | | | 1.02068E+16 | | | |
| External Windows | 5.88542E+17 | 1.56448E+17 | 7.44989E+17 | 79% | 21% | |
| Glazing | 5.88542E+17 | 1.56448E+17 | 7.44989E+17 | 79% | 21% | |
| Internal Walls | 2.79775E+16 | 3.88857E+17 | 4.16835E+17 | 7% | 93% | |
| Walls | 2.54581E+16 | 2.72985E+17 | 2.98443E+17 | 9% | 91% | |
| Binder | | | 2.71644E+16 | | | |
| Plaster | | | 1.15741E+14 | | | |
| Paint | | | 1.37817E+15 | | | |
| Walls (lightened) | 2.5194E+15 | 4.19771E+16 | 4.58918E+16 | 9% | 91% | |
| Binder | | | 8.35416E+15 | | | |
| Plaster | | | 3.50052E+16 | | | |
| Paint | | | 4.82402E+14 | | | |
| Floor | 5.62567E+16 | 1.15838E+18 | 1.21464E+18 | 5% | 95% | |
| Floor Slab | 2.14124E+16 | 8.72399E+17 | 8.93811E+17 | 2% | 98% | |
| Floor Slab | 3.48443E+16 | 2.85984E+17 | 3.20828E+17 | 11% | 89% | |
| Roof Slab | 5.62567E+16 | 1.15838E+18 | 1.21464E+18 | 5% | 95% | |
| Roof | 2.14124E+16 | 8.72399E+17 | 8.93811E+17 | 2% | 98% | |
| Roof | 3.48443E+16 | 2.85984E+17 | 3.20828E+17 | 11% | 89% | |
| | 1.15503E+18 | 9.26017E+18 | 1.04152E+19 | 11% | 89% | 100% |

Table C-10. Manufacturing emergy estimation of Building #4, specific emergy of Renewable Substitutability (RS) and non-renewables (NR).

| Item | Emergy (sej) | | | (%) | | |
|---|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR | Total |
| GROUND WORK | 1.58213E+16 | 3.25776E+17 | 3.41597E+17 | 5% | 95% | 7% |
| Basement foundation | 6.02189E+15 | 2.45348E+17 | 2.51369E+17 | 2% | 98% | |
| Basement foundation | 9.79938E+15 | 8.04282E+16 | 9.02276E+16 | 11% | 89% | |
| STRUCTURAL FRAME | 2.555E+16 | 2.09701E+17 | 2.35251E+17 | 11% | 89% | 5% |
| Columns, beams | 2.555E+16 | 2.09701E+17 | 2.35251E+17 | 11% | 89% | |
| GROUND FLOOR | 1.27772E+18 | 4.9646E+17 | 1.77418E+18 | 72% | 28% | 36% |
| External Wall | 9.33684E+14 | 3.80553E+16 | 3.8989E+16 | 2% | 98% | |
| Façade brick | 9.33684E+14 | 1.00118E+16 | 1.09455E+16 | 9% | 91% | |
| Structural Wall | | | 1.43641E+13 | | | |
| Thermal Insulation | | | 2.67161E+16 | | | |
| Interior finish | | | 1.63148E+13 | | | |
| Interior finish | | | 1.29671E+15 | | | |
| External Windows | 1.27088E+18 | 3.37829E+17 | 1.60871E+18 | 79% | 21% | |
| Glazing | 1.27088E+18 | 3.37829E+17 | 1.60871E+18 | 79% | 21% | |
| Internal Walls | 5.90597E+15 | 1.20576E+17 | 1.26482E+17 | 5% | 95% | |
| Walls | 1.61299E+15 | 1.72959E+16 | 1.89089E+16 | 9% | 91% | |
| Binder | | | 1.91348E+15 | | | |
| Plaster | | | 7.25549E+15 | | | |
| Paint | | | 0 | | | |
| Walls (lightened) | 4.29298E+15 | 4.60332E+16 | 5.03262E+16 | 9% | 91% | |
| Binder | | | 9.1614E+15 | | | |
| Plaster | | | 3.83877E+16 | | | |
| Paint | | | 5.29015E+14 | | | |
| FIRST FLOOR | 1.31543E+18 | 1.30896E+18 | 2.62439E+18 | 50% | 50% | 53% |
| External Wall | 9.33684E+14 | 7.39904E+16 | 7.49241E+16 | 1% | 99% | |
| Façade brick | 9.33684E+14 | 1.00118E+16 | 1.09455E+16 | 9% | 91% | |
| Structural Wall | | | 1.43641E+13 | | | |
| Thermal Insulation | | | 6.26512E+16 | | | |
| Interior finish | | | 1.63148E+13 | | | |
| Interior finish | | | 1.29671E+15 | | | |
| External Windows | 1.27088E+18 | 3.37829E+17 | 1.60871E+18 | 79% | 21% | |
| Glazing | 1.27088E+18 | 3.37829E+17 | 1.60871E+18 | 79% | 21% | |
| Internal Walls | 5.90597E+15 | 1.20576E+17 | 1.26482E+17 | 5% | 95% | |
| Walls | 1.61299E+15 | 1.72959E+16 | 1.89089E+16 | 9% | 91% | |
| Binder | | | 1.91348E+15 | | | |
| Plaster | | | 7.25549E+15 | | | |
| Paint | | | 0 | | | |
| Walls (lightened) | 4.29298E+15 | 4.60332E+16 | 5.03262E+16 | 9% | 91% | |
| Binder | | | 9.1614E+15 | | | |
| Plaster | | | 3.83877E+16 | | | |
| Paint | | | 5.29015E+14 | | | |
| Floor | 1.88568E+16 | 3.8828E+17 | 4.07137E+17 | 5% | 95% | |
| Floor Slab | 7.17727E+15 | 2.92421E+17 | 2.99598E+17 | 2% | 98% | |
| Floor Slab | 1.16795E+16 | 9.58595E+16 | 1.07539E+17 | 11% | 89% | |
| Roof Slab | 1.88568E+16 | 3.8828E+17 | 4.07137E+17 | 5% | 95% | |
| Roof | 7.17727E+15 | 2.92421E+17 | 2.99598E+17 | 2% | 98% | |
| Roof | 1.16795E+16 | 9.58595E+16 | 1.07539E+17 | 11% | 89% | |
| | 2.63452E+18 | 2.34089E+18 | 4.97542E+18 | 53% | 47% | 100% |

Table C-11. Manufacturing emergy estimation of Buildings #1 to #4, specific emergy of Renewable Substitutability (RS) and non—renewables (NR).

| Building | Emergy (sej) | | | (%) | |
|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR |
| Building #1 (1963), Old office | 9.67E+17 | 3.25E+18 | 4.21E+18 | 30% | 77% |
| Building #2 (1963), Old Wet lab | 2.23E+17 | 1.14E+18 | 1.36E+18 | 16% | 84% |
| Building #3 (1975), New Wet lab | 1.16E+18 | 9.91E+18 | 1.11E+19 | 10% | 90% |
| Building #4 (1999), New office | 2.63E+18 | 2.38E+18 | 5.01E+18 | 53% | 47% |
| Total | 4.98E+18 | 1.67E+19 | 2.16E+19 | 23% | 77% |

Table C-12. Maintenance emergy estimation of Building #1.

| Item | Emergy (sej) | | | (%) | |
|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR |
| Maintenance Existing | | | | | |
| Glazing | 3.6E+17 | 9.5E+16 | 4.5E+17 | 79% | 21% |
| Glazing | 5E+17 | 1.3E+17 | 6.3E+17 | 79% | 21% |
| Replacement | | | | | |
| Glazing | 3.8E+17 | 6E+16 | 4.4E+17 | 86% | 14% |
| Glazing | 5.3E+17 | 8.3E+16 | 6.1E+17 | 86% | 14% |
| Renewable resources (15%) | | | 1.6E+17 | | |
| RS, NR & total emergy (difference) | | | | | |
| Glazing | 2.5E+16 | -4E+16 | -1E+16 | | |
| Glazing | 3.4E+16 | -5E+16 | -1E+16 | | |
| | 5.9E+16 | -8E+16 | -3E+16 | | |

Table C-13. Maintenance emergy estimation of Building #2.

| Item | Emergy (sej) | | | (%) | |
|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR |
| Maintenance Existing | | | | | |
| Glazing | 5.5E+16 | 1.5E+16 | 7E+16 | 79% | 21% |
| Glazing | 1.3E+17 | 3.4E+16 | 1.6E+17 | 79% | 21% |
| Replacement | | | | | |
| Glazing | 5.9E+16 | 9.2E+15 | 6.8E+16 | 86% | 14% |
| Glazing | 1.4E+17 | 2.1E+16 | 1.6E+17 | 86% | 14% |
| Renewable resources (15%) | | | 3.4E+16 | | |
| Renewable resource & total emergy | | | | | |
| Glazing | 3.8E+15 | -5E+15 | -2E+15 | | |
| Glazing | 8.8E+15 | -1E+16 | -4E+15 | | |
| | 1.3E+16 | -2E+16 | -5E+15 | | |

Table C-14. Maintenance emergy estimation of Building #3.

| Item | Emergy (sej) | | | (%) | |
|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR |
| Maintenance | | | | | |
| Existing | | | | | |
| Glazing | 7.1E+16 | 1.9E+16 | 9E+16 | 79% | 21% |
| Glazing | 7.1E+16 | 1.9E+16 | 9E+16 | 79% | 21% |
| Glazing | 5.9E+17 | 1.6E+17 | 7.4E+17 | 79% | 21% |
| Replacement | | | | | |
| Glazing | 7.6E+16 | 1.2E+16 | 8.8E+16 | 86% | 14% |
| Glazing | 7.6E+16 | 1.2E+16 | 8.8E+16 | 86% | 14% |
| Glazing | 6.3E+17 | 9.8E+16 | 7.3E+17 | 86% | 14% |
| Renewable resources (15%) | | | 1.4E+17 | | |
| Renewable resource & total emergy | | | | | |
| Glazing | 4.9E+15 | -7E+15 | -2E+15 | | |
| Glazing | 4.9E+15 | -7E+15 | -2E+15 | | |
| Glazing | 4.1E+16 | -6E+16 | -2E+16 | | |
| | 5.1E+16 | -7E+16 | -2E+16 | | |

Table C-14. Maintenance emergy estimation of Building #4.

| Item | Emergy (sej) | | | (%) | |
|---|---|---|---|---|---|
| | RS | NR | Total | RS | NR |
| Maintenance | | | | | |
| Existing | | | | | |
| Glazing | 1.3E+18 | 3.4E+17 | 1.6E+18 | 79% | 21% |
| Glazing | 1.3E+18 | 3.4E+17 | 1.6E+18 | 79% | 21% |
| Replacement | | | | | |
| Glazing | 1.4E+18 | 2.1E+17 | 1.6E+18 | 86% | 14% |
| Glazing | 1.4E+18 | 2.1E+17 | 1.6E+18 | 86% | 14% |
| Renewable resources (15%) | | | 4.7E+17 | | |
| Renewable resource & total emergy | | | | | |
| Glazing | 8.8E+16 | -1E+17 | -4E+16 | | |
| Glazing | 8.8E+16 | -1E+17 | -4E+16 | | |
| | 1.8E+17 | -3E+17 | -8E+16 | | |

# APPENDIX D

Table D-1. Emergy quantities and transformities for scenario #1.

| R-value | Cooling | Heating | Total Savings | Electricity (Cooling) | Natural Gas (Heating) | Emergy Cooling Heating | Material Emergy | Transformity |
|---|---|---|---|---|---|---|---|---|
| h sf F/Btu | Btu | Btu | Btu | kWh | Therms | sej | sej | sej/J |
| 0 | 1.46E+09 | -1.01E+09 | 0.00E+00 | 2.27E+05 | 2.14E+03 | 1.41E+19 | 7.13E+18 | |
| 11 | 1.48E+09 | -8.27E+08 | 1.63E+08 | 2.22E+05 | 1.72E+03 | 1.36E+19 | 8.57E+18 | 1.29E+06 |
| 14 | 1.49E+09 | -7.82E+08 | 2.02E+08 | 2.20E+05 | 1.61E+03 | 1.34E+19 | 9.99E+18 | 1.10E+06 |
| 17 | 1.49E+09 | -7.63E+08 | 2.18E+08 | 2.19E+05 | 1.56E+03 | 1.34E+19 | 1.14E+19 | 1.08E+06 |
| 20 | 1.49E+09 | -7.34E+08 | 2.43E+08 | 2.18E+05 | 1.48E+03 | 1.32E+19 | 1.29E+19 | 1.02E+06 |
| 23 | 1.50E+09 | -7.12E+08 | 2.61E+08 | 2.17E+05 | 1.42E+03 | 1.31E+19 | 1.43E+19 | 9.95E+05 |
| 26 | 1.50E+09 | -6.97E+08 | 2.73E+08 | 2.16E+05 | 1.38E+03 | 1.31E+19 | 1.57E+19 | 9.97E+05 |
| 29 | 1.50E+09 | -6.86E+08 | 2.83E+08 | 2.15E+05 | 1.35E+03 | 1.30E+19 | 1.71E+19 | 1.01E+06 |
| 32 | 1.50E+09 | -6.77E+08 | 2.90E+08 | 2.15E+05 | 1.32E+03 | 1.30E+19 | 1.86E+19 | 1.03E+06 |
| 35 | 1.50E+09 | -6.70E+08 | 2.96E+08 | 2.14E+05 | 1.30E+03 | 1.29E+19 | 2.11E+19 | 1.09E+06 |

Table D-2. Emergy quantities and transformities for scenario #2.

| R-value | Cooling | Heating | Total Savings | Electricity Cooling & Heating | Emergy Cooling Heating | Material Emergy | Total Emergy | Transformity |
|---|---|---|---|---|---|---|---|---|
| h sf F/Btu | Btu | Btu | Btu | kWh | sej | sej | Sej | sej/J |
| 0 | 1.46E+09 | -1.01E+09 | 0.00E+00 | 2.74E+05 | 1.58E+19 | 7.13E+18 | 2.29E+19 | |
| 11 | 1.48E+09 | -8.27E+08 | 1.63E+08 | 2.59E+05 | 1.49E+19 | 8.57E+18 | 2.35E+19 | 1.37E+06 |
| 14 | 1.49E+09 | -7.82E+08 | 2.02E+08 | 2.55E+05 | 1.47E+19 | 9.99E+18 | 2.47E+19 | 1.16E+06 |
| 17 | 1.49E+09 | -7.63E+08 | 2.18E+08 | 2.53E+05 | 1.46E+19 | 1.14E+19 | 2.60E+19 | 1.13E+06 |
| 20 | 1.49E+09 | -7.34E+08 | 2.43E+08 | 2.50E+05 | 1.44E+19 | 1.29E+19 | 2.72E+19 | 1.06E+06 |
| 23 | 1.50E+09 | -7.12E+08 | 2.61E+08 | 2.47E+05 | 1.42E+19 | 1.43E+19 | 2.85E+19 | 1.04E+06 |
| 26 | 1.50E+09 | -6.97E+08 | 2.73E+08 | 2.45E+05 | 1.41E+19 | 1.57E+19 | 2.98E+19 | 1.03E+06 |
| 29 | 1.50E+09 | -6.86E+08 | 2.83E+08 | 2.44E+05 | 1.41E+19 | 1.71E+19 | 3.12E+19 | 1.04E+06 |
| 32 | 1.50E+09 | -6.77E+08 | 2.90E+08 | 2.43E+05 | 1.40E+19 | 1.86E+19 | 3.25E+19 | 1.06E+06 |
| 35 | 1.50E+09 | -6.70E+08 | 2.96E+08 | 2.42E+05 | 1.39E+19 | 2.11E+19 | 3.51E+19 | 1.12E+06 |

Table D-3. Emergy quantities and transformities for scenario #3.

| Glazing Type | Total Savings | Electricity (Cooling) | Electricity (Lighting) | Electricity (Lighting Savings) | Natural Gas (Heating) | Material Emergy | Total Emergy | Transformity |
|---|---|---|---|---|---|---|---|---|
| | Btu | kWh | kWh | kWh | Therms | sej | sej | sej/J |
| Single | 0.00E+00 | 2.15E+05 | 1.72E+05 | 2.93E+04 | 1.81E+03 | 2.22E+19 | 4.53E+19 | 4.30E+10 |
| Double | 1.75E+08 | 2.15E+05 | 1.73E+05 | 2.90E+04 | 1.77E+03 | 3.73E+19 | 6.04E+19 | 2.09E+10 |
| Triple | 2.60E+08 | 2.11E+05 | 1.73E+05 | 2.86E+04 | 1.76E+03 | 5.23E+19 | 7.52E+19 | 1.99E+10 |

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# INDEX