RE(DE)FINING NET ZERO ENERGY: RENEWABLE EMERGY BALANCE OF ENVIRONMENTAL BUILDING DESIGN

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ABSTRACT

Approaching a Net Zero Energy (NZE) building goal based on current definitions is flawed for two principal reasons – they only deal with energy quantities required for operations, 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. This paper develops a method to maximize renewable resource use through emergy (spelled with an "m") analysis. A "Renewable Emergy Balance" (REB) in environmental building design is proposed as a tool to maximize renewable resource use through disinvestment of all non-renewable resources that may be substituted with renewable resources.

INTRODUCTION

Net Zero Energy definitions are still in the early phase of development 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 (i.e., at the site or source levels), and their quantification (i.e., energy quantity or energy costs), the renewable supply options- based NZE definitions are established by way of demand-side location of on-site renewable capacities. These improvements can be derived from the buildings' energy consumption and/or generation (Toricellini et al., 2006) can be categorized as Net Zero Site Energy, Net Zero Source Energy, Net Zero Energy Costs and Net Zero Energy Emissions. 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" offer definitions based on the location of the site of the renewable contributions.

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. 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 to exist, e.g., the energy required for building manufacturing, maintenance, etc., In current NZE practice, this vast quantity of energy is unaccounted for and ignored for simplification purposes and perhaps also because up to this time there has not been a way to efficiently and accurately quantify these requirements in a uniform manner. In addition, current definitions and calculations for NZE do not include the energy flows from the sun, wind, rain, geological cycles and so-forth from the beginning and by including them using the emergy methodology, we demonstrate how a complete energy and material balance for buildings can be quantified.

(b) NZE definitions do not establish an "energy threshold" which ensures that buildings are optimized for reduced consumption of resources 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 fulfil 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 inputs from and outputs to 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.

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 for its sub-systems. 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 lifetime, reiterating the notion that one may not withdraw non-renewable resources "at will" as there is only a finite quantity of those materials on this planet for use during its lifetime. Outputs may include the work products of that particular building. Some of the methods widely used are Life Cycle Assessment (LCA), emergy analysis, etc. LCA is a tool that primarily focuses on the impact of emissions and resource consumption (Guinee et al., 1993a; 1993b). 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, the 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 LCA lacks a rigorous thermodynamic framework which is elemental for analyzing ecosystems and in certain situations it may even violate thermodynamic laws (Hau, 2005). 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 the energy used in operation. 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 LCA; 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 resources by renewable resources to achieve a net energy balance.

Emergy Analysis

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; 1996) through the development of integrated environmental accounting methods can offer a holistic solution for such an analysis. In addition to providing a thermodynamic framework for analyzing energy transformations in building design and construction, emergy analysis offers several indices for comprehensive evaluation of a building system and its sub-systems.

Solar emergy is the available solar energy previously used-up, both directly and indirectly, to make a service or a product (Odum, 1971; 1983; 1996). Solar energy is used as the common denominator to express all resources, services and goods in terms of their relative ability to do work in a system. Thus, any product or service uses a common unit, "solar emergy Joule" (semJ), as the unit of emergy. 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 unit of available energy of a quantity (e.g., a Joule of a product or service). Its units are solar emjoules per Joule (semJ/J). Specific emergy is the emergy value per unit mass of material (e.g., semJ/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 a quantity of available energy by its transformity. Available energy is energy with the capacity to do work, (i.e., it has an energy potential relative to its environment). 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 made by different production processes. In the context of Energy Systems Theory (Odum, 1994), transformity measures the position of any energy flow or storage in the universal energy hierarchy (Odum, 1996). Additionally, transformities are measured relative to a baseline.

The baseline is developed using the three primary energy sources to the planet, i.e., solar radiation, deep heat generated from residual heat and radioactive decay within the earth, and the gravitational attraction of the sun and moon (Odum, 1996; Campbell, 2000). Transformities used in this paper use 9.44E+24 sej/yr baseline from Odum (1996). Several research projects have been conducted to develop transformity values, most notably Buranakarn (1998) for building materials, who used this baseline in his work. Buranakarn's work on material transformities have been extensively used in other researchers' work and as a result it has been well vetted. These numbers undoubtedly will be improved in the future, but the first order validity of these results would not expect to change. 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 is chosen for this paper as a tool to evaluate environmental building design.

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 a., 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 the emergy of renewable resource use relative to a finite limit or potential as a way to optimize building design before any renewable or non-renewable resources are expended.

RENEWABLE EMERGY BALANCE

Building materials may be broadly classified as being derived from renewable and/or non-renewable resources. From the initial formation over its lifetime, each resource may be categorized by these two resource types. While the use of renewable resources can be beneficial for sustainability (i.e., renewable resources must be used at a rate that does not exceed their natural rate of replacement to be considered sustainable), a portion of the non-renewable resources may be exploited to further develop renewable resources (Daly, 1990; Odum and Odum, 2001).

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

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, renewability and the non-renewability of materials are appropriately identified. This requires the identification and listing of non-renewable resources that have the potential to be substituted by renewable resources. Thus, the use of non-renewable resources to improve system capacity to exploit renewable resources permanently will aid the development of a quasi-sustainable solution. Such resources that may be replaced with renewable resources possess the property "Renewable Substitutability."

For buildings, the novelty of investing non-renewable resources to boost permanently renewable resource use will shift a building towards self-sustenance in renewable emergy terms or toward a "Renewable Emergy Balance." Thermodynamically, an REB building preserves a balanced Renewable Substitutability through investment (or progressive improvement) of all non-renewable resources with Renewable Substitutability to utilize renewable resources. The central aspect of a Renewable Emergy Balance is the computation of an explicit quantity of renewable resources integrated over the building's lifetime, 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 1 illustrates the cumulative emergy use of a typical building. The duration (in years) between phases A and B represents the emergy content of the building materials through formation, extraction and manufacturing. The duration between points B to C represents the building lifetime during which the building uses energy for its day-to-day operations and for maintenance. Phases B1 and B2 represent building component replacement times according to the maintenance schedule followed during the building's lifetime.

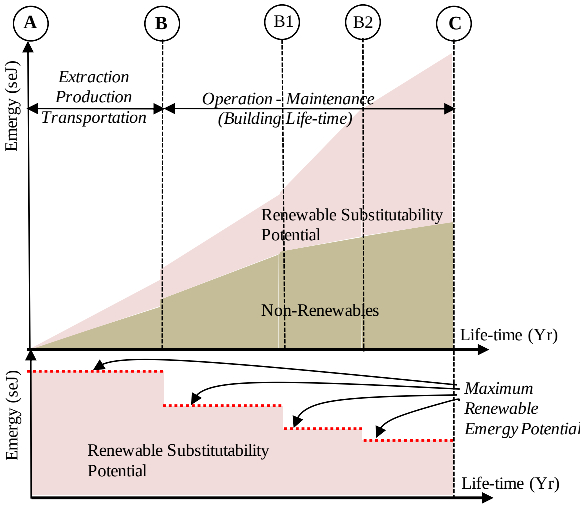

Figure 1. Cumulative energy use of a typical building over its life-time.

Using emergy analysis and through the identification of the Renewable Substitutability of all non-renewable resources, the emergy content may be split into non-renewables with Renewable Substitutability potential and unsubstitutable non-renewables, i.e., non-renewable resources that cannot be substituted with renewables using the best available technology. This identification of Renewable Substitutability is a significant component of the Renewable Emergy Balance.

This notion underscores the reality that non-renewable resources without Renewable Substitutability may not be altered back to their original structure without expending available energy. Non-renewable resources may not be replenished to their native forms, unlike the renewable resources, particularly after diverse transformations that are required to make a product. In other words, non-renewable resources with Renewable Substitutability require less energy to replenish as compared to such resources without Renewable Substitutability.

However, for those non-renewable resources with Renewable Substitutability, there is a potential to be replaced by renewable resources and this should be exploited to move toward the construction of more sustainable buildings. Through emergy analysis, this definite quantity (the maximum potential) to achieve Renewable Emergy Balance can be calculated. Moreover, as conscious decision-making prevails over material selection (as indicated in phases B1 and B2), the Renewable Substitutability split between the potentially substitutable resources and the hard core non-renewable resources 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 lifetime.

The maximum potential is a moving target that improves based on improvements in renewable resources technology. Thus, the Renewable Emergy Balance over the lifetime of a building is achieved by attaining the maximum renewable emergy potential. The advantage of this method is that the trend may be projected for the entire building lifetime. Based on the actual realization of the building's 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.

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 lifetime of the building, if all non-renewable resources with Renewable Substitutability are replaced by renewable resources, the building achieves a Renewable Emergy Balance status. This process fits well within the quasi-sustainability principle of "a prosperous way down" (Odum and Odum, 2001).

This paper 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. The objective of this paper is to develop a maximum limit for renewable resource substitution, assess the performance of systems and maximize renewable resource use. The paper 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. For more details, refer Srinivasan et al (2011a).

RENEWABLE EMERGY BALANCE ASSESSMENT

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

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 2. The manufacturing and maintenance emergy analysis component enables the calculation of emergy values split into renewable resources, non-renewable resources with Renewable Substitutability and non-renewable resources, per se. This is followed by the building operations emergy component. In this component, building emergy use during operation is split into the three independent emergy portions i.e., renewable, renewable substitutable or non-renewable resources. If the building is an existing facility, the operational 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 the energy used in operations.

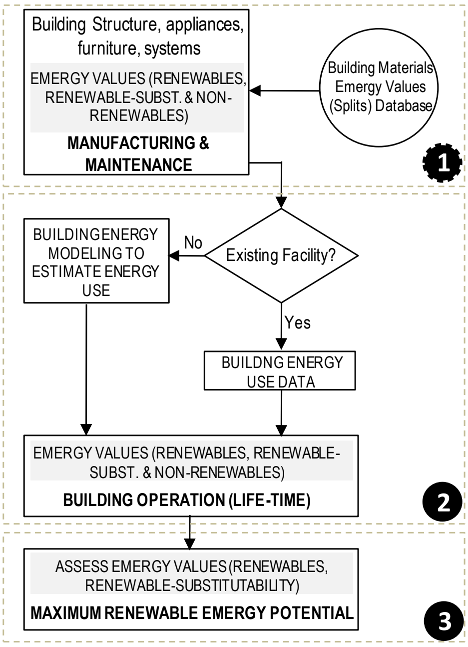

Figure 2. Renewable Emergy Balance assessment structure.

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

CASE STUDY OF AN EXISTING FACILITY

The US EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory (NHEERL), Atlantic Ecology Division at Narragansett, RI conducts sediment, water quality and ecosystem research in a variety of environments ranging from freshwater through marsh and estuarine to near shore marine environments along the Atlantic coast of the United States from Florida to Maine. The Main Office building, Wet Lab and Wet Lab Addition comprise the main facility buildings at the center of the site. 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 is an expansion constructed in 1999.

Results – Systems Diagram

The building-environment system boundary includes the building structure and surrounding property. The conceptual system diagram is shown in figure 3. The system does not include building occupants. The boundary of the building system is defined as the building envelope (represented as a rectangular box). The components are organized from left to right in a hierarchical order based on emergy quality (transformity), for example, heating cooling, building structure, and lighting are ordered from low to high energy quality. Also, the external forcing functions are ordered in a similar manner around the boundary 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 for the building, heating or cooling may be necessary; these quantities of heat are represented as storages.

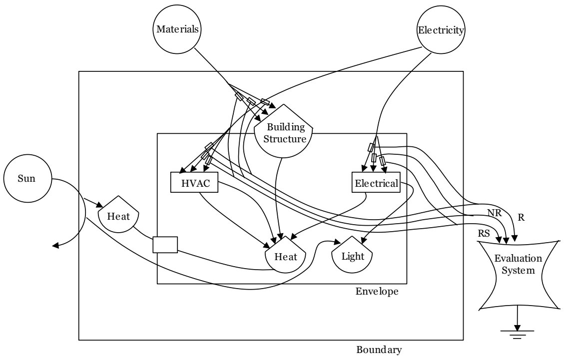

Figure 3. Systems diagram with emergy pathways.

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 light. 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.

Results – Emergy Evaluation

Since the building envelope can be comprised of varied types of envelope configurations such as spandrel glazed surfaces, masonry structures, etc., the modeling program, 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. Based on the location, building orientation and annual weather, the envelope and internal lighting loads equaled 2.19E+09 BTUs. This is the operational energy use of the buildings to maintain ASHRAE 55 interior condition standards. In 2009, total electricity generation in the U.S. was made up of 10.6% renewable generation (DOE, 2010). For this case study, Renewable Substitutability of 10% was assumed for the operational energy sources. Emergy analysis in building structure manufacturing shows 23% Renewable Substitutability for all buildings. New office building shows the highest Renewable Substitutability, at 53%, due to large window-to-wall ratio compared to the other buildings.

The cumulative emergy quantities due to buildings' manufacturing requirements are plotted over the buildings' lifetimes in figure 4. The material reuse at the end of building life-time is discussed in Srinivasan et al (2011b). The horizontal axis tracks the buildings' life-times (typical building life-time considered for this paper is 100 years after which it ceases to perform for the intended purposes). Since the buildings were constructed during different time periods, the cumulative emergy quantities peak when all buildings were entirely built and operational. Using the emergy splits, the Renewable Substitutability and non-renewable content is plotted.

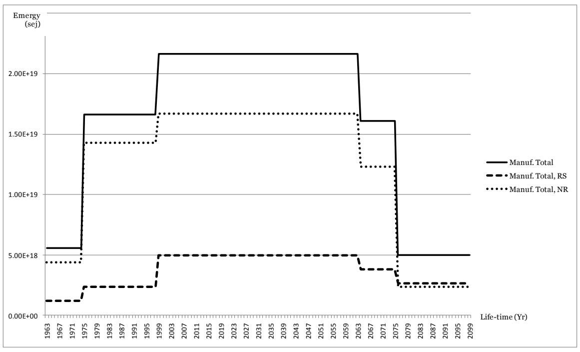

Figure 4. Emergy contributed by building manufacturing (in sej).

Using the maintenance schedule, the replacement of glazing was simulated. Glazing is replaced every 30 years. The conventional float glass is replaced with traditional recycled float glass product, table 1. The Renewable Substitutability of the replacement glass is high compared to conventional float glass. Therefore, after replacement, the Renewable Substitutability of the building‘s stored emergy will increase. 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.

Table 1. Glass products used.

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

Figure 5 shows the emergy values from building maintenance. 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 the overall quantity of emergy in the replacement parts is greater than one-half of the total.

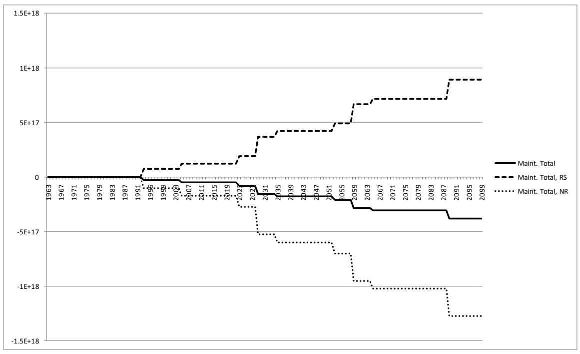

Figure 5. Emergy in building maintenance (in sej).

Figure 6 shows the cumulative emergy storage when both manufacturing and maintenance are combined. Note that there is an increase in the quantity of emergy in the Renewable Substitutability category (dashed line) owing to the increased Renewable Substitutability potential of the replacement glass. Due to the increased Renewable Substitutability potential of the replacement glass installed, the Renewable Substitutability curve improves over the lifetime of the building. A decrease in the non-renewable portion is noticed as the percentage of non-renewables decreases after maintenance is performed.

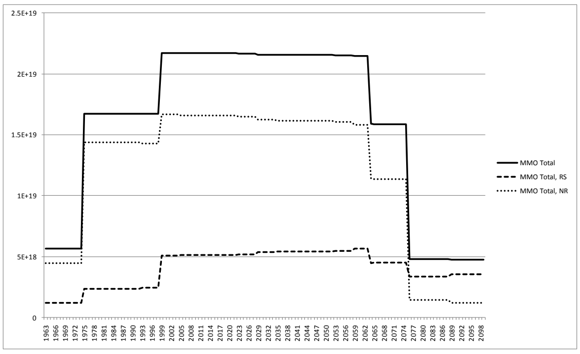

Figure 6. Emergy values after combining building manufacturing and maintenance (in sej).

Figure 7 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' lifetime (as shown by vertical bars). In this scenario, as renewable resources are not included, the maximum renewable emergy potential does not converge to zero in order to balance the potential for Renewable Substitutability. Thus, there is no improvement over time to move the system toward a Renewable Emergy Balance.

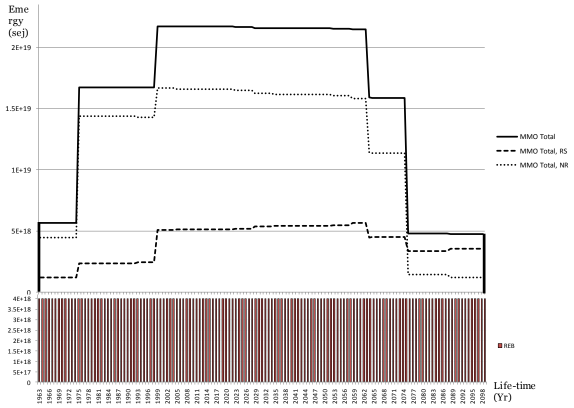

Figure 7. Emergy values after combining building manufacturing, maintenance and operational energy use (in sej).

To understand the influence of maximizing renewable resource use, a new scenario was examined. In this scenario, it was assumed that the replacement glass product included 15% (of the total emergy quantity) renewable resources. The cumulative effect of this scenario is shown in figure 8. Through inclusion of renewable resource use in building maintenance, as an example, the maximum renewable emergy potential approaches zero (represented as vertical bars below the graph), thereby, moving toward an REB through increasing the Renewable Substitutability of the building. For any given year during the buildings' lifetime, this illustration can be used to determine the renewable energy substitution that would be required to achieve REB. Thus, by introducing a 15% renewable resource in the replacement the glass product, a significant improvement is noticed in movement toward a Renewable Emergy Balance condition.

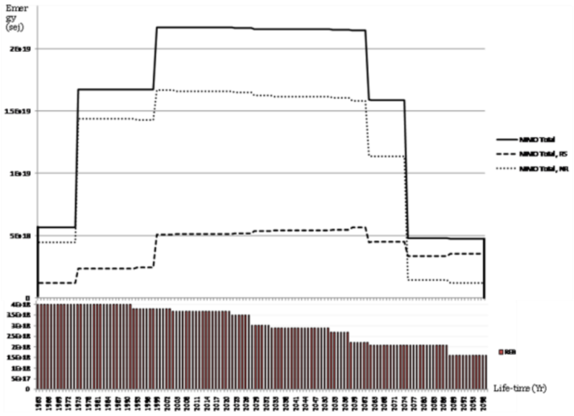

Figure 8. Emergy storaged in the buildings after combining building manufacturing, maintenance and operational energy use (in sej). In this scenario, a 15% renewable resource content is simulated during maintenance (replacement of glazing per maintenance schedule).

CONCLUSION

The following lists the major contributions of this paper made to the environmental accounting of buildings –

(a) development of a method to assess the Renewable Emergy Balance of a building. Renewable Emergy Balance buildings preserve a high standard of sustainability by optimizing the use of renewable energy and materials over the entire life-cycle of the building from formation-extraction-manufacturing to maintenance and operation;

(b) maximize renewable resource use through progressive disinvestment of all non-renewable resources that may be substituted with renewable resources, thereby contributing to the overall sustainability of the geobiosphere;

(c) development of methods to determine 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; and

(d) alleviate any ambiguity related to the limit or benchmark that is set to achieve higher levels of sustainability.

If this approach was adopted to guide building construction, it would expand conscious decision-making to make buildings more sustainable 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.

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