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Ecosystem Biomimetics: Energy System Diagrams for Characterization of Environmental Performance of Buildings

Abstract: Ecosystems biomimetics in architecture means learning from ecosystems; that is, learning from complex, resilient, self-organized systems in nature, and transferring valuable ecosystem's patterns into the architectural field. However, the methodology is incipient and biomimetic tools have to cross disciplines to convey meaning for both ecology and architecture; so qualitative and quantitative tools need to be developed in order to stimulate research. In this paper, an ecological engineering tool, the energy systems diagrams as defined by ecologist H. Odum, is used to represent more than 20 sustainable-rated buildings under the light of ecological systems. The buildings selected are certified projects under the LEED, Living Building Challenge (LBCH) or Passive House (PH) rating systems. The results show that ecological systems diagrams are effective instruments for characterization of the environmental performance of buildings in terms of energy and material flows; and may be serviceable as a shared language between disciplines. The validation of ecological systems diagrams as a useful biomimetic tool gives ground for further research on quantitative instruments to develop a more diverse methodology of ecosystems biomimetics.

Keywords: Biomimetics, Biomimicry, Ecomimetics, Sustainable Architecture, Green Building, Energy System Diagrams, Construction Ecology

1. Introduction

1.1. Biomimetics in Architecture

Biomimetics, biomimesis, or biomimicry means learning from nature to solve human problems (Benyus 1997). It also has been described as the transfer of knowledge from biology towards the engineering fields (Gruber 2011), and another definition describes biomimetics as the adaptation of mechanisms and functions of biological sciences in engineering, design and other disciplines (DTI 2007). Examples of human technology copying nature can be found throughout history. Famous examples include Leonardo da Vinci´s airplane drawings, and the invention of Velcro™ by George de Mestral through the observation of cocklebursattached to his dog´s fur. In architecture, the works of John Paxton (Crystal Palace, London, UK), Antoni Gaudi (e.g. Sagrada Familia, Barcelona, Spain) or Frei Otto (Munich Olympic Stadium, Munich, Germany) are in some aspects related to the biomimetic process; however, only during the last decade has architectural biomimetics been the subject of rigorous research. This research has been motivated by technological and computational advances, as well as by successful biomimetic results in other disciplines. A more recent example of biomimetics in architecture is the design of the Eastgate Building in Harare by Mick Pierce (built in 1996), which mimics a termite mound to optimize heating and cooling.

A commonly-accepted defining feature of biomimetics is transdisciplinarity. In biomimetic architecture, transdisciplinarity means that biologists, ecologists, engineers and designers collaborate in order to generate knowledge. Nevertheless, this is a difficult task and much effort is placed on defining the biomimetic approach and its methods for transferring natural patterns into buildings.

1.2. A biomimetic Classification for architecture

Pedersen (2007) has created a framework to classify architectural biomimetics according to the phenomena in nature that are the source of inspiration: organisms, organisms' behavior, and the functioning of ecosystems. Organism biomimetics refers to the study of one organism or one part of an organism (e.g. lotus leaves for Lotusan™ paint); behavioral biomimetics means that one function of an organism or species is examined in the context of its surroundings; finally, ecosystem biomimetics involves mimicking a group of functions and processes that relate biotic and abiotic components. This document focuses on this latter level of biomimetics that has also been described as ecomimicry, ecomimesis or ecomimetics.

Some benefits of ecosystem biomimetics are that it can encompass organism and behavior biomimetics; it accommodates the combination of biomimetic strategies with other building sustainable methods; and it can be applied to a wide variety of structures (from residential houses to urban zones). Finally and more importantly, ecosystem biomimetics has the potential to positively affect the environmental performance of buildings (Pedersen 2007). Some characteristics of certain ecosystems that could be mimicked in the building environment include:

- Effective use of solar energy;
- Thermodynamic efficiency
- Complexity
- Informational richness

- Adaptability

However, biomimetics is not necessarily equivalent to sustainability or an excellent environmental performance of buildings. A given biomimetic design might be relatively unsustainable compared to other alternatives; for example aircrafts, whose design was originally inspired by birds, but consume huge amounts of fossil fuels and pollute the atmosphere. To develop an ecosystem biomimetic approach that is also environmentally oriented (i.e. results in less use of non-renewable resources and less pollution), it is necessary to explicitly address the issue. Some architectural parameters related to the environmental performance of buildings are: water consumption, energy use, greenhouse gas (GHG) emissions, indoor air quality, waste management, orientation and insulation of the buildings, materials and user behavior. These parameters will be considered in the development of an ecosystem biomimetic methodology.

2. Problem: Biomimetic Methodology

A complete and exhaustive methodology on architectural biomimetics does not exist. It is widely accepted, however, that the biomimetic process can be approached from two different perspectives: the top-down perspective and the bottom-up perspective (DTI 2007; Pedersen 2007; Helms, Vattam, and Goel 2009; Gruber 2011). In the first case, a design or engineering problem is described and a solution is sought in the natural realm. In the bottom-up approach a professional from the natural science disciplines identifies an interesting phenomenon in nature and applications are sought in human technology. Case studies of each of these approaches are presented in the literature. Helms et al. (2009), for example, describe a number of steps from problem-definition to principle-application, and Gruber (2011) reports cases from research and student projects. Despite the acceptance of the top-down and bottom-up approaches, the lack of qualitative and quantitative tools impedes progress towards an effective biomimetic methodology. However, three tools are identified in the report from the Department of Trade and Industry in the UK (DTI 2007). First Bio-TRIZ, which is a problem-solving technology based on TRIZ (Theory of Inventive Problem Solving) that works with an extensive database comprising over three million patents (BioTRIZ, 2012); second, a complementary database at the Max Planck Institute; and finally a lexicon research method. None of these tools are specifically focused on ecosystem biomimetics. The present document addresses this point and presents a qualitative tool adapted from ecological engineering as a common language for the characterization of ecosystems and architectural systems. The document is organized as follows; first, there is an introduction to energy systems diagrams as defined by Odum (1994); second, the correlation between architectural components and ecological components is detailed; and finally several case studies are analyzed to evaluate the appropriateness of this tool as a common conceptual platform for knowledge transfer between architecture and ecology.

3. Energy systems diagrams from ecological engineering

3.1. Ecological Engineering

The term "ecological engineering" was first coined by Howard T. Odum in the early 1960's (Mitsch and Jørgensen 2003), and he defined ecological engineering as the "environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources" (Mitsch and Jørgensen 2003). Afterwards, Mitsch and Jørgensen (2003) defined ecological engineering as "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both." This involves the restoration of damaged ecosystems and the development of new ecosystems in order to solve environmental problems. Included in these problems are natural resource depletion and excessive GHG emissions. Furthermore Mitsch and Jorgensen (2003) listed five essential characteristics of ecological engineering: "(1) it is based on the self-designing capacity of ecosystems; (2) It can be the acid test of ecological theories; (3) It relies on system approaches; (4) It conserves non-renewable energy sources; and (5) It supports biological conservation".

The third characteristic, the system approach, is essential for this work. The word 'ecosystem' is an abbreviation of 'ecological system': "an organized system of land, water, mineral cycles, living organisms, and their programmatic behavioural control mechanisms" (Odum 1994). A system is a set of components interacting with one another. Von Bertalanffy (2008) states that "there are principles which apply to systems in general, whatever the nature of their component elements or the relations or 'forces' between them"; and Odum applied this holistic approach from systems theory to ecology in order to develop his energy systems diagrams.

3.2. Energy Systems diagrams

The energy systems diagram is a “methodology for converting verbal models into system network diagrams showing mathematic, energetic, cybernetic and hierarchical attributes simultaneously for many purposes” (Odum and Peterson 1996); that is, energy systems diagrams are a language that represents the organization of systems and their flows of energy. This language can be used to characterize environmental systems as well as other social or human systems.

When Odum (1994) began representing flows of energy in ecological systems, he turned toward the electrical engineering language, and found that the symbols and signs used in electronic circuits were able to represent organization and energy dynamics in ecosystems. Before long the energy systems diagrams “grew out of recognition and appreciation for open system thermodynamics of ecosystems, general systems theory, and simulation” (Brown 2004). The energy systems diagrams can be explained through their elements and the different steps for building them.

The elements of an energy systems diagram can be split into: sources, state variables, energy flows, and the boundary. The sources are the external sources of energy. The state variables, or components, represent the elements in the system that store and/or transform energy. Energy might be represented as materials, information or ‘pure energy’ (Odum 1994). The energy flows, or pathways, represent the energy per unit time; and flows have no storage capacity. The boundary defines the limits of the system under study, and separates the components from the external sources or driving forces. Odum selected different symbols to represent these elements and their variations. Table 1 shows the qualitative descriptions of the symbols used in this document. Brown (2004) describes the process of diagramming as a three-stage process: (1) identify the external sources of energy and define the boundary of the system; (2) draw the components; and (3) describe the outputs. Odum placed the elements in the diagram from left to right according to the increase in their energy quality. When Odum defined higher energy quality he was referring to that energy “that is more concentrated and in a form capable of special actions when fed back” (Odum, 1994). This energy quality is measured by the amount of solar calories needed to generate one calorie of another type of energy; so, for example, the source representing sun’s energy in a diagram will be on the left side of the source representing fossil fuels energy.

4. Equivalences between systems diagrams and architectural structure

The energy systems diagrams can be used to represent the flows of energy in many different systems. Mainly, they have been used to represent environmental systems; however, other social or economic systems can be represented using the diagrams. Odum, for example, applied them to explain the "functions and relationships of a familiar system" (Odum 2007) and also to characterize a city (Odum 1994). More recently, a group of researchers used energy systems diagrams to represent a building in the framework of emergy (with an m) analysis (Srinivasan et al. 2012). In the present document the energy systems diagrams are used in order to validate two ideas. First, that energy systems diagrams can represent the environmental performance of buildings. Second, that energy systems diagrams can be used as a platform for transferring patterns from ecological systems towards architectural systems. In the aforementioned examples by Odum (1994; 2007) and Srinivasan (2012) it is clear that energy systems diagrams can represent certain characteristics of buildings. This document will show that the energy systems diagrams can also represent parameters commonly used to determine the environmental performance of buildings (e.g., water consumption, energy use intensity, air quality), and that the sum of these parameters gives a holistic image of the environmental performance of a building.

The process of representing buildings using the energy systems diagrams requires a correlation between the symbols defined by Odum (1994) for the ecological engineering field and the building components. Table 1 presents the symbols used in this work and their equivalencies with architectural elements.

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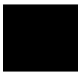
Table 1: Correlation between energy system symbols and their definitions in ecological engineering and architecture.

Symbol	Ecological Engineering		Architecture	
	Definition	Examples	Definition	Examples
Source 	"Outside source of energy delivering forces according to a program controlled from outside."	Sun Water Wind	Outside source of energy delivering forces according to the functional needs of the building.	Fossil Fuels Municipal Water Materials Information Natural sources (e.g., sunlight, wind, rain)
Storage 	"A compartment of energy storage whithin the system storing a quantity as the balance of inflows and outflows; a state variable"	Nutrients Detritus	Unit for energy storage in the building. It might be 'pure energy', materials or information.	Building envelope Water tanks Green roofs
Producer 	"Unit that collects and transforms low-quality energy under control interactions of high-quality flows."	Shore Plants Phytoplankton	Unit that collects and transforms low-quality energy under control interactions of high-quality flows of energy. The results are higher-quality energy flows necessary for the functioning of the building.	Photovoltaic panels Thermal Panels Wind turbines
Interaction 	"Interactive intersection of two pathways coupled to produce and outflow in proportion to a function of both"	Chemical reactions	Unit that receives two energy flows and transforms them into a proportional energy flow of both.	Inverter Solar pump Heat pump Fog catcher
Consumer 	"Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow"	Fish Zooplankton Bacteria	Unit that transforms energy quality and can also store it and use it in order to maximize the inflows of energy. The functioning of these units is not based on efficiency, but rather on maximum useful power.	Building systems (hydraulical, lighting, hot water, heating, electrical, etc.) Garden Pond People

Description of symbols used in energy system diagrams as defined by Odum (1994). The examples accompanying the ecological engineering definition of the symbols refer to an aquatic ecosystem (ibid). This is not an exhaustive table of examples and symbols.

5. Representation of buildings using the energy systems diagrams

5.1. Criteria for case studies selection and description of diagraming process

Two basic criteria were followed to select the buildings represented using the energy systems diagrams: (1) buildings needed to embrace environmental measures in terms of their design and performance; (2) enough data should be available for the representation of the buildings and also for the analysis of the results.

As a result of these criteria a total of 29 buildings were selected from the U.S. Green Building Council (USGBC, 2012) database, the Living Building Challenge database (International Living Future Institute, 2012), and the Passive House database (Passive House Institutions, 2012). The 29 buildings have had included, at some degree, environmental principles in their design. In addition, the above mentioned organizations have public databases with enough data to develop this exercise. Lastly of the rating systems used to compile these lists, the Passive House rating system offers an approach focused on energy consumption reduction, while the other two rating systems emphasize additionally other environmental parameters such as water consumption, indoor air quality or materials selection.

The buildings selected from the USGBC database were taken from those rated under the LEED for New Construction v2.1 and LEED for New Construction v2.2. The main reason is that the New Construction classification comprises all types of buildings (e.g. residential, offices, commercial, educational) and it provides complete information on all the building components. Versions 2.1 and 2.2 provide more recent data. Data was accessed between June-September 2012.

Once the 29 buildings were selected, an exhaustive review of the available data was conducted before the diagraming phase started. First, the boundaries of the building systems were defined: an external boundary representing the building site boundary; and an internal boundary representing the building envelope. Then, the sources or external driving forces were identified, followed by the description of the components of each building. The sources and the components were arranged in order of energy quality from left to right (Odum 1994). Flows of energy and component interactions were then indicated. Where data were unavailable, two options were offered. The first option was an assumption of interactions among components when that interaction was essential for the functioning of the building (e.g. there is no data for water consumption, but the building has a hydraulic system; therefore, water inflow has to be represented). The second option was to ignore the element or interaction in the diagram when data were unavailable; this was more common (e.g., if no data suggested the presence of control equipment, then that unit would not be represented in the diagram).

Energy flows were categorized as per Table 2.

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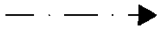
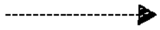
Table 2: Description of energy flows represented in the energy system diagrams.

Energy Flows		
Symbol	**Name**	**Definition**
	Inflows	Flow of energy entering the system or a component in the system
	Outflows	Flow of energy exiting the system.
	Control flows	Feedback flows of information that control the flows of a stock
	Recycle flows	Flows that represent the energy that is reused within the system
	Heat sink	Flows of energy dispersed as heat

5.2. Energy Systems Diagrams Representation

Energy systems diagrams of 29 buildings were developed. In this document four diagrams are shown at full scale. All remaining diagrams can be provided if requested, but are omitted in this document to facilitate the reading. The diagrams selected are representative of each of the rating systems, and display a wide variety of design strategies.

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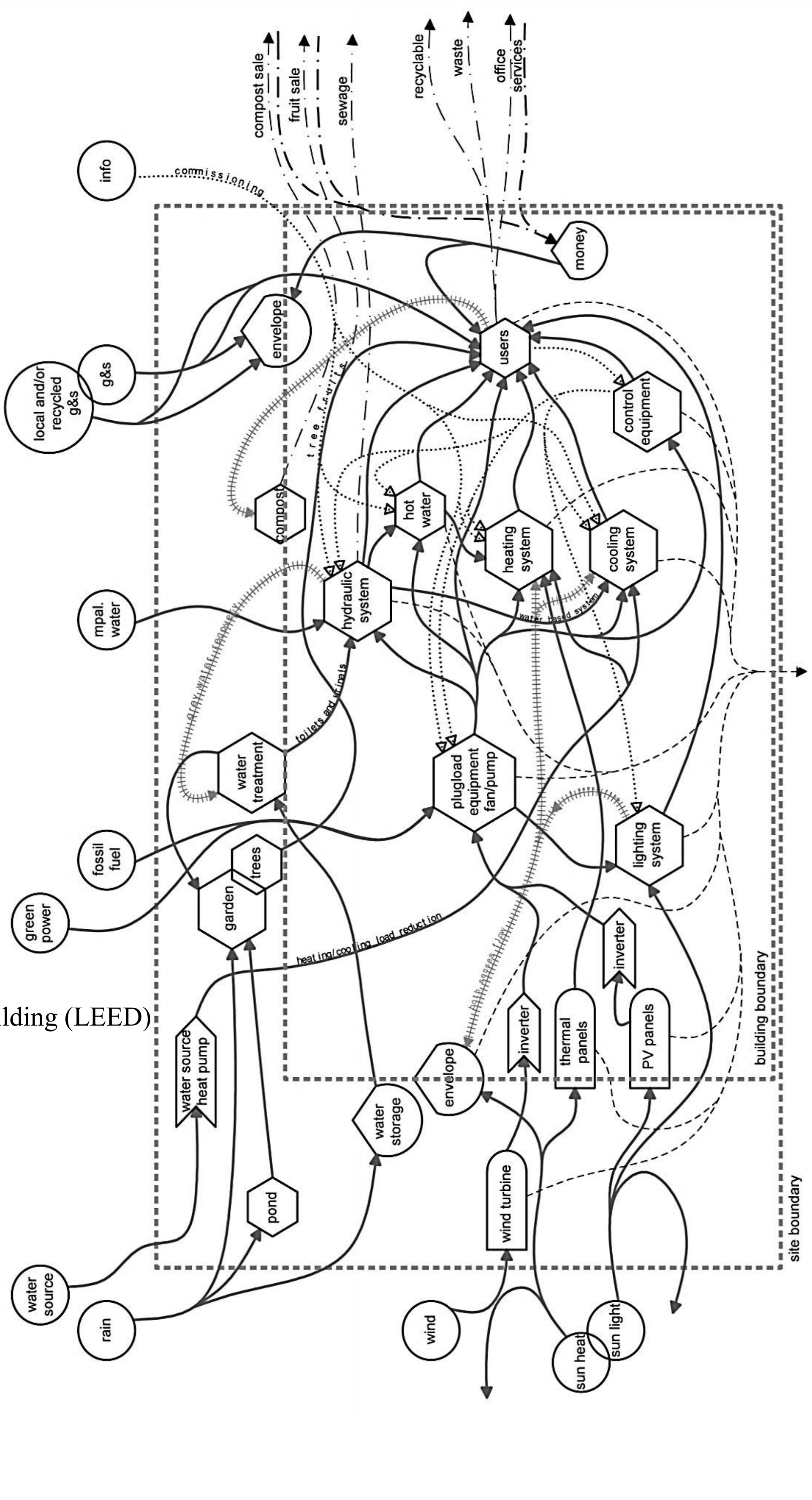

Great River Energy Building (LEED)

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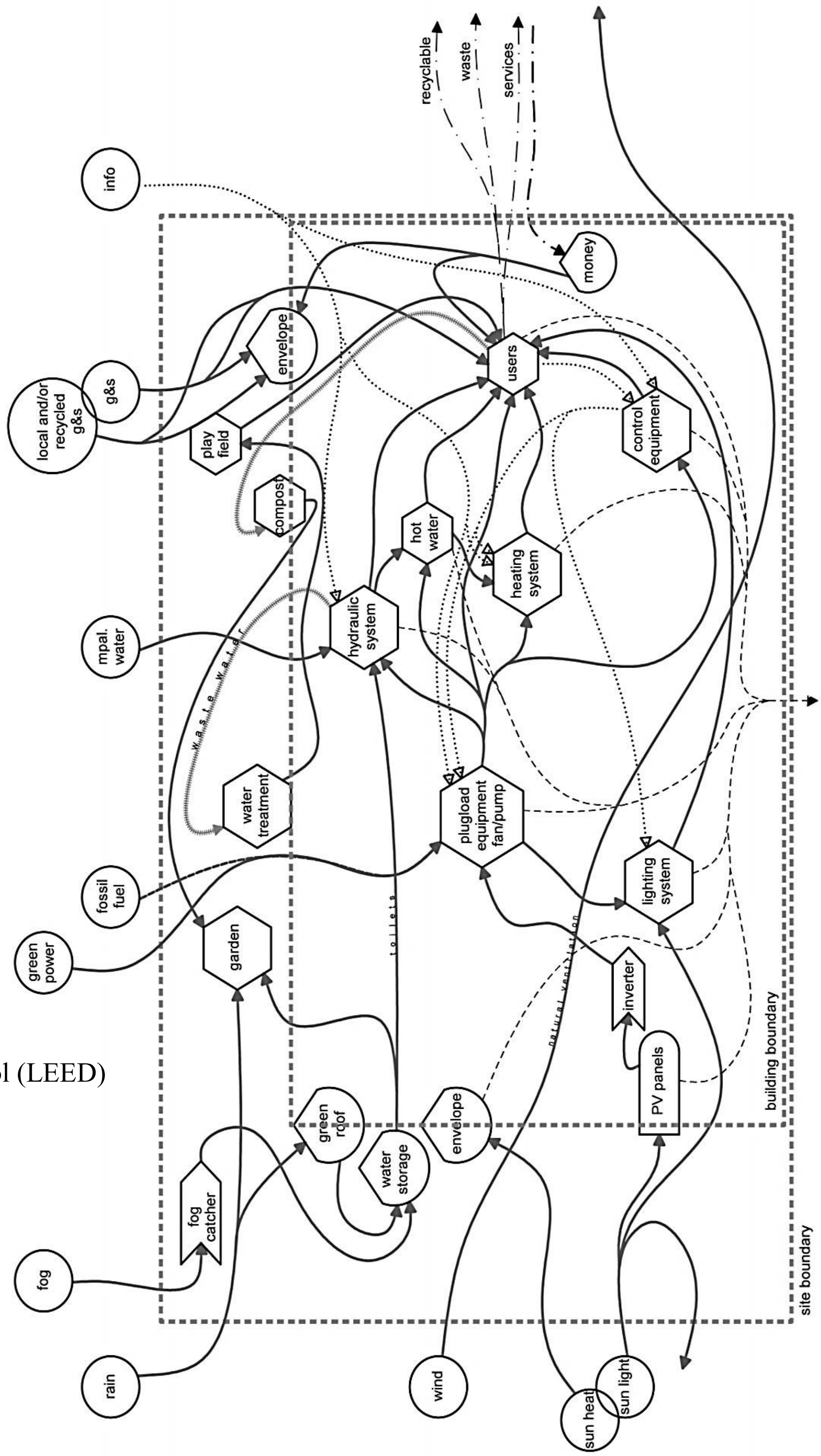

igure 2: Chartwell School (LEED)

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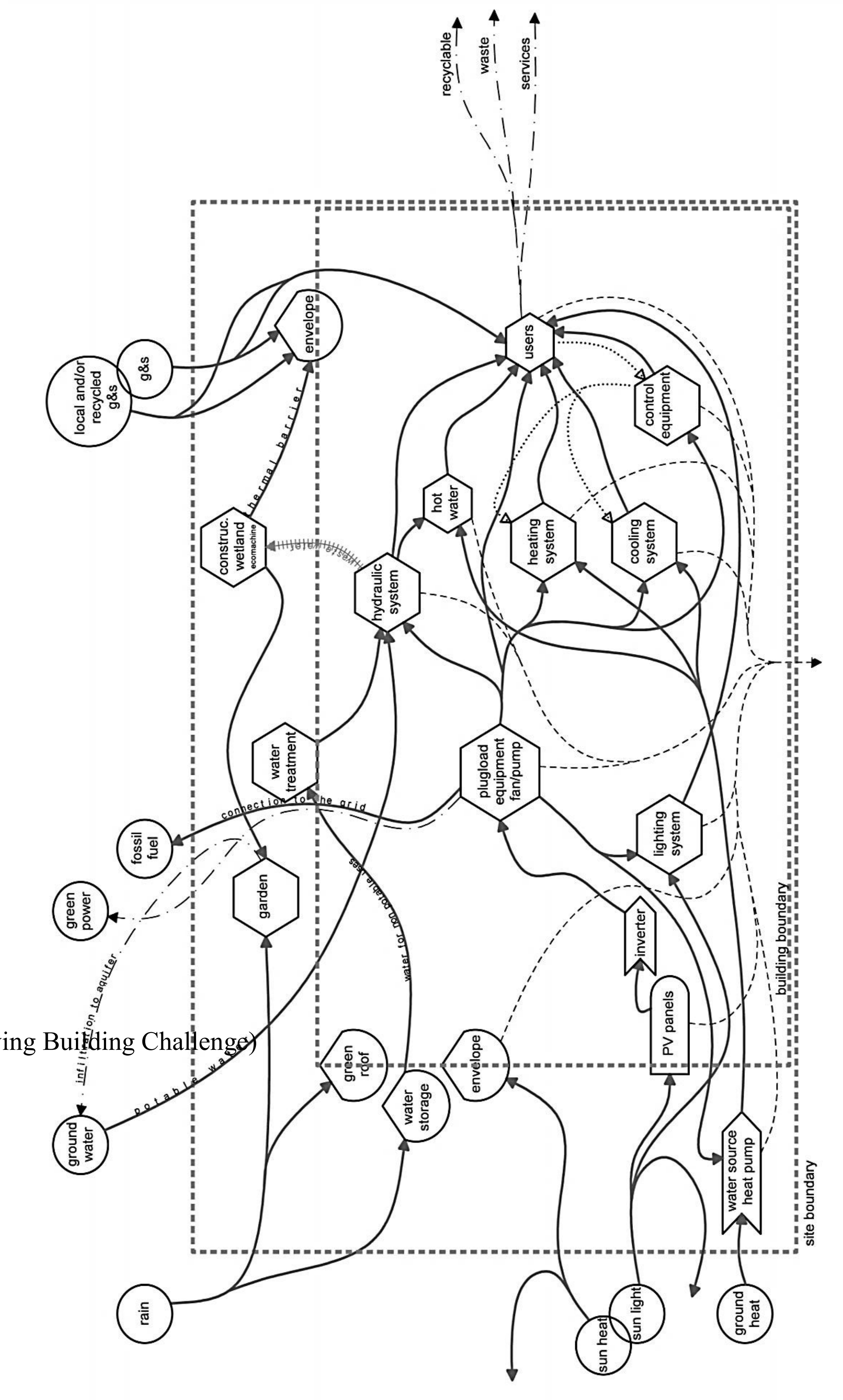

3: Omega Center (Living Building Challenge)

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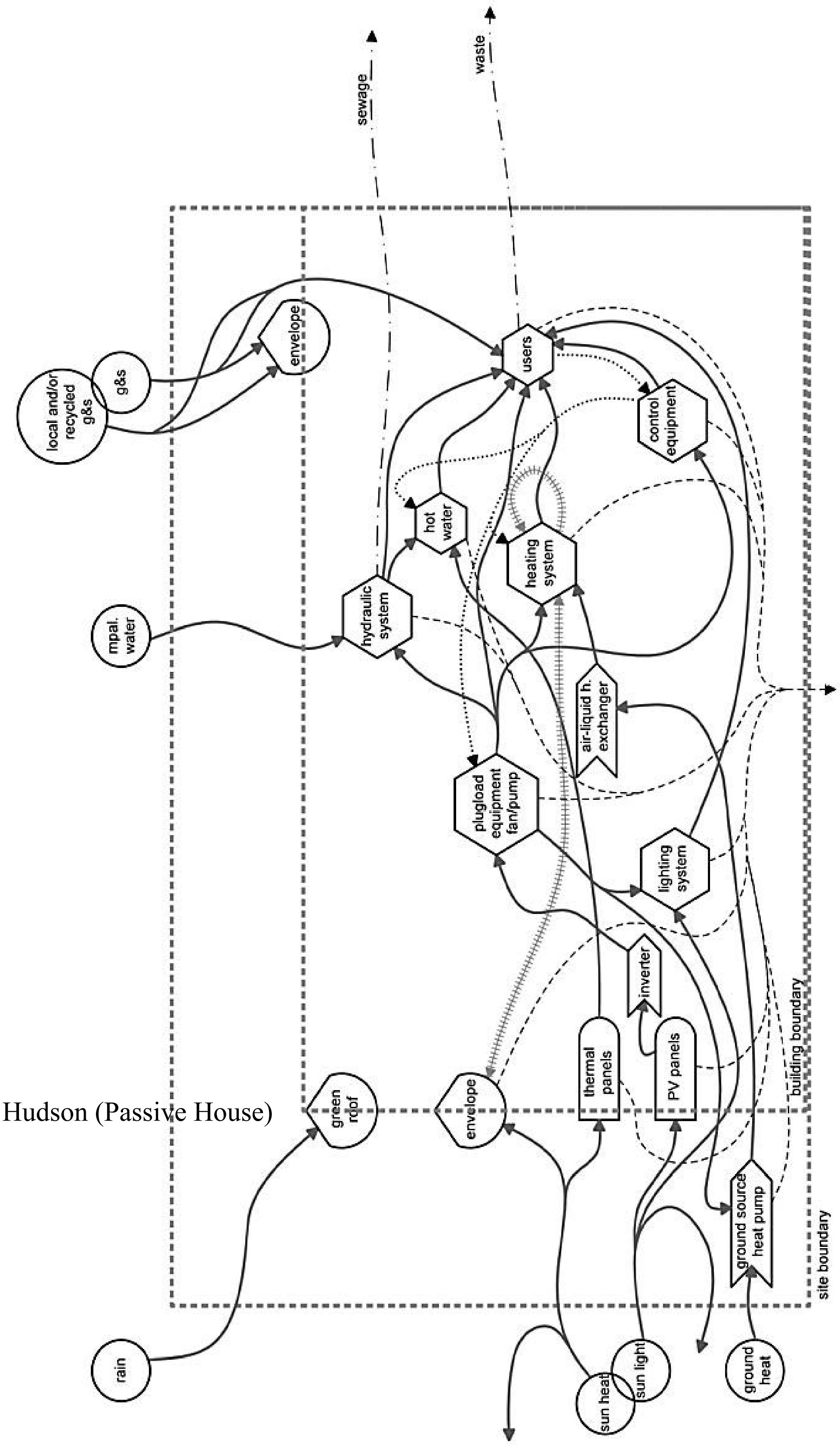

ure 4: Family House in Hudson (Passive House)

5.3. Analysis of the energy systems diagrams

Each of the buildings shows several design strategies oriented towards environmental performance optimization. The energy systems diagrams are able to represent these design strategies and the multiple interactions that these strategies sometimes involve. For instance, the Chartwell School diagram (Figure 2) indicates rain water entering the building system and interacting with at least seven different components of the building (green roof, garden, water storage, hydraulic system, users of the building, water treatment plant, and playing field). In addition, the rainwater goes through several processes and transformations (storage, filtering, disposal, recycling, and reuse). The Chartwell School diagram also represents all the other environmental strategies implemented in the building in a holistic way; and it is able to characterize the diverse interactions among the components in a manner that is easily understood.

In addition to drawing the energy systems diagrams, an analysis of the parameters was carried out. The purpose of this analysis was to show the relationship between architectural parameters and energy systems diagrams parameters. Several parameters related to the environmental performance of buildings were selected: annual water consumption (l m^{-2} yr^{-2}), energy use intensity (kwh m^{-2} yr^{-2}), annual energy breakdown (kwh m^{-2} yr^{-2}), annual percentage of renewable energy produced on-site (kwh m^{-2} yr^{-2}), rating system, certification level, and building size (m^2). Parameters associated with the energy system diagrams were chosen, for instance: type and number of components, components' interactions (connectivity), energy flows, and energy quality ratio. Table 3-A presents the available data on architectural parameters of environmental performance from the rating system's websites (USGBC, Living Building Challenge and Passive House); while table 3-B presents the parameters from the energy systems diagrams.

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from the rating systems' databases (LEED, Living Building Challenge, Passive House)

Buildings' Performance	Building Type	AWC l/m2	EUI* Kwh/m2	Total Annual Energy Breakdown (Kwh/m2)												TA RE POS (Kwh/m2)	
				H	%	C	%	L	%	P/E/ F	%	HW	%	O	%	Kwh/m2	%
LEED BUILDINGS NC v2.2																	
PRESIDENT LINCOLN´S COTTAGE	Museum	337,00	293,62	29,36	10,00	44,32	15,09	116,34	39,62	96,67	32,92			6,93	2,36	0	0,00
NUEVA SCHOOL	Education	164	74,20	20,27	27,32	0,87	1,17	22,49	30,31	16,14	21,75	14,43	19,45			23	31,00
ATLANTIC FLEET DRILL HALL	Military		379,00													0	0,00
SIGLER OFFICE AND WAREHOUSE	Office + Warehouse	129	77,00	12,80	16,62	7,39	9,60	19,94	25,90	32,84	42,65	4,09	5,31			0	0,00
GREAT RIVER ENERGY BUILDING	Office		201,93	28,80	14,26	19,52	9,67	30,07	14,89	99,90	49,47	4,51	2,23	15,09	7,47	31	15,35
IFAW WORLD HEADQUARTERS	Office		213,84	66,75	31,21	15,29	7,15			99,74	46,64	5,62	2,63			0	0,00
YALE SCHOOL OF FORESTRY AND ENV.	Education		83,93	6,86	8,17	6,06	7,22			0,0049	0,01			70,91	84,49	19,05	22,70
MATAROZZI-PELSINGER OFFICES	Office		58,44													20,88	35,73
KAUST CAMPUS	Education		251													19,33	7,70
LEED BUILDINGS NC v2.1																	
BOSTON CHILDREN'S MUSEUM	Museum	173	562	329,63	58,65	41,27	7,34									0	0,00
ORNL JOINT INSTITUTE FOR COMPUTATIONAL SCIENCE	Education	260	479,21													0	0,00
GISH APARTMENTS	Residential	259	56,78	10,6	18,67	4,59	8,08	8,22	14,48	16,78	29,55	16,48	29,02			6,08	10,71
AIR FORCE WEATHER AGENCY HEADQUARTERS	Military		238,16	45,98	19,31	39,88	16,75	25,7	10,79	126,58	53,15					0	0,00
0142 CNT RENOVATION	Offices	275	178,94	61,29	34,25	19,77	11,05			93,9	52,48	4,23	2,36			9	5,03
JEWISH RECONSTRUCTIONIST CONGREGATION	Religious		157,33													0	0,00
SHANGRI LA BOTANICAL GARDENS	Museum		56,5	0,19	0,34	37,11	65,68	10,74	19,01	24,93	44,12	0,71	1,26			6,64	11,75
CHARTWELL SCHOOL	Education	3810	85,59	40,44	47,25	0	0,00	11,96	13,97	15,04	17,57	11,19	13,07			12,35	14,43
LIVING BUILDING CHALLENGE																	
HAWAII PREPARATORY ACADEMY	Education	34	34,75	0		0		5,71	16,43	29,03	83,54					71,15	204,75
OMEGA CENTER	Education	125	41,35													67,23	162,59
TYSON LIVING LEARNING CENTER	Education	178	77,42													83,58	107,96
ECO SENSE	Residential	340	107,75													10,64	9,87
PAINTERS HALL	Office		65,71	6,44	9,80	6,44	9,80	17,07	25,98	34,64	52,72	1,16	1,77			73,31	111,57
IDeAs Z2 DESIGN FACILITY	Office		66,68													68,44	102,64
PASSIVE HOUSE																	
FAMILY HOUSE, HUDSON, US	Residential		66	12	18,18											66	100,00
RURAL REGENERATION CENTER, U	Education		86	15	17,44											0	0,00
STANDINGS COURT RESIDENCES, U	Residential		98	14	14,29											0	0,00
DAS BIOHAUS, US	Education		83	14	16,87											0	0,00

AWC:Annual Water Consumption; EUI:Energy Use Intensity; H:Heating; C:Cooling; L:Lighting; P/E/F:Plug-Loads/Equipments/Funs-Pumps; HW:Hot Water; O:Others; TA RE POS:Total Annual Renewable Energy Producton on Site

***In terms of Site Energy for LEED and Building Challenge. In terms of Primary energy for Passive House**
For Passive House Buildings. Calculation of Site Energy equivalent: for US buildings Assumption: source energy electricity and a Primary Energy factor of 3,34 according to the ENERGY STARS Performance Ratings (http://www.energystar.gov/ia/business/evaluate_performance/site_source.pdf?8ae2-9c3a). For UK buildings: Assumption: source energy electricity and a Primary Energy factor of 2,58 according to SAP 2012 from the UK (www.bre.co.uk)

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rameters as per data obtained from the energy system

Diagrams' Parameters	S R	S n-R	NoCp BB	NoCp SB	Stocks Pr	Stocks St	Stocks Cm	Flows Inflows T	Flows Inflows R	Flows Inflows n-R	Flows Outflows T	Flows Outflows R	Flows Outflows n-R	Connectivity Inflows E1	Connectivity Inflows E2	Connectivity Inflows E3	Connectivity Inflows E4	Connectivity Inflows E5	Connectivity Inflows E6	Connectivity Inflows E7	Connectivity Outflows E1	Connectivity Outflows E2	Connectivity Outflows E3	Connectivity Outflows E4	Connectivity Outflows E5	Connectivity Outflows E6	Connectivity Outflows E7	R-P	C-P	Energy Quality E1	Energy Quality E2	Energy Quality E3	Energy Quality E4	Energy Quality E5	Energy Quality E6	Energy Quality E7
LEED BUILDINGS NC v2.2																																				
PRESIDENT LINCOLN´S COTTAGE	3	5	9	1	0	1	8	15	4	9	4	1	3	4	3	3	5	6	4	9	2	3	8	5	3	2	4	5	7	1	3	2	3	3	4	5
NUEVA SCHOOL	5	4	12	1	1	2	9	17	7	10	4	1	3	4	3	4	3	5	4	9	2	3	8	5	3	2	4	4	5	1	4	3	4	6	5	7
ATLANTIC FLEET DRILL HALL	3	5	9	3	0	2	10	16	5	9	3	0	3	4	3	3	3	4	3	9	2	3	8	4	3	2	4	3	5	1	3	2	3	3	4	5
SIGLER OFFICE AND WAREHOUSE	3	5	10	3	0	2	11	11	4	7	4	0	4	4	3	2	4	4	3	10	2	3	9	5	3	4	4	4	7	1	3	2	3	5	4	6
GREAT RIVER ENERGY BUILDING	6	5	14	7	3	2	13	20	10	10	6	3	3	4	3	5	5	7	4	10	2	3	8	6	3	3	5	5	7	1	5	4	5	7	6	8
IFAW WORLD HEADQUARTERS	4	4	8	2	0	1	9	10	4	6	3	0	3	4	2	1	2	3	2	7	2	3	8	5	3	3	3	4	0	1	3	2	3	5	4	6
YALE SCHOOL OF FORESTRY AND ENV.	6	3	13	3	2	2	10	14	9	5	3	0	3	4	3	3	4	5	3	9	2	3	10	4	3	2	4	3	7	1	5	4	7	6	6	7
MATAROZZI-PELSINGER OFFICES	4	5	11	1	1	2	7	18	7	11	3	0	3	4	3	3	4	4	3	9	2	3	8	3	3	3	4	3	4	1	5	4	5	7	6	8
KAUST CAMPUS	5	4	12	2	2	1	9	16	10	6	2	0	2	3	3	3	4		4	8	1	2	8	5		2	4	1	6	1	5	4	5		6	7
LEED BUILDINGS NC v2.1																																				
BOSTON CHILDREN'S MUSEUM	4	5	9	4	0	3	10	17	6	11	3	0	3	5	3	3	4	4		8	3	3	8	3	3		4	4	5	1	3	2	5	3		4
ORNL JOINT INSTITUTE FOR COMPUTATIONAL SCIENCE	3	5	10	1	0	1	10	14	3	11	4	1	3	4	3	3	3	6	4	9	2	3	8	4	4	4	5	6	2	1	4	3	4	6	5	7
GISH APARTMENTS	5	4	11	2	1	1	12	6	6	6	3	1	2	4	3	2	3	3	2	9	2	3	9	4	2	2	5	2	3	1	5	4	5	6	6	7
AIR FORCE WEATHER AGENCY HEADQUARTERS	3	5	9	1	0	1	9	9	4	5	4	1	3	3	3	2	3	2	2	9	1	2	8	4	2	2	5	0	6	1	3	2	3	3	4	5
0142 CNT RENOVATION	5	4	12	2	1	1	11	13	7	6	3	1	2	3	3	4	4	2	2	9	1	2	8	5	2	2	4	0	6	1	5	4	5	5	6	7
JEWISH RECONSTRUCTIONIST CONGREGATION	4	5	10	1	0	2	9	11	4	7	3	0	3	4	3	2	4	4	2	9	2	2	8	4	3	3	4	1	6	1	3	2	3	5	4	6
SHANGRI LA BOTANICAL GARDENS	5	5	12	6	1	2	10	22	10	12	4	2	2	3	3	3	5	4	3	10	1	2	9	5	2	2	5	0	5	1	5	4	6	8	7	9
CHARTWELL SCHOOL	6	5	13	5	1	3	11	18	8	10	3	1	2	3	3	5	4	4	2	9	1	2	7	4	2	3	6	2	4	1	5	4	5	7	6	8
LIVING BUILDING CHALLENGE																																				
HAWAII PREPARATORY ACADEMY	5	2	16	5	2	5	11	13	9	4	5	3	2	3	3	2	2	3	2	9	1	2	9	4	2	3	5	1	4	1	5	4	5	7	6	8
OMEGA CENTER	5	2	12	5	1	3	11	12	8	4	5	3	2	3	2	1	3	2	2	9	1	2	9	4	2	2	4	1	1	1	5	4	5	6	6	7
TYSON LIVING LEARNING CENTER	4	2	12	4	1	2	12	10	6	4	5	3	2	4	3	1	2	4	2	9	2	2	9	5	4	2	5	8	4	1	5	4	5	5	6	7
ECO SENSE	6	3	13	2	2	3	9	15	10	5	3	2	1	4	3	3	2	5	2	8	2	2	7	4	2	3	6	4	3	1	5	4	5	8	6	9
PAINTERS HALL	4	3	11	1	1	1	8	10	5	5	5	2	3	3	3	1	2	3	2	8	1	2	10	4	2	2	5	0	3	1	5	4	5	5	6	7
IDeAs Z2 DESIGN FACILITY	4	3	11	2	1	1	9	10	5	5	5	2	3	3	3	2	2	4	1	9	1	2	9	3	2	3	5	0	3	1	5	4	5	7	6	8
PASSIVE HOUSE																																				
FAMILY HOUSE, HUDSON, US	4	3	13	1	2	2	7	11	6	5	2	0	2	4	2	2	2	5	3	8	2	2	7	4	3	2	3	3	4	1	5	4	5	7	6	8
RURAL REGENERATION CENTER, U	4	3	8	2	0	2	7	8	4	4	2	0	2	3	3	2	4	4	3	7	2	2	7	4	3	2	3	3	6	1	3	2	3	3	4	5
STANDINGS COURT RESIDENCES, U	2	3	8	0	1	1	6	7	3	4	2	0	2	3	2	1	2	4	3	6	2	2	6	4	3	3	2	3	0	1	3	2	3	5	4	6
DAS BIOHAUS, US	3	3	9	1	1	1	7	8	4	4	2	0	2	3	3	1	3	6	4	7	2	2	8	4	4	3	3	2	6	1	3	2	3	5	4	6

S:Sources; NoCp: Number of Components; R:renewable; n-R:non renewable; BB:Building Boundary; SB:Site Boundary; Pr:Producer; St:Storage; Cm:Consumer; R-P:Recycle Pathways; C-P:Control Pathways

E1:Envelope Unit; E2:Lighting System Unit; E3:Plugload Equipment Unit; E4:Hydraulic System Unit; E5:Heating System Unit; E6:Hot Water Unit; E7:Users Unit

The analysis of the data showed interesting correlations between the architectural parameters and the energy systems diagrams developed for the buildings in question. Figure 5 presents the relationship between the energy quality ratio and the amount of energy consumed; that is, those buildings that have a higher number of energy transformations occurring within the system tend to use less energy.

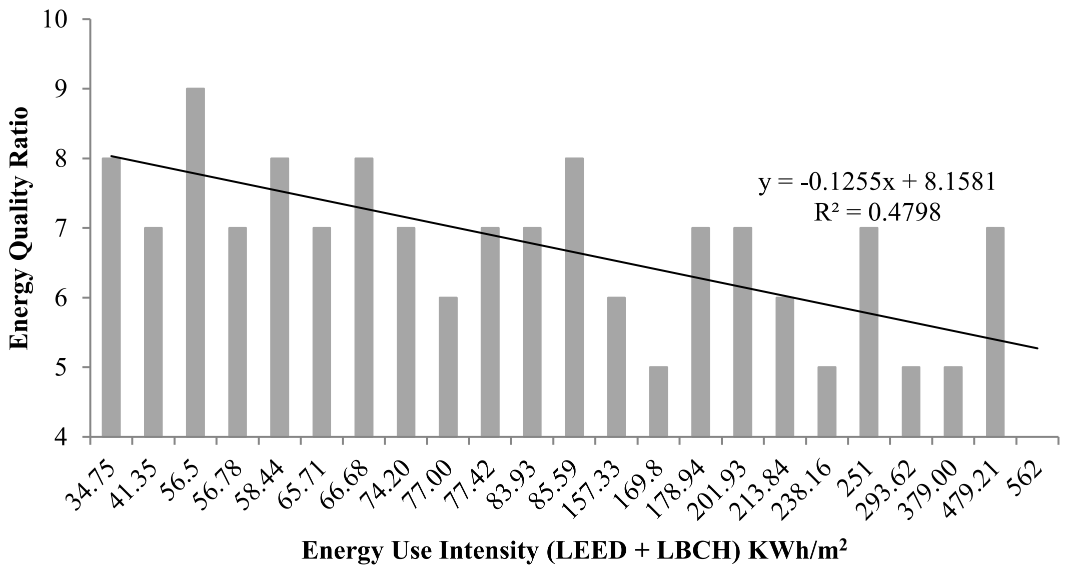

Figure 5: Energy Quality Ratio vs. Energy Use Intensity (EUI). The energy quality ratio is proportional to the EUI with a slope of -0.1.

In Figure 6 there is a stronger trend showing that the energy quality ratio is related to the percentage of renewable energy produced on site; that is, buildings with higher production of renewable energy tend to have a higher number of transformations of energy.

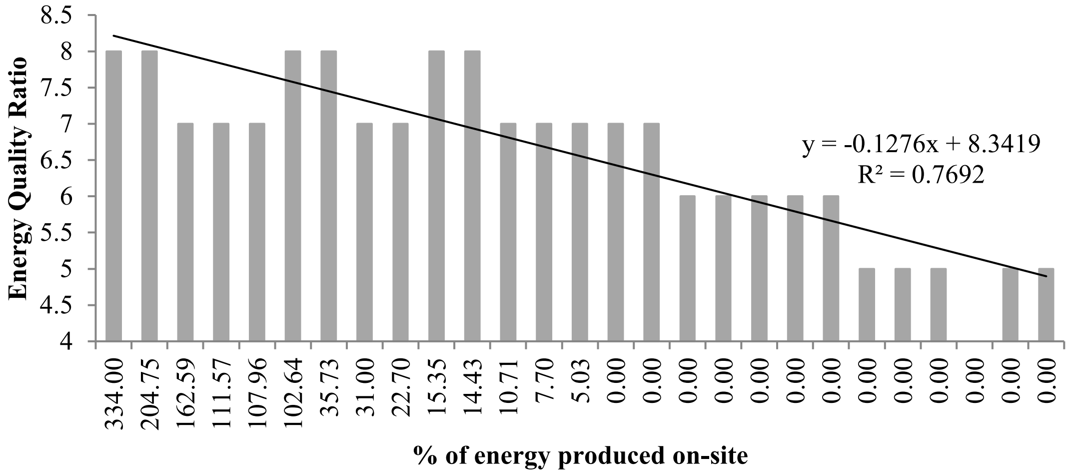

Figure 6: Energy Quality Ratio vs. On-site Energy. The energy quality ratio is proportional to the percentage of the energy produced on-site with a slope of -0.1.

There are also interesting links between the LEED certification level and the energy systems diagrams parameters. For example, a higher score in the LEED rating system is linked to a higher number of renewable inflows (Figure 7), a higher number of renewable energy sources (Figure 8) and a higher number of components in the building system (Figure 9).

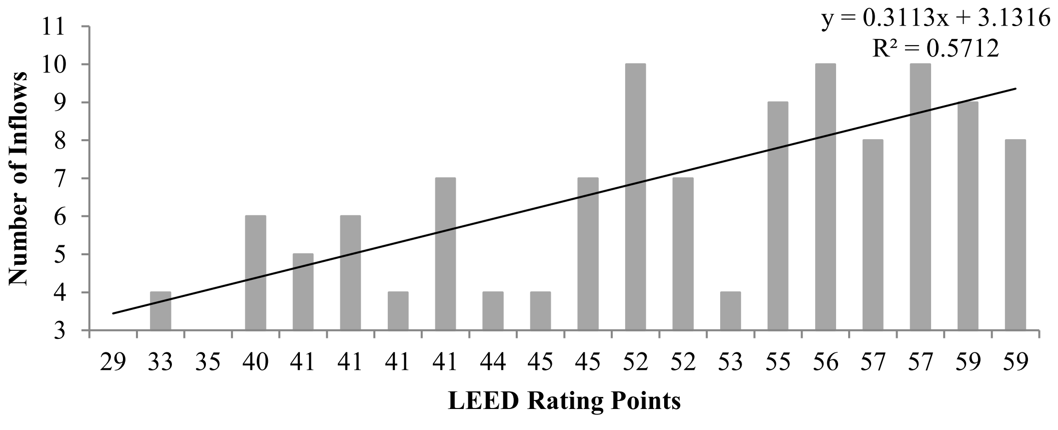

Figure 7: Renewable inflows vs. LEED rating points. The number of renewable inflows is proportional to the LEED rating points with a slope of 0.3.

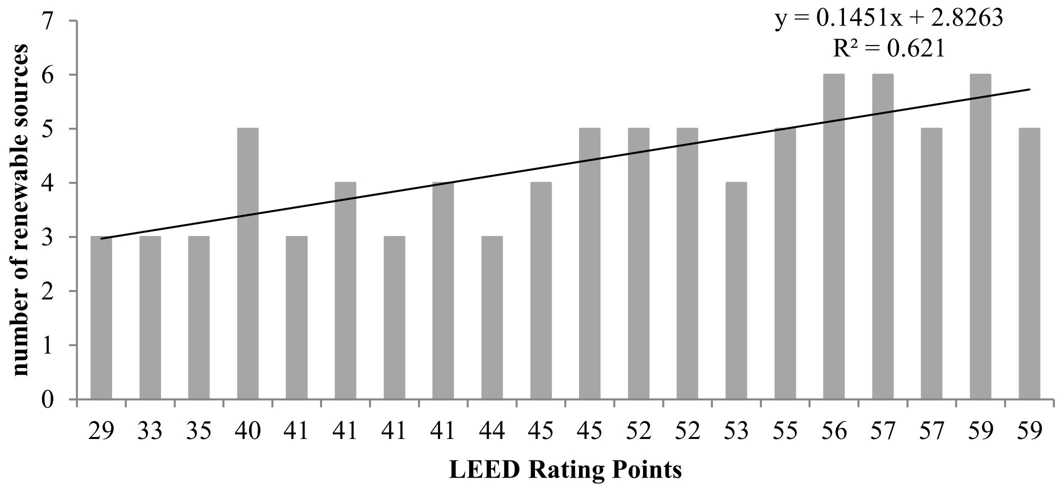

Figure 8: Renewable sources vs. LEED rating points. The number of renewable sources is proportional to the LEED rating points with a slope of 0.1.

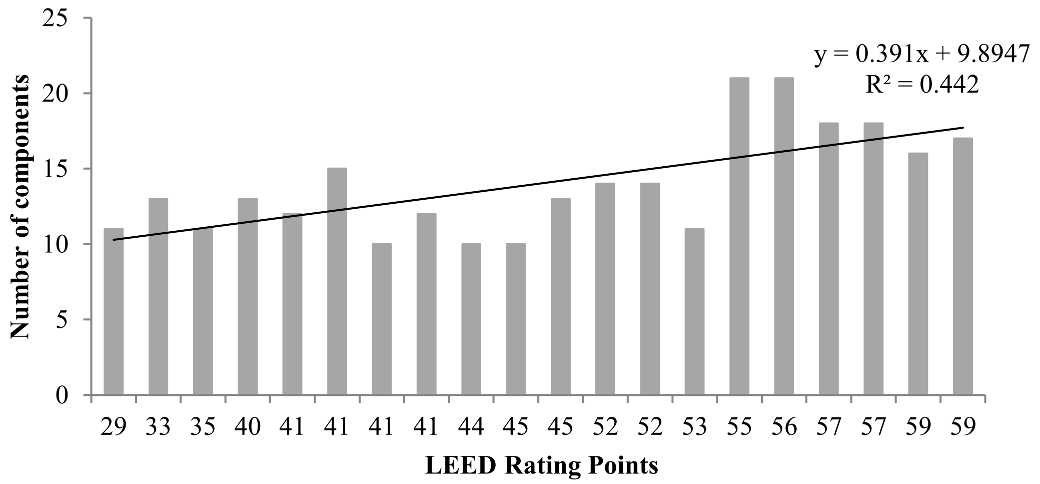

Figure 9: Number of components vs. LEED rating points. The number of components of the systems diagrams is proportional to the LEED rating points with a slope of 0.4.

6. Discussion and conclusion

The drawing of the energy systems diagrams and analysis of the available data indicated that there were differences among the rating systems of these organizations that could affect the graphs shown above. Because the Passive House certification focuses on energy use reduction, the data available on their website mostly related to those strategies that accomplished the rating system requirements. Therefore, little or no data was offered regarding other design strategies. Conversely, the LEED and Living Building Challenge rating systems provided a more holistic approach, and a wider variety of data was available to build the energy system diagrams. However, buildings from the Passive House database showed the lowest levels of energy use when compared to those selected from the other two rating systems. This suggests that the rating systems organizations could benefit from considering the requirements of their peer rating systems. Buildings, like ecosystems, are complex systems, and they could be designed not from a single, reductionist perspective but from a holistic one.

Regardless of the differences among rating systems, several conclusions emerge from this study. The energy systems diagrams graphically represent the flows of energy and the organization of environmental systems; and by doing this they are also representing their underlying patterns (i.e., reiterated behavior). These patterns are characterized using parameters such as energy sources, energy quality, energy flows, energy storage, system structure, and system interactions. In this document, it is shown that these parameters can also be applied to characterize buildings. So the first conclusion is that buildings can be represented using the energy system diagrams.

Moreover, the abovementioned parameters show a correlation with those parameters commonly used to define the environmental performance of buildings; that is, energy use intensity, energy production on-site, and certification levels. This correlation allows us to conclude that the energy system diagrams not only represent buildings, but they also can represent the environmental performance of buildings. For example, a diagram with long energy chains or a diagram with several producer units, are both more likely to correspond to a building that has environmental strategies integrated in its design. However, it is the whole system rather than a single flow, which can give more insight about the environmental performance of a building.

Based on the above statements, the final conclusion is that the energy systems diagrams have potential as a useful platform for characterizing patterns of structure and dynamics that might be used in architectural design. In other words, the energy system diagrams might be employed as a qualitative ecomimetic tool for analyzing energy patterns in ecosystems and for finding correlations with energy patterns in buildings. This analysis, when done with the proposed tool (i.e., the energy system diagrams), allows communication at a very abstract and qualitative level between architecture and ecology. The energy system diagrams can show, for example, how a desert ecosystem manages the flows of water; and by comparing the ecosystem flows and organization with a specific building we can gain more insight about potential ecomimetic strategies. Not all energy ecosystem patterns are likely to be transferred, nor is that the intention of an ecomimetic approach. By using the energy system diagrams a trans-disciplinary language is proposed to advance the construction of an ecomimetic methodology.

Future work will have to be done to illustrate pattern transferring. Also, future work will be focused on developing a quantitative ecomimetic tool in order to measure those parameters in ecosystems patterns to be transferred.

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