Clark's Crow: a design plugin to support emergy analysis decision making towards sustainable urban ecologies

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Abstract

Architects working with city planners and developers in the shaping of urban environments typically consider multiple factors in isolation, from urban design and socio-economic relationships to data analyses. Analyses regarding urban life cycle scenarios are exemplar of this trend, with considerations made in isolation at the later stages of the design-development process when the scope for decisions which could ultimately affect the sustainability of an urban environment is much more limited. This paper defines our effort to introduce a new tool, named "Clark's Crow", which aims to address this shortcoming by promoting awareness of the impact of different design options through a biophysically based ecological accounting method in the early stages of urban design-development. The tool is used within existing architectural design environments with an aim to offer a socio-ecological analysis during the design decision-making process. Clark's Crow is underpinned by the emergy analysis method, which aims to consider both the energy, material, and information flows of a system, such as an urban ecology, and to understand both the work of the techno-sphere in constructing our urban environments and that of the geo-biosphere in sustaining such development. Clark's Crow facilitates emergy analysis in the early stages of urban design, thereby allowing queries

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regarding material and energy flows to be addressed in conjunction with design choices at this initial stage. In this paper, we demonstrate the effectiveness and features of Clark's Crow through a case study of development using next generation systems in Manhattan, New York, depicting how an emergy analysis approach can lead to an understanding of the value and impact of speculative buildings towards sustainable design-development.

Keywords: design tool, emergy analysis, built environment, urban ecologies, sustainable urban design

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1. Introduction

The development of urban environments from a socio-economic perspective is greatly influenced by the health of our urban ecosystem and surrounding natural environment. Buildings and the built environment play a major role in urban ecosystems. In the U.S. alone, the building sector accounted for 41% of primary energy consumption and 30% of material use in 2010 (DOE, 2012). As illustrated in Figure 1, the materials and energy vectors that are directly used by the building sector are part of the so-called techno-sphere (which comprises our economies and societies), but they are ultimately reliant on the availability of ecological goods and services in the geo-biosphere (including the provision of primary energies and materials, as well as the dilution and recycling of emissions). Urban systems place a burden on the geo-biosphere through the indirect exploitation of these ecological goods and services, as well as through the release of unintentional emissions which, unless diluted through biological processes, may ultimately lead to environmental overloading. How we process, recover, restore and regenerate both the technical "nutrients" of the techno-sphere and the biological nutrients of the geo-biosphere within urban ecosystems is thus a crucial question when considering sustainable urban development.

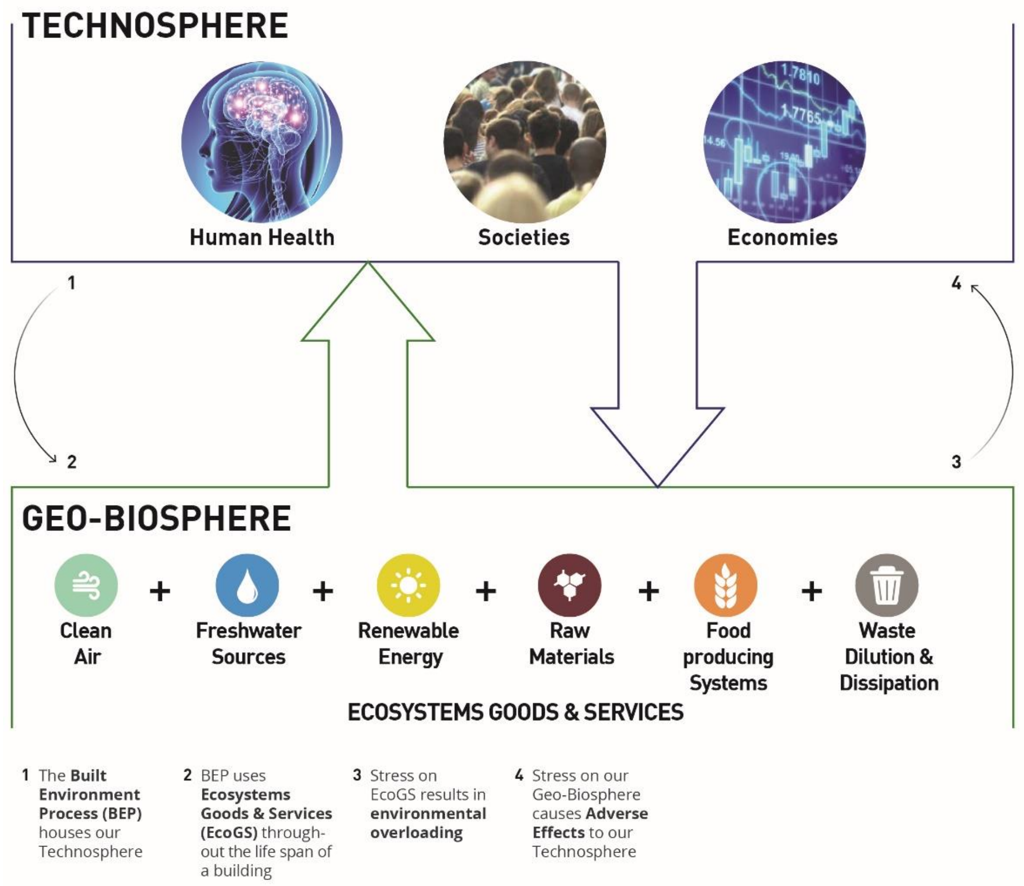

Figure 1: The relationship between the Techno-sphere and the Geo-biosphere. Urban environments house the work of the techno-sphere from socio-economic activity to human health and well-being. In order to function, they rely on ecosystem resources of the geo-biosphere.

Urban systems are often treated as linear processes, focusing solely on the operational stage of buildings in terms of their direct use of energy and waste management. Over the last four decades, however, a number of material and energy accounting methods have been developed in order to speculate and give a quantitative estimate of the relationship between the resources of the geo-biosphere and the material and energy flows within the techno-sphere, such as Embodied Energy Analysis (Costanza, 1980), Life Cycle Assessment (LCA) (ISO, 2006), and Emergy Analysis (Odum, 1988; Odum, 2007; Odum & Odum, 2000). Through the introduction of the concept of "embodied energy" and other life-cycle considerations, the scope of analysis has thus been enlarged to include the material and energy flows taking place beyond the building operation phase. As illustrated in Figure 2, the actual scope of analysis depends on the individual method. In particular, emergy analysis adopts the broadest scope (Brown & Herendeen, 1996) by also including the work of the geo-biosphere that is required to provide the primary resources (Raugei, et al., 2014) and to absorb, dilute and recycle the emissions (Ulgiati & Brown, 2002; Reza, et al., 2014). It has been argued that the adoption of such extended boundaries makes emergy analysis particularly suited to estimating the "responsibility" that is bestowed upon the user through their use of natural resources (Raugei, et al., 2014). Also, in terms of urban design-development, considering both the biological and technical factors coherently within the same method greatly increases the scope of the analysis and allows considering cities as the product of "urban metabolism" (Zhang, et al., 2009).

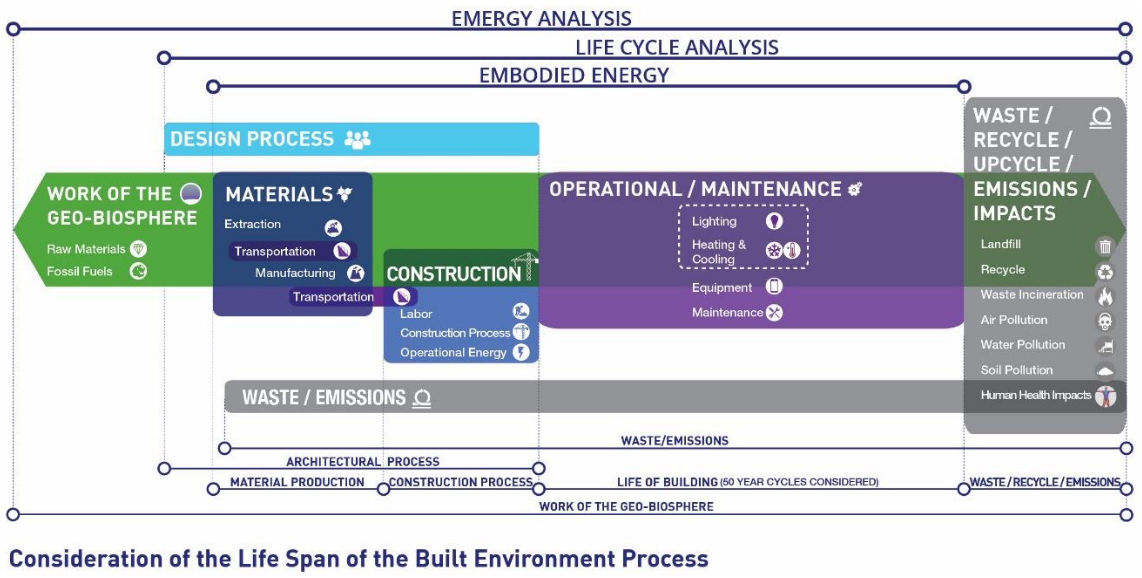

Figure 2: Consideration of the Life Span of the Built Environment Process (BEP). Different assessment methods focus on various scopes of a system's "life cycle". In terms of buildings, the scope of analysis may include any segment of the following: extraction of raw materials, manufacturing of materials, the construction process, the operational and maintenance phase and/or the end of life design.

As regards the practical implementation of these methods, tools such as Athena Institute EcoCalculator (Athena Institute & Hershield, 2017), SCALE (Marvuglia, et al., 2013), and EIOLCA (Carnegie Mellon University Green Design Institute, 2008) use one or a combination of methods to allow for analysis of the urban ecosystem in terms of estimated material and energy resource use and their potential environmental impacts in terms of emissions. Specifically, the EcoCalculator uses LCA, SCALE combines emergy and LCA, and EIOLCA builds upon economic input-output analysis using embodied energy analysis and LCA. These tools aim to provide a user-friendly means to encourage such analysis and provide guidance on the relative environmental impacts of different design decisions with respect to energy and material resource use and emissions throughout the supply chain.

However, typically urban design-development decisions such as massing, building orientation, building operational energy use, and daylighting occur during the early design stages within existing architectural design environments. Subsequent analyses, such as those involving building and urban life cycle performance aspects occur in isolation using existing tools such as those mentioned above. From a study of existing life cycle scenario analysis tools which are used in urban design-development, it was clear that due to the nature of these tools the analysis occurs in isolation of other design considerations, which typically employ different design software. Our study concluded, as did others (Besserud & Hussey, 2011; Reinhart, et al., 2013; Aly Etman, et al., 2016), that limited progress has been made in the integration of urban design analyses methods into a common tool, software, or workflow. One somewhat isolated example of integration is represented by a tool named Tally (KT Innovations, et al., 2016), which aims to facilitate LCA analysis within building information modeling (BIM). This tool has proven useful in providing LCA on demand, during the time frame and within the environment in which buildings are created.

This paper focuses on the application of the emergy analysis method to buildings and the built environment within the urban ecosystem, and aims to investigate if the inclusion of emergy analysis during the early stages of design can have a positive impact towards sustainable urban design-development. To this end, we created a novel tool named “Clark’s Crow” (Aly Etman, et al., 2016; Keena, et al., 2016; Keena, et al., 2016), which is designed to operate as a plug-in for existing design platforms commonly used by architects, so as to integrate emergy analysis during the early stages of design rather than as an isolated analysis to be carried out later. Section 2 explains that Clark’s Crow is a plugin to Grasshopper (McNeel, 2013) where typically plugins are named after biological entities (animals, insects etc.). Hence, we chose to name the plugin ‘Clark’s Crow’, short for Clark’s nutcracker, a bird with tremendous long-term spatial memory. In this paper we demonstrated the potential of Clark’s Crow through a case study of a speculative urban design in New York which employs next generation systems towards a self-reinforcing and healthy urban environment.

2. Material and methods

2.1 Choice of the most suitable existing design platform commonly used in architectural and building design practice

Based on the assumption that emergy information will be most effective during the schematic and initial stages of the design when disproportionate decisions on building materials, building morphology, building components, and building systems are most typically made (Srinivasan & Moe, 2015), the first step of our worked consisted in a review of the existing design platforms used at these stages. The time span is especially important, as it is an indicator of the potential for emergy information to have dramatic effects on how we approach environmental conscious design of urban systems.

One of the main criteria was to identify information already inherent in these software packages that could be leveraged as the input parameters to an emergy analysis. We found Rhinoceros (a 3-D modeling environment that is often used by designers in the early stages of urban design) and its scripting environment Grasshopper (McNeel, 2013) (with multiple plug-ins that allow for performance evaluation during the design process) to be the existing design platform that best met our leveraging criteria. Clark's Crow was therefore developed as a plug-in for Grasshopper. Pre-existing Grasshopper plug-ins targeted at urban studies include Ladybug (Roudsari, et al., 2013) for climate analysis and Honeybee (Roudsari, et al., 2014) for operational energy and daylight considerations. In particular, our analysis highlighted that the Grasshopper Honeybee plugin for building energy simulation has the potential to supply some of the required raw data needed for an emergy calculation of building materials (i.e. material density, material thickness) and operational energy (i.e. the data can be pulled from the results of the building energy simulation including the energy consumption to meet heating, cooling, lighting, and equipment loads). The emergy analysis also entails renewable input parameters that require Typical Meteorological Year (TMY) (Wilcox & Marion, 2008) data for solar radiation, wind speed, and annual rainfall. These data can be accessed from the Ladybug plugin within Grasshopper which pulls data from EnergyPlus Weather[2] (EPW) (U.S. Department of Energy (DOE), 2016) files in the format of TMY data. The Ladybug and Honeybee plugins connect to EnergyPlus (EP) for material libraries[3], energy simulation parameters and weather files in the format of EPW data. Other user inputs such as site area and surface area of building material can be accessed directly from the 3D model of the design. A more detailed list of the required emergy analysis parameters that can be leveraged from the Grasshopper Plugins Ladybug and Honeybee, as well as from the 3d Model, is reported in **Table 1**. The aim of Table 1 is to outline the necessary parameters to perform an emergy analysis of the built environment which have been considered in the design and development of Clark's Crow. In particular, Table 1 highlights in detail those parameters, which are leveraged from existing architectural design tools (i.e. Ladybug,

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[2] The US Department of Energy's building simulation software named EnergyPlus, includes global weather data provided in EnergyPlus weather format. It is derived from twenty sources including Typical Meteorological Year (TMY) data. A TMY file is collated weather data, derived from a 1991-2005 period of recorded files. It represents a typical range of weather phenomena for a specific location (Wilcox & Marion, 2008). EnergyPlus Weather (EPW) files are freely available on the EnergyPlus website (U.S. Department of Energy (DOE), 2016) and architects commonly use them to access a specific location of interest.

[3] The US Department of Energy's building simulation software named EnergyPlus, contains an extensive database of materials and construction types including their properties from ASHRAE and other sources as outlined in ASHRAE handbook 2009 (Handbook, A.S.H.R.A.E.;, 2009). The EP material library is accessed within the design environment of Grasshopper for Rhino using the Honeybee plugin. Clark's Crow has built upon this library and adapted it for use in the plugin by adding UEVs to the library accessed from the ISAER database and from literature. Each UEV in Clark's Crow adapted material library has been referenced so that the provenance of the each UEV can be tracked.

Honeybee, and 3D model geometry) and those that it was necessary to incorporate into the development of Clark's Crow.

As outlined in sub-sections 2.2 and 2.3, the next steps were to identify the remaining relevant parameters and indicators required for an emergy-based environmental impact assessment.

Table 1: Identification of required parameters to carry out an emergy analysis.

Input Categories	Raw Data Equations	Units	References
Material Production & Construction Phase: Purchased inputs from outside the system boundaries			
Fossil fuels	**annual consumption**	J/yr	Brown et al, 2011
Raw Materials	**volume * density**	kg	Buranakarn, 1998
Building Materials	**volume * density**	kg	Buranakarn, 1998
Labor	hours worked * energy consumed per working hour	J	Braham, 2015
Transportation	mass transported * distance travelled * energy used per km	J	Brown et al, 2011
Construction Phase: Site Specific Locally-sourced Renewable and Non-renewable inputs			
Solar energy	**total annual insolation (EPW data)* SITE AREA**	J/yr	Braham, 2015
Wind energy	**SITE AREA** * air density * drag coefficient * geostrophic velocity	J/yr	Braham, 2015
Rain (chemical potential)	**annual rainfall rate (EPW data) * SITE AREA** * Gibb's free energy of water * runoff coefficient	J/yr	Braham, 2015
Net Topsoil Loss	**SITE AREA** * erosion rate	J	Brandt-Williams 2002
Operational and Maintenance Phase: Purchased inputs from outside the system boundaries			
Thermal energy	**annual operation**	J/yr	Pulselli et al, 2009

Electricity	**annual operation**	J/yr	Pulselli et al, 2009
Material Maintenance	**volume * density**	kg	Buranakarn, 1998
End of Life Phase: Purchased inputs from outside the system boundaries			
Material recycle, by-product or reuse	**volume * density**	kg	Brown et al, 2003

Key: Parameters in **boldface** are leveraged from the Ladybug and Honeybee plug-ins; parameters in **BOLDFACE CAPITAL LETTERS** are from the 3D Model.

2.2 Identification of the additional parameters needed to run an emergy analysis

Emergy is calculated as indicated in eq. (1) (Brown & Ulgiati, 1997):

$$\textit{Emergy} = \textit{Exergy of item} * \textit{Unit Emergy Value (UEV)} \tag{1}$$

Exergy of item is the Gibbs free energy (also referred to as "available energy") of the item calculated with respect to a standard reference environment that is assumed to approximate the average environmental conditions in the Earth's crust, oceans and troposphere (Szargut, et al., 1988). A Unit Emergy Value (UEV) is defined as the total amount of exergy of one type (usually solar) directly and indirectly required to generate a unit of exergy of another type (Odum, 1988). UEV is the general term for three ratios: 1) transformity, 2) specific emergy and 3) emergy per unit money. Transformity is expressed in units of solar emergy joules (or "emjoules") per Joule (sej/J) (Brown & Ulgiati, 1997). Specific emergy is expressed in units of solar emjoules per unit of mass (e.g., sej/kg). Emergy per unit money defines monetary values in terms of emergy, and is expressed in units of solar emjoules per unit of currency (e.g., sej/$) (Srinivasan, et al., 2012). In order to run an emergy analysis UEVs for the input items listed in **Table 1** are required. Unfortunately, at present a fully integrated and methodologically consistent database of UEVs is not yet available, which means that for the time being we had to resort to sourcing UEVs from The International Society for the Advancement of Emergy Research (ISAER) open source database, as well as from existing literature. However, in principle the Clark's Crow tool is not bound to any specific UEV source and remains open to switching to newer and more robust databases if and when they become available.

2.3 Identification of the most relevant emergy indicators for the assessment of urban systems and buildings.

Brown & Ulgiati (1997) outline a number of indicators to evaluate the sustainability of whole economies and large-scale processes as a function of their demand for locally-available renewable emergy (R), locally-available non-renewable emergy (N), and "feedback" (F) emergy inputs that are purchased and imported from outside the system's boundaries. These indicators are the emergy yield ratio (EYR=(R+N+F)/F), the environmental loading ratio (ELR=(N+F)/R), the emergy investment ratio (EIR=F/(R+N)), and the emergy sustainability index (ESI=EYR/ELR), and their trends analyzed over time also provide useful information about the dynamics of economic systems within the carrying capacity of the environment in which they develop.

However, if one were to apply these same indicators to much smaller systems than the ones for which they were originally conceived - such as the urban systems that are our intended focus of application - their usefulness to differentiate between alternative systems, and ultimately their meaningfulness, would be greatly reduced (Raugei, et al., 2005). That is because, according to the originally proposed clear-cut classification of the inputs, practically all non-renewable emergy inputs to the system would have to be classified as F, since the urban system boundaries hardly ever include any primary energy sources such as oil wells, coal mines, mineral ore mining sites, etc. In fact, the only locally-sourced non-renewable emergy input (N) would often be the (comparatively minor) top soil loss. Also, again because of the relatively limited size of the system, as well as the lower transformity of the locally sourced renewable inputs (typically, sunlight and/or rainfall), in most instances the sum of the local inputs (R+N) would be far smaller than that of the "purchased" inputs (F), which would invariably result in EYR ≈ 1, very high EIR and ELR, and very low ESI. Furthermore, the conventional interpretation of these indicators would also fail to apply. For instance, when calculated for whole economies, the EYR provides a measure of the ability of the system to exploit local resources as opposed to imported goods, and a higher value is often preferred as it indicates that the system is comparatively more reliant on local resources and is therefore more "independent". However, when calculated on the much more limited scale of an urban system, a larger value of N may often only be indicative of a greater loss of top soil (e.g., as a result of turning a large area into a parking lot instead of keeping it as a grassy patch or garden); in such cases, the ensuing higher EYR is hardly meaningful as a measure of “improved” performance.

In seeking the most relevant emergy indicators for the assessment of urban systems and buildings, we therefore decided to focus on the total emergy budget (**U**) - i.e., the sum of all the emergy inputs to the system, which is a cumulative indicator of the total environmental support that is directly and indirectly required -and on the share thereof that may be traced back to renewable resources (**%R**). In principle, accurately calculating the latter indicator would require the adoption of a network-based approach akin to the one used in LCA, whereby all the supply chains of all the direct inputs to the system are analyzed in detail, and all the upstream indirect energy and material inputs are individually classified as renewable or non-renewable. However, in practice, this approach is extremely resource-intensive and time-consuming, and it would only be feasible by integrating emergy analysis into LCA and leveraging the existing extensive life cycle inventory databases – a goal that has been argued for, but which has not yet been achieved (Raugei, et al., 2014). In the Clark’s Crow tool, therefore, all construction materials and directly used fuels are considered as ~100% non-renewable, (this was deemed a reasonable assumption, with the possible exception of wooden materials, which are however not used in the case studies presented). Instead, a streamlined analysis of the %R of the upstream supply chain for the electricity inputs is performed, based on the available information on the composition of the local grid mix and pre-existing emergy analyses of the individual electricity generation technologies. As already discussed in Section 2.2, it is important to note that Clark's Crow remains open to switching to newer and more robust sources of emergy data if and when they become available. Also, the addition of the 'emergy material' component allows users to add a new material and input its properties to determine its UEV, which could facilitate the customization of renewable materials in the future.

As a closing methodological remark, it is also important to note that the %R indicator, when calculated as done here in emergy terms, will differ from a corresponding %R indicator that could be (and has been before) calculated in primary energy terms. Specifically, %R (emergy) will often be lower than %R (energy). This is due to the fact that, typically, non-renewable resources (e.g., fossil fuels, metals, minerals, etc.) are characterized by larger UEVs than renewable ones (e.g., sunlight, rain, wind, etc.), due to the longer time-scales and larger energy inputs that are required for their formation.

3. Calculation

3.1 Clark's Crow Emergy Analysis tool and User Interface

As already explained, the development of the emergy analysis plug-in was articulated in three main steps: 1) to the extent possible, pulling necessary data from the existing

Grasshopper plug-ins and 3D Model as outlined in **Table 1** to feed emergy inputs to the new plug-in; 2) incorporating UEV data from an existing external database (e.g., the ISAER database) and from existing literature; 3) developing custom Grasshopper components for the plug-in to perform emergy analysis and calculate emergy indicators. As illustrated in Figure 3, the plug-in itself consists of four main sections, respectively named: 0) Clark's Crow; 1) Setup; 2) Simulation; 3) Indicators.

Figure 3: Clark's Crow workflow in Grasshopper for Rhinoceros. Screenshot of Clark's Crow plugin user interface within Grasshopper showing four sections: 0) Clark's Crow, 1) Setup, 2) Simulation, 3) Indicators. Each section has components to address different aspects of modeling an emergy simulation and generating an emergy analysis.

The first section has four Grasshopper components: the first one carries all the main classes including the Unit Emergy Values (UEVs), while the others refer to these classes to run analyses within Rhinoceros. "Emergy Construction", "Emergy Surface", and "Emergy Material" are containers for a collection of properties that represent the emergy of a specific material, surface, or building construction.

The Setup section allows users to define the construction, surface, or material type (Figure 4) of a building or massing and subsequently in the simulation phase, obtain an emergy analysis for the specified geometry.

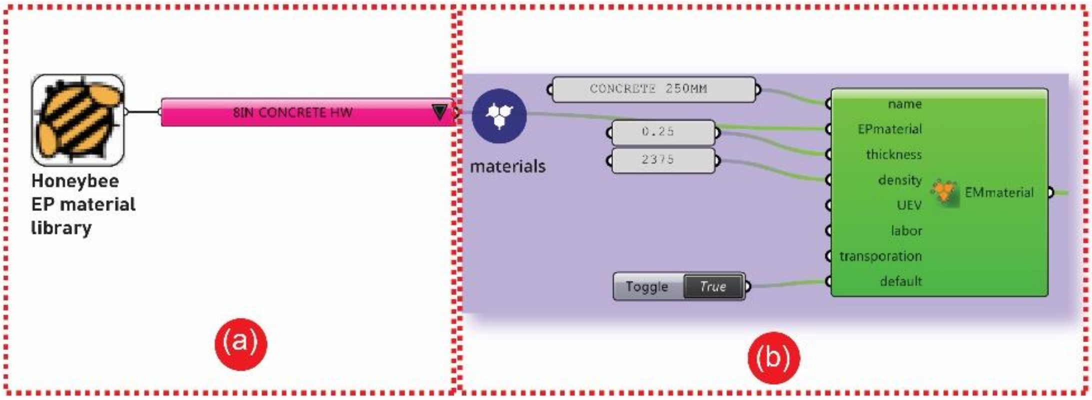

Figure 4: Clark's Crow Integration into Grasshopper and the Emergy-Material component. (a) The Emergy-Material component use EnergyPlus (EP) materials library, which is currently accessed within the design environment of Grasshopper for Rhinoceros using the Honeybee plugin. (b) This component allows users to define a material type for a building in terms of its emergy analysis inputs.

These components use the EnergyPlus (EP) materials library, which is currently accessed within the design environment of Grasshopper for Rhinoceros using the Honeybee plugin. This library provides building material properties needed for emergy calculation such as material densities and thicknesses. The 3D model geometry of the urban massing provides the surface area which, when multiplied by the thickness, gives the material volume used. The volume times the material density provides the raw data need for the 'create material, surface or construction' components. Clark's Crow has built upon this material library and adapted it for use in the plug-in, by adding UEVs to the library as a new material property (Figure 5). Each UEV added to Clark's Crow adapted material library has been referenced so that its provenance can be tracked. The deconstruct component allows the user to understand a construction or material type in terms of its constituent parts and therefore provides a better understanding of the makeup of an emergy construction or material.

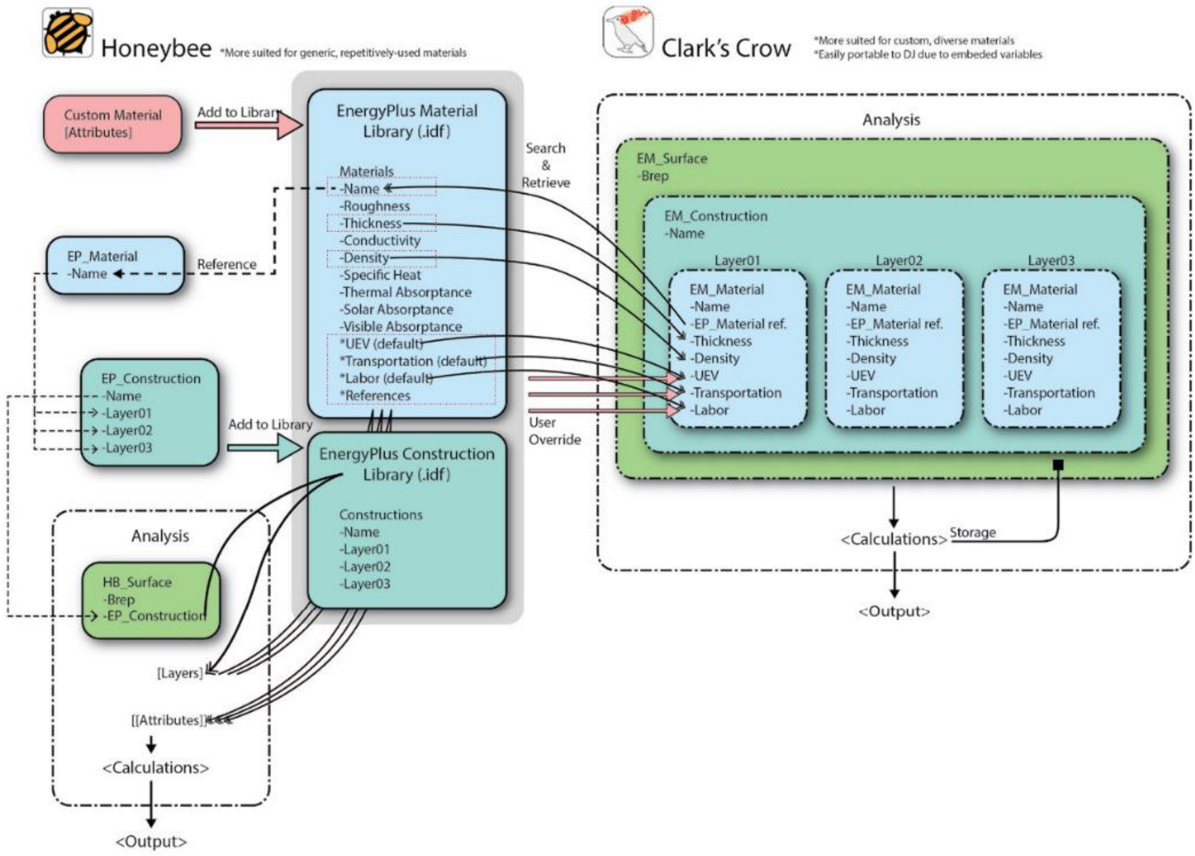

Figure 5: Clark's Crow Process Diagram. Clark's Crow leverages the EnergyPlus Materials Library from HoneyBee and allows for emergy calculation and analysis through the use of the adapted library with cited UEV material values and the Rhino 3D urban model geometry. Honeybee relies on continuous references to the core EnergyPlus library. Honeybee searches the library for the name of the construction associated with the wall, and returns a list of the material layers by name. Then searches these materials to retrieve numerous properties about the material, including thickness, thermal conductivity, density etc. The main advantage to this workflow is that once the user defines a custom material or construction, it is then saved into the library, and only needs to be referenced by name from then on. The main disadvantage is the inefficiency of documenting and searching a list by name once the library grows exponentially in size. Clark's Crow differs fundamentally from Honeybee in that where a user might only need a single library entry

to define a material for use in Honeybee, the user instead needs many entries to differentiate that same material between source location, transportation, embedded labor, and every other detail required to calculate emergy.

The third stage is the Simulation section. Within this section are components which calculate the emergy of renewable resources (Figure 6), perform an emergy simulation, and allow for customized labor and transportation inputs. The Renewable Emergy component is based on a location input using the existing Grasshopper Plugin 'Ladybug' which accesses EnergyPlus Weather (EPW) files allowing the user calculate the total renewable emergy for a particular site location in terms of renewable resources of solar irradiation, wind, and rainfall. The EPW file as well as the area of the site are the inputs to this component.

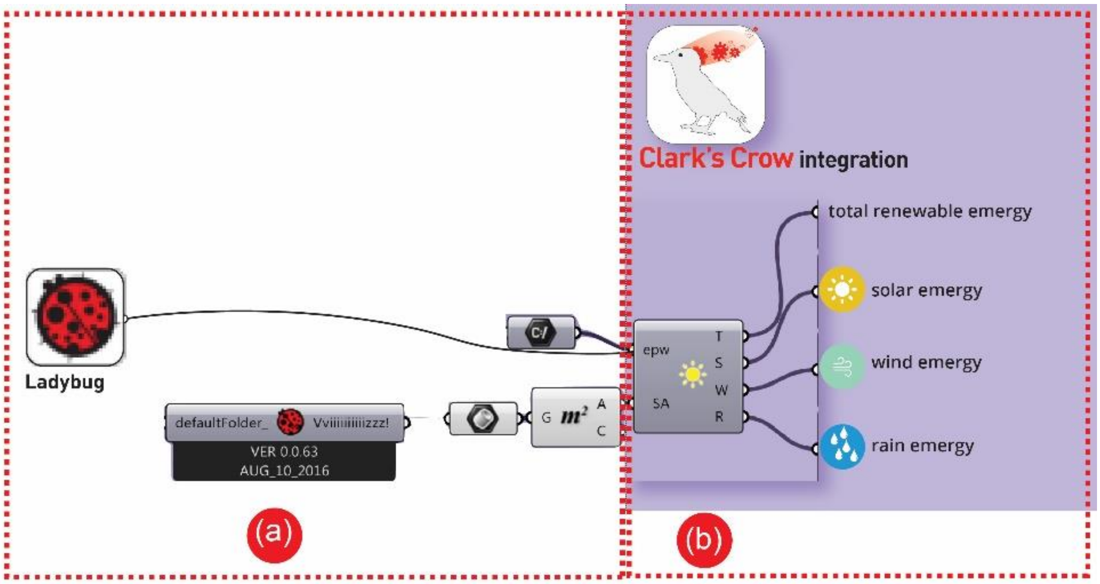

Figure 6: Clark's Crow Integration into Grasshopper and the Renewable Emergy component. Renewable flows are calculated for solar, wind and rain resources using Renewable Emergy component. (a) Location specific weather data is incorporated from EnergyPlus Weather (EPW) files through accessing the existing Grasshopper plugin Ladybug, which allows the user pick a location

and obtain the EPW file. (b) The aspects in the box at right indicate the novel Clark's Crow component for calculating location and site specific renewable flows.

The Emergy Simulation component (Figure 7(d)) allows the user input the variables needed to run an emergy simulation for a building design or set of buildings. The inputs include the annual operational energy consumption (Figure 7 (c)) including the source(s) of energy for the building to meet the building loads[4], the UEV times raw data for all building surfaces, the UEV times raw data for labor (i.e., labor used in the construction), the UEV times raw data for Transportation (i.e., transportation from manufacturing location to site location). The operational energy for urban environments can be calculated using the Honeybee plugin and is an input to the emergy simulation component. The labor and transportation components can be customized by the user. In particular, the transportation component incorporates Google maps API (Google, 2016) allowing the user to easily specify the location of origin, the destination, and the mode of transport as it calculates the distance and fuel consumed (Figure 7 (b)). This becomes an input to the emergy simulation component. The labor component customizes the raw data used in an emergy calculation. Its inputs include the hours worked per year and the

[4] An operational energy simulation calculates the building loads, including heating, cooling, lighting, and equipment loads. Typically, the lighting, equipment, and cooling loads are met via electricity. The heating loads can be meet via a range of energy sources and fuels.

calories consumed per day. The Labor component output then modifies the labor UEV, which subsequently becomes an input to the emergy simulation[5] (Figure 7 (a)).

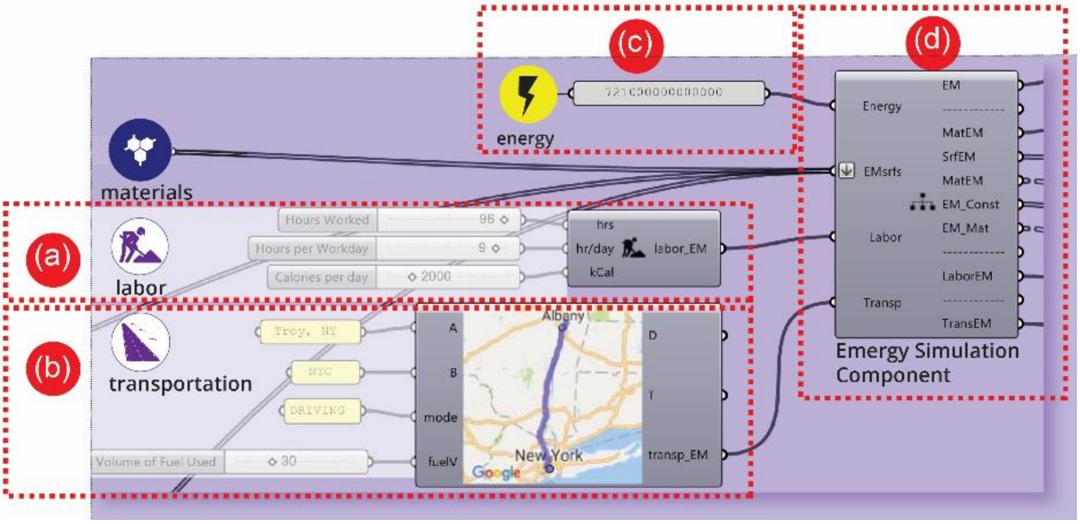

Figure 7: View of the network setup of components in creating an emergy analysis (a) labor component for customization of the construction labor values; (b) transportation component allows customization of the transportation from manufacturing location to construction site; (c) Operational energy input from energy simulation using plugin such as Honeybee; (d) Emergy Simulation Component performs an emergy analysis with building materials, energy, labor and transportation inputs.

The fourth section titled ‘Indicators’ includes emergy indicators relevant to building and urban design. As outlined in Section 2.3, the most relevant indicators at the urban system

[5] Given that labor for building construction is mainly manual, we chose to employ this method in calculating labor emergy rather than basing it on economic values for salaries and wages.

scale include the total emergy budget (U), the percentage Renewable (%R), and the UEV of the system. The indicators component outputs these indicator values.

4. Results

4.1 Case Study: New York City urban development speculation demonstrating the use of Clark's Crow for emergy simulation

In order to demonstrate Clark's Crow, a New York city block of 197 m * 60.9 m was selected as a case study, shown in Figure 8. The block was selected to represent a typical Manhattan residential block. It is located in the East village between 1st and 2nd avenue, and 7th street and St. Marks Place. This block is composed of 58 plots which for simplification purposes were assumed to be similar in size, 30m deep * 7.0 m wide. The buildings, guided by the existing dominant typology, have a back yard of 10.5 m with a building footprint of 130.2 m2 (18.6 m * 7.0 m). The buildings are composed of five floors each.

4.2 CAD Modelling and IDF parameters

The case study block and its context were modeled in the CAD software Rhinoceros. The buildings were modeled using the graphical algorithm editor Grasshopper3D as simple boxes (18.6 m depth * 7.0 m width * 15 m height) with a window to wall ratio of 40% for both facades. The Honeybee plugin was used to generate the energy (IDF) model of the buildings and to interface with EnergyPlus as well as assigning the building loads, occupancy schedules, and construction materials. The envelope construction material was selected as masonry wall, composed of masonry brick (100mm) with 50mm mineral fiber insulation, 200m concrete hollow block. The fenestration consists of 24mm double-glazing. The floors consist of poured concrete on steel decks. For the roof area, we considered two scenarios, outlined further in Section 4.3. The first scenario contains a concrete slab and steel beam roof construction and the second scenario considers the roofing areas covered by an Integrated Concentrating Solar Façade (ICSF)[6] system (Novelli, et al., 2015; Dyson, et al., 2010). The concentrating solar system intercepts and manipulates the direct-normal component of insolation, but allows the diffuse insolation to provide daylight to living space while reducing glare and heat gain (Aly, et al., 2015). The modules ability to continuously track the sun (by rotating around both horizontal and vertical axes), the location of the high efficiency concentrator photovoltaic (CPV) cell, the morphology of the individual modules, and the use of a flat Fresnel-like primary optical element (Novelli, et al., 2015), combine to create multiple benefits in terms of energy generation and natural daylighting. Residential occupancy schedules and load are assigned to all the buildings. The Central Park, New York EPW file was used in the energy simulation.

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[6] The Integrated Concentrating Solar Façade (ICSF) system is typically used on facades or vertical surfaces of buildings, hence its name. However, it can also be integrated into horizontal surfaces of buildings such as the roofs. In this paper we propose the use of the system as an integrated concentrating solar 'roof' however we will continue to name the system ICSF.

4.3 Energy analysis

The building's operational phase energy simulation was conducted with the whole building energy simulation program "EnergyPlus V8-6-0". The annual results, for an ideal air loads systems with 18ºC and 25ºC thermostat setpoints, are then broken down for cooling, heating, equipment, and lighting loads into 6.96 kWh/m^2, 22 kWh/m^2, 15.6 kWh/m^2, and 12.94 kWh/m^2 respectively. In terms of operational energy we compared two scenarios: 1) the first scenario assumed that the buildings used energy from a local utility source, i.e. natural gas for heating and electricity for cooling, lighting, and equipment use; 2) the second scenario assumed the roof was covered with an ICSF system, that captures renewable solar energy and produces electrical energy to offset the electrical building loads. This system is acting as a shading device to the roof since it does capture the direct solar rays and convert them into renewable energy. As a result, the energy profile of the buildings with the ICSF system on the roof is a little bit different for cooling, heating, equipment, and lighting loads as 6.43 kWh/m^2, 24.3 kWh/m^2, 15.6 kWh/m^2, and 12.94 kWh/m^2 respectively. As per section 3, the materials and the energy consumption values were passed to the Clark's Crow plugin to be included into the emergy calculations.

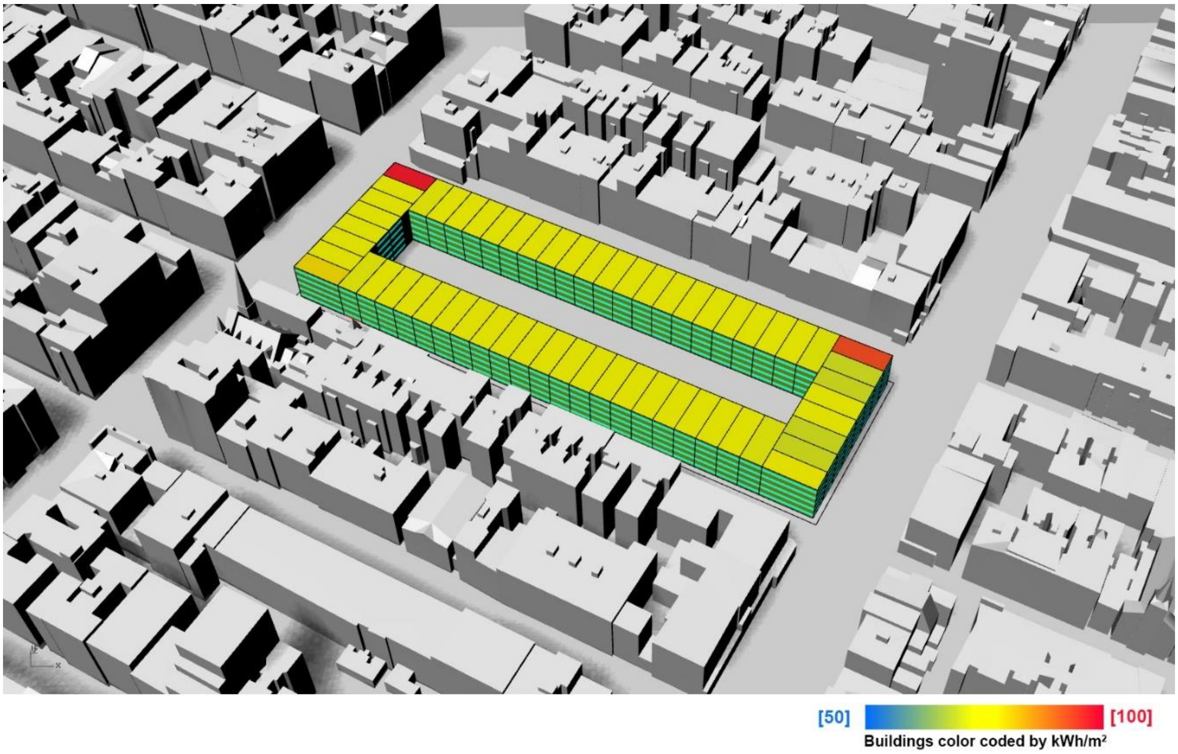

Figure 8: An axonometric view of the buildings color-coded per EUI (kWh/m^2) of operational energy. The different building orientations has slightly affected the total operational energy which varies from 53 kWh/m^2 to 62 kWh/m^2 (north facing corner units shown in orange) with an average of 57.5 kWh/m^2.

4.4 Emergy analysis

Figure 9 provides aggregated energy systems diagrams for both Scenarios #1 and #2 respectively. The scenarios indicate different design options. The diagrams highlight the categorization of input flows to the speculative urban developments, primarily the on-site renewable flow of solar energy, the non-renewable on-site input flow of topsoil, the material flows, the labor and transportation services as part of the construction processes, and the investment of operational energy for the building's usage. The primary differences between the two diagrams illustrating both scenarios include the reduced total material input and the larger operational energy inflow of Scenario #1 versus the slightly greater material inflow and the smaller energy investment of Scenario #2 (which is natural gas only, since the electricity generated on-site via the ICSF system is enough to completely offset the operational electricity inflow). A net electricity flow is also shown in the diagram of Scenario #2 to indicate the excess electricity produced by the ICSF system that is sold back to the grid. The value of all emergy flows are shown via the energy flow arrows, and assume a lifespan of 50 years for both speculative development options. Scenario #2 assumes a 30 year life span for the ICSF and hence assumes the replacement of the system into account every 30 years. The authors would like to point out that the ICSF system continues to be researched and developed and therefore, the associated emergy values carried out in this analysis are estimates based on current knowledge, and bear uncertainties as outlined in Appendix A. As the system continues to be developed, a more detailed emergy evaluation will be carried out in the future to reflect the emergy of the system in more detail. **Table 2** lists all material and energy inflows for the manufacturing, construction and operational building phases, as well as the results of a complete emergy analysis for the case study over an assumed lifespan of 50 years, with notes detailing the assumptions taken for the calculation of each inflow. These notes also help outline the built-in assumptions embedded in Clark's Crow when calculating a typical urban development. It is important to mention that the UEVs of materials outlined in **Table 2**, typically assume that the economic services related to the extraction and manufacturing stages of material production have also been taken into account in the calculation; however, we are aware of inconsistencies inherent in the numbers, as not all the cited literature explicitly identifies if the reported UEVs are with or without services. Having this information would help differentiate between the resulting bio-geophysical emergy budget (i.e. without services) and the translation of emergy in monetary terms (i.e. with services) which, due to economic volatility, can lead to additional uncertainty. Certain literature does contain a thorough identification of the breakdown of the UEV values for construction materials, with and without services, namely Buranakarn, 1998, however, we chose not to use these values, which being quiet dated have economic values embedded in the services calculations which were perceived as being less reliable than using more recent UEV calculations as indicated in **Table 2** 'references' column. Also, for those literature UEV values for which a specific 'emergy baseline' was not explicitly indicated, the authors have here verified the baseline that was applied. In the majority of cases this was 15.83E+24 seJ/yr (Odum, 2000) but the baseline values of 9.44E+24seJ/yr (Odum, 1996), 9.26e+24seJ/yr (Campbell, et al., 2005), and 15.2 E+24seJ/yr (Brown & Ulgiati, 2010) were also used. The authors have updated all values to reflect the new emergy baseline of 12E+24seJ/yr (Brown, et al., 2016). **Table 3** then shows aggregated inflows and the differences between the two scenarios, namely the sources of operational energy and roof construction as outlined in

Section 4.2 and 4.3. The addition of ICSF in Scenario #2 changes the materiality of the roof construction and the energy performance of the urban development during the operational phase of the building life span. At the same time, it can be argued that the total 'net' emergy budget for Scenario #2 may be calculated as the difference between the sum total of the emergy inputs to the building (U) and the emergy associated to the net electricity delivered back to the grid by the ICSF system (the UEV of the ICSF-generated electricity being calculated as the ratio of the emergy inputs specifically required for its construction and operation, divided by the total electricity produced – *cf.* footnote (i) of Table 2). In other words, the revised 'net' emergy budget for Scenario #2 presented in Table 3 corresponds to assuming that only the share of the ICSF system that is necessary to precisely offset the electricity demand of Scenario #1 may be considered to be part and parcel of the building, whereas the 'excess' ICSF surface and its additional electricity generation are considered as a stand-alone system, whose separate emergy budget can be subtracted from that of the building itself.

The percentage renewable indicator (%R) as outlined in Section 2.3, is calculated for the case study. The New York state electricity mix (Energy Information Administration, 2017) that is used in Scenario #1 is derived from 8.6% renewable emergy sources for its production. Notably, this percentage is different from the straight 27% of electricity that is supplied by "renewable" technologies (hydro and wind), since: (i) the latter fails to take into account the embedded non-renewable energy used for the materials and services needed to construct the power plants, and (ii) as explained in Section 2.3, most non-renewable resources have larger UEVs than renewable ones. In contrast, the electricity produced by the rooftop ICSF system used in Scenario #2 has a very low % R (emergy) of 0.004%. However, definite attention should also be paid to the UEVs of the electricity generation values, as a lower UEV is an indication of environmental benefit. In this case study the UEV of New York gird electricity is 1.93E+05 compared to a UEV of 1.3E+05 sej/J for ICSF on-site generated electricity. The UEV of New York gird electricity is 1.5 times greater than the UEV of ICSF electricity. Thereby, the intensity of biosphere support is 1.5 times lower for ICSF electricity generation than for the New York state electricity. It is also crucial to note that the additional material and energy needed for the production of the ICSF roof result in a total emergy budget for the first year of operation of the building in Scenario #2 that is only negligibly higher than in Scenario #1(less than +1% increase). In fact, both Scenario #1 and #2 result in the exactly same emergy budget after as little as one year. This emergy crossover point between the two scenarios highlights the time it takes for the additional material and energy inputs for the ICSF production to be “paid back” in emergy terms (Figure 10). When considering the full 50 year life span, Scenario #2 ends up showing a significantly lower emergy budget of 1.56E+20 sej, as opposed to 1.75E+20 sej for Scenario #1, principally as a consequence of the fact that Scenario #1 relies on additional energy from local utilities to meet all of its operational energy demands. The inclusion of the ICSF system therefore results in lower overall demand for bio-geochemical support.

Finally, given the inherent uncertainty in the estimation of an urban development lifespan, we carried out a sensitivity analysis to consider the difference in total emergy budget for the two scenarios considering 50, 70 and 90 year lifespans. The results showed 1.75E+20 (50yrs), 2.02E+20 (70yrs), 2.29E+20 (90yrs) for Scenario #1; and 1.56E+20 (50yrs), 1.84E+20 (70yrs), 1.92E+20 (90yrs) for Scenario #2. This indicates that Scenario #2 would be further favored by a longer building lifespan, despite the requirement for one additional replacement of the ICSF system.

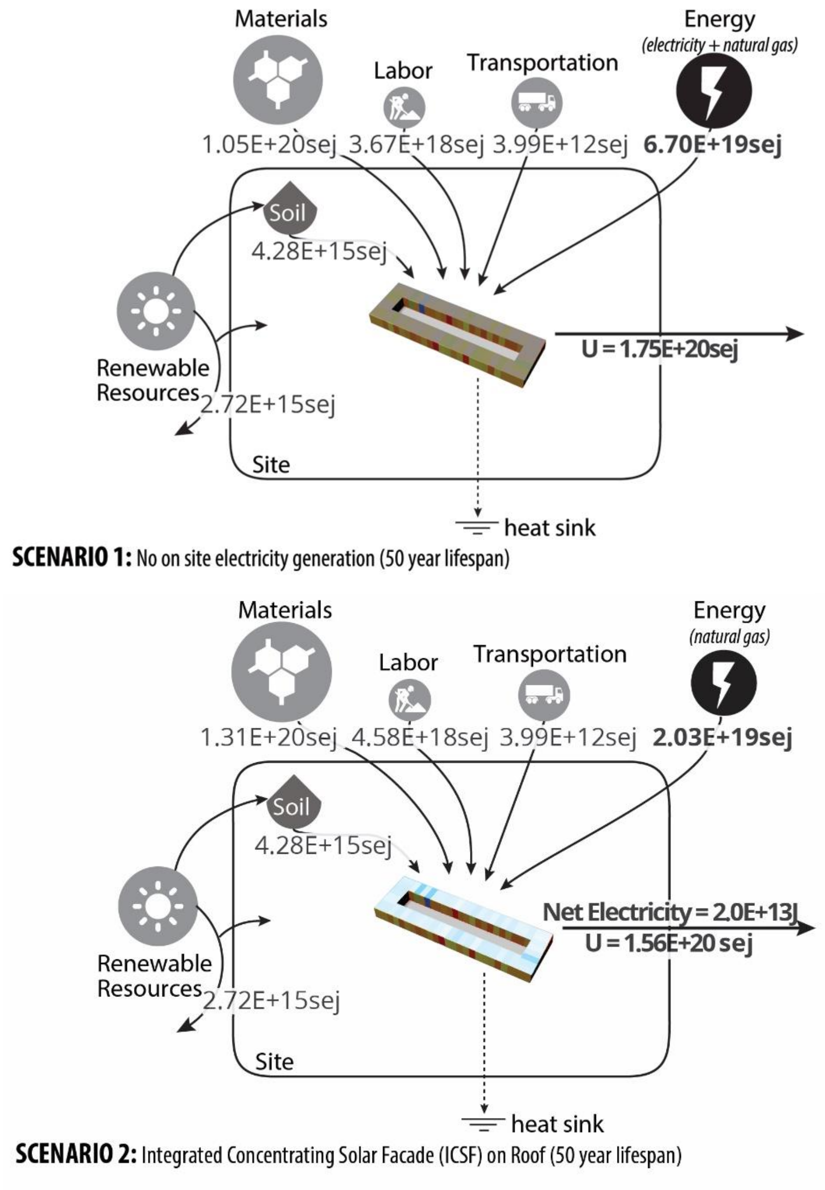

Figure 9: Energy circuit diagrams of Scenario #1 and #2: the energy circuit diagram take the material and energy flows associated with the manufacturing, construction and building operation (assuming 50 years) into account. The diagram for Scenario #2 also shows the on-site solar energy generation through the ICSF, which can entirely offset the electrical demands of the development and produce a net ICSF electricity generation of 2.0E+13J to be sold back to the grid.

Table 2: Emergy Analysis of Speculative Urban Development (6.1E+03 urban plot with 58 five-story buildings) according to Scenarios #1 and #2 being analyzed, for 50 years of operation i.e. considering the manufacturing, construction and operational processes.

No.	Item	Units	Raw Data (units/yr)	UEV (sej/unit)	References	Emergy for development lifespan (sej/50 years)	% R
Renewable and Non-Renewable Site Specific Resources:							
1	Solar energy [a]	J	2.72E+15	1	(Odum, 1996)	2.72E+15	100
2	Net Topsoil Loss [b]	J	7.85E+08	1.24E+05	(Brandt-Williams, 2002)	4.28E+15	0
Material and Construction Phases: Purchased inputs from outside the system boundaries							
3	Brick [c]	kg	1.33E+05	2.79.E+12	(Braham, 2015)	2.16E+19	0
4	Mortar Joint [c]	kg	2.58E+03	2.51E+12	(Pulselli, et al., 2009)	3.76E+17	0
5	PVC Vapor Barrier [c]	kg	2.05E+00	7.47E+12	(Pulselli, et al., 2009)	8.90E+14	0
6	Insulation -Mineral Fiber [c]	kg	7.92E+01	4.00E+12	(Braham, 2015)	1.84E+16	0
7	Concrete hollow block [c]	kg	3.12E+05	1.37E+12	(Pulselli, et al., 2008)	2.48E+19	0
8	PVC Vapor Control Layer [c]	kg	2.05E+00	7.47E+12	(Pulselli, et al., 2009)	8.90E+14	0
9	2 layers of Gypsum Fiberboard [c]	kg	1.36E+04	2.49E+12	(Pulselli, et al., 2009)	1.97E+18	0
10	Acrylic paint [c]	kg	3.67E+03	3.24E+12	(Braham, 2015)	6.90E+17	0
11	Double Glazing [c]	kg	5.20E+03	1.08E+12	(Pulselli, et al., 2009)	3.25E+17	0
12	Aluminum [c]	kg	6.99E+01	1.61E+13	(Pulselli, et al., 2009)	6.55E+16	0
13	Floors_ Concrete Slab [c]	kg	5.11E+05	1.37E+12	(Pulselli, et al., 2009)	4.06E+19	0
14	Floors_ Steel beams [c]	kg	1.70E+04	5.26E+12	(Pulselli, et al., 2009)	5.18E+18	0
15	Roof_ Structural Steel beams [c]	kg	3.39E+03	5.26E+12	(Pulselli, et al., 2009)	1.04E+18	0
16a	(Scenario #1) Roof _ Concrete Slab [c]	kg	1.02E+05	1.37E+12	(Pulselli, et al., 2009)	8.13E+18	0
16b	(Scenario #2) Roof _ ICSF system [d]	m^2	1.51E+04	1.30E+05	Appendix A	3.41E+19	0.004
17	Material Transportation [e]	J	7.69E+07	5.19E+04	(Brown, et al., 2011)	3.99E+12	0
18a	(Scenario #1) Construction Activities [f]	J	3.90E+11	9.40E+06	(Pulselli, et al., 2007)	3.67E+18	0
18b	(Scenario #2) Construction Activities [f]	J	4.87E+11	9.40E+06	(Pulselli, et al., 2007)	4.58E+18	0
Operational Phase: Purchased inputs from outside the system boundaries							
19a	(Scenario #1) Operational Electricity [g]	J	2.42E+14	1.93E+05	(Self-established)	4.67E+19	8.6
19b	(Scenario #2) Net Operational Electricity from outside the system boundary [g]	J	0	-	(Keena, et al., 2016)	0	0

20	Operational Energy (natural gas) [h]	J	1.50E+14	1.35E+05	(Brown, et al., 2011)	2.03E+19	0
(Scenario #1) Total Emergy Inputs (U)						**1.75E+20**	2.5
(Scenario #2) Total Emergy Inputs (U)						**1.56E+20**	~0
On site Electricity Generation using ICSF							
21	(Scenario #2) Net ICSF Electricity generation [i]	J	2.0E+13	1.30E+05	(Keena, et al., 2016)	2.6E+18	0.004

[a] **Solar energy**

Total annual insolation (EPW data from Ladybug)* Site Area
Total annual insolation (derived from Ladybug EPW file for Central Park, New York output) = 4.53E+09 $J/m^2/yr$
Site Area = 1.20E+04m^2

[b] **Net Topsoil Loss**

Energy content in organic soil = 5.4kcal/g (Ulgiati et al., 1992)
Erosion rate estimated at 7.0 g/m2/yr (Pimentel et al., 1995) with 0.04% organics in soil.
The net loss of topsoil is (farmed area)(erosion rate) = (1.24E+05m^2)(7.0 g/m2/yr) = 8.68E+05
The annual energy of soil used or lost = (net loss topsoil)(% organic)(energy cont./g organic)(4186 J/ kcal)
The annual energy of soil used or lost = (8.68E+05)(0.04%)(5.4kcal/g)(4186 J/kcal) = 7.85E+08 J
UEV = 1.24E+05 (Brandt-Williams, 2002)

[c] **Construction Materials**

Emergy of building material = (material volume * material density)(UEV of building material sej/g)

[d] **(Scenario #2) Roof _ ICSF system Construction Materials**

This is the (area of the roofs)(the emergy of 1m^2 of ICSF module)(n replacements/ 30 yrs) = (130.2m^2 *58)(2.26E+15)(2) (Keena, et al., 2016; Brown, et al., 2012) See Appendix A for ICSF Emergy Analysis table.

Assuming a lifetime of 30 years (Frischknecht et al., 2016), therefore a replacement of the system after 30 years is considered.

Note: as discussed earlier, these figures bear uncertainties as the system continues to be developed. Appendix A highlights areas where future and more detailed data can allow for greater certainty in determining the total emergy of ICSF. However, based on current knowledge and informed estimations, we have carried out an initial assessment of the total emergy associated with the ICSF.

[e] **Material Transportation _ not including ICSF system**

Transportation = (mass transported)(distance travelled)(energy used per km)(UEV of transportation) (Brown, et al., 2011)

[f] **Construction Activities (Labor)**

Labor = (hours worked)(energy consumed per working hour)(UEV of labor) (Pulselli, et al., 2007)

[g] **Operational Energy: Electricity**

Total emergy = (annual emergy)(lifetime)
Lifetime = 50 years
Annual emergy = (annual electricity consumption in J)(UEV per Joule of the electricity mix used in the generation of electricity in New York).
UEV values referenced from (Häyhä, et al., 2011; Brown & Ulgiati, 2004; Brown & Ulgiati, 2002)
Total annual Electricity consumption for the site = 4.83E+12 J

Electricity grid mix in New York is 0.43% Oil, 37.73% Natural Gas, 1.5% Coal, 33.23% Nuclear, 22.61% Hydroelectric, 4.61% Non-hydroelectric Renewables (assuming wind in this case) (Energy Information Administration, 2017)
Oil-fired electricity = 2.07E+10
Natural Gas-fired electricity = 1.82E+12
Coal-fired electricity = 7.23E+10
Nuclear lectricity = 1.61E+12
Hydroelectricity = 1.09E+12
Non-hydroelectric renewable electricity (wind) = 2.18E+11
Oil-fired electricity UEV = 1.12E+05
Natural Gas-fired electricity UEV = 2.17E+05
Coal-fired electricity UEV = 2.18E+05
Nuclear electricity UEV = 2.55E+05
Hydroelectricity UEV = 8.49E+04
Non-hydroelectric renewable electricity (wind) UEV = 8.34E+04
Oil-fired electricity emergy = 2.32E+15
Natural Gas-fired electricity emergy = 3.95E+17
Coal-fired electricity emergy = 1.57E+16
Nuclear electricity emergy = 4.09E+17
Hydroelectricity emergy = 9.28E+16
Non-hydroelectric renewable electricity (wind) emergy = 1.82E+16
Total annual electricity emergy = 9.33E+17
UEV of electricity (this study) = 1.23E+18/4.83E+12 J = 1.93E+05
%R Energy = 27% = (23% Hydroelectricity + 4% Non-hydroelectric renewable electricity (wind)
%R Emergy = 8.6% = (7% Hydroelectricity emergy + 1.8% Non-hydroelectric renewable electricity (wind) emergy)
Derived from (Brown & Ulgiati, 2004), the total % renewable for Non-hydroelectric renewable electricity (wind) emergy is 85% and total % renewable for Hydroelectricity emergy is 70%. When applied to the electricity grid mix for New York the % renewable emergy results in 7% coming from Hydroelectricity emergy and 1.6% coming from Non-hydroelectric renewable electricity (wind) emergy, totaling in 8.6% renewable emergy sources for the electricity grid mix.

[h] Operational Energy (natural gas for heating)
Total emergy = (annual emergy)(lifetime)
Lifetime = 50 years
Annual emergy = (annual heating energy consumption in J)(UEV of natural gas) (Brown, et al., 2011)

[i] (Scenario #2) Net ICSF Electricity generation
Total annual Direct normal radiation per roof is 1096 kWh (m^2 yr) (from Ladybug using EPW file Central Park, New York)
Total renewable sunlight energy shining on ICSF is (irradiance per roof m^{2*}year)(roof area) (50 years) = (1096 kWh)(130.2m^2*58)(3.6e+06 J/kWh)(50 yrs) = 1.49E+15 J
Module Efficiency is 22% (Novelli, et al., 2017; Dyson, et al., 2010; Dyson, et al., 2007)
Performance Factor is 80% (Frischknecht, et al., 2016)
Electricity generation of ICSF roof modules is (Total renewable sunlight energy shining on ICSF)(module efficiency)(performance factor) = 1.49E+15 J (22%)(80%) = 2.62E+14 J
UEV of ICSF-generated electricity = (Renewable sunlight energy shining on ICSF + Emergy for Production of ICSF) / Electricity Generation = (1.49E+15 + 3.41+19)/2.62 E+14 = 1.30E+05 sej/J
Share of Renewable emergy for ICSF-generated electricity = (Renewable sunlight energy shining on ICSF)/(Renewable sunlight energy shining on ICSF + Emergy for Production of ICSF)
= 1.49E+15 /(1.49E+15 + 3.41E+19) = 1.49E+15 / 1.59E+19 = 0.004%
Net ICSF Electricity Generation: ICSF = Onsite generation – Onsite Consumption = 2.62E+14 J – 2.42E+14 J = 2.0E+13 J

Table 3: Results Comparison of Scenario #1 and Scenario#2 showing key metrics over 50-year urban development life span.

Item	Scenario #1 (sej/ development life span)	Scenario #2 (sej/ development life span)
Renewable and Non-Renewable Site Specific Resources:		
Total Emergy of Renewable & Non-Renewable Site Specific Resources	**7.00E+15**	**7.00E+15**
Materials:		
Total Construction Materials (except roof)	9.57E+19	9.57E+19
Scenario #1 Roof (Steel beam and concrete slab)	9.16E+18	
Scenario #2 Roof (ICSF with steel structure)		3.52E+19
Total emergy for material flows	**1.05E+20**	**1.31E+20**
Services:		
Transportation & Labor during Construction Process	**3.67E+18**	**4.58E+18**
Energy inputs and outputs:		
Consumption: Natural Gas from Local Utility	2.03E+19	2.03E+19
Consumption: Electricity from Local Utility	4.67E+19	0
Net ICSF Electricity Generation: ICSF	-	-2.60+18
Total emergy for energy flows	**6.70E+19**	**1.77E+19**
Total Net Emergy budget :	**1.75E+20**	**1.53E+20**

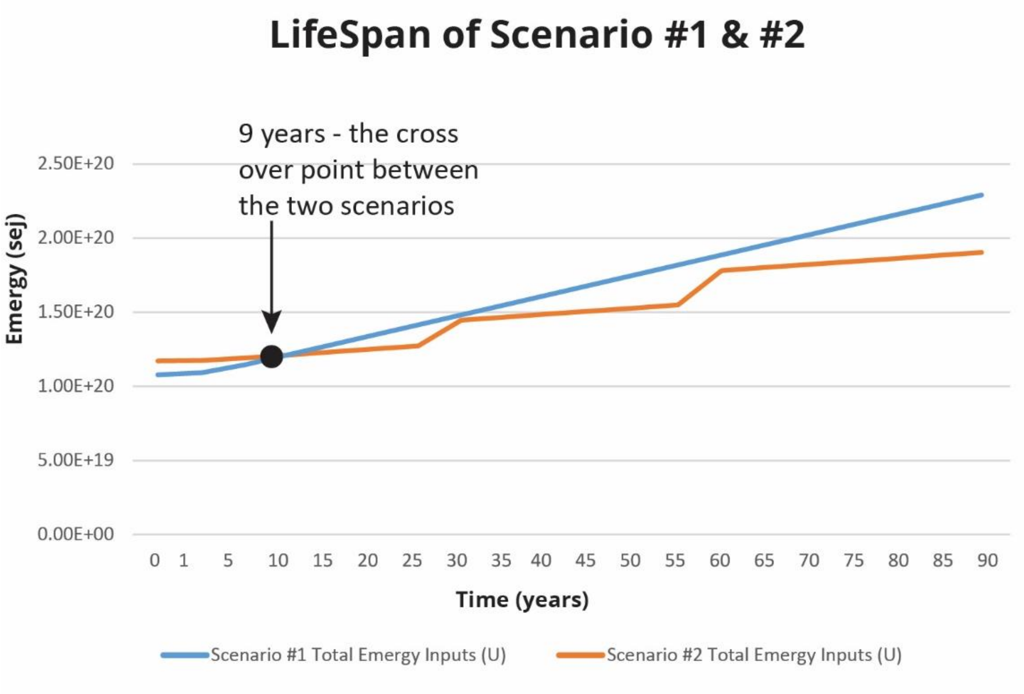

Figure 10: Evolution of total emergy budget (U) over time for both Scenarios.

4.5 End of Life Considerations

The scope of life cycle associated with material UEVs is not consistent throughout the literature. Many material UEVs consider cradle to gate, while others take account of end of life (EoL) considerations. The primary reference for UEVs of building materials used in the case study is Pulselli et al., 2009, which in turn uses data from Buranakarn, 1998 and from a follow-up paper by Brown and Buranakarn, 2003. These studies define UEVs of building materials that encompass demolition, collection and landfill as the end of life treatment of these materials following a conventional solid waste disposal system of municipal solid wastes. Hence, this case study assumes a single use and a municipal solid waste disposal system for the majority of the materials, which are referenced as Pulselli et al., 2009. However, unfortunately a few of the UEVs referenced in Table 2 result from analyses adopting inconsistent boundaries; for instance, the UEV for concrete, (Pulselli et al, 2008) does not consider the EoL at all. In order to shed more light on the emergy impacts arising from the EoL stage, we chose to investigate further those materials which represent the largest emergy inputs to this case study, namely brick (14%), concrete (42%), and steel (5%). Table 4 compares the difference in emergy of recycling versus demolition for these three materials. Two EoL trajectories are followed: closed-loop recycling for concrete and steel and by-product use for brick. Closed-loop recycling is a process whereby materials are reused as inputs in the production of the same or similar products. In the case study, concrete and steel are recycled with concrete being broken up and used as aggregate in a new concrete production cycle, and steel being reused as recycled steel (Brown & Buranakarn, 2003). By-product use involves a recycle process where the by-product of one process is used as an input in another material production process. In the case of brick, wood waste (a by-product) acts as a substitute for a portion of the fuel used in the firing of bricks, thereby reducing the quantity of purchased fuel needed. The final column of Table 4 defines the mean UEV considering two use cycles, for comparative analysis *vs*. the demolition only and recycling options. In the case of brick and steel, when considering the use of the material in two building cycles, it proved more emergy efficient to recycle the material and gain two building life cycles from it, than to demolish it and recreate the material for the next new-built building. Instead, concrete proved more emergy efficient to demolish rather than recycle. Although outside the scope of this paper, (Bala Gala, et al., 2015) provides a more in-depth discussion on EoL approaches from an emergy methodological viewpoint.

Table 4: End of Life Considerations

Material		End of Life (EoL) assuming Demolition [b] (E12 sej/kg)				End of Life (EoL) assuming Recycling [c] (E12 sej/kg)					
	UEV [a] (E12 sej/kg)	Demolition	Collection	Landfill	**UEV (one cycle, incl. EoL demol.)**	Collection	Sorting	Disposal	Recycle[e]	**UEV (one cycle, incl. EoL rec.)**	**UEV [f] (mean over two life cycles)**
Brick	2.79	0.11	0.02	0.008	**2.93**	0.02	-	0.03	0.00001	**2.83**	**1.49**
Concrete	1.37	0.11	0.02	0.008	**1.51**	0.13	0.01	0.008	3.65	**5.18**	**2.66**
Steel	5.26	0.11	0.02	0.008	**5.40**	0.13	0.005	0.008	2.34	**7.75**	**3.94**

[a] UEV as referenced in **Table 2** Brick (Braham, 2015), Concrete (Pulselli, et al., 2008), Steel (Pulselli, et al., 2009).
[b] End of Life assuming Demolition = (UEV + Demolition + Collection + Landfill)
[c] End of Life assuming Recycling = (UEV + Recycling + Collection + Sorting + Disposal)
[d] Cycle: Next Cycle Possibility for Material
[e] Recycle: Emergy required to recycle material (E12 sej/kg) the recycle process assume the Brick will be used as a by-product, the concrete will be recycled for reuse and the steel will be recycled for re-use.
[f] UEV averaged out over two life cycles assuming = ½ * [(UEV + Collection + Sorting + Disposal + Recycling) + (Demolition + Collection + Landfill)].

5. Discussion

5.1 Clark's Crow tool: A user-friendly tool facilitating emergy analysis of urban ecologies

By developing Clark's Crow within Grasshopper for the Rhinoceros 3D modeling environment, existing tools were leveraged, such as the Honeybee plugin for energy modeling and the Ladybug plugin for environmental analysis, to access parameters necessary for an emergy analysis. A major functionality of Honeybee is to simulate building energy, hence the tool already includes much of what is needed to calculate emergy within Grasshopper: a material and construction library, components that can create custom materials and constructions, and components that then analyze and output results. However, in terms of computational functionality, Clark's Crow differs fundamentally from Honeybee in that whereas a user might only need a single library entry to define a material for use in Honeybee, the user needs many entries to differentiate that same material between source location, transportation, and the embedded labor details required to calculate emergy. For instance, an 8-inch concrete wall in New York City will have nearly the same thermal properties as an 8-inch concrete wall in Montreal, but their emergy values may differ significantly. An awareness of the differences that labor and transportation can add to the total emergy of a construction material led to the development of Clark's Crow components that allow the user customize these factors; for example, using the transportation component the distances from material manufacturing facility to construction site can be defined, or the labor associated with the construction process can be specified for a particular project. These component developments, along with components for renewable on-site emergy calculation, aim to provide a more accurate emergy analysis; however, the inherent inconsistencies in current UEV data are a limitation in the tool, making some resulting values less reliable. Nevertheless, the fundamental value of an emergy approach in the design of urban ecologies, specifically at the early stages, is believed by the authors to warrant further investigation, and hence the development of the user-friendly Clark's Crow tool.

5.2 Review of the insights gleaned from the case study

Our case study, of a speculative urban design proposal, aimed to demonstrate the potential of Clark's Crow. Through the use of two scenarios which depicted two different design options, we highlighted how the tool allows designers to understand the differences in materials, services, renewable resources and operational emergy over the lifespan of an urban development. The tool allowed for two design options to be considered: one which accessed its energy from a local grid and another which offset some of its operational energy via an onsite integrated concentrating solar system (ICSF) on the roofs of the urban development. The total emergy budget indicator of the two scenarios highlighted that Scenario #2 would have a lower emergy budget after as little as nine years after construction, due to the use of onsite solar energy to generate electricity and the associated reduced demand for energy investment from outside the system boundary. The %R emergy indicator, identified the 2.5% (Scenario #1) and ~0% (Scenario #2) of the total emergy budget which could be traced back to renewable resources in the two scenarios. This somewhat counter-intuitive result is explained by the fact that the electricity produced by the ICSF system is accounted for as taking place within the system boundary, which results in a reduced overall demand for externally-supplied operational electricity (and the associated emergy). Given that our study of the

New York State electricity grid mix identified that 8.6% of the underlying emergy was renewable (R), a reduced net demand for externally-sourced electricity leads to a lower (rather than higher) overall %R for the sum of all emergy inputs to the system. However, it must be borne in mind that in fact, in Scenario #2 the actual electricity demand for the building's operational life span is met by the ICSF system, which results in a lower total emergy budget, and a net delivery of on-site generated electricity back to the grid.

6. Conclusions

The goal of Clark's Crow is to facilitate the integration of emergy analysis into the early stages of building and urban design. From a review of existing tools which adopt life cycle methods of analysis we concluded that there has been limited progress in the integration of these methods into the early phases of the urban design process and workflow. This led us to develop Clark's Crow, a tool that operates within an architectural environment commonly used by architects and urban designers in the early stages of design development. The goal being that if life cycle considerations are taken account of in the early stages of design development they may have greater potential in effecting design decisions, which can ultimately define the outcome of the urban development and its greater environmental impacts over its lifetime.

Anticipated future work includes integrating more robust UEV data into Clark's Crow, if and when it becomes available. With clarification on the exact inputs of construction material UEVs, for example, Clark's Crow can be further developed to include indicator components which can differentiate between the bio-geophysical components (without services) and the more variable socioeconomic components (with services). This can help users get a greater understanding of the aspects of the urban system that greatly add to the emergy budget, and which aspects result in the greatest impact over the lifespan of a building or urban design.

Currently, Clark's Crow utilizes a process of embedded variables for emergy calculation. This means that for every material and construction used in a project, there exists a separate data object that stores all relevant variables for faster access. Imaginably, the main disadvantage of the Clark's Crow process is larger file sizes as all the data (including the results) becomes stored internally. The flip side to this, however, is that the project becomes much easier to export and share since it is not dependent on a user-populated library. The authors of this paper envisage that future work will investigate the potential for easy outputs of the results both in tabular format as is currently favored in emergy analysis, as well as novel visualization strategies to better understand the results in terms of their effect on an urban development and the dynamic nature of the results, in line with the lifespan of urban developments towards more ecologically informed urban designs. Such developments would facilitate the overarching goal of this research, i.e., to investigate how considering a broader scope of built environment lifespan during the initial design process can promote greater awareness of the work of the geo-biosphere in sustaining urban developments.

Appendix A

No.	Item	Unit	Raw data (unit)	UEV (sej/unit)	Emergy (sej)	References
	ICSF COMPONENTS - Emergy evaluation of 1m² of ICSF					
Module						
1	Triple Junction solar cell: semiconductor[a]	kg	-	various	3.70E+12	See footnote (a)
2	Fresnel lenses: PMMA [b]	kg	2.94	4.91E+09	1.44E+10	Brown et al., 2012
3	Heat sinks: aluminum [c]	kg	3.17	1.61E+13	5.12E+13	Pulselli et al., 2009
4	Two-element lens: glass [d]	kg	0.30	1.08E+12	3.20E+11	Pulselli et al., 2009
5	Module form and back-shields: PMMA [e]	kg	27.40	4.91E+09	1.35E+11	Brown et al., 2012
Frame						
6	Frame to hold cells: glass [f]	kg	9.53	1.08E+12	1.03E+13	Pulselli et al., 2009
7	Stringers: aluminum [f]	kg	0.28	1.61E+13	4.54E+12	Pulselli et al., 2009
8	Hanger end caps: aluminum [f]	kg	5.62	1.61E+13	9.08E+13	Pulselli et al., 2009
9	Multi-links: aluminum [f]	kg	0.08	1.61E+13	1.27E+12	Pulselli et al., 2009
10	Mounting plate: aluminum [f]	kg	6.57	1.61E+13	1.06E+14	Pulselli et al., 2009
11	Axles: steel [f]	kg	0.23	5.26E+12	1.19E+12	Pulselli et al., 2009
12	Metal Connectors: steel [f]	kg	0.11	5.26E+12	5.95E+11	Pulselli et al., 2009
Tracker						
13	Optical Rotary Encoder: aluminum [g]	kg	17.25	1.61+13	2.79E+14	Pulselli et al., 2009
14	Stepper motors: various [h]	kg	41.79	various	1.70E+14	Brown et al., 2012; EPA, 2010.
Electricity						
15	Inverter: various [h]	kg	58.41	various	3.17E+14	Mason et al., 2006;
16	Transformer: various [h]	kg	0.97	various	3.96E+12	Pulselli et al., 2009;
17	Cables [h]	kg	0.13	various	4.95E+11	Brown et al., 2012
Other						
18	Controllers [i]	kg	0.28	various	1.27E+12	Pulselli et al., 2009; Brown et al., 2012
19	Sensor -pyrheliometer: various (majority steel) [i]	kg	0.56	5.26E+12	2.95E+12	Pulselli et al 2009
Transportation						
20	Supplier to manufacturing site [j]	tkm	225.98	various	3.47E+13	Buranakarn, 1998
21	Manufacturing site to construction site [j]	tkm	798.40	8.40E+11	6.67E+14	Buranakarn, 1998
Assembly and Installation						
22	Energy and machinery: crude oil [k]	J	162000000	1.17E+05	1.12E+14	(Brown, et al., 2012)
23	Labor [l]	$	271.50	1.90E+12	5.15E+14	
	Total Emergy of 1m2 of ICSF with labor and services				**2.26E+15**	
	Total Emergy of 1m2 of ICSF without labor and services				**1.74E+15**	

Notes:
UEVs reflect the global baseline of 12.0E+24 seJ/unit.

[a] Triple Junction solar cell

A disaggregated inventory of technology-specific inputs is withheld for confidentiality, but was available and used to calculate the reported Emergy value. Primary resources = Germanium substrate (we are assuming single crystal Si used as a substitute for Germanium which has no available UEV), Gallium, Indium, Arsenic, Phosphorus UEVs from (Cohen, et al., 2007); the invested energy required to process wafers into cells estimated after (Kim, et al., 2008; Fthenakis & Kim, 2013) expressed in average crude oil equivalents UEV= 1.17E+05 (Brown, et al., 2012)

[b] **Fresnel lenses: PMMA**
emergy of Fresnel Lenses = (material volume * material density)(UEV of material sej/g)
Assuming EVA and plastics (as crude oil) as no UEV for PMMA is available in the literature
UEV = 4.91E+09 (Brown, et al., 2012)

[c] **Heat sinks: aluminum**
Emergy of heat sink = (material volume * material density)(UEV of material sej/g)
UEV = 1.61E+13 (Pulselli, et al., 2009)

[d] **Two-element lens: glass**
This is a two-element Köhler-type integrator lens PrimaryOptical Element (POE) and Secondary Optic (SOE)
Emergy of two-element lens = (material volume * material density)(UEV of material sej/g)
UEV = 1.08E+12 (Pulselli, et al., 2009)

[e] **Module form and back-shields: PMMA**
emergy of back-shields = (material volume * material density)(UEV of material sej/g)
Assuming EVA and plastics (as crude oil) as no UEV for PMMA is available in the literature
UEV = 4.91E+09 (Brown, et al., 2012)

[f] **Frame materials**
emergy of frame materials = (material volume * material density)(UEV of material sej/g)
Material mass (kg) calculated from dimensional, technical drawings of the system.

[g] **Optical Rotary Encoder: aluminum**
Emergy of optical rotary encoder = (material volume * material density)(UEV of material sej/g)
UEV = 1.61E+13 (Pulselli, et al., 2009)

[h] **Motors, Inverter, Transformer and Cables**
Material compositions of electrical parts were estimated from (Mason, et al., 2006) Materials include Steel, Aluminum, Copper, Plastics. UEV values referenced from (Pulselli, et al., 2009; Brown, et al., 2012)

[i] **Controller and Sensor**
Material compositions of controller and sensor were estimated from (Fthenakis & Kim, 2013; Hukseflux, 2013). UEV values referenced from (Pulselli, et al., 2009; Brown, et al., 2012)

[j] **Transportation**
Transportation depending on material source included Class 2 light truck, Class 8 combination truck and Ocean freighter for materials from overseas. Each distance was calculated in tkm. UEV for transport taken from (Buranakarn, 1998)

[k] **Assembly and Installation – energy and machinery**
Energy and machinery for the assembly and installation of the system was estimated from (Fthenakis & Kim, 2013; Perez, et al., 2012) and expressed in average crude oil equivalents UEV= 1.17E+05 (Brown, et al., 2012)

[l] **Labor – module construction services**

(Average price of resource) * (emergy/money ratio of economy of interest), where UEV of system is expected to increase between 20-30% with the addition of labor (Brown, et al., 2011) Note: In this case UEV increase of 29%.
Average price of resource = ($543/$m^2$*50%). Note: System retail price (from manufacturer) is $50/sf (i.e. $543/$m^2$) = $543/$m^2$ and Labor is assumed 50% of retail cost (Friedman, et al., 2013)
Emergy money ratio of the U.S. economy = UEV from (CEP, 2008)

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