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# Environmental exergonomics: sustainability analysis of energy systems considering impacts on eco-systems services.

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**Abstract:**

Exergy analysis methods place a major emphasis on technological and economical optimization of energy systems but have limited ability to address their environmental impacts. Several approaches have been proposed to include the environmental aspects in the energy system optimization. The Extended Exergy Accounting (EEA), incorporates the technological exergy analysis and importantly it also includes the exergetic balance of labor and environmental remediation expenditures. Exergonomics links between invested and current exergy expenditures and allows to find optimal exergy efficiency of systems using a single goal function. However, it is not only pollution the system designer should reduce. The designer should build the system that will minimize the pollutions and the risk during the system life cycle, an approach known as Design for Environment (DfE). In this paper we expand the Exergonomics tool towards DfE of renewable energy systems and develop sustainability metric for energy systems using exergy, an approach we describe as Environmental Exergonomics. In Environmental Exergonomics the energy system objective function in addition to technological/mechanical system efficiency and capital efficiency also includes environmental efficiency, quantified by the changes in eco-exergy. Eco-exergy, a term evolved in ecology, described the ability of eco-system to do a work. In ecology, the eco-exergy content of the system is related to the information encoded in the living systems (Shannon-Entropy) and is calculated relatively to a reference environment of the same system at the same temperature and pressure, but as an inorganic soup with no life, biological structure, information or organic molecules. The inclusion of the eco-exergy into the energy system analysis is the next step that will allow for the sustainability analysis of the energy systems in the context of the eco-system services of their environmnet.

**Keywords:**

Energy system design, sustainability, eco-system services, eco-exergy, environmental footprint.

# 1. Introduction

Optimization of energy systems efficiency is a major focus of the power plant designers [1], [2]. In the recent years a major focus has been made for the inclusion of sustainability parameters in the energy systems management, not always appreciated in the early works. Early attempts to quantify and optimize an energy system's efficiency date back to the 19th century when Carno defined the maximum possible efficiency of the heat engine. The technology optimization, however, does not account for the capital and environmental efficiency, crucially important in the energy system decision making. Therefore, several approaches have been proposed in the last century to quantify and optimize additional energy systems parameters. These approaches can be divided into two major categories: energy based optimization and exergy based optimisation. The major differences between them is the energy based approached do not take into account irreversible changes induced by the energy system. Both of them do not account for the changes in the eco-systems induced by energy systems. In the following paragraphs I give a brief summary of both approached and then define the new method that includes the environmental eco-system changes in the energy system optimisation.

## 1.1. Energy based methods for energy systems optimization

At the beginning of the 20th century, Soddy proposed to use energy as a major currency of "wealth" (and capital) [3]. He proposed to use energy as a currency in an assessment of the performance and optimization of anthropic systems. One of the major concerns with the technological and economical approaches for energy systems analysis that followed Soddy is their limited ability to address the environmental impacts of the energy systems. Life Cycle Assessment (LCA), or its advanced version known as Environmental Life Cycle Assessment (ELCA) methodology, aims at the environmental impact analysis of the system associated with all the stages of a system's life "from cradle to grave" [4],[5]. This approach has been used in the context of energy system evaluation and optimization [4], [5]. The bases of the LCA method are 1) the compilation of the product or system inventory of relevant energy, material inputs, and environmental stresses and 2) evaluating the potential impacts associated with identified inputs and releases. The recently introduced Ecological-LCA incorporated the ecological resources and surrounding ecosystems such as supporting, regulating, provisioning and cultural services [6]. However, based on the First Law of energy conservation, the LCA with its variations do not take into account all the energy carriers and inevitable irreversibility of processes [7].These irreversibility effects can be analysed using the concepts from the Second Law of thermodynamics [8], [9].

## 1.2. Exergy based methods for energy systems optimization

Studies on the irreversibility of the process that occur in the anthropic energy conversion systems led to the concept of "energy available to do a work," [10] coined "exergy" by Rant [10]. The goal of the optimization is to maximize the exergy produced by the system per invested exergy [11]. However, first exergy analysis methods put a major emphasis on the technological optimization of the energy system and did not account for capital and environmental expenses.

To address the problem of capital optimization of the energy systems in the context of exergy analysis, the thermoeconomics approach was proposed [12], [13]. In thermoeconomics, the system optimization is performed on a single cost function which incorporates both technology and capital parameters. In this case, an additional function is needed to connect the technology and the capital investment. The capital parameters can include the non-energy costs of the system such as capital, interest, overhead, labor, maintenance, insurance, and environmental technologies costs. The goal of optimization using this approach is to maximize the exergy of the system per capital. This approach, however does not account for the environmental impacts.

To address the issues of processes irreversibility in environmental impact assessment, Exergetic LCA proposed to use exergy as a quantifier; however, leaving outside the economic analyses of the system [14]. The economic aspects have been included in the further introduced environomic approach that added a monetary, but not exergy, value to the 'environmental penalty' functions [15], [16]. The Extended Exergy Accounting (EEA) converted exergy to the only unit of the system efficiency analysis [7], [17]. EEA incorporates the technological exergy analysis and, importantly, it also includes the exergetic balance of labor and environmental remediation expenditures. EEA suggested to assess the system impact on the environment by including the exergy costs required to bring the energy system effluents to the balance with the environment in terms of heat and chemical compositions [7].

An additional approach for the optimization of an energy system's physical economic efficiency using exergy was introduced Yantovsky and is coined Exergonomics [18]**.** Exergonomics links invested and operational exergy expenditures and allows one to find optimal exergy efficiency of energy systems [18], [19]. Yantovsky also suggested that "for more reliable decision making, the simultaneous optimization of three target functions: exergy, money, and pollution, is needed" [18]. However, it is not only pollution from the system that the designer should reduce. The designer must also consider the multiple complex effects the energy system—especially a large scale renewable energy system—has on the eco-system services of the surrounding environment.

## 1.3. Environmental Exergonomics

Minimizing the effects of anthropogenic products on eco-system services is known as Design for Environment (DfE)[20]. Although DfE has been used in consumers' products, it has not been yet applied for the energy systems to the best of our knowledge. Moreover, for decision makers in the field of energy systems, there is a need for an assessment methodology and index that will enable comparison of various systems' efficiencies, including their impacts on the surrounding eco-system services.

The goal of this paper is to expand the Exergonomics methodology toward DfE of renewable energy systems and to develop a sustainability metric for energy systems using an exergy metric. The currently used approaches and metrics look at the interaction of the energy system with the environment in the dual manner where the energy system and the environment are separate entities: the system affects the environment [21]. Thus, the exergy fluxes are analyzed between the energy systems and the environment. This separation, however, is not valid for the sustainability analysis, where the system is viewed as a part of the environment.

Different from classical energy conversion systems and economic evaluation where the exergy per invested money can be calculated, it is hardly possible to put a monetary tag on the changes caused to the eco-systems by constructed large-scale energy infrastructure. Neither is it possible to completely prevent the changes in the eco-systems due to those constructions, which require large deployment of land [22]–[25]. However, it is inevitable to include the ecosystem services changes into the objection function of energy system efficiency. This requires allocation of certain exergy values to the eco-system services. In this work, I suggest that this depletion of the eco-system resources can be quantified by their exergy content change. Thus, the depletion of the eco-system resources presents another exergy flow into the energy system.

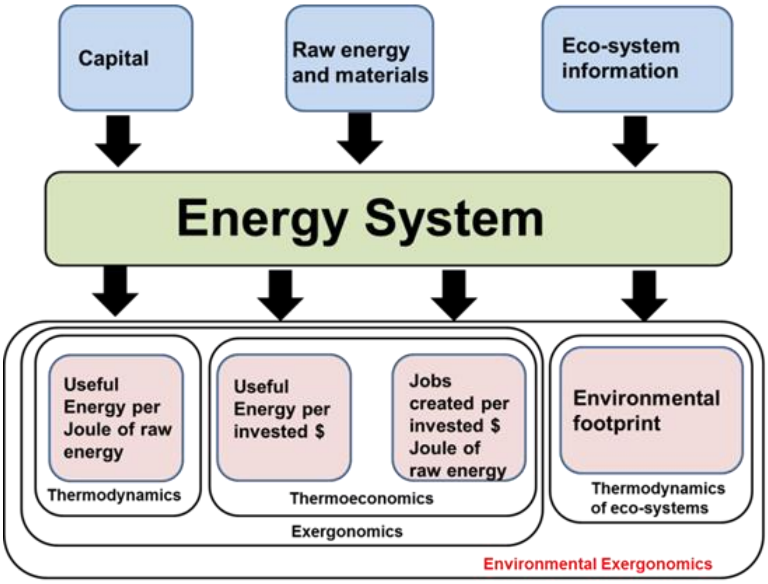

*Figure 1. Environmental Exergonomics for energy systems*

Interestingly, the ability of the eco-systems to perform useful work has been investigated using thermodynamic approaches and exergy terms in ecology [26]–[29]. In ecology, the eco-exergy content of the system is related to the information encoded in the living systems (Shannon-Entropy). It is calculated relative to a reference environment of the same system at the same temperature and pressure, but as an inorganic soup with no life, biological structure, information or organic molecules [30]. The inclusion of eco-exergy into the energy system analysis (**Figure 1**) is the next step that will allow for the sustainability analysis of the energy systems in the context of the ecological systems they are a part of, and it will provide a methodology and metric for energy systems DfE. The main difference of *Environmental Exergonomics* from previously proposed methods for energy system analysis is the inclusion of the exergy flow from the eco-systems in which the energy system is installed. This environmental exergy flow is measured by the changes of the eco-exergy (embedded information and the total biomass) of the eco-system. The inclusion of the eco-exergy allows for direct assessment of the sustainability of the energy system by the comparison of systems impact on the environmental eco-systems.

# 2. Energy systems optimization with Environmental *Exergonomics* approach

## 2.1. Definition of the system scope

The energy system in the production scale requires a significant construction work either on land or sea. If the system performance is measured in units of exergy, then in the most general case (**Figure 2**), the inputs to the process are represented by an exergy stream of raw materials ($e_m$) and energy supply ($e_e$), capital inflow ($e_c$) and human labor ($e_l$), and information, represented by eco-exergy ($e_{eco}$). The first three terms have been proposed previously [7], [17]–[19]. The last term, information, which can describe the eco-system's ability to perform work in exergy terms, is a new aspect introduced in this model. The outputs are the desired products/delivered exergy, ($e_d$), byproducts ($e_b$), exergy rejection to the environment ($e_e$), materials waste ($e_w$), and eco-exergy information (loss or gain) ($e_{eco\text{-}c}$). In this analysis I use the word "information" to describe the condition of the existing eco-systems, as defined by Shannon entropy function of state [31],[32]. As both physical and informational exergies are conserved in these systems, the system will experience continuous physical and informational exergies losses.

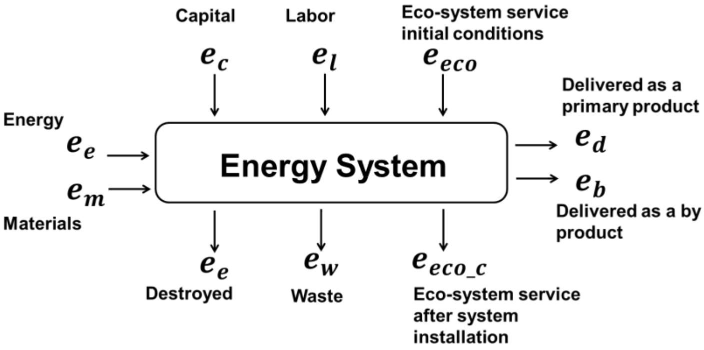

*Figure 2. Environmental Exergonomics exergy flow diagrams of a generic process.*

## 2.2. System boundaries and time history

The energy system includes the physical, capital, and environmental components. The physical boundaries for the analyzed energy systems are the boundaries of the physical territory (land) where the system is constructed. For example, this can include the land dedicated to solar panels or wind turbine installation, land dedicated to energy crops growth, or areas of the sea dedicated to off-shore algae growth. The capital boundaries include the capital invested in the system construction, maintenance, and deconstruction. The environmental boundaries include the eco-systems that are located in the area that is occupied by the plant or that are affected by the plant construction. The system also includes the produced products, wastes, jobs, and local eco-systems. The exergy time history of energy unit—including construction exergy current ($\dot{e}_c$), operation exergy current ($\dot{e}_{con}$), and deconstruction exergy current ($\dot{e}_d$), as well as the exergy currents changes in surrounding eco-system ($\dot{e}_{eco}$)—are summarized in **Figure 3.**

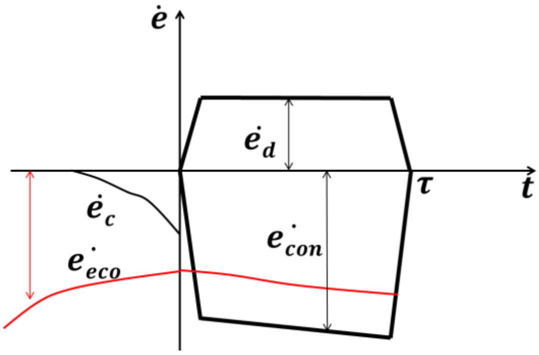

*Figure 3. The history of an energy system, including its effects on the environment. $\dot{e}_c$ is the exergy current for system contruction; $\dot{e}_d$ is the exergy current for system deconstruction, $\dot{e}_{con}$ is the exergy current for the production and $\dot{e}_{eco}$ is the eco-exergy current of the surrounding eco-systems.*

## 2.3. Environmental Exergonomics Efficiency.

Under assumption that each of the input and output factors can indeed be described using physical and informational exergy functions, the efficiency of a system using Environmental Exergonomics method is described in Equation 1:

$$\eta_{ENV} = \frac{1}{\frac{1}{\eta} + \frac{1}{K} + \frac{1}{E}} \tag{1}$$

where $\eta_{ENV}$ is the total sustainable energy system efficiency, or the main criterion for environmental exergonomics;$\eta$ is the technological/mechanical system efficiency, based on the operational exergy flow [18]:

$$\eta = \frac{\delta_0}{\delta_i} \tag{2}$$

where $\delta_i$is the inlet exergy current and $\delta_0$ is the output exergy current.

$K$ is the net exergy capital coefficient, the ratio of delivered exergy to invested exergy (capital) [18]:

$$K = \frac{\frac{de_d}{dt}\tau}{e_c + e_l} \tag{3}$$

where $e_d$ is the delivered exergy, $e_c$ is the invested exergy needed for system construction and $e_l$ is the invested labor, and $\tau$ is system operation time.

And $E$ is the ecological or eco-system efficiency of the energy conversion system based on the eco-exergy flow. We will use a ratio of eco-exergy before and after energy system construction and use:

$$E = \frac{\frac{de_d}{dt}\tau}{e_i} \tag{4}$$

where $e_i$ is the consumed eco-exergy, which is described by the reduced ability of eco-system to perform work:

$$e_i = e_{eco\_0} - e_{eco\_\tau} \tag{5}$$

## 2.4. The Main Criterion in Environmental Exergonomics.

The inverse quantity of $\eta_s$ (defined as $\eta_s = \frac{1}{\frac{1}{\eta}+\frac{1}{K}}$ ) was previously proposed as the main criterion in Exergonomics, which is subjected to minimization [18]. Diverging from [18], in this work I incorporate the information part of exergy into the objective function (eco-exergy), thus providing a quantitative tool to measure the contribution of the eco-system's services to the system efficiency. Therefore, I define the Environmental Exergonomics main criterion function as:

$$Z_{env} = \frac{1}{\eta} + \frac{1}{K} + \frac{1}{E} \tag{6}$$

Importantly, $Z_{env}$ is an expansion of functions previously proposed in Exergonomics, Exergy Life Cycle Assessment and Extended Exergy Accounting. The major difference from those functions is the inclusion of eco-exergy for optimization of sustainable energy systems during planning.

Assuming that $K$ and $E$ are independent, for the arbitrary functions K(η) and E(η):

$$\frac{dZ_{env}}{d\eta} = -\frac{1}{\eta^2} + \frac{-\frac{dK}{d\eta}}{K^2} + \frac{-\frac{dE}{d\eta}}{E^2} \tag{7}$$

For $\frac{dZ_{env}}{d\eta} = 0$:

$$\eta^2 = \frac{K^2 E^2}{-E^2 \frac{dK}{d\eta} - K^2 \frac{dE}{d\eta}} \tag{8}$$

and thus

$$Z_{min} = \frac{(-E^2 \frac{dK}{d\eta} - K^2 \frac{dE}{d\eta})^{1/2} + K + E}{KE} \tag{9}$$

and

$$\eta_{opt} = \frac{KE}{(-E^2 \frac{dK}{d\eta} - K^2 \frac{dE}{d\eta})^{1/2}} \tag{10}$$

where $\eta_{opt}$ is the optimum efficiency of the system. A correlation between $K$ and η, and $E$ and η, are study specific.

# 3. Exergy currents determination

## 3.1. Physical exergy currents.

Physical exergy is defined as the maximum amount of reversible work that can be produced by bringing the temperature, pressure, velocity, and position within a gravitational field, and by bringing chemical composition into equilibrium with the defined reference state. Equation 11 describes the physical exergy of the system in the most general form [21]:

$$\delta = [h - h_0 - T_0(s - s_0)] + \sum_i (\mu_i c_i - \mu_0 c_0) \tag{11}$$

The first term of the equation includes the classical thermodynamic properties—enthalpy ($h$), temperature ($T$), entropy ($s$)—known for many substances and mixtures in a wide range of states. The second term is the chemical exergy of basic system elements ($\mu$), and is the chemical potential. For all properties, sign “0” stays for the value of the property in the standard conditions.

## 3.2. Capital exergy currents.

The capital exergy currents can divided into monetary and labor currents. This subdivision and separation of the labor current from the monetary investment proposed by Sciubba [7], [33] emphasizes the important impact of energy systems on workers and society. The detailed analyses of capital exergy currents can be found in the references [7], [33]. For simplicity, in this work, the capital exergy current is defined as the exergy required to build the unit and the exergy equivalent of working hours invested by the system stuff during the system's life time:

$$e_{c+l}=e_c + e_l \tag{12}$$

where $e_c$ is the exergy required to build the unit, and

$$e_l = K_{labor} \cdot n_{workers} \cdot WH \tag{13}$$

where $K_{labor}$ is the exergenic equivalent of labor [17], and WH is the work hours in a year.

## 3.3. Eco-exergy currents.

The physical and capital exerg currents have been analyzed in the literature [18]. Here I propose to include the eco-exergy into the objective function of the energy system's exergy model development. The term eco-exergy was developed in ecology [34]. The concept of eco-exergy was first applied to ecology in 70's [35], [36] and the last four decades led to the formulation of the "maximum exergy principle in ecology", which described the formation of biodiverse communities in terms of thermodynamics [37].
Eco-exergy has been used in ecology to express emergent properties of ecosystems arising from self-organization processes in the evolution of their development [27]. Exergy has also been used as an objective function in ecological models to assess the changes and concentrations of various species in the eco-system under stress [37].

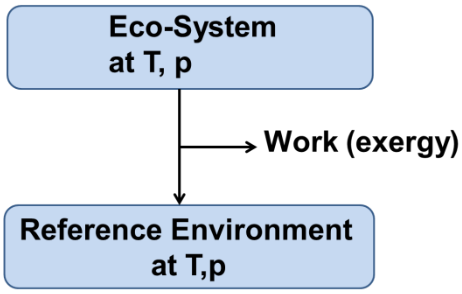

*Figure 4. Eco-exergy definition*

Eco-exergy is a measure of the maximum amount of work that an eco-system can perform when it is brought into thermodynamic equilibrium with its environment [34] (**Figure 4**), Eco-exergy has been used as an ecological indicator, used to assess ecological condition and ecosystem health [38]. The most recent definition of eco-exergy is [39] :

$$e_{eco} = \sum_{i=1}^{n} (f_i B_i \beta_i) \tag{14}$$

where $f$ is the work energy per unit of biomass [39], which in average is 18.7 kJ $gr^{-1}$, but can be higher for high fat biomass (for example: birds [39]). $B_i$ is the biomass weight of the species, $i$ ( gr), and $\beta_i$ is the weighting factor available in Appendix A [40]. $\beta_i$ is equal to RTK, where R is the gas constant, T is absolute temperature, and $K$ is Kullback's measure of information based on information embedded in the genes of the species [41].

The impacts assessment of the energy systems on the local and global eco-systems are rare [23]. In the case of renewable energy systems, their real scale installation requires deployment of the large territories of land/sea [42]. This, in turn, may cause change to local biodiversity and may affect even larger eco-system services [22]. These novel uses of the land/sea affect the habitant, food and water availability, and preying strategy in animal species. It can also lead to the introduction of invasive species that decrease the natural biomass biodiversity [43]. The effects on human health, mostly due to the deforestification and release of pathogenic microorganisms from soil have also been mentioned [44]. The above-mentioned examples of ecological changes in areas with energy system installations can affect the biodiversity and thus the exergy of the ecosystem. The change in the eco-exergy in the area in which the energy system is installed can be calculated using Equation 15:

$$e_i = \sum_{i=1}^{n} (f_i B_i \beta_i)_o - \sum_{i=1}^{n} (f_i B_i \beta_i)_\tau \quad (15)$$

where the first term stays for the eco-exergy of the ecological system before energy system installation, and the second term stays for the eco-exergy of the ecological system after the system deconstruction. It is important to mention that several authors mentioned that installation of the renewable energy system can increase the biodiversity in used areas [45]. Thus, $e_i$ is the exergy lost or gained by the area in which the eco-system is constructed.

## 4. Case Study: Crop choice for Bioenergy production predicates the total energy system exergy losses associated with eco-exergy.

Bioenergy is one of the oldest renewable energy sources [46]. Due to the multiple environmental and political problems associated with the fossil fuels, there is a constant interest in bioenergy utilization as an alternative to fossil energy sources to produce electricity, heat, and transportation biofuels. However, further deployment of land for bioenergy crops will affect the natural habitant of species. It is estimated that over 4,000 of the assessed plant and animal species are threatened by agricultural intensification" [47]. One of the challenges in the development of bioenergy biomass sources is the minimisation of the environmental impacts especially, minimizing impacts on biodiversity. Robertson et al compared the impact of 3 bioenergy crops on the richness and total biomass of terrestrial arthropod communities [48]. This study showed that arthropod community-wide biomass was affected by crop type, forest cover, and landscape diversity, predicted roughly 750% increase in biomass in switchgrass and a 2700% increase in biomass in prairie compared with corn [48]. The total biomass of arthropod (per sample) as reported was 1,044.50±223.67 µg/sample for corn fields ($B_{corn}$); 8,847.10±1,978.38 µg/sample for the switch grass fields ($B_{switchgrass}$), and 29,485.40±6,593.25 µg/sample for the prairie ($B_{prairie}$). The eco-exergy losses (per sample) due to arthropod biomass loss, if the monoculture switchgrass or corn are used as bioenergy crop instead of a prairie , can be calculated using the following Equations 16 and 17 and Table 1 (Appendix A, exergy values for crustaceans are used):

$$e_{i\_\mathrm{crustaceans\_switchgrass}} = f\beta_{\mathrm{crustaceans}}(B_{\mathrm{prairie}} - B_{\mathrm{switchgrass}}) \quad (16)$$

$$e_{i\_\mathrm{crustaceans\_corn}} = f\beta_{\mathrm{crustaceans}}(B_{\mathrm{prairie}} - B_{\mathrm{corn}})$$

or

$$e_{i\_\mathrm{crustaceans\_switchgrass}} = 18.7\frac{KJ}{gr} \cdot 270 \cdot 0.021\frac{gr}{sample} = 104\ \frac{KJ}{sample} \quad (17)$$

$$e_{i\_\mathrm{crustaceans\_corn}} = 18.7\frac{KJ}{gr} \cdot 270 \cdot 0.029\frac{gr}{sample} = 143.5\frac{KJ}{sample}$$

Therefore, switching from corn to switchgrass as bioenergy feedstock crop would save up to 38% of exergy destroyed due to the eco-exergy losses associated with arthropod biomass and biodiversity changes.

## Conclusion

The construction, deployment, and operation of energy systems have multiple effects on the ecosystems in which the energy system is constructed. In this work, a method to measure the effects of the constructed energy systems on environment using exergy currency is proposed. The loss of biodiversity or ability of the eco-system system to work is translated to the exergetic losses of the energy system measured by eco-exergy. Thus, they can be optimized during the system design. We have shown that the choice of bioenergy crop can save up to 38% of exergy losses associated with the damage to the arthropod community. The proposed method will enable energy systems sustainability comparison and will therefore aid decision-making and design for environments of energy systems.

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# Appendix A

*Table 1. Species Eco-exergy Weighting Factors* [30, 34] .

| **Species** | **Exergy conversion factor, $\beta$** |
|---|---|
| Bacteria | 8.5-12 |
| Archaea | 13.8 |
| Yeast | 18 |
| Cyanobacteria | 15 |
| Green microalgae | 20 |
| Macrophyta | 67-298 |
| Rhodophyta | 92 |
| Fungi | 61 |
| Worms | 91-133 |
| Sponges | 98 |
| Seedless vascular plants | 158 |
| Insects | 167-446 |
| Moss | 174 |
| Crustaceans | 230-300 |
| Mollusca | 297-450 |
| Flowering plant | 393-543 |
| Fish | 499-800 |
| Amphibia | 688 |
| Reptilia | 833 |
| Aves | 980 |
| Mammalia | 2127 |
| Homo sapiens | 2173 |