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Environmental exergonomics for sustainable design and analysis of energy systems

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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. Although several approaches, such as Extended Exergy Accounting and Exergonomics, have been proposed to include pollution costs in the energy system optimization, environmental impacts of energy systems are much more complex, as energy systems affect the entire eco-systems services in the areas they are installed. Therefore, energy systems should minimize the adverse impacts on the surrounding eco-system services. In this paper we introduce a method for analysis and optimization of energy systems using technological, economic, and environmental exergy flows. For environmental exergy flow analysis, we included the eco-exergy component in the system objective function. Eco-exergy provides a Second Law derived measurement of the eco-system ability to do work. The disruption of eco-system services, such as reduction of biodiversity, is reflected in a reduction of eco-exergy. Therefore, we propose to include the minimization of the eco-exergy losses in the sustainable energy systems optimization. To demonstrate the method, we analyzed the eco-exergy losses associated with the reduction of the birds' biomass in the EU (European Union) fields dedicated to renewable energy systems. Specifically, we show that the EU renewable energy installations in 2008 lead to addition, today unaccountable, 5 PJ exergetic losses associated with the reduction in the biodiversity and biomass.

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1. Introduction

Sustainable energy management is a major challenge for the modern society. Various scenarios have been developed in attempt to forecast the future energy demands and potential sources [1–6].

However, under any scenario, optimization of energy systems efficiency is a key factor in sustainable energy management for all types of energy generating facilities, and thus has been a major focus of the power plant designers [7,8]. The major goal of the current energy system development efforts is to provide the needs of the growing population with the minimum possible damage to the environment and eco-system services. The challenge in this complex anthropogenic-natural framework is to quantify the efficiency of the systems.

Early attempts to quantify and optimize an energy system's efficiency date back to the 19th century when Carnot defined the maximum possible efficiency of the heat engine. The technology optimization, however, does not account for the capital efficiency, crucially important in the energy system decision making. Therefore, at the beginning of the 20th century, Soddy proposed to use energy as a major currency of "wealth" (and capital) [9]. 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 is their limited ability to address the environmental impacts of the energy systems. LCA (Life Cycle Assessment), or its advanced version known as ELCA (Environmental Life Cycle Assessment) methodology, aims at the environmental impact analysis of the system associated with all the stages of a system's life "from cradle to grave" [10,11]. This approach has been used in the context of energy system evaluation and optimization [10,11]. 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,

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provisioning and cultural services [12]. 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 [13]. These irreversibility effects can be analyzed using the concepts from the Second Law of thermodynamics [14,15]. 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," [16] coined "exergy" by Rant [17]. The goal of the optimization is to maximize the exergy produced by the system per invested exergy [18]. 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, the thermoeconomics approach was proposed [19,20]. 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 [21]. 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 [22,23]. The EEA (Extended Exergy Accounting) converted exergy to the only unit of the system efficiency analysis [13,24]. 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 [13].

A different approach for the optimization of an energy system's physical economic efficiency using exergy was introduced Yantovsky and is coined Exergonomics [25]. Exergonomics links invested and operational exergy expenditures and allows one to find optimal exergy efficiency of energy systems [25,26]. Yantovsky also suggested that "for more reliable decision making, the simultaneous optimization of three target functions: exergy, money, and pollution, is needed" [25]. 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.

Despite the variety of the previously suggested methodologies, none of them captures technological efficiency, capital efficiency and environmental efficiency in the single analysis. The goal of this paper is to close the gap between anthropogenic energy generating systems and eco-system services exists. Minimizing the effects of anthropogenic products on eco-system services is known as DfE (Design for Environment) [27]. 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. Here I propose 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 [28]. Thus, the exergy fluxes are analyzed between the energy systems and the environment. Although this approach might be useful for the classic fossil fuel conversion energy systems (when concentrated fossil fuel is extracted from the Earth and transported and processed through the energy dense transportation channels), this approach is rarely valid for the most of the renewable energy systems. Usually, the renewable energy systems collect the distributed energy from large areas. Indeed, in the cases of solar, wind, wave and biological energy, increasing the system capacity and efficiency requires the increased use of land and water. Importantly, this growth requires the depletion of the eco-system resources [29].

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 [29–32]. 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.

Interestingly, the ability of the eco-systems to perform useful work has been investigated using thermodynamic approaches and exergy terms in ecology [33–36]. 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 [37]. The inclusion of eco-exergy into the energy system analysis (proposed in this paper as *Environmental Exergonomics* (Fig. 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. In the first part of the paper, I define the thermodynamic cycle and exergy currents of the energy systems, accounting for eco-system services. In the second part, I derive the theoretical framework for calculation of system efficiency and define the major criteria for the *Environmental Exergonomics* that allows for systems optimization. In the third part, I demonstrate the application of *Environmental Exergonomics* on the renewable energy generation in the case of land deployment at the European Union. This approach will expand the arsenal of tools available today for the sustainability analysis of renewable energy systems and will allow the joint technological, economic, and ecological analysis of the energy systems.

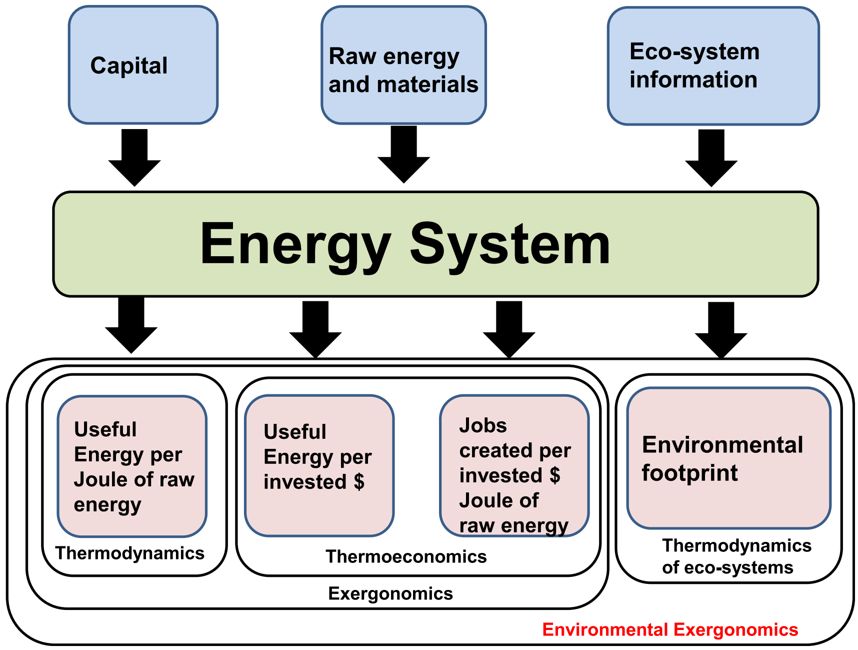

Fig. 1. Environmental Exergonomics for energy systems analysis.

2. System cycle

The renewable energy system in the production scale requires a significant construction work either on land or sea. The system converts one form of dispersed renewable energy (solar, wind, wave of biomass) into the concentrated energy products, such as electricity of transportation fuels. If the system performance is measured in units of exergy, then in the most general case (Fig. 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 [13,24–26]. 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 [38,39]. As both physical and informational exergies are conserved in these systems, the system will experience continuous physical and informational exergies losses.

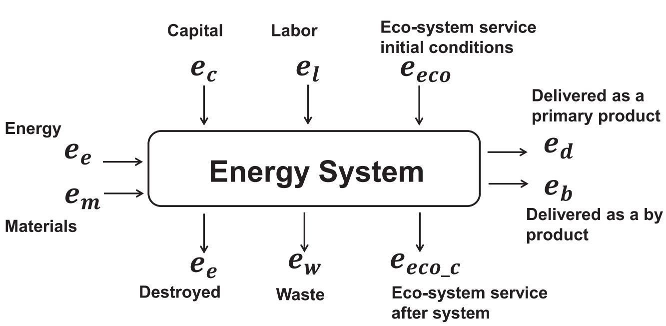

Fig. 2. Environmental Exergonomics exergy flow diagrams of a generic process.

The exergy diagram for the *Environmental Exergonomics* exergy flow, which includes the eco-system's eco-exergy losses, is shown in Fig. 3 in comparison to classic Szargut exergy flow diagrams.

3. System boundary

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 Fig. 4.

4. 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 η_{ENV} is the total sustainable energy system efficiency, or the main criterion for environmental exergonomics;

η is the technological/mechanical system efficiency, based on the operational exergy flow [25]:

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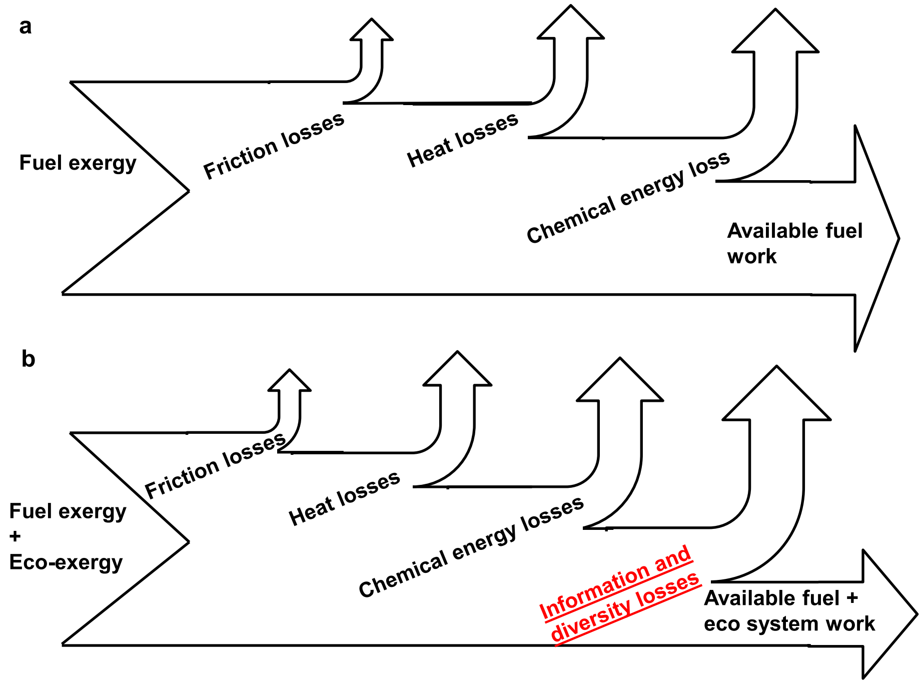

Fig. 3. Exergy flow diagram. a. Szargut exergy flow diagrams. **b.** *Environmental Exergonomics* exergy flow diagram.

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

where δ_i is the inlet exergy current and δ_0 is the output exergy current.

K is the net exergy capital coefficient, the ratio of delivered exergy to invested exergy (capital) [25]:

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

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 τ 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:

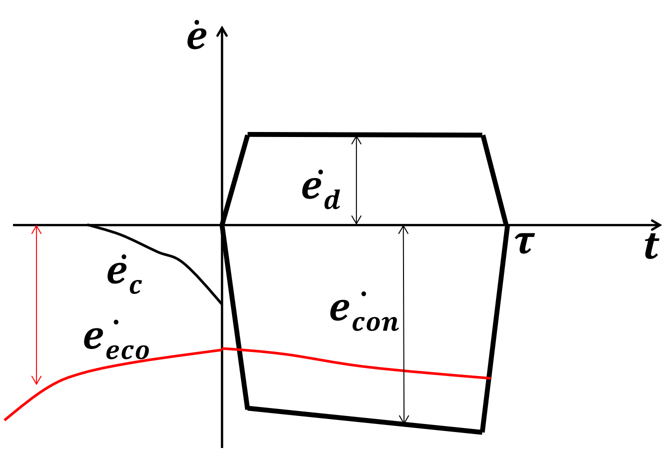

Fig. 4. The history of an energy system, including its effects on the environment.

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

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

$$e_i = e_{eco_0} - e_{eco_\tau} \tag{5}$$

5. The main criterion in environmental exergonomics

The inverse quantity of η_s (defined as $\eta_s = 1/1/\eta + 1/K$) was previously proposed as the main criterion in Exergonomics, which is subjected to minimization [25]. Diverging from Ref. [25], 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 $dZ_{env}/d\eta = 0$:

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

and thus

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

and

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

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

The assumption in this model is that η, K and E can be analyzed in parallel is valid as long as we use the tools developed in separate disciplines for the analysis. However, if a correlation between the these efficiencies is founds, as suggested in the early works of Szargut [40] further functional analysis using a single parameter, for example η or monitary cost is possible [25].

6. Calculations of exergy currents

6.1. 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 [28]:

$$\delta = [h - h_0 - T_0(s - s_0)] + \frac{(V - V_2)^2}{2} + g(z - z_0) + \sum_i (\mu_i c_i - \mu_0 c_0) \tag{11}$$

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 and third terms are a result of measured position (z) and velocity (V) relative to the reference state, and their exergy and energy contents have the same numerical value as proposed in Ref. [41]. The fourth term is the chemical exergy of basic system elements (μ), and is the chemical potential. For all properties, subscript "0" stays for the value of the property in the standard conditions.

6.2. Capital exergy currents

The capital exergy currents can be divided into monetary and labor currents. This subdivision and separation of the labor current from the monetary investment proposed by Sciubba [13,42] emphasizes the important impact of energy systems on workers and society. The detailed analyses of capital exergy currents can be found in the references [13,42]. 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 [24], and WH is the work hours in a year.

6.3. Eco-exergy currents

Two previously mentioned currents have been analyzed in the literature [25]. The major novel part of the approach presented in this work is the inclusion of eco-exergy into the objective function of the energy system's exergy model development. The term eco-exergy was developed in ecology [43]. The concept of eco-exergy was first applied to ecology in 70's [44,45] 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 [46].

Eco-exergy has been used in ecology to express emergent properties of ecosystems arising from self-organization processes in the evolution of their development [34]. 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 [46].

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 [43] (Fig. 5), Equation (14):

$$e_{eco} = RT\sum_{i=0}^{n}\left[\left(C_i \ln\left(\frac{C_i}{C_i^{eq}}\right) + \left(C_i - C_i^{eq}\right)\right]\right. \tag{14}$$

Where R is the gas constant, C_i is the concentration of species i in the system and C_i^{eq} is the concentration of species i in the reference environment. The term eco-exergy evolved from the use of entropy the information theory, where entropy is the average amount of information contained in each message received [39]. In application to eco-systems, the information is coded in the genetic load of the organisms. In early works, Jorgensen et al. [43] proposed the following equation for the calculation of an eco-system's exergy [46].

$$e_{eco} = RT\left(\mu_1 - \mu_1^{eq}\right)\sum_{i=1}^{N} C_i - RT\sum_{i=2}^{N}\left(C_i \ln\left(P_{i,a}\right)\right) \tag{15}$$

where $\mu_1 - \mu_0$ is calculated from standard chemical potentials of the organic matter, C_i is the concentration of the species in the environment, and $P_{i,a}$ is the probability of producing the component i at thermodynamic equilibrium. $P_{i,a}$ can be found from the number of permutations among which the characteristic amino acid sequence for the considered species. Since living organisms

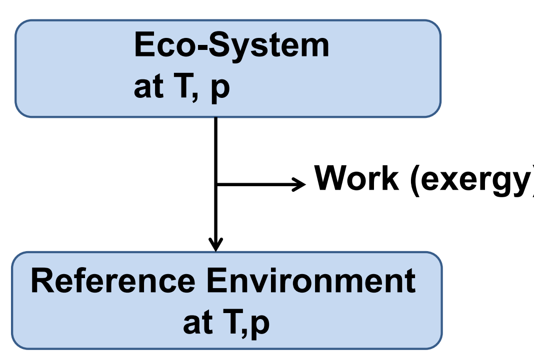

Fig. 5. Eco-exergy definition.

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use 20 different amino acids and each gene determines on average 700 amino acids, P can be evaluated using Equation (16) [46]:

$$P_{i,a} = 20^{-700G} \tag{16}$$

where G is the number of genes (for the standard table).

Eco-exergy has been used as an ecological indicator to assess ecological condition and ecosystem health [47]. The most recent definition of eco-exergy is [48]

$$e_{eco} = f\sum_{i=1}^{n}(B_i\beta_i) \tag{17}$$

where f is the work energy per unit of biomass [48], which in average is 18.7 kJ gr^{-1}. B_i is the biomass weight of the species, i (gr), and β_i is the weighting factor available in tables in Appendix A, [49]. β_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, Equation (16) [50]. The Kullback's measure of information defines the incremental changes in the system information as a result of the transition from a 'reference state (io)' to a current one (i) as follows [50]:

$$K = \sum_{i=1}^{n} p_i ln\frac{p_i}{p_{i0}} \tag{18}$$

The impacts assessment of the large scale renewable energy systems on the local and global eco-systems are rare and often comes in comparison with fossil fuels alternatives [30]. The installation of large scale renewable energy facilities or cultivation of real scale bioenergy crops requires deployment of the large territories of land/sea [51]. This, in turn, may cause change to local biodiversity and may affect even larger eco-system services [29]. 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 [52]. The effects on human health, mostly due to the deforestification and release of pathogenic microorganisms from soil have also been mentioned [53]. 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 (18):

$$e_i = f\sum_{i=1}^{n}(B_i\beta_i)_o - f\sum_{i=1}^{n}(B_i\beta_i)_\tau \tag{19}$$

where the first term (subscript "0") stays for the eco-exergy of the ecological system before energy system installation, and the second term (subscript "τ") 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 [54]. Thus, e_i is the exergy lost or gained by the area in which the eco-system is constructed.

7. Environmental exergonomics of industrialized biomass for bioenergy production

The introduced Environmental Exergonomics method can be applied on a system, regardless of the specifics of the primary resources, size, time of operation, products and wastes. The unique property of the method is that it allows for direct comparison between a system's impacts on the embedding eco-systems services, measured by eco-exergy. In this part of the paper, I give an example of the application of Environmental Exergonomics in the expanding bioenergy sector. I demonstrate the application of eco-exergy concepts through analyzing the diminishing birds populations in Europe, which is thought to be a direct output of intensive agriculture [55].

Biomass is the oldest renewable energy sources [56]. In the last decades, there has been an increased interest in biomass utilization as an alternative to fossil energy sources to produce electricity, heat, and transportation biofuels. However, in contrast to the ancient societies that could utilize the available naturally biomass as a source of primary energy generation, the size of the current world population and increasing personal energy demands make it impossible to rely upon the naturally grown biomass harvesting [57]. Therefore, advanced agricultural methods have been explored in the recent decades for the increase of biomass yields. These methods include breeding of energy crops, genetic engineering of energy crops, and development of advanced agricultural techniques for cultivation [57]. The latest include precise irrigation, fertilization, and pest management. Although seasonal crop rotation has been used by small farmers worldwide and has been recently proposed for industrial energy biomass farming [58], the mainstream of bioenergy crop cultivation remains monoculture agriculture [59,60]. These intensification methods lead to multiple side effects on the explored field eco-systems [61]. Indeed, "agriculture remains the largest driver of genetic erosion, species loss, and conversion of natural habitats. Over 4000 of the assessed plant and animal species are threatened by agricultural intensification" [62].

This loss of biodiversity is one of the most prominent effects of industrial agriculture [61]. In the context of energy systems, the loss of biodiversity—or loss of information—can be described by the entropy generation [63]—or exergy loss—of the energy system as suggested in Environmental Exorgonomics. The suggested exergy diagram for the industrial biomass to bioenergy process appears in Fig. 6. The major currents of exergy include solar exergy, converted by plants to biomolecules; fossil fuels for fertilizes manufacturing; deployed fields eco-system services and capital. The three major sources of exergy losses are 1) loss on photosynthesis (solar energy conversion to biomass), 2) losses on processing: cultivation, transportation, conversion, distribution, final product combustion biodiversity and 3) eco-exergy losses.

The example of calculation of exergy losses for the bioenergy production appear in Refs. [64–67]. These reports, however, do not count the losses associated with the destruction of the eco-systems

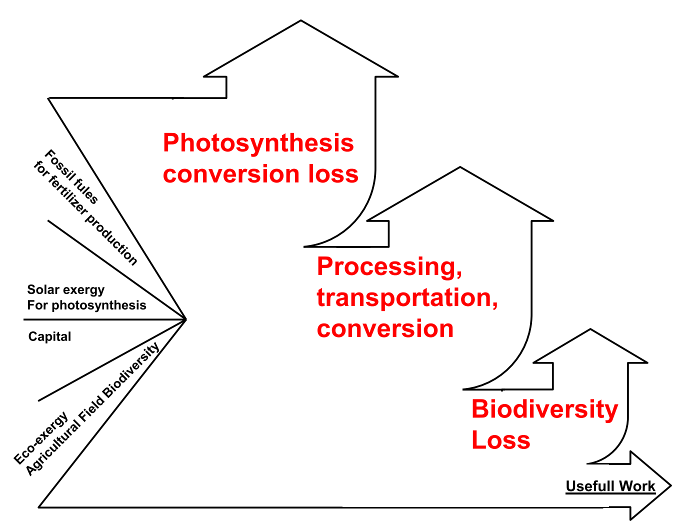

Fig. 6. Exergy diagram for a bioenergy system.

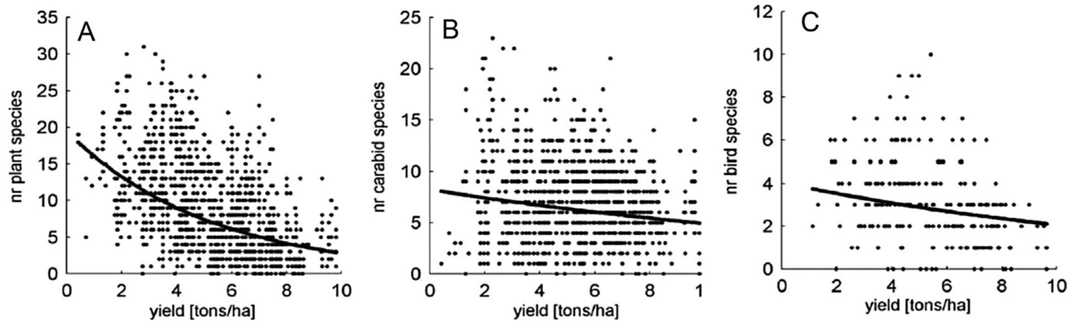

Fig. 7. Effects of cereal yield (ton/ha) on: (A) the number of wild plant species per sampling point, (B) the number of carabid species per sampling point, (C) the number of ground-nesting bird species per farm. Trend lines were calculated using GLMM, including the two surrounding landscape variables as covariates, and field, farm, and study area as nested random effects. Republished from Ref. [61] with permit.

(eco-exergy losses). An example for the eco-exergy losses calculation was given by Jørgensen, who calculated that the removal of 1 ha of forest leads to the losses $0.7 \cdot 10^7$ GJ of eco-exergy [68] (e_i in terms of Equation (18)).

A broad 2010 study on the environmental effects of intense agriculture in Europe showed that on average, an increase in cereal yield from 4 to 8 ton ha^{-1} results in the loss of plants (5–9 species), carabids (2–7 species), and birds (1–3) species (Fig. 7) [61].

The most recent survey of European birds has show a decrease of 421 million individuals, or 7000 tons of biomass [55]. Previous studies have indicated that cereal yield alone explained over 30% of the variation in birds population trends [69]. The eco-exergy losses in Europe due to bird biomass loss can be calculated using the following Equations (19) and (20) and Table 1:

$$e_{i_{aves}} = f\beta_{aves}(B_{aves_{1980}} - B_{aves_{2009}}) \tag{20}$$

Or

$$e_{i_{aves}} = 18.7\frac{KJ}{gr}\cdot 980\cdot 7\cdot 10^9 gr = 1.3\cdot 10^2 PJ \tag{21}$$

In 2008, 180.6 million ha of the EU 27 was dedicated to agricultural production [70]. If all the eco-exergy loss is driven by the current agriculture, the eco-exergy loss of the bird population is about 719 MJ ha^{-1}. It is also estimated that 7.8 million ha of agricultural land was directly devoted to the agriculture of biomass for renewable energy for the EU-27 in 2008 [71]. Under the mentioned assumptions, this means the European biomass renewable energy sector contributed to about 5PJ losses of the eco-exergy embedded only in the information lost with the reported birds biomass and diversity losses.

8. Recommended procedure for the determination of energy systems effects on eco-exergy

Complete assessment of land deployment effects on the biodiversity and eco-exergy is not possible today. What is possible is conduction of a preliminary feasibility study that will identify the major species that can be affected due to system installation. The effect of the system on these species should be quantified during all phases of system operation. These species should also serve as biomarkers for the energy system effects during installation, use, and deconstruction. The monitoring of these species will allow for system stabilization and control methods and will also enable more precise comparison between different systems types and locations. Such a monitoring tool will provide a quantitative method to compare systems sustainability.

9. Conclusions

Most of the large scale renewable energy systems have been under scrutiny to assess their environmental effects. The construction, deployment, and operation of these 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 renewable energy systems 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. Thus, they can be optimized during the system design. This 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 1Species Eco-exergy Weighting Factors [37,43].

Species	Exergy conversion factor
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

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