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Evaluation of two hydropower plants in Brazil: using emergy for exploring regional possibilities

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Two Brazilian hydropower plants (Jupiá and Porto Primavera) located in the same watershed were explored in terms of the global resources needed to support these enterprises using a donor-side approach. Emergy theory and methods although commonly used by environmental scientists, may seem difficult to interpret for policy and decision-makers. Because of this, the possibility of transforming emergy flows and indices into money and area measures is explored in the present paper. Both hydropower plants deliver the same power and rely on practically the same infrastructure but involve very different flooded areas. Indirect areas calculated in terms of emergy show the different spatial distribution of resources. Some realistic alternatives for development were explored from both environmental and economic perspectives by using the emergy investment ratio and taking into account the matching between the enterprises emergy flows and the regional ones.

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1. Introduction

Diverse aspects of emergy accounting in the production of hydroelectricity have been addressed in previous works. The first approach, which we considered as the more traditional emergy accounting form, identified and quantified all the inputs (defined as all the necessary resources required to construct the infrastructure and keep the hydroelectric plant in operation), in order to obtain the total emergy required to generate electricity via a hydroelectric plant. This former approach was adopted by some authors (Ulgiati and Brown, 2002; Brown and Ulgiati, 2004; Zhang et al., 2014). The emergy of the main product, electricity, is calculated through the addition of the emergy flows of all the inputs considered (without double counting). The transformity of the hydroelectric-generated electricity for the studied plants is calculated by dividing the sum of the emergy flows related to all inputs by the energy (expressed in J) generated.

The second approach focused on the benefits (not only electricity but also others) and costs in emergy terms derived from the hydroelectric plant construction and operation. In this way, benefits and impacts as a consequence of the construction of the dam are identified and quantified (Brown and McClanahan, 1996; Kang and Park, 2002; Cui et al., 2011; Pang et al., 2015). Not only the main product of the enterprise is taken into account but also those indirectly generated as a consequence. Brown and McClanahan (1996) concluded that the loss of sediment was the largest impact while among the benefits, electricity production was the largest followed by irrigation. Within this approach the transformity of hydroelectric-generated electricity is assumed from the literature. Always in emergy accounting, but especially when working under this approach, the system's frame must be well defined in order to clearly establish the extent of positive and externalities considered. In addition, the concept of benefits or cost is plausible of different “readings” according to the expertise of the analyst, pressure of the stakeholders' profile and interests, or subjective economic interests.

In general, benefits include: economic returns, social benefits (employment generation), service of regulating the river flow thus preventing dangerous situations downstream (floods or water shortage), water supply, recreation and fisheries (Von Sperling, 2012). As negative impacts: social disruption, sediment

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Abbreviations: DA, direct area; ED, empower density; EIR, emergy investment ratio; EIR_{SP}, emergy investment ratio of São Paulo State; ELR, environmental loading ratio; $Empd_R$, renewable empower density of the region; EMR, emergy per money ratio; Em*R$*, Em real; ESI, emergy sustainability index; EYR, emergy yield ratio; F, purchased resources; HP, hydro power plant; I_j, environmental resources; IA_F, purchased indirect area; IA_N, non-renewable indirect area; N, non-renewable resources; PP, Porto Primavera; R, renewable resources; Y, total emergy requirement.

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deposition, siltation, loss of genetic patrimony, climatic alteration and emission of greenhouse gases, are considered among others (Von Sperling, 2012). The inclusion of one or others of these costs and benefits into the emergy accounting depends on the extent of the system.

Although emergy accounting is today much more adopted as a useful and accurate methodology to access the global use of resources and evaluate environmental impact, a fact evidenced by the huge number of scientific papers published in the last ten years, it may be considered inaccessible for the uninitiated. This fact creates barriers for a straightforward language among researchers, government, policy makers, and the population as a whole. In order to solve that limitation, the translation of emergy terms to more accessible concepts as money and area (Odum, 1996), make the concept more understandable for managers, stakeholders and decision-makers. The latter approach was also explored by some authors to evaluate hydropower through the emergy theory. The topic was explored in terms of an emergy-modified ecological footprint (He, 2012) and in terms of support area (Ulgiati and Brown, 2002).

In the present paper two aspects will be approached since the resource water can be considered from two points of view, not necessarily divergent; its capacity for generating electricity due to potential energy and its intrinsic value since water is a vital natural resource for the survival of humans and ecosystems. Water reservoirs not only represent the capacity of water to store energy but also represent the confinement of the resource, a fact that might lead to the lack of this resource in more deprived regions. The decision of the most important or urgent use of water and its allocation is not trivial and requires a global vision in order to avoid controversial or subjective visions and prioritize objectively the real necessities. Its condition of provider of eco-services should demand a resource management system that assures an adequate and sustainable supply and avoids the deterioration of water ecosystems. In the present paper we treat the duality of water functions as a hydroelectric power source and as an irreplaceable resource in an integrated way.

Emergy accounting enables this interdisciplinary approach to handle the two cited aspects of water and establish a scientific decision-making frame as well as collaborate to develop policy for regional development-planning.

The aim of the present paper is to explore the use of emergy theory and methods to help in the decision-making of water management taking into account the “dual” role of water. For this purpose two hydroelectric plants located in Brazil were studied, one considered as a traditional hydro plant and the other with a smaller reservoir, considered as a Run-of-River with Modified Peaking hydro plant. The traditional emergetic indices were calculated as well as the indirect areas, related to purchased and non-renewable resources. Some alternatives for development in order to attain more sustainable designs were evaluated in terms of the emergy investment ratio (EIR) and by means of the concept of matching energy qualities (Odum, 1996).

2. Materials and methods

2.1. Emergy environmental accounting

Emergy accounting (Odum, 1996), a methodology based on thermodynamics, systems theory and ecology, was developed to account for all the global resources used to accomplish a process, product or service in a common basis as solar energy. It has turned into a scientific sustained tool to help environmental policy and decision-makers.

Since only a brief assessment will be provided here, the reader may refer to other literature (Odum, 1996; Odum et al., 2000).

Solar Emergy is defined as the available solar energy used up directly or indirectly to make a service or product. Its unit is the solar energy joules (sej).

The inputs flows are classified in three categories of resources: R, as renewable resources, N as non-renewable resources and F, coming from the economy (Odum, 1996). The resources contained within the former two categories are provided by the environment and are economically free. The outputs may include products, services and also emissions that are released to the environment. The total emergy requirement, Y is defined as $Y = R + N + F$. the sum of all the independent flows that enter the system.

Evaluation starts with energy systems diagramming, and for doing so, it is necessary to define the boundary of the system as well as the internal components and external sources. Specific symbols are used, where each have energetic and mathematical meanings (Odum, 1996).

Operationally, each input that enters the system has to be quantified and the raw data expressed in compatible units with the transformation factors that will convert, via multiplication, the raw data flows into emergy flows. The transformation factors include solar transformity (the solar energy required to make 1 J of a service or product), solar emergy per mass unit and emergy per money ratio (EMR).

The identification of the flows by the emergy environmental accounting enables the calculation of emergy indices. Only a brief description of the indices is provided here but complete information can be found elsewhere (Odum, 1996; Brown and Ulgiati, 1997). The emergy yield ratio, EYR, is the ratio of the emergy of the output (Y), divided by the emergy of purchased inputs (F). The emergy yield ratio, EYR, is a measure of the ability of a process to exploit and make available local resources by investing outside resources. It provides a measure of the appropriation of local resources by a process, which can be read as a potential additional contribution to the larger economy, gained by investing resources already available (Raugei et al., 2005).

The investment ratio, EIR, is the ratio of purchased inputs (F) to all emergy fluxes derived from local free resources $(R + N)$.

The environmental loading ratio, ELR, is the ratio of non-renewable (local and purchased) to renewable emergy flows. The higher this ratio, the bigger the distance of the technological development from the natural process that could have developed locally. In this sense, we can say that the ELR is a measure of the load on the environment.

The emergy sustainability index, ESI aggregates the measure of yield and environmental loading indices $(ESI = EYR/ELR)$.

The empower density of the enterprise $ED = (R + N + F)/\text{area}$, is the emergy per unit time per unit area and is a measure of activity.

The methodology enables us to convert resource use evaluated in emergy terms into the area demanded to supply those resources. When it is assumed that all the purchased requirements for the enterprise could be substituted by the local renewable resources of the region (Geber and Björklund, 2001), the “indirect area” is expressed as: $IA_F = F/Empd_R$; where $Empd_R$ is the renewable empower density of the region (sej km^{-2} yr^{-1}). According to Geber and Björklund (2001), this allows comparison of the direct and the indirect area demand, the direct area being that area directly occupied by the hydroelectric plants and reservoirs. As in Geber and Björklund (2001), the renewable larger input to the region was the contribution from rain.

Additionally, another indirect area, expressed as $IA_N = N/Empd_R$, is presented here and comparison among the three indices performed to explore to what extent space could substitute for purchased and non-renewable inputs required for hydropower

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