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Emergy analysis for addressing the complexity of climate actions

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In this Commentary, we advocate the use of emergy (spelled with "m") analysis to address and quantify – alongside with the scientific ones – the legal and social aspects that take part in the planning of climate policies and actions. Emergy analysis is suitable to approach the complexity of both local and global climate-related issues, offering a peculiar epistemology that overcomes the anthropocentric nature of current measures. At the same time, it allows the assessment of both nature and human-based flows of resources within a thermodynamic quantitative framework.

The science of emergy

The idea of Nature as the only real source of wealth has been concealed by monetary accounting, currently used to evaluate even the so-called "ecosystem services". This has created a growing cognitive dissonance, hindering the adoption of metrics based on biophysical and thermodynamic laws to which everything is subject. The global challenges posed by climate and ecosystemic emergencies urgently address the need to move beyond this paradigm and to reset our perspective, adopting systemic approaches for planning effective climate actions. In this context, an original and innovative proposal, almost underutilised in the legal, political and social aspects of climate actions, is offered by the emergy theory. The foundations of emergy analysis (EMA) stem from the work of Howard T. Odum[1–3]. It has been applied in a surprisingly wide range of fields[4,5], including ecology, economy, biophysics, chemistry, and sociology. In particular, the emergy evaluation of complex systems at all scales has become one of the most comprehensive approaches in the study of systems that encompass non-human and human elements.

Emergy is defined as the available energy of one kind that is used directly and indirectly in transformations to make a product or service. It represents a scientific measure—under the same energetic unit (solar emjoule, sej)—of all the resources "invested" to have something. Emergy Assessment converts each resource input into a common unit, representing *the overall memory* of the energy used—directly or indirectly—for the provision of that input. The conversion in emergy units is performed using coefficients called unit emergy values (UEVs), collected in an inventory published and updated by the United States Environmental Protection Agency[6]. It is based on the results of emergy research worldwide, providing validated UEVs for all possible categories of resources. Each UEV also accounts for the indirect environmental support embodied in human labour and services, adopting an upstream donor-side perspective instead of the more conventional downstream user-side one. This latter perspective connects the value of something to its human user in terms of willingness to have it, prize, and usefulness. The donor-side perspective, however, considers everything that must have occurred in the creation of a systemic output. The overall investment in terms of resources becomes, therefore, the quantitative measure of its value. The computation of the resources conversion into the common unit of solar emergy is guided by the thermodynamic principles, in terms of: (i) quantification of the amount of energy involved in all the transformation processes (first principle), and (ii) quantification of the irreversible loss of heat associated with these processes (second principle). Energy transformations occurring in a system involve various types of energy (radiative, mechanical, chemical), work, and heat, all necessary to create and maintain the complexity of the system, whose operation entails the production of entropy (second principle). Emergy accounting evaluates the overall "energetic cost" to create and maintain a certain system, in particular, any system that includes both natural and human activities. All the resource flows are comprehensively computed, allowing for the evaluation of the respective contributions from both humans and the environment. In this sense, EMA is the only currently used method that provides a direct *quantitative* non-monetary accounting of the relative work of the environment[7,8]. It must be emphasized that the overall energy required to create an environmental resource that has been degraded is equivalent to the energy required to replenish or regenerate it, that is, to keep it available over time. This is actually the physical core of the sustainability science.

Emergy and policy making

Emergy studies have increasingly been used for addressing the sustainability of complex ecosystems, also concerning their response to climate change and to mitigation and adaptation issues[9]. Nevertheless, the analysis has never been applied so far to address social and legal elements from the perspective of climate actions, despite its unique potential to provide a quantitative accounting. This is a focal point of our discussion. Emergy theory can represent a novel approach to climate actions for several reasons:

1. It can offer a comprehensive quantification of the (non-monetary) value of ecosystem services, an evaluation that is fundamental for any integrated sustainability planning[10,11].
2. From a legal standpoint, emergy analysis can quantify both environmental and social damages at any level, even before the damage occurs, enabling the assessment of climate-related legal actions. In fact, several courts and juridical bodies do not accept climate litigations that cannot quantify damages that have not yet happened. As reported by the UN Global Climate Litigation document[12], more than 2000 climate-related cases are currently filed in 65 jurisdictions, including international and

regional courts, tribunals, or other adjudicatory bodies. In this respect, the discussion during COP 28 about the creation of a "loss and damage fund" perfectly illustrates the need for a comprehensive and science-based metric.

3. Emergy may quantify—in units of available energy—other legal aspects that play a role in the setting up of climate actions, for example, how much a legal or social constraint can affect the overall non-monetary cost of an action, thus providing a metric useful for comparing different policy-making options.
4. Since emergy analysis includes all the resources (both environmental and human-related) managed in a complex system, it may identify potential social and legal leverage points for intervention, i.e., those elements of the system where relatively small external inputs can trigger a general rearrangement of the system functioning.

In practice, Emergy analysis of a system's operation provides a comprehensive family of emergetic sustainability indicators[2,4], each one analysing the relative costs of resource flows. They are separately classified in terms of environmental, local, imported, renewable, non-renewable, human-related and economic contributions. This allows for the comparison of the effectiveness of different planning and actions from all points of view and across different space and time scales.

It should be stressed that EMA is not a method for tracking the transmission of energy. Rather, it measures the transformation that exergy (available energy) undergoes during the growth of complexity within systems[13]. From a thermodynamic standpoint, emergy is not an observable state variable. It is not conserved; for example, in the case of co-products by a system, all emergy inputs are attributed to each product, as each has required the same investment. EMA does not provide a "photograph" of a system, but rather it is a picture of its dynamics, in terms of interactions with its environment and resulting self-organization. In fact, Emergy indicators, unlike "traditional" ones, are typically ratios between two or more flows that are dynamic quantities expressed in the same emergetic units.

Given this conceptual framework, it is clear how emergy evaluation can be an important and unique tool in decision-making processes related to climate actions. As stated by Campbell and Lu[9], "Managers (…) should have as a primary goal the development and implementation of policies that will maximize the emergy power flowing through their systems and thereby maximize system's functional integrity or health. (…) The relative emergy power generated provides managers a general criterion to use in choosing among alternative systems" and actions. This clarifies why emergy can be especially useful in integrated climate actions.

EMA and other sustainability assessment methods

Life Cycle Assessment (LCA) in its various forms is the standardized method that is most commonly used worldwide to assess sustainability. It quantifies, in terms of "impact categories", all emissions and resource consumption and depletion associated with the products of a system's operation. Impact categories are defined either as "upstream" (e.g., resource depletion, primary energy requirements, land use, etc.) or "downstream" (e.g., greenhouse gas emissions, water acidification and eutrophication, human and eco-toxicity, etc.). LCA analysis thus accounts for all the environmental effects, and it is used to improve the environmental performance as well to determine suitable indicators for decision-making procedures, since it can provide an analytical tool to compare different strategic options. LCA and EMA methods share the use of similar data inventories, but emergy provides a radically different indication of the potential impact associated with resource use, because of its basic conceptual aspects. EMA works within a donor-side framework, accounting for both the resources provided by Nature—independently of when they were provided and of the actual usefulness—and those related to humans' activities and society. But while LCA accounts for resources under human control, EMA also accounts for flows that are outside market dynamics, including the so-called ecosystem services. Moreover, energy-consuming flows not associated with significant matter and energy carriers, particularly those related to the social and cultural dimensions, such as labour resources and information provision, are not included in standard LCA, while EMA computes these "costs" under the same energetic unit of emergy. LCA and EMA are not in conflict, as they represent complementary viewpoints that give complementary evaluations and information. For example, Maiolo et al.[14] report on the use of EMA and LCA for the sustainability assessment of aquafeed plants, pointing out how only the former approach addresses the systemic organization of resource flows, providing indicators to determine the critical points of the system. Other thermodynamic-based methods overlook part of the energy flows related to environmental processes that have been necessary anyway[15]. Many examples from literature are focussed on the differences and the synergies between analytical methods[16–20]. EMA has been compared, for example, to Exergy analysis[21] and Embodied Energy[22]. Moreover, it has also been used in the assessment of cultural information flows[23], in Economics[7,10,24] and in social systems[8,25]. EMA is currently used in the quantitative determination of ecosystem services flow[26], and this is why it is particularly suitable as a metric for legal action as well. As pointed out by Ingwersen[18] emergy is the only measurable quantity that links resources used in a life cycle to the environmental processes necessary to replace these used resources, resulting, therefore, in the most suitable measure of the long-term sustainability of a system.

EMA and the SDGs agenda

An example clarifying the possible role of emergy in climate actions concerns the factual failure of the 2030 Agenda for Sustainable Development. We are halfway through its expected realization, but as pointed out by economist Jeffrey Sachs in the Sustainable Development Report 2023[27], "*At the global level, (…) not a single SDG is currently projected to be met by 2030, with the poorest countries struggling the most*." Unfortunately, the SDGs have been fragmented by the United Nations Committees into 35 groups, 169 targets and 244 indicators, making it virtually impossible to capture the systemic nature of most of the problems addressed by the respective goals. This is an attempt to make the problems more manageable by fragmenting the global emergency into a multitude of specific aspects, hoping that solutions can be addressed separately, without considering the mutual interference they exert on each other. This criticism has been addressed by the scientific community and properly documented in *Nature's* recent literature[28,29]. Emergy analysis may set up a specific family of emergy indicators, each one quantifying the synergies and the trade-offs, interconnections that rule the complexity and that, if neglected, become the ultimate cause of failure. The epistemological fallacy behind the failure of the SDGs is strongly linked to a concept of development based on the user-side perspective. This has affected all the legal systems that enacted that paradigm. Current environmental law, both in the Environmental Impact Assessment (EIA) and in the quantification of damages, addresses a fragmentation of reality, failing to capture the complexity that characterizes unified systems. The emergy analysis could overcome these contradictions, which arise from an inefficient compartmentalization of reality. Nevertheless, the potential of emergy has already been explored for groups of SDG-related issues in the so-called "nexus" studies[30,31], for example, by exploring the interconnections between the emergy flows in the food-energy-water system. Emergy assessment quantifies the resource flows required for the functioning of any system, including both the environment and human activities. In principle, this allows for the inclusion of all the interconnections between different SDGs (and between different items within the same SDG) in the definition of physical-based numerical indicators, which consider both trade-offs and synergies in the evaluation of sustainability. Since EMA is an integrated method that takes into account, by definition, all factors, it is suitable for addressing quantitatively the SDGs-related analyses.

Conclusions

Emergy may well represent a new metric in the design of climate actions, offering a comparative evaluation of different policies and scenarios. Design issues can also be considered[32], particularly those that challenge the anthropocentric mindset of an ontological separation between humans and Nature. Such a shift would recognize the intrinsic value of Nature, as well as the role of the laws of thermodynamics that maintain life on the planet. Such a change of legal paradigm implies the recognition of a new fundamental norm, based on emergy as a common foundational aspect of social, legal and economic forms of human relations with the world. In this Comment, we advocate the establishment of a research based on emergy analysis, to develop:

- A suitable metric to quantify legal concepts, such as the intrinsic value of Nature, in Environmental Impact Assessments or in the quantification of loss and damage in climate actions.
- A tool for quantifying under the same unit both environmental and human-related elements as defined in the environmental policies.
- A comprehensive narrative potentially bridging the languages of science and politics, both of which are crucial in setting effective climate actions.
- Unified participatory platforms to foster societal change through the application of Nature's rights, providing objective and verifiable criteria.

Data availability

No datasets were generated or analysed during the current study.

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F.G. conceptualized, wrote, and revised the paper. S.B., M.C. and L.C. contributed to the conception and writing of the paper.

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