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# THE REPRESENTATION OF ENERGY AND THE ENERGETICS OF REPRESENTATION

## an essay on the epistemology of energy

**Marcos Henrique Godoi**[1]
Universidade Federal de Uberlândia
marcos.godoi@ufu.br

**Jairo Dias Carvalho**[2]
Universidade Federal de Uberlândia
jairodc@gmail.com

**Abstract**

Epistemology of Energy is a subfield of the emerging Philosophy of Energy that deals with how its representation shapes energy use and its implications. While current energy transition strategies emphasize technological solutions to reduce greenhouse gas emissions, this narrow focus neglects other critical dimensions, such as biosphere integrity and the concurrent supply of ecosystem services necessary for a sustainable society. The concept of energy, usually abstract in physics, must account for its qualitative diversity in practical applications. This work examines the relationship between the metabolism of energy in organisms and societies and the challenges of transitioning to clean energy systems. Addressing environmental issues requires a comprehensive approach considering the complex interplay of social metabolism and ecosystem dynamics. Simplistic dichotomies of "clean" versus "dirty" energy fail to capture the multidimensional nature of sustainability. We conclude that a broader epistemological framework is essential to design effective energy policies that integrate ecological, social, and technological considerations.

**Keywords**: epistemology; philosophy of energy; energy transition.

# A REPRESENTAÇÃO DA ENERGIA E A ENERGÉTICA DA REPRESENTAÇÃO

## um ensaio sobre a epistemologia da energia

**Resumo**

A Epistemologia da Energia é um subcampo do emergente campo da Filosofia da Energia, que trata de como sua representação molda o uso da energia e suas implicações. As mudanças climáticas, fruto do crescimento da produção industrial ao longo dos últimos dois séculos e meio e da matriz fóssil de energia que abasteceu este processo, tornam necessária uma transição energética que substitua essa matriz. Enquanto as estratégias atuais de transição energética enfatizam soluções tecnológicas para reduzir as emissões de gases de efeito estufa, esse foco restrito negligencia outras dimensões críticas, como a integridade da biosfera e o concomitante fornecimento de serviços ecossistêmicos que são essenciais para uma sociedade sustentável e funcional. O conceito de energia, tratado geralmente na física como uma quantidade abstrata, deve considerar sua diversidade qualitativa nas aplicações práticas, sob pena de não ser capaz de torná-las operacionais, algo que se verifica facilmente no tratamento deste conceito por parte das engenharias. O presente trabalho examina a relação entre o metabolismo da energia em organismos e sociedades e os desafios de transitar para sistemas de energia que não excedam a capacidade do ambiente de metabolizar seus efeitos. Para isso, propõe-se que as questões ambientais requerem uma abordagem abrangente que considere a complexa interação entre o metabolismo social e a dinâmica dos ecossistemas. Dicotomias simplistas de energia "limpa" versus "suja" não capturam a natureza multidimensional da sustentabilidade, e interessam mais a grupos sociais que se beneficiam pela padronização de processos usando

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[1] Doutor em Desenvolvimento Econômico pela Universidade Estadual de Campinas. Pesquisador no Centro de Pesquisas Econômico-Sociais do Instituto de Economia e Relações Internacionais da Universidade Federal de Uberlândia.

[2] Doutor em Filosofia pela Universidade Federal de Minas Gerais. Professor Titular do Instituto de Filosofia da Universidade Federal de Uberlândia.

tecnologias sob os quais podem manter o controle. Concluímos que um arcabouço epistemológico mais amplo é essencial para projetar políticas energéticas eficazes que integrem considerações ecológicas, sociais e tecnológicas.

**Palavras-chave**: epistemologia; filosofia da energia; transição energética

## LA REPRESENTACIÓN DE LA ENERGÍA Y LA ENÉRGICA DE LA REPRESENTACIÓN

un ensayo sobre la Epistemología de la Energía

**Resumen**

La epistemología energética es un subcampo del campo emergente de la filosofía energética, que se ocupa de cómo su representación da forma al uso de energía y sus implicaciones. El cambio climático, el resultado del crecimiento de la producción industrial en los últimos dos siglos y medio y la matriz de energía fósil que ha suministrado este proceso, es necesaria una transición de energía que reemplazara esta matriz. Si bien las estrategias actuales de transición de energía enfatizan las soluciones tecnológicas para reducir las emisiones de gases de efecto invernadero, este enfoque restringido descuida otras dimensiones críticas, como la integridad de la biosfera y el suministro concomitante de servicios ecosistemas que son esenciales para una sociedad sostenible y funcional. El concepto de energía, generalmente tratado en física como una cantidad abstracta, debe considerar su diversidad cualitativa en aplicaciones prácticas, de lo contrario, no puede hacerlos operativos, algo que se verifica fácilmente en el tratamiento de este concepto por ingeniería. El presente trabajo examina la relación entre el metabolismo energético en los organismos y las sociedades y los desafíos de la transición a los sistemas de energía que no exceden la capacidad del medio ambiente para metabolizar sus efectos. Para esto, se propone que los problemas ambientales requieren un enfoque integral que considere la interacción compleja entre el metabolismo social y la dinámica de los ecosistemas. Simplemente las dicotomías de la energía "limpia" versus "sucia" no capturan la naturaleza multidimensional de la sostenibilidad, y más interés para los grupos sociales que se benefician de la estandarización de procesos utilizando tecnologías bajo las cuales pueden mantener el control. Concluimos que un marco epistemológico más amplio es esencial para diseñar políticas energéticas efectivas que integren consideraciones ecológicas, sociales y tecnológicas.

**Palabras clave:** epistemología; filosofía de energía; transición energética.

## 1 INTRODUCTION

As a part of the more comprehensive ecological transition, the energy transition is one of the main themes when we think about where our society is heading. However, we cannot deal with this issue as a purely operational problem that can be solved with the right technologies and engineering solutions. The energy transition is also about how we understand energy and its uses.

The energy transition process we are living through today is far from being the first. Before the industrial age, energy sources to fuel human production were based on the flow of matter like wind or water, caused by, ultimately, the sun, and on animal power. These sources have obvious limitations: the flow of matter is not controlled by humans, and it cannot, therefore, either be expanded or be used reliably; and the physical constitution and nutrition give the limitations of animal power. Nonetheless, these were the energy sources first used even at the beginning of the Industrial Revolution, being applied to the cotton spinning industry which was the focus of innovation then (Viollet, 2017).

But if the previous energy transitions of history were linked to both the availability of the sources and adequacy to its end use, the one we currently experience is a product of the effect of Greenhouse Gases (GHG) on the planet's climate. Instead of being a source problem, as was thought in the 1960s (Meadows et al. 1972), the real problem the energy transition from fossil fuels is trying to deal with is a sink problem (Daly, 1990), a problem about the consequences of energy use, which is linked to the kind of source it comes from. As of 2022, fossil fuels have an 82% share of total energy consumption (BP Global, 2023). In the business-as-usual scenario from the International Panel for Climate Change, it is expected a rise in global mean temperatures of 4.4°C, which would result in more extreme heat events, a huge loss of biodiversity, especially in the equator, and a reduction of up to 35% in food production, among other effects (IPCC, 2023).

For these reasons, we must transition from fossil energy sources to ones that are carbon-neutral, or which at least are less intensive in GHG emissions. But this is not easy: changing energy sources implies changing energy systems, as a different energy source will need different ways for storage, and transmission, and will have different kinds of impact that also need to be mitigated. This is one of the major flaws in the current energy transition: it is too centered on carbon.

This work is a part of the emerging field of Philosophy of Energy, in which we situate the Epistemology of Energy (Heuterbise, 2020). To deal with the problems above, the paper is separated into four sections, besides this introduction. The first one discusses how energy is represented in the mind. The second one deals with the idea of energy systems as metabolism and the need to dissipate its impacts so that entropy does not increase. The third will link this discussion of how energy is metabolized and represented to the current energy transition. Conclusions follow.

## 2 ENERGY AND ITS REPRESENTATION IN THE MIND

The representation of energy in Western philosophy begins with Aristotle and his concept of energeia. In the interpretation of Aryeh Kosman, energeia can be understood as the activity-of-being, which means the activity that is proper to that species of being. It is related to the actualization of the being's potential (Hjertholm, 2023). In more recent times, when Newton began to build the conceptual edifice that became modern physics, he used the concept of force to explain what moved the bodies. Later scientists, continuing Newton's work, wrote about different kinds of force that explained the behavior of electricity, heat, and chemistry (Boudri, 2013). These were predecessors to the modern concept of energy, but these were still considered to be different substances. The inception of the concept of energy was hindered by the caloric theory of heat, introduced by Lavoisier, which insisted on this mistake. It was only with Rumford that heat began to be understood as motion (Muller, 2007). Although the word "energy" was already in use in the 18th Century, it only attained its current meaning in the 19th Century. In its beginning, it was usually a synonym for activity, as it was seen as a result of motion. The term had a slow expansion of its meaning, from what we know as kinetic energy to other forms of energy. The idea of energy as a substance was only definitely abandoned with Maxwell's work, which gave the modern definition of energy by considering energy everything that can be converted from or to motion (Lopes Coelho, 2009).

It is easy to understand how the idea of different energies, each one considered as a substance, could be seen as obvious by the scientists of that age. When we deal with energy in everyday life, it is always necessary to specify which form of energy we are discussing. There is no qualityless energy: energy is always kinetic, electric, thermal, etc. In contemporary physics, the situation is the opposite: energy is understood as a non-substantial quantity. So, what exactly do we mean when we talk about energy?

The most common concept of energy is the ability to do work. Work here is physical work, defined as the ability to move a body with a given mass in space for some distance. By this definition, energy forms that cannot be converted into mechanical effects would not be considered energy, like heat in a body colder than its environment (Lancor, 2012). The term "energy forms" is essential to understanding energy in everyday life. As energy cannot flow without the simultaneous flow of at least one other substance-like quantity, energy will be categorized in accord with that substance-like quantity (Falk; Hermann; Schmid, 1983). An agent will mostly deal with energy by manipulating its material carrier, with instruments that are specific to that kind of carrier.

Although theoretical physics does not make a substantial distinction among energy forms, these distinctions are necessary for human action. Energy forms are usually divided into two groups: kinetic and potential. Kinetic energy is the energy involved in motion and includes: mechanical energy, the movement of macroscopical bodies; thermal energy, or heat, as it is produced by the random movement of molecules and atoms, is a measure of how fast these particles are moving; and electromagnetic energy, the movement of charged particles. The first form of kinetic energy does not need further explanation to be understood as a kind of motion; the second, thermal energy, is also easy to fathom, as the movement of microscopical particles that is felt as heat is caused by collision with other microscopical bodies, in much the same way as mechanical energy, but in another scale. The difference is due to our lack of capacity to track an immense number of particles. The third one, electromagnetic energy, needs some more explanation.

Electromagnetism is probably the hardest energy form to be reduced to kinetic energy. The movement of electrons is not produced by the transmission of energy by direct contact, but by the way particles with different charges behave to each other. But to understand why even this energy form is still, in the end, kinetic energy, we first need to understand what charge is in physics. Just as macroscopic bodies with masses can be moved by gravitational force, electrically charged bodies are moved by electric forces. As force in a mechanical system, which is conserved as energy is transferred from one body to another, the same happens in a system of bodies subject to electric forces. They also can be quantized, which is discrete quantification in which the fundamental unit is the charge of one electron or proton (Young; Freedman, 2012). Therefore, we cannot tell exactly what a charge is, only its effects on charged bodies (Boss; Souza Filho; Noronha, 2008).

But this mathematical description is just an abstraction: it accurately describes the movements of charged particles subject to electromagnetic forces. The explanation is just backward: from the movement of particles we observe and model, we postulate a force only determined by the movement of bodies and its associated effects on matter.

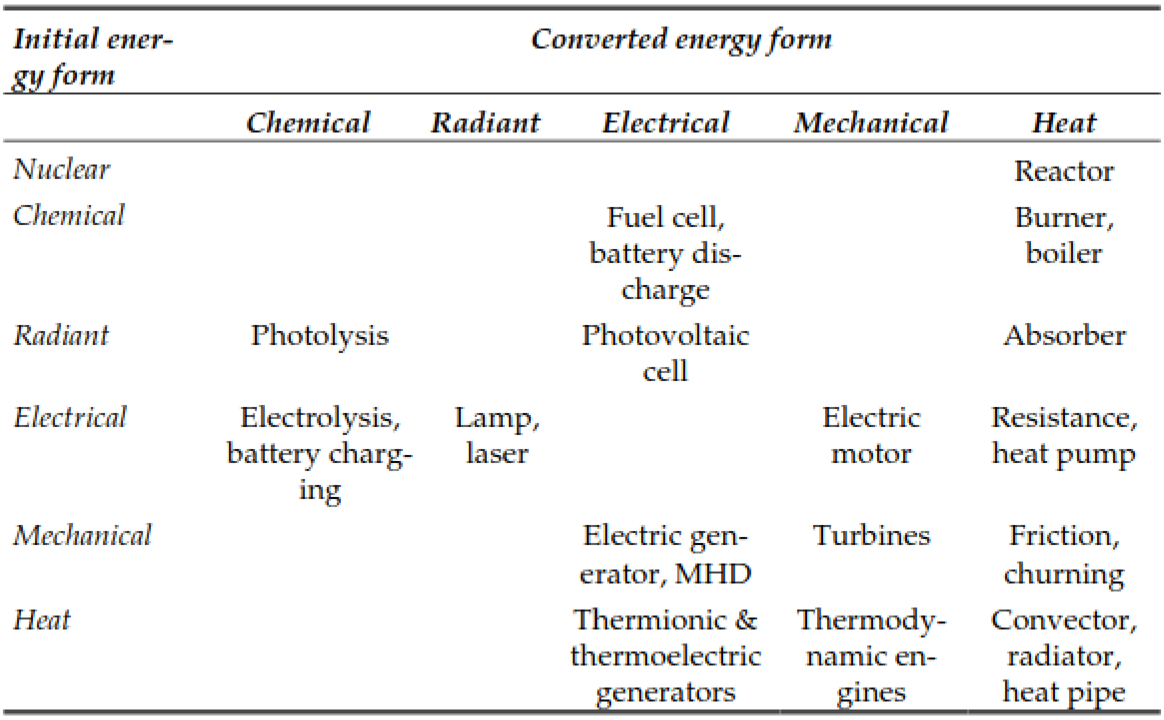
Potential energy forms, on the other hand, are forms of stored energy. The correspondent of mechanical energy in this group is gravitational potential energy, in which something that can “fall”, i.e., is being prevented from being attracted to another body that exerts a gravitational pull on it, has an amount of energy equal to this pull and to what would be released as it “fell’; electromagnetic potential energy, in which a charge differential is yet to be resolved by interaction with other charged particles; and nuclear potential energy, which is based in the two fundamental forces of strong and weak nuclear force, which binds the atoms together. We could add chemical energy, the energy that binds the atoms in molecules by covalent bonds.

A further complication appeared with the 19th-century discovery of thermodynamic processes. In Newtonian physics, as we deal only with the movement of bodies, all processes are reversible, being only changes in the positions of such bodies. However, this framework was developed to understand the movement of bodies caused by external factors. The development of steam engines in the late 18th Century posed a new problem: the movement caused by a heat engine. In this case, a transformation happening inside the system provides the force. Carnot was the first to note a phenomenon that would reach its definite form with Clausius: that heat can only be transferred from the hotter body to the colder one, and always with some loss, as some energy would become work. This conversion to work cannot be complete unless the temperature of the cold body is absolute zero. So, there will always be some energy loss that does not become useful work. This breaks the reversibility assumption, as the ability to do work will always tend to zero in time. This is the second law of thermodynamics, the entropy law (Muller, 2007).

With this, a novel distinction was introduced in physics: the one between free and dissipated energy, the former being one that can do work and the latter cannot. This distinction is not substantial, as the previous ones. Nevertheless, it does involve a conversion between two energy forms, heat and motion. If heat cannot fully become motion, how can these not be considered two different energy substances? The answer was provided by Boltzmann at the end of the 19th Century, showing that this is a result of thermal movement, the random movements of atoms and molecules. The spatial configuration of these bodies is called complexion by Boltzmann, and some are more probable than others (Enders, 2021). The entropy increase derived from these heat losses would make the system evolve to a more probable state of matter, eliminating the necessity of a substantial distinction among energy forms.

Energy forms are considered in Physics to be superfluous at best, and detrimental to understanding the concept of energy at worst (Duit, 2014). But if we leave pure physics to see its application in engineering, we notice that it is impossible to avoid energy forms. The figure below shows a board in a book about energy conversion:

**Figure 1 -** Conversion of Different Energy Forms



| *Initial energy form* | *Converted energy form* | | | | |
|---|---|---|---|---|---|
| | ***Chemical*** | ***Radiant*** | ***Electrical*** | ***Mechanical*** | ***Heat*** |
| *Nuclear* | | | | | Reactor |
| *Chemical* | | | Fuel cell, battery discharge | | Burner, boiler |
| *Radiant* | Photolysis | | Photovoltaic cell | | Absorber |
| *Electrical* | Electrolysis, battery charging | Lamp, laser | | Electric motor | Resistance, heat pump |
| *Mechanical* | | | Electric generator, MHD | Turbines | Friction, churning |
| *Heat* | | | Thermionic & thermoelectric generators | Thermodynamic engines | Convector, radiator, heat pipe |

Sorensen (2007, p. 4)

As we see, to deal with energy in practice, we cannot avoid energy forms. In most recent books, the term energy forms is swapped for energy types (Demirel, 2012), energy stores (Duit, 2014), and energy carriers (Falk; Hermann; Schmid, 1983), among others. But the overall idea is still there: if physics deals with energy as an abstract quantity, not directly observable and impossible to measure directly (Lancor, 2012), this can only happen in theory or mathematical modeling. In real life, we have to deal with qualitatively different forms of energy. In the next section, it will be seen how energy is treated by living organisms, that need free energy to keep living.

## 3 ENERGY METABOLISM AND THERMODYNAMICS

When it started to become clear that the effects of the growing economies on the environment could not be ignored, in the 1960s, many different approaches were proposed to understand and deal with this issue. Among them was Georgescu-Roegen’s (1971) theory that understood economic activities as entropic processes. For him, human societies depend on low-entropy resources that are transformed, by economic processes, into useful objects. The main goal of the economy is, in this framework, to generate utility that is consumed when goods and services are provided. On the other hand, when these products are fully consumed and their utility exhausted, they become high-entropy waste. As this waste accumulates in the environment, the system loses order and problems arise.

It is easy to see this happening in the case of fossil fuels: they are found in nature in the highly organized forms of coal and oil. Once they are used to provide energy, they become (mostly) $CO_2$, which then spreads to the whole atmosphere. In their organized form, they are buried so they do not interfere with the climate. But once they become $CO_2$, they become a hazard, since they absorb heat and warm the atmosphere, interfering with the metabolism of living beings and ecosystems.

Georgescu-Roegen representation of society and economics as thermodynamic processes, rather than reversible mechanistic ones, comes from an understanding of humans as part of nature, as any other living beings. At least since the 1940s, life has been understood as a thermodynamic phenomenon. Schrodinger's (1944) seminal work on the topic describes life as depending on the ingestion of low-entropy matter that will, in its normal activity, be metabolized into high-entropy waste. Although accurate, this description does not explain much: how exactly does low-entropy matter allow living beings to keep their organization, as opposed to other thermodynamic systems that evolve towards equilibrium, a state in which they are most disorganized?

To understand why this is so, we need first to understand how an organism deals with its entropic nature. If we formalize an organism's dynamics into a mathematical model, we will have a formal system that represents its behavior. This formal system has two kinds of parameters: constitutive ones, which describe simultaneity relations by which its components, in a lower level of the system's hierarchy, are causally entailed, producing its current form; and the parameters that describe the organism's interaction with its environment, which are relations of temporal succession. Using this framework, we can use a biological metaphor for any formal system: the constitutive parameters are like an organism's genome; the phenotype, the actual values measured of the organism; and the environment, the parameters directly linked to the temporal dynamics that represent the relation between what is inside and what is outside the organism. This latter kind of parameter is always linked to some defined environmental quality (Rosen, 2012, pp. 340-350).

For us to understand how this ingestion of low-entropy matter could keep the organism's organization, it is essential to understand that, although matter is ultimately composed of bodies that have no intrinsic quality (the qualities of materials, for example, emerge from how they are organized in their molecular structure), only quantities (extension and mass), the organism would not be able to navigate such an undifferentiated world . Instead, the organism has to be able to find food (energy sources) and hide from dangers. To do this, the organism's form is given by the causal entailment of its components on its lower levels (Rosen, 2012, p. 379). This form produces the organism's perspective, which allows it to do what is necessary to keep being alive.

As with any other thermodynamic system that operates far from equilibrium (Prigogine; Stengers, 1981), organisms depend on an energy source that comes into the system for it to continue its metabolism. But this cannot be a generic energy source: it must be the specific form demanded by the organism's constitution. And because of the pressures of natural evolution, the fittest organisms will be the ones that can more easily find this source. Therefore, the very representation the organism will make of the environment it lives in will be based on the specific qualities that are relevant to its survival. This has been known in the literature by the concept of Umwelt, developed by the German biologist Jacob von Uexkull (Allen; Hoekstra, 2015).

So, what the organism absorbs when it ingests low-entropy matter is not organization per se, as Schrodinger believed, but the input demanded by its form, in its qualitative specificity. But quality is not formless: anything the organism is ingesting, is a body in itself, having its structure. This structure is given by the causal entailment of its components, which can be more or less complex in itself. If the organism is ingesting something that was once alive, we will have many causal relations occurring at different levels to produce its form. If not, it will be a molecule whose form is determined by the covalent bonds of its constitutive atoms. In any case, this form has to be compatible with the form of the organism that will metabolize it, or else metabolism would be impossible, since metabolism is always the processing of one body by another. The simplest example possible is the key-lock theory of the functioning of an enzyme: the geometric compatibility between the molecules allows the enzyme to metabolize another substance. Although there is currently a more advanced theory on this issue, the induced fit theory, it does not contradict the former theory, only adding to it in the case of more flexible enzymes (Koshland Jr., 1994).

Hence, it is a specific kind of organization compatible with the organism's form and allows its components to perform the functions needed for its survival and reproduction. The form of the organism is a product of the interaction of its predecessors with the environment, which does change itself too with time. Evolution can be understood as this continuous interaction between the environment and the organisms living in it, with the metabolism of each affecting the other and causing it to change and adapt (Schwartzman, 2010).

Because of this, only the specific form demanded by the organism's form can be considered, low-entropy matter for it. Despite how organized and complex could be any other substance, it will not be represented by the organism as a source of free energy. In much the same way, when the low-entropy input is metabolized, the byproduct of this metabolism is something that can be considered high-entropy matter for the organism that expels it, but not for some other kind of organism. The main difference between living and non-living thermodynamic systems can be summarized by the specific character of free energy for living beings, as opposed to non-living, far-from-equilibrium thermodynamical systems that admit more different energy inputs to the system (Prigogine; Stengers, 1981), and not that organism absorb organization, as Schrodinger (1944) would put it. That is not to say that things the organism did not evolve to use do not affect it, as radiation would, for example. But suppose some unexpected input affects a non-living, far-from-equilibrium thermodynamical system. In that case, it will not destroy its form and ability to metabolize as it would with a living one (that would most likely die after the effect).

Therefore, when an organism expels the byproducts of its metabolism, it increases the entropy of its environment, as represented from its perspective, its umwelt. This happens because not only its byproducts are useless for it, but also because their accumulation in the environment means that there are no other organisms able to metabolize them. As every metabolism is based on bodies interacting with other bodies, the presence of useless bodies can interfere with the metabolism of the organisms that constitute the ecosystem. To return to an example already presented in this paper, the accumulation of $CO_2$ in the atmosphere warms it, which interferes with the metabolism when the processes are sensible to temperature changes.

But when there are in the ecosystem other organisms that can metabolize the byproducts of each other's metabolism, entropy is kept constant. From a specific organism's perspective, the others' byproducts are not high-entropy matter, but low-entropy instead. The existence of a living being is dependent on this circularity: inside an organism, its components are causally entailed in such a way that what is a byproduct for one many times is a free energy source for another. This is what constitutes the form of the organism, in terms of its genome, and makes life possible as we understand it (Rosen, 2012, p. 379). When we go higher into the ecosystem, its stability is also improved by the diversity of its components, allowing it to survive perturbations more easily the more species are involved in this circularity (Loreau, 2022).

So, to consider something as low-entropy or high-entropy matter, we have to consider the perspective of who represents the energy source. When we look at non-living thermodynamic systems, this is not obvious because these systems, although they may operate far from equilibrium, are much simpler than living organisms. Even so, a thermodynamic system operating far from equilibrium must be complex to some extent, or it will inexorably tend to equilibrium. What a system must present to avoid thermodynamic equilibrium are bifurcation points, in which its dynamic changes as a result of an intensification of an energy flux entering the system (Prigogine; Stengers, 1981). The different subsystems that allow an organism to do more with the same energy input, without accumulation of entropy in its inside can be considered bifurcations to the overall system's dynamics (Rosen, 2012, pp. 300-305). Bifurcations are the source of complexity, and the more there are, the more complex a system can be without needing further energy inputs. This is true about organisms, ecosystems, and also about societies (Allen; Tainter; Hoekstra, 2003).

Since we now understand how energy flows into and out of complex systems, we will now proceed to see how this holds up when we apply it to society.

## 4 ENERGY TRANSITION

As mentioned in the introduction, the energy transition we are currently living through is not the first one. Fouquet (2010) reviewed 14 past transitions, understood as the switch from an economic system dependent on one or a series of energy sources and technologies to another economic system, to show that each new system was cheaper than the old one. But this conclusion can be misleading, as the cost of producing from the new energy source was often more expensive than the last. The answer to the apparent paradox is that the new economic system had other advantages than the old one, such as ease of use, flexibility, and cleanness. As these advantages also have value to the consumer, the result was a "bigger package" of goods for a price slightly higher, and that can become cheaper in time with gains of efficiency through learning and scale (Grubler; Nakicenovic; Victor, 1999). Furthermore, price volatility from an energy source can also be a factor to motivate energy transition (Allen, 2009).

Nonetheless, transition from one energy system to another is not only a technological issue. For instance, Lee & Yang (2019) found out that while democratic countries are leading the transition from fossil fuels to nuclear and renewable energy, autocracies are holding onto carbon-based energy. The explanation, according to the authors, is that autocracies privilege the maintenance of the regime. The lack of accountability also makes the shift to another energy system improbable. Fischer-Kowalski et al. (2019) argue that at the beginning of the transition from biomass-based fuels to fossil fuels, social revolutions happened as a result of the increased availability of energy. The authors estimate that an interval of 0.47 to 7.71 GJ/capita/year marks the "critical phase" for social revolutions in the considered energy transition. That is, as the energy per capita increases to 0.47 GJ/year, social revolutions become more probable until they reach the "safe zone" beyond 7.71 GJ/year. To explain this, the authors bring many hypotheses, ranging from the behavior of complex systems that change radically when a bifurcation point is reached to the conflict over the new energy sources.

When we deal with energy transition and, from a wider perspective, energy management in society, we need to go beyond the technical matters into the way energy is represented by different agents, as this can be a source of social conflict. As our current energy transition is not based just on increasing energy use, but mainly on switching a "dirty" energy matrix for a "clean" one, conflicts will arise on environmental issues. But to understand this, we have to ask ourselves: what exactly is a clean energy source?

Although there were already studies linking the atmospheric greenhouse effect to fossil fuel consumption in the late 1930s, these were ignored until evidence piled up in the 1970s. By 1990, human-induced global warming was recognized by most in the scientific community as a fact (Corfee-Morlot; Maslin; Burgess, 2007). Climate change due to the accumulation of GHG risks disrupting food production and living conditions around the world. As it is mostly a result of burning fossil fuels, the natural response was to move in the direction of an energy transition to mitigate the problem.

Since the public debate on climate change started with the problem of GHG emissions and the greenhouse effect, it is not surprising that the focus is on technologies that reduce them. But the same public debate often ignores other risks to the global climate's stability, also with harmful consequences. To understand this, we have to deal with the relationship between climate, ecosystems, and human welfare.

The effects of the biosphere on regulating the atmospheric composition and the carbon cycle in a way that improves its survivability have been known at least since Lovelock & Watson's (1982) work. Today, we know that just the physical presence of vegetation controls climate drivers such as soil moisture, light environment, and temperature. It also influences biogeochemical aspects by emitting a series of reactive trace gases that are a function of meteorological and climatological conditions at the surface. These emissions and subsequent products can influence atmospheric processes such as the attenuation of radiation, the formation of GHG, and the alteration of clouds and precipitation. These processes can create negative or positive feedback loops (Steiner, 2020) that are essential to stable far-from-equilibrium thermodynamic systems.

Furthermore, our societies don't only need a stable climate to live. There's a range of other ecosystem functions that are vital to human lives, such as providing food, fresh water, and materials, and regulatory functions such as disease regulation and the already mentioned climate regulation. These functions we call ecosystem services (MEA, 2005). They come from the linkages among different species inhabiting different ecological niches in each ecosystem that comprise the biosphere. As the behavior of these species makes them provide other species with actions or materials that are fundamental for their living, they fulfill a function for the whole ecosystem.

As seen in the previous section, this is exactly how the ecosystem, being a complex thermodynamic system, can be stable, constraining its entropy production. In the same way that there exists an ecosystemic metabolism that results from each organism's way of being and at the same time provides the different species in the ecosystem with suitable conditions to live, there is also a social metabolism that links human societies to the overall biosphere. It is defined by the relation between natural resources and services use and the social structures and functions (Madrid; Cabello; Giampietro, 2013).  In the analysis of social metabolism, it is necessary to consider its viability concerning external constraints and its feasibility concerning internal constraints. The former is related to the limits of the environment in which a particular society exists, especially in the way that this environment (which is also a system) provides society with its necessary inputs and how it absorbs its subproducts. The latter is related to its dynamics, which includes the internal autocatalytic loop that is characteristic of complex systems and the ability of internal components (subsystems) to produce and deliver the required supply of energy and materials that are needed by other components (Giampietro; Mayumi; Sorman, 2011).

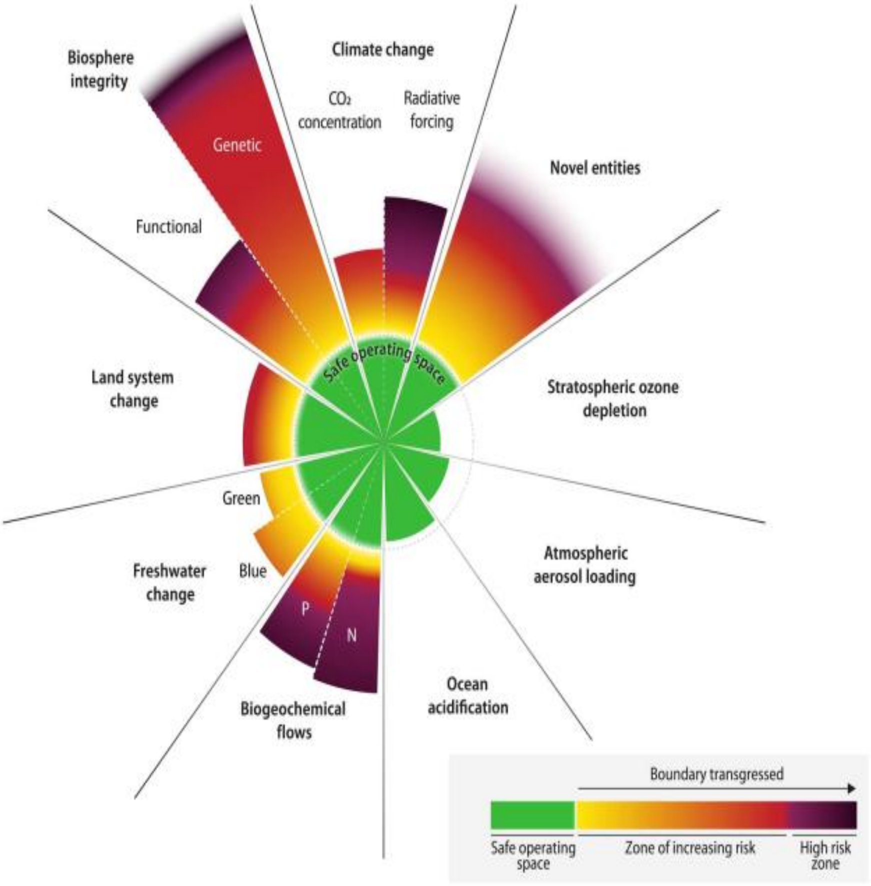
If we understand the energy system that fuels a modern society as a subsystem of the overall social metabolism, then for the whole society to be sustainable, in the sense of keeping a constant level of entropy, its subproducts must be dissipated by other systems. But these subproducts can never be reduced to a single measure, as it would be in the way modern physics represents energy, as an abstract quantity. As they must be metabolized by other specific systems, the subproducts will always need to be considered in their specificity. Hence, different energy forms will need qualitatively different metabolic processes.

When we reduce the concept of energy to an abstract quantity, devoid of any quality, we cannot understand how energy flows in living systems. Accordingly, when we conceive the problem that the energy transition tries to resolve as a switch between dirty and clean energy, we also cannot deal adequately with the environmental problems caused by the increased scale of social metabolism that is an effect of the amount of energy entering the system.

An immense number of qualitatively different processes comprise the biosphere, and what is considered free energy or high-entropy refuse depends on the specific form of the organisms that metabolize it. For this reason, it is not only the scale of the metabolism (the amount of Joules) that determines if it is sustainable, but if the different processes happen at compatible rates, making one subsystem produce what the other needs in the right amount and other eliminate possibly toxic residue in a rate that does not allow it to accumulate.

When we apply these ideas to the energy transition, it becomes clear that the distinction between clean (carbon-neutral) and dirty energy muddles the qualitative diversity of processes that makes it possible for a complex system to exist far from thermodynamic equilibrium. As it only considers one dimension, GHG emissions, new technologies introduced are selected by the market considering only the potential to curb such emissions. Nonetheless, climate change and, more broadly, environmental issues are about much more than only the greenhouse effect. Figure 2 below shows some of the problem’s amplitude:

**Figure 2** - Planetary Boundaries



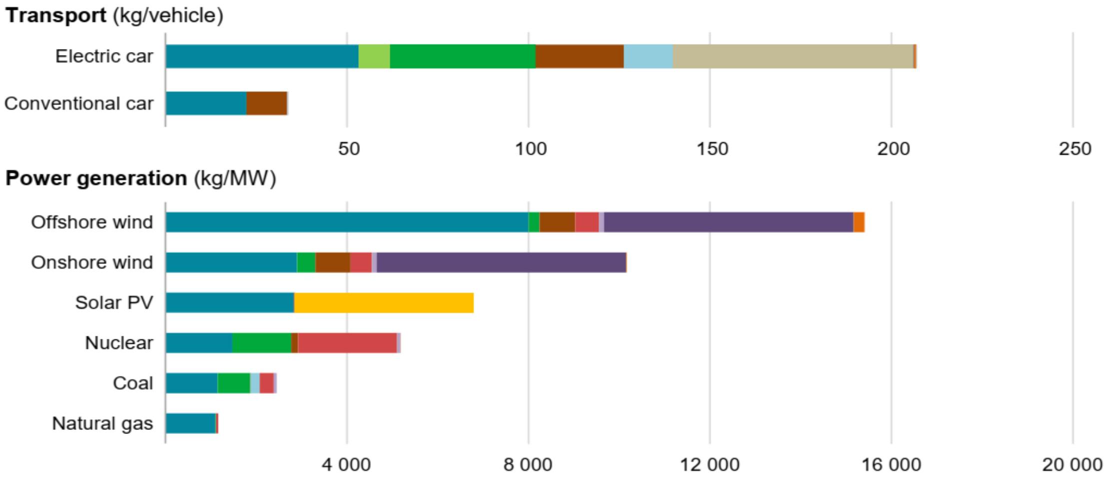
Richardson *et al.* (2023, p. 4)

In this paper, Richardson et al. (2023), based on earlier works, show that there are at least nine planetary boundaries. These boundaries represent components of the Earth system critically affected by human action.  Six of them are already out of the safe operating space, and the GHG emissions are only one of them.

As we have seen, human life and welfare depend on the ecosystem services provided by the biosphere, which are in turn a result of the metabolism of different species that comprise the ecosystem metabolism. Each of these boundaries would affect these metabolisms and the concurrent services that come from them. Land system change means the natural environments that are swapped for agricultural land, forfeiting its services. Biosphere integrity means the diversity of species and their functional relations that are essential for ecosystem metabolism. Novel entities are new chemical compounds that are emitted without robust knowledge about their risks. Freshwater change means the appropriation of water by humans, which can be harmful when too little water is left for the ecosystem to operate adequately. Similarly, biogeochemical flows are also about the appropriation of chemical elements that are vital for agriculture but also for the ecosystem's existence, and the lack of it can endanger the integrity of these ecosystems. Ocean acidification, stratospheric ozone depletion, and atmospheric aerosol loading, although they are still at safe levels, can also be harmful to environmental conditions that are needed for different species' way of life.

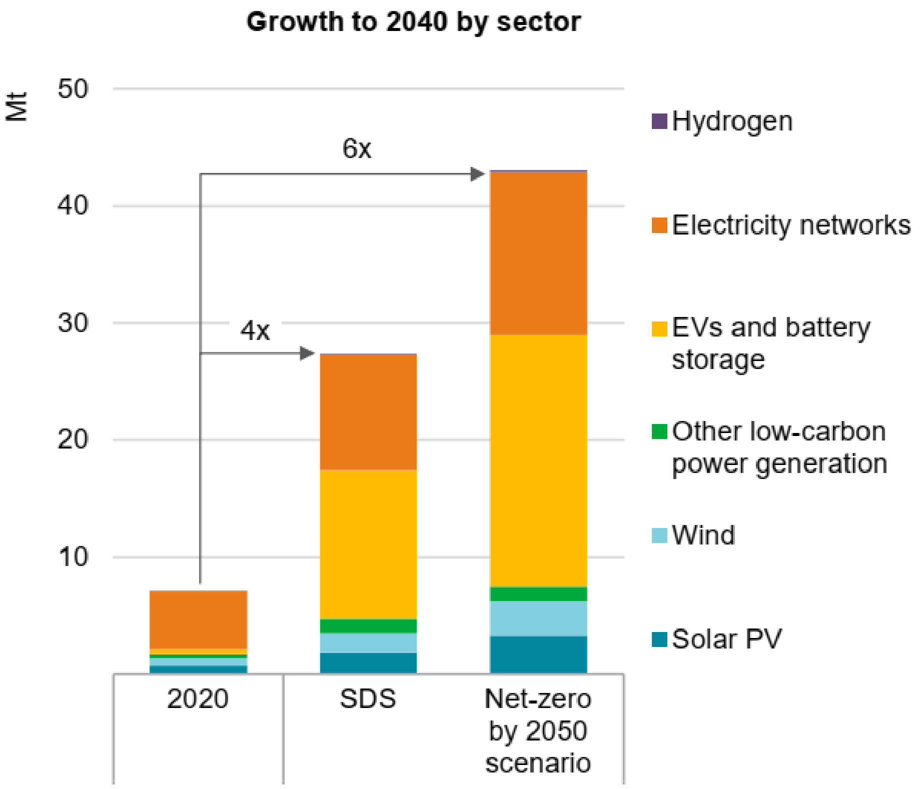
Since the challenges are multiple, it is doubtful that an energy transition based on only one of them will solve the problem without creating many new ones. One example where we can easily see it is in the industries of electric cars and also in solar and wind energy generation. Figures 3 and 4 below present the problem:

**Figure 3** - Mineral Use in Different Clean Technologies



IEA, 2022, p. 6

**Figure 4 -** Mineral Demand for Clean Energy by Scenario



IEA, 2022, p. 9.

Figure 3 shows a problem often overlooked: although electric cars, wind, and solar power are much less intensive in GHG emissions, they need much more minerals than their fossil-based counterparts. Figure 4 shows that to achieve the United Nations' Sustainable Development Goals (SDS) it would be needed about four times more minerals than we currently use, and to reach a net-zero carbon emissions scenario, stopping global warming would be needed six times more.

Mining is well-known to be a very impactful activity. The impact is strongly associated with the basic processes involved in mining and mineral processing. Surface mining needs land clearing before the excavation, and it also pollutes the air with dust and particulates. After excavation, ore is crushed, and that also contributes to air and water pollution. Methods to purify the ore also have as residues air pollutants and solvents that can pollute water (Jain, 2015). Especially, the rare earths needed for batteries are concentrated from very low grades in the ground and then dispersed into various equipment for processing in small quantities (Haque et al., 2014). This means that a great area will be needed to mine even a relatively small quantity of these minerals.

Therefore, increased mining will severely worsen the situation of the boundaries of land system change and freshwater change, and it can also affect the biosphere integrity if the mining operation is done in a preserved ecosystem. All these will further reduce the supply of ecosystem services needed for production and human welfare, making the entropy increase again, but now in a different way. This rationale also applies to other dimensions that are not considered when we mind only the GHG emissions.

## 5 CONCLUSIONS

The energy transition happening today is often treated solely as a technical issue. The idea is that there is a technological solution that can solve these problems without any further changes in the fabric of society, without any major changes in the way we organize the production and distribution of goods and services. This is the rationale behind the idea of representing energy as either clean or dirty.

On the contrary, the way we represent energy is arguably as important as the technological solutions we strive to create. Even when we separate the technical issues from anything else, the research problems that scientists try to resolve are strongly influenced by which ones are currently being financed. If the focus goes only to reducing GHG emissions, then the other environmental problems that are a direct result of the unbalanced growth of the social metabolism are going to be at best left unsolved, and at worst are going to become even more harmful as the technical solutions introduced to reduce GHG emissions or increase their capture can interfere with the ecosystem services that regulate them.

But beyond just giving the experts a wrong goal, or at least one that is too simplistic to improve the situation, is not the only problem. At stake, are the interests of social groups that comprise society, and some of them are already pretty invested in some technologies and governance forms to be open to solutions that are at odds with the way they have historically kept their power and richness, their position in the social hierarchy. With the funds in their hands, powerful players can steer the investment on alternatives for dealing with a real problem in directions that further consolidate their position, instead of putting it in danger. This can make the efforts to keep the biosphere integrity innocuous, as solutions that only care about GHG emissions can be harmful to other processes in the ecosystems that keep other human waste from accumulating up to toxic levels.

To be an actual solution for the problems derived from the explosive growth of the social metabolism in the last hundred years, we need something as complex as the problems themselves. The vast number of qualitatively different metabolic processes need to be addressed by an equally vast and diverse number of institutions, each one constrained by the others but also capable of making decisions and autonomously taking action. In this way, the information processing needed to keep human activities inside the carrying capacity in each specific quality of its interactions with the biosphere is distributed in a way that makes it possible. The reduction of the diversity of energy forms into only dirty and clean energies, separated by a single criterion, net GHG emissions, hides most of the information needed for proper decision-making, brewing troubles as it tries to solve what is seen as the most important problem.

Although physics represents energy as a single abstract quantity that only explains how the movement of actual bodies fits the predictions of mathematical models, it is impossible to deal with energy in production and consumption without considering the specificity of different energy forms. Nonetheless, what energy forms we will represent in decision-making processes about matters that can have worldwide effects is of the utmost importance. A set of energy forms that are too narrow can be advantageous to some in society who intend to keep control over these decision-making processes, suppressing the complexity of the issue to avoid sharing authority about their results. But it undermines the societies' ability to deal with the question effectively. A better understanding of the epistemology of energy is needed to go beyond the technical issues and delve into the problem in all its complexity. The present work tries to establish these issues as essential to the discussion of Epistemology of Energy, further setting in motion this important and new field of research.

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