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Constitutive Explanations as a Methodological Framework for Integrating Thermodynamics and Economics

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Abstract: The common approach to integrating thermodynamics and economics is subsuming thermodynamic aspects among the set of constraints under which economic activity takes place. The causal link between energy and growth is investigated via aggregate econometric analysis. This paper discusses methodological issues of aggregate analysis and proposes an alternative framework based on recent developments in philosophy of science, in particular of the life sciences. "Constitutive explanations" eschew the covering law approach to scientific explanation and concentrate on the identification of multi-level architectures of causal mechanisms that generate phenomena. This methodology has been productively employed to organize cross-disciplinary research, and I suggest that it can also provide a framework for integrating thermodynamics and economics, since this also requires the combination of several scientific disciplines. I present the example of the "rebound effect" as a kind of constitutive explanation and put it in the context of urbanization as a complex mechanism that is the defining feature of economic growth in physical terms.

Keywords: constitutive explanations; causal mechanisms; energy and growth; rebound effect; urbanization

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1. Introduction: Towards an "Economics of the Anthropocene"

Whether thermodynamics is essential for the analysis of economic processes is a question that deeply divides Ecological Economics and so-called "mainstream economics" [1,2]. Yet, if we look at the current status of Ecological Economics, the majority of research contributions converges increasingly with mainstream economics, in the sense of applying standard economic models and methods of quantitative analysis [3]. This trend is criticized by more radical positions in Ecological Economics, often based on ethical arguments [4]. In this paper, I develop an alternative, but complementary view: I argue that the thermodynamics perspective has been weakly grounded in philosophy of science and methodology, and that this is mostly responsible for the slow integration of thermodynamic reasoning into economics. Thus, this contribution is not about original research in the field, but presents a philosophical approach to the issue of cross-disciplinary integration. I use examples taken from existing research to demonstrate that this methodological perspective has also important consequences for arranging and interpreting established knowledge into a unified paradigm for economics and thermodynamics.

So far, thermodynamic aspects have been included in economics in terms of energetic and environmental constraints on economic growth [5,6]. Indeed, available energy can be seen as the most universal resource that is necessary for all economic activity in terms of "production" [7]. So, research has been focused on the question whether and how far the availability of energy determines economic growth. There is a range of methodological issues here, in particular what the appropriate measure of energy is, what the appropriate form of the production function is, and which econometric method is the right one to prove causality from energy to growth [8]. Here, I do not need to go into the details of these issues but pose a more fundamental question: Is this aggregate and macro-level approach the best one for identifying causal processes that link thermodynamic phenomena with economic ones?

Conventional economic methodology assigns the pivotal role to human intentionality in understanding causal processes in the economy. Economic phenomena are explained either as human responses to constraints, following an optimization procedure (which might be bounded, based on incomplete information, and so on, in order to achieve more realistic explanations), or as resulting from human efforts to change those constraints (such as migration or innovation). Correspondingly, as far as the energy–growth link is concerned, thermodynamics would not explain economic growth, but only the energetic constraints under which growth occurs. Growth is an outcome of human actions, but does not directly manifest underlying physical principles in terms of causation. In other words, energy is a means of human economic activity, but the related physical theories cannot obtain the status of primary causal explanations [9].

In this paper, I will show that in a different methodological perspective, we can re-arrange many existing approaches and results of research on thermodynamics and growth. As a result, thermodynamics does not only provide a rationale for the constraints under which growth operates, but provides the foundations for understanding the causal processes that drive growth (for a related view, [10]). This insight can be reaped if we adopt the methodology of "constitutive explanations" that has been recently explored by philosophers as the most appropriate methodological framework for understanding and arranging research in the life sciences [11]. The idea is simple: We approach economic growth as the output of a "machine" that consists of a very large number of interacting mechanisms. This machine consists of human individuals, technological artefacts, institutions that govern the interaction among these two, parts of the biosphere, and even the Earth system. Most aforementioned research on the energy–growth link offers a distinct empirical perspective on this machine, which treats the machine as a black box, connecting energy inputs with growth as the output. However, from the viewpoint of constitutive explanations, explaining the regularities in this link requires opening up the black box and identifying the particular mechanisms that come together in generating these patterns.

I claim that this perspective is the most appropriate one in approaching the human economy as the central phenomenon in the emerging "Anthropocene" [12]. In Hayek's words, this means approaching the Anthropocene as "result of human action, but not of human design". Whereas the economic perspective on energy as constraint suggests that the specific forms of the energy-growth link are reflecting human design, I argue that the machinery that connects energy and growth is beyond human design, manifesting the interplay of complex evolutionary processes on different levels that are covered by different disciplines, such as physics, biology or economics, which need to be integrated in a constitutive explanations framework.

I will put forward my argument in three steps. I start with discussing methodological problems and challenges of the conventional approach towards the energy–growth link which go beyond mere technical issues and touch upon fundamental ontological perspectives on the underlying causal mechanisms. I continue with introducing the constitutive explanations framework which is the, so far, most developed approach to organizing multidisciplinary research in both the natural and the social sciences, thus opening up new vistas on the integration between thermodynamics and economics. I present an exemplary application, namely the role of rebound effects in the larger setting of urbanization as a physical process, *i.e.*, the accumulation and maintenance of support structures for human life. Thus, I argue that investigating the causal mechanisms driving urbanization is the appropriate approach to understanding the energy–growth link, beginning with defining pertinent measurement approaches.

2. Energy and Growth: Methodological Pitfalls of Aggregate Analysis

In this section, I present a number of reasons why the common approach of aggregate analysis is valuable, but not sufficient for understanding the causal linkages between energy and growth, which is so far the pivotal issue in any serious attempt at integrating thermodynamics and economics. I begin with discussing the limitations of GDP as a thermodynamically relevant measure of growth and as a phenomenon of economic production. Next, I argue that the aggregate analysis cannot give a causal account of why energy throughputs increase in the first place, and finally I discuss the standard economic view which assigns a central role to human intentionality as a causal driver of growth, arguing that institutional and technological evolution is partly autonomous with human design.

2.1. Measuring Economic Activity by GDP

Most research on the energy–growth link accepts the idea that economic growth is measured by GDP data: For example, in one of the most advanced approaches by physicists in understanding the energy–growth link, Ayres and Warr ([6]: 133ff, 197ff) explicitly argue that GDP is a proper measure of economic activity, and that energy is a physical constraint on growth of GDP. The focus on GDP data has always been criticized by Ecological Economists [13], but mainly from the normative perspective, in arguing that GDP insufficiently reflects human well-being and the status of the biosphere (Ayres and Warr vote in favor of GDP since they explicitly do not refer to welfare considerations). Yet, there is also a more standard problem with GDP data as an appropriate measure of economic activity: By definition, they only measure economic activities that are mediated by markets and are therefore evaluated at market prices (which Ayres and Warr recognize, but seem to regard as irrelevant). So, for example, government activity is insufficiently reflected in GDP (being only evaluated at costs, but not value added), and household production is excluded. This certainly creates problems with assessing long-term trends, which involve, for example, the "marketization" of household production, or comparisons across countries with different economic structures. That means, whereas energetic throughput can be measured in terms of material data that cover the entire energy consumption of the economy, the GDP data only reflect a part of the thermodynamically active economic processes, weighted by market prices.

The use of GDP data is, of course, a TINA ("there is no alternative") approach as there are no serious alternatives of measuring aggregate economic activity. So, measurement issues are rarely reflected upon when considering the energy–growth link (for example, the authoritative review by Stern [14] does not deal with this question). Yet, the question remains to what extent the large error margins of proper statistical representation of economic activity in GDP also affect the robustness of econometric results measuring the energy–growth link. However, there is a more fundamental problem here.

In fact, when it comes to estimating the contribution of energy to economic growth, the literature is well aware of the limitations of GDP in measuring economic activity: Energy, as evaluated by market prices, would only be represented in terms of value added of the energy sector, and therefore appears to be much less significant as a driver of growth than other economic inputs, in particular labor, because the contribution of energy industries to total GDP is small; this reasoning can be theoretically undergirded if the assumption is made that the neoclassical cost share theorem applies (which is problematic) [15]. Accordingly, researchers who wish to expose the role of energy in growth do not use the market valuations but material measures of energy input, thus actually mixing up different measurement standards (in the corresponding production functions, capital is measured in monetary terms, labor in hours per annum, and energy in physical magnitudes, with different specifications, see e.g., [16]; [5]: 197ff, 334ff; [6]: 205ff, 262ff, who, however, proceeds with transformations into dimensionless magnitudes via referring to a base year). Interestingly, this raises similar questions for energy as have been raised for measuring labor, in particular with regard to the "quality" of energy (which compares with distinguishing educational levels, hence different qualities of human capital, in measuring labor input) [14].

However, the same reasoning also applies for GDP as measuring output: Notwithstanding, apparently only Kümmel [6] also develops a physical measure of output in order to achieve partial qualitative homogeneity of measures in his aggregate estimations. An important case in point is population growth as a form of physical production. If we concentrate on GDP, the thermodynamic aspects of population growth are mainly hidden in the contribution of agriculture and the food sector to GDP, thus falsely suggesting a decreasing relative significance of human metabolic energetics. This would correspond to Engel's Law which states that expenditure for food declines with growing income, thus also accompanied by a decreasing importance of agriculture in GDP. However, human metabolic energetics [17], as calculated by the daily energetic throughput, *i.e.* the basic metabolic rate, adds up to an estimated amount of 0.7–4.9 $\times$ 10^{12} W for world population, which comes close to the energy conversion happening in oceanic circulation (an estimated 2–7 $\times$ 10^{12} W) [18], so remains to be a substantial element in the thermodynamics of the Earth system. This observation points to a principled issue in considering the thermodynamics–economics link: Many contributions focus on the radiation flows, as these allow assessing the relative contribution of economic growth to entropy production. From this perspective, solar and terrestrial radiation flows are orders of magnitudes larger than human-generated flows. This is another version of aggregate analysis and would suggest that with adequate technological measures (especially, utilization of solar energy) the human impact of Earth System thermodynamics would be kept close to negligible [19]. However, if we look at the conversion processes in economic production in the first place, the human impact has already achieved tremendous scales, and has been recognized in positing the transition to a new geological age, the Anthropocene. In other words, it is not only necessary to clarify the relationship between thermodynamics and economics, but also, which aspects of the thermodynamic analysis are relevant in terms of causal impacts. This corresponds to a shift away from aggregate economic analysis of growth in terms of GDP to structural analysis.

Against this backdrop, in the thermodynamics perspective population growth is the most elementary form and essential component of economic growth and production, thus obliterating the often made distinction between growth of GDP and of GDP per capita. This issue is important when considering the trajectory of growth in the very long run: Research on the energy–growth link is almost exclusively focused on the industrial age, if only for limitations of data availability, as long as GDP is in focus [20]. However, this is a period that is deeply shaped by the consumption of fossil carbon resources. The earlier Neolithic revolution in agriculture did not trigger GDP growth per capita but sustained population growth, which, of course, also translates into absolute GDP growth, grounded in the energy–growth link, as epitomized in the case of China [17,20,21]. Before the advent of the demographic transition, the Industrial Revolution also fostered population growth, mainly via the improvement of agricultural productivity. Yet, even the subsequent demographic transition did not stop the expansion of the human appropriation of net primary productivity (HANPP, with net primary productivity referring to the net assimilation of carbon by plants) [22,23]. Here, we see a similar effect as with energy conversion technologies generally: Although one can notice great advances in the efficiency of resource use, in absolute terms human appropriation of energetic resources has grown nevertheless. These developments are not covered in the GDP data: Actually, efficiency improvements in terms of value-added at market prices are reflected in the declining share of agriculture in GDP. However, this seriously distorts a realistic view on the thermodynamics of growth: Agriculture still represents more than two thirds of HANPP (which in turn amounts to roughly 30% of net primary production).

To sum up this section, the use of GDP data for empirically determining the energy–growth link seems problematic as GDP data insufficiently reflect the thermodynamic aspects of economic production, both in terms of coverage and structure. This creates principled problems for any attempt to identify causal regularities governing the energy–growth link on the aggregate level, although one great advantage of this would be to obviate the need for detailed modelling of economic processes for practical purposes, such as forecasting future trends in global warming as caused by economic growth [24,25]. So, we face the challenge of how to identify a measure of economic activity that overcomes the limitations of GDP. Based on the methodology of constitutive explanations, I will outline one solution in Section 3.3.

2.2. Identifying Causal Mechanisms

The second problem with the prevailing approach is that it does not provide a full explanation of the supposed causality from energy to growth. This is a general econometric issue, as correlation may not reflect causality, and is mostly solved by adopting advanced econometric methods such as Granger causality and co-integration techniques. Yet, these improvements cannot substitute for a theory of the causal mechanisms that would undergird the econometric correlations in the first place [26]. In other words, econometric evidence notwithstanding, we do not yet know why and how energy drives growth. This is reflected in the complexity of the econometric interdependencies, the role of control variables, or the variance of results over sample sizes, time periods or geographic areas [8]. In order to make sense of these results, and eventually take them as compelling evidence for energy operating as a cause of growth, opening up the black box of causal mechanisms is absolutely necessary.

This observation refers to two different stages of identifying causal mechanisms. The first is simply exploring the specific causal tracks which connect energy throughput with growth: After all, the Soviet Union expanded energy throughputs continuously, but failed to sustain growth in the longer run, thus continuously falling back in the comparison with capitalist countries (and this comparison is of course hampered by the difficulties of comparing GDP data across fundamentally different economic systems). This reveals the drawback of approaching thermodynamic issues from the angle of constraints: The relationship between energy and growth would be mainly seen as reflecting a release of the constraints, thus presuming that this will be sufficient for triggering growth. Though, obviously, a full explanation would require identifying the precise mechanisms by which this causal consequence occurs in some cases, and in others does not. In this regard, approaching energy as a constraint is similar to treating the quantity of money as a constraint in aggregate economic processes: You can pull a rope, but cannot push it. As long as the specific causal mechanisms are not made explicit (in the case of money, mediated via the financial sector), econometric analysis cannot achieve unequivocal results. As for energy, this explains in a most simple way why releasing energetic constraints which became binding at a certain time may strengthen the econometric correlations, whereas under conditions of less binding constraints, such as resulting from technological improvements of energetic conversions and energy savings, these might become less significant for a considerable period of time [16]. Yet, this by no means implies that there are no causal mechanisms that link energy and growth in the latter case.

This leads us to consider the second stage of causal analysis: Why does energy throughput increase at all? If energy is a constraint, how does it happen that this constraint is released? If energy and growth are closely correlated, this amounts to the question why growth appears to be a necessary state of the economy, and why this is realized via growing energetic throughputs. Let me make this point as clear as possible by means of a naive hypothetical example: Imagine a "stationary" society of hunter-gatherers, who, however, are literate. This society might appreciate new artistic creations in poetry as a measure of welfare and individual well-being. So, growth by artistic innovations is perfectly possible, resulting in a growing stock of poems, but without increasing energy throughputs, the economy remaining in a stationary state (for more realistic examples of a similar kind, see [27]).

In Ecological Economics, this question is often answered by pointing towards capitalist dynamism. Correspondingly, the assumption is that changing the economic system, for example along the lines of "degrowth", would be the king's way of resolving the ecological dilemma [28]. However, at this point, the previous argument on population offers a fresh perspective [20]. Whereas economics cannot fully explain why economies necessarily have to grow in order to be sustainable as economic systems, but in tension with ecological sustainability, biology has a theorem on the necessity of growth, in terms of population growth. In evolutionary biology, population growth is a necessary feature of biological systems because the corresponding reproductive strategies are the only evolutionary stable ones. This also implies that population growth will tend towards exhausting the accessible energetic resources, that is, will fully exploit the given constraints, in the long run. In this view, it is also straightforward explaining the expansion of constraints, as harnessing new energetic resources is always an evolutionary advantage which will feedback to further population growth.

The biological argument for a necessary energy–growth link applies to most of human history as well, especially the time between the Neolithic agricultural revolution and the first stages of industrialization. Yet, it does not automatically transfer to economic growth as normally measured by economists. In this context, it is important noting that the two great economic revolutions, the Neolithic and the Industrial, had very different consequences as far as the link between growth and individual well-being is concerned: Over the entire time span in between, the agricultural revolution even decreased the individual level of well-being (indeed, being a "fall from paradise"), whereas the hallmark of growth in the industrial era was, in the longer run, the increase of individual welfare, reflected in growth of GDP per capita. This raises the question why this change of modes happened, and whether the fundamental mechanisms have changed that connect energy and output. An important case in point is China, which had established a peculiar cultural and institutional system that was geared towards the exploitation of bioenergy and renewable energy by means of labor-intensive technologies, resulting in strong population growth until the mid-20th century [21]. Full-scale industrialization only started in 1949, and became the leading force in growth only after 1978, combined with the political enforcement of the one-child policy: Within just three decades, this resulted into a radical switch to the mode of growth in terms of increasing GDP per capita. So, we can argue that China is the case in point for a highly developed civilization in which the "Malthusian" energy–growth link was operational until most recently, undergirded by the prevailing social norms, moral values and socio-political institutions, sustained by an evolutionary growth pattern in a market-based economy, and stabilized by self-reinforcing demand for labor in a regime of dear energy and cheap labor.

In conclusion, the "energy as constraint" view fails to shed light on the precise causal mechanisms that determine the thermodynamics of growth. Especially, even if the econometric black box model would present firm evidence on energy determining growth, we cannot explain why the energetic throughput increases in the first place. Here, biology offers an explanatory template, as population growth can be seen as driven by energetic throughputs in the context of a peculiar mechanism of evolution, *i.e.*, Darwinian selection. I will come return to this topic in Section 3.3, proposing a simple measure of growth that refers to population as the basic category, yet covers both modes of growth.

2.3. The Role of Human Intentionality and Design

The third issue directly follows from the previous discussion, as the Chinese example represented a substantial share of the world economy before industrialization, and China appears to resume this role today again. What we see in the historical Chinese case is a complex system of mechanisms that come together in creating a particular form of the energy–growth link. This system emerged evolutionarily in the past, without a human mastermind designing it.

Many Ecological Economists would argue that growth is not a necessary state of the economy, also including population growth, because this is subject to human decisions and intentions: The dramatic recent shift of the Chinese growth pattern has been partly triggered by the intentional adoption and enforcement of one-child policy. Humans are seen as being autonomous from the forces of biological evolution and therefore can cut the causal link between energy and growth. This argument is salient in many attempts at refuting thermodynamic approaches to the economy, as they relate to the general point that human individual and social behavior cannot be reduced to physical laws [9,29]. This argument does not deny that physical laws operate as constraints: After all, we cannot fly even if we wished. Yet, constraints can leave sufficient leeway for autonomous human action, also directed at overcoming the constraints: We can build airplanes. The same argument applies on energy as a constraint: There is no physical law that enforces certain behaviors on us that causally connect energy and growth, or imposes a growth imperative on us.

So, the "energy as constraint" view actually reconciles the two otherwise opposing strands of thought on energy and the economy: Ecological economists argue that we have to accept the constraint and design strategies for degrowth; Neoclassical economists would argue that human inventiveness would expand the constraint by technological innovation. Both parties agree on the central condition for their arguments: Human beings are free to choose and design their fate, which is not inexorably determined by laws of nature.

The methodological problem with this view is that it opposes human intentionality and causality in a non-transparent way, and that it assigns a pivotal role to the former in driving economic evolution, without properly recognizing the role of supra-individual processes and structures [20,30]. However, in fact, even in economics there are different views. Indeed, the majority of economists would agree with the idea that human beings are masters of their fate. That does not deny the complexity of economic systems, especially at the interface between politics and the economy. So, politico-economic factors might overwhelm rational responses to constraints, but in principle we could implement the best solutions. Yet, this optimism about institutional design has been put into doubt by dissenting schools of thought, such as the disciples of Hayek [31]. In their view, institutional evolution is not fully controlled by human design, and given the limitations of human knowledge, attempts at attaining full control would mostly even have disastrous consequences.

If we apply this line of thinking on the energy–growth link, as a first step this would suggest that causality might not be fully mediated by human intentionality, but that autonomous causal linkages would operate on the level of supra-individual structures, thus in fact also constraining human choices. For example, a Hayekian might ask whether the shift to an institutional regime of degrowth would be feasible in a world with competing states that do not (and probably cannot) reach a consensus on this. This is illustrated by the success story of capitalism: Capitalist institutions have crowded out many institutional alternatives, leaving small leeway for non-capitalist arrangements, such as in certain niches like the NGO sector. Then, the causal pathway from energy to growth would be mediated by this global systems' competition, and would not fall under the scope of human choice. The case of China is most instructive in this regard: In the Imperial economy, no individual could rationally choose to break the specific link between energy and growth, given the institutions and structural conditions (sometimes labelled the "high-level equilibrium trap" [32,33]). Systems' competition triggered by Imperialist aggression caused the catastrophic destruction of the old system, and the process of building a new system is just being completed today. Economic growth is a political priority, only secondarily interpreted in terms of individual well-being, and primarily seen as a manifestation of political power and status in the global concert of nations. The difficulties in integrating China into a global regime of containing CO_2 emissions reflect the inherent dynamics in these political and economic processes that create a distinct manifestation of the energy–growth linkage.

In other words, the question is whether institutional evolution is driven by autonomous forces that cannot be fully controlled by the human agents that act under these institutions. Of course, this reasoning depends on our optimism regarding a global convergence of political views and institutional preferences. However, there is another domain more directly related to the energy–growth link where similar considerations loom large: this is the domain of technology.

Both Ecological and Neoclassical economists would agree on the idea that technology is designed by human actors and does not exert independent causal power on human behavior. However, this idea is by no means taken for granted outside the disciplinary scope of economics, reaching from Science and Technology Studies to Evolutionary Biology. This is a vast field, and I only want to present the central point (for more detail, see [34]; *cf.* [12]). This is the alternative view that technological evolution proceeds independently from human design, though being mediated and triggered by human action. This position is maintained, for example, in recent extensions of evolutionary theory aka Darwinism to the level of artefacts produced by humans (and, as being part of the extended phenotype, by many animals as well) [35–38]. Artefacts create evolutionary niches, and therefore adaptive forces of its own that feedback to biological and cultural evolution [39]. In other words, technology evolves partly autonomously, becoming a part of the environment of humans, and thus also obtains an independent force driving further biological and cultural evolution. Such a biological view, *mutatis mutandis*, also matches with some positions in Science and Technology Studies which claim that technological evolution is partly autonomous in the sense of following its own regularities and dynamics, with human actions just being triggers: Once a particular invention has taken place, it necessarily opens up structured and directed trajectories of further development, and individual human design cannot overlook these trajectories in the future, thus failing to obtain full control [40].

These perspectives raise a radical question: Are we really designers of technological evolution, or is our intentionality subject to functions defined by technological evolution? I argue that the standard economic approach in fact assumes the latter, in spite of upholding the former view as an expression of ideological and philosophical frames prevailing in economics. Again, China is a case in point, as compared to England, in the times of the Industrial Revolution. From the thermodynamic perspective, we can interpret technology as a physical mechanism that causally connects reservoirs of available energy with sinks into which it is dissipated [10]. Coal is such a reservoir. The emerging technological system of the Industrial Revolution (steam engine, mining technologies, railways, *etc.*) vastly enhanced the accessibility of this energetic source, a potential that was inexorably realized via the market prices that signaled changing relative scarcities of inputs, in particular labor and energy [41]. The major difference with China is the fact that this technological system did not emerge, partly for endogenous reasons (such as very high transport costs of coal) [33]. So, in England, market competition guided individual decisions to speed up the dissipation of energy stored in coal. As argued earlier, the spread of the carbon economy across Europe was then decisively driven by systems' competition (that is, political and military); here, human design partly acted against market signals, as in France.

My point is that this economic action was not "freely" chosen by the economic agents, exactly because they follow an optimization calculus which is also imposed on them by the competitive capitalist system. In fact, the early users of the new technology were almost totally ignorant about the future consequences, and there was high uncertainly about its potential. Rationality and optimization impose a certain behavior, because those agents who do not follow the gradients defined by the price vector, will lose out in competition. So, the evolutionary dynamics of markets actually turned individual behavior functionally relative to the energetic dissipation processes mediated by the emerging technology. So, a radically different view of the Industrial Revolution is that technology piggybacked on human social and economic systems, thus triggering a rapid diffusion of certain artefacts, akin to a symbiotic system. Going one step further, we might say that technology evolves like any other "natural" phenomenon by which physical processes emerge that release a certain "hang-up" of available energy in a particular state, which prevented the dissipation of energy along potential gradients. These processes are specific "mechanisms": So, technology is a mechanism that activates gradients of energetic dissipation [42]. Human action puts technology into place, but is also driven by gradients of costs and benefits of utilizing energy that are defined in the economic system, directly reflecting the prevailing physical conditions of relative scarcity of resources.

The methodologically essential point in this argument is that we would not subsume human behavior to a "law of nature" in the sense that thermodynamic laws, in this case in particular the Second Law, would be directly seen as determining human action. However, we also do not simply assert that thermodynamics only explains certain constraints of these actions. Instead, we introduce a much more complex pattern of causal explanation which approaches human action as an element in more encompassing systems in which it may assume a function [43]. This function is mediated via institutional and technological structures that manifest an autonomous evolutionary dynamics, driven "by human action, but not by human design". We would approach the "technosphere" as the evolutionary extension of the biosphere, and approach it as part and parcel of a complex system of interlocking mechanisms which ultimately drive the dissipation of energy in the Earth system [34,44].

3. Causal Mechanisms in the Analysis of the Energy–Growth Link

3.1. Constitutive Explanations: Basic Principles

Given the difficulties that I outlined in the previous section, we need a fresh methodological approach to the thermodynamics–economics relationship. I propose that this is the perspective of constitutive explanations, or the identification of causal mechanisms. This has been recently developed as an alternative to the regularity-based notion of causality, which is basically following the covering law model of scientific explanations, and introduces a mechanistic notion of causality that is independent from the notion of regularity. In the former view, causality is the regular co-occurrence of causes and effects that is governed by universal laws. The pertinent discussion in the Philosophy of Science has amply demonstrated that this methodological framework may only apply for certain parts of physics but fails to describe the methodology of most other sciences, beginning with chemistry [45,46]. This is particularly true for sciences dealing with complex systems. A foremost example is the neurosciences, for which so far the alternative approach has been elaborated in most detail, developing a mechanistic model of causality without referring to universal laws in an essential way [47,48]. I think that this explanatory model is most appropriate also for defining a methodological framework for the relationship between thermodynamics and economics.

Further, there is the important development that mechanistic explanations are also increasingly employed in the social sciences [49,50]. That means, we can unify the methodology of the sciences and the social sciences within one single framework, thus opening up the view on mechanisms in the domains of the former and the latter as closely interacting phenomena in specific integrative models of constitutive explanation. For example, in the neurosciences, the explanation of empathy rests upon the identification of specific neurophysiological mechanisms that generate emphatic behavior, but at the same time it is impossible to identify a general regularity without referring to the symbolic domain in human sociality in which the difference between the in-group and out-group is specified that drives the activation of emphatic mechanisms [51]. In the following, I argue that the same applies for the thermodynamics–economics link: A constitutive explanation combines mechanisms of different levels into one overarching systems view. In the previous example of the comparison between China and England during the period of European industrialization, that would include larger ecological structures, physical and engineering aspects of energy utilization, the reflections of these in economic parameters such as prices, or the specific patterns of the social organization of the utilization of technology, including aspects such as the fundamental religious and philosophical views of nature.

This observation can be generalized. The systems in question are multi-level in the ontological sense: In the neurosciences, there are chemical mechanisms on the molecular level in the human brain, there are higher levels of neuronal connectivity, there are interactions between brain areas, and finally there is a direct causal involvement of extra-somatic phenomena such as signs mediated via sensory perceptions. Therefore, the neurosciences are actually a multi-disciplinary endeavor: the complexity of the phenomena is reflected in the complexity of interacting and diverse disciplinary explanations, as has been also transpiring in the previous remarks about comparing England and China. As a consequence, constitutive explanations are also non-reductionist: Contrary to common philosophical stances that relate the notion of causality to the goal of reductionism, thus also suggesting the ultimate reduction of social phenomena to natural ones, constitutive explanations adopt a naturalistic ontology of causal explanations, but recognize the independent ontological status of social phenomena, in particular [52].

In simplest terms, a constitutive explanation describes the specific mechanisms that come together in generating a certain result, given certain inputs, and make the architecture explicit that governs the interactions of these mechanisms [11,53]. This is the "constitution" of the system in question. That means both causes and effects are seen as being aspects of the state of the system at a particular point of time, and there is no reference to a universal law that directly explains this co-occurrence (although for single and elementary causal processes as parts of the larger mechanistic set-up laws may hold). This deserves emphasis: If we aim at a constitutive explanation of the energy–growth link, we do not actually care about "prime movers", but approach energy (*i.e.*, input) and growth (*i.e.*, output) as co-instantiations of the interplay of mechanisms in the productive system "economy", which may manifest phenomena of non-linearities and interactions between bottom-up and top-down causal processes, to name just two examples of architectural complexity. For example, this is salient in the difficulties to unequivocally establish whether energy drives growth or growth drives energy in the highly aggregate black box models [8]. This systems view on causality avoids the fallacy of interpreting the relationship between causes and effects in a reductionist manner, thus enforcing an "either-or" dilemma.

Thus, constitutive explanations open up the black box between inputs and outputs. Therefore, econometric analyses are not seen as having conclusive explanatory power. This is because in complex and evolutionary systems, correlations for high levels of aggregation do not explain why and how the regular co-occurrence of inputs and outputs is actually produced by the system. Especially, there are difficult problems in identifying and assessing the role of non-occurrences and omissions as causal forces, and there is no necessary relationship between high probability of inputs and high probability of outputs. Therefore, statistical correlations have heuristic value, but should be always undergirded by the detailed identification of underlying mechanisms. This defines an essential difference to common economic methodology.

Constitutive explanations have a general structure which consists of four steps [54]. The first step is the analysis of individual phenomena on a particular ontological level. For example, in the neurosciences this might be the chemical mechanisms that operate at synapses; in the social sciences, these might be individual decisions. The second step is to analyze the interaction between different individual phenomena in a certain context, such as the interplay of synapses in a certain structural segment of the brain, or the individual transactions on a market. The third step is to explain aggregate phenomena that emerge from these interactions, such as certain brain states which might relate to certain higher level phenomena such as certain perceptions, or certain states of markets such as trends of prices. The fourth step is to understand the feedback mechanisms that work from the aggregate level to the individual level, such as brain states impinging on the activity levels of individual synapses, or market states that impact on individual decisions. For all these steps, it is essential to empirically identify concrete and specific mechanisms that explain the observed phenomena, thus resulting in a specific architecture which is the conceptual frame for the constitutive explanation.

Finally, constitutive explanations lean towards a manipulability account of causality [55]. That means, identifying causes relies on the criterion whether the relevant phenomenon can be manipulated in order to achieve a particular effect; so, the approach directly ties up with the central role of the experiment in the sciences. Manipulability also includes the identification of "natural experiments" in which we can clearly describe a constitutive set-up and trace crucial phenomena that operate as causes of subsequent developments. So, taking the example of China again, as we have seen, a broad and detailed discussion of the different possible causes for her failure to industrialize endogenously has increasingly focused on the central role of coal as a source of energy, and the differences between the induced relative prices of energy and labor in England and China. In this context, manipulability in the social sciences also goes along with the local nature of many processes, thus highlighting the importance of medium-range theorizing, as opposed to universal laws [56]. In the example, the launch of the Industrial Revolution in Europe was initially driven by local price structures in the spatially circumscribed regions of coal mining, and the following diffusion dynamics was determined also by many other factors, as mentioned previously [41].

3.2. Rebound Effects as a Case of Constitutive Explanations

What does the model of constitutive explanations imply for integrating thermodynamics and economics? Let me illustrate the logic of mechanisms with one important example, the so-called rebound effect in energy economics. Whereas in the aggregate approach to the energy–growth link the rebound effect would only play a marginal role (as in [5]), in the constitutive explanations methodology rebound effects and their precise causal architecture would assume a core position. Indeed, many authors recognize this fact, but lacking a concise methodological beacon, would not reach the appropriate theoretical conclusions, thus approaching the phenomenon as a mere empirical issue (see e.g., [17]: 271f).

The rebound effect relates to a most universal pattern of economic and ecological dynamics that already transpired in the previous brief discussion of HANPP: human appropriation of net primary production has grown incessantly, yet with continuously improving efficiency. The rebound effect means that enhancing the efficiency of energy usage might induce individual behaviors which do not result in absolute savings of energy but in growing absolute amounts of energy flows. This effect was first identified by the British economist Jevons in his famous book "The Coal Question" in which he argued that technological progress in mining and exploiting coal in England will even sharpen the scarcity of coal as demand will grow even stronger than supply [57]. In the discussion of the rebound effect, we observe the same difficulties regarding the identification of causality as discussed in the previous section: Researchers investigate whether improvements in energetic efficiency are causes of the effect of absolutely growing energetic throughputs. In the constitutive explanations view, both causes and effects are aspects of the complex system that consists of many mechanisms that come together in generating this pattern.

There are different venues to explore the rebound effect. One venue is the economic approach in the narrow sense that would aim at presenting a theoretical model of growth in which the effect would occur as a universal regularity [58,59]. The basic idea is that enhancing energy efficiency would also increase total factor productivity, which feeds back on growth and triggers growing demand for energy. However, whether such a regularity can be theoretically established heavily depends on a number of additional assumptions, such as the mathematical form of the production function. Another reason for the inconclusiveness of these economic modelling efforts may be, as Sorrell states [57]: "The 'rebound effect' is an umbrella term for a variety of mechanisms that reduce the potential energy savings from improved energy efficiency". This observation indeed suggests the necessity of shifting the methodological perspective.

If we analyze the rebound effect in terms of the four step model of constitutive explanations, we start out from the individual level, *i.e.*, the individual decisions to produce and consume coal (this corresponds to "direct rebound effects". Next, these are reflected in individual-level activities of substitution and complementary activities (the "indirect rebound effects"). We then look at the interactions between those individual decisions on the marketplace, resulting in specific market states, that is prices for coal, applied technologies and so forth. This results in adaptations of the economy through time (the "economy-wide rebound effects"). So, the rebound effect is a complex set of interacting mechanisms [60]. There are mechanisms that are involved in individual decision making, such as connecting preferences, prices and decisions. These mechanisms can be complex in turn, for example when we introduce expectations about future prices. Next, there are mechanisms of the interactions between individuals: These are often describable in terms of "institutions" that shape the specific forms of markets and result in certain regularities of interactions, such as, for example, the contracts that govern the use of energy. There is a large number of such transactional mechanisms that interact on the marketplace: Hence, the market itself is a complex mechanism at a higher level of organization. One particular effect on the market level is the emergence of market prices. Market prices are essential determinants of individual decisions. Here, the loop is closed back to individual decisions.

We can also approach the rebound effect as a "type" of mechanism. A type of mechanism amounts to a theoretical hypothesis, but it is easy to see that this is not based on a universal theory, but is a medium-range theoretical concept: It applies in specific regions of time and space, and does not work universally. Whether and how the rebound effect works is an empirical question, and requires opening up its black box. Yet, at the same time, the rebound effect is essential for predicting future trends in the relationship between energy and economic growth. In the current context, what is most significant is the fact that the empirical rebound effects are mostly below unity when considering single mechanisms, such as the effects of energy-saving devices for the utilization of a single product consuming energy, but may turn out to be larger than unity once one considers full-scale technological systems (such as the steam engine and its ramifications). Therefore, the rebound effect also points towards an essential challenge in constitutive explanations: This is identifying the proper boundaries of the mechanisms in question, both in space and time. In the case of the rebound effect, one aspect is the embeddedness of single technological devices into larger technological systems, with the important example of so-called "general purpose technologies" which diffuse across a large number of specific domains of application, and the other is the spatial interaction between different economic systems via international economic linkages. For example, Information and Communication Technology (ICT) is a complex amalgam of technological devices that define a "general purpose technology". Looking at single devices, many observers perceive strong potential for energy savings, but the picture is much less clear for the evolution of the entire pattern of ICT applications, including their worldwide diffusion [61].

The ICT example is illuminating because it also shows that the analysis of mechanisms also needs to be based on universal theories, as far as their fundamental characteristics are concerned. For understanding the relationship between ICT and growth, it is absolutely necessary to properly identify the causes of energy consumption by ICT. At the heart of this issue lies a foundational ontological and physical question, namely what is the relationship between energy and information, and how does this play out under specific technological conditions [62,63]: The central, still disputed question is whether and how memory and the erasure and superscription of information go along with thermodynamic costs which obey to the Second Law; if so, one would end up with a most universal rationale as to why the expansion of ICT must go along with rebound effects that are larger than one, if we consider the entire ICT technological system on a global scale. It is not enough just to consider current energy savings and current energy consumption of particular ICT devices in order to ground predictions about future developments. So, mechanism analysis needs to be based on a precise understanding of the different constituent phenomena, which ultimately also includes reference to fundamental physical laws. However, that does not imply that these laws can directly offer causal explanations of the relationship between energy, information and growth. The causal explanation rests upon the analysis of the complete multi-level system of interacting mechanisms.

So, in the constitutive explanations framework, the rebound effect is not only an excellent case for illustrating the power of this approach in appreciating practiced approaches in empirical energy economics and examining them on a systematic methodological basis, but also reveals that it might suggest more general hypotheses about the types of mechanisms that determine the energy–growth link. So, the methodological appreciation has direct consequences also for theoretical and empirical work (compare the assessment by Sorrell [57], also referring to Ayres and Warr [5], with the marginal treatment of the effect in their work; similarly, Kümmel [6] only mentions rebound effects in the context of a citation). In the next section, I show how this shift of methodological perspectives suggests fresh approaches to some of the issues raised in the second section of this paper.

3.3. The Mechanism of Growth: Urbanization as a Physical Phenomenon

One important example for rebound effects is the growth of electricity usage which has been recurrently triggered by declining costs of producing electricity. In this context, one particularly interesting phenomenon is the absolute growth of energy throughput used for lighting, which is driven by falling energetic and other costs. On the one hand, for single lighting devices, it is mostly straightforward establishing rebound effects that are clearly smaller than unity or even negative, thus indeed resulting not only in higher energetic efficiency, but even absolute savings (as a recent example, [64]). However, if we look at the trends in the long run, and broaden the perspective to the global dimensions of the diffusion of lighting, the rebound effects appear to be at least unity or even larger than unity [65,66]: That would imply lighting alone is an important driver of expanding energetic throughputs in economic growth (consuming roughly 7 percent of total global energy consumption). In explaining this phenomenon, there are different cross-disciplinary aspects, such as the biological and cultural determinants of the human need for lighting, and the obvious fact that the saturation point has not yet been achieved. However, there is also the observation that improvements in lighting have effects on productivity and creativity, especially with regard to the extension of human activity into night times [67]. This argument extends the mechanisms underlying the rebound effect considerably, as there is a feedback from growth to the demand for lighting which is not directly triggered by cost considerations.

Indeed, changes and trends of intensity of night lighting, as observable via satellites on a global scale, have been recently identified as one of the most reliable indicators of GDP growth and levels of GDP per capita [68]. The underlying rationale is that the expansion of economic activity implies the extension of activities into nighttime, both work and leisure. This close relationship raises the interesting possibility to define alternative means of measuring economic activity that have a direct categorial affinity to thermodynamics, and avoid the difficulties that arise from the reconciliation between monetary valuations and thermodynamic measures. In other words, if economists can use lighting as an indirect indicator of GDP, we can also invert this relationship and treat lighting as one parameter by which the growth of economic activity can be measured in physical magnitudes, without referring to GDP at all. At the same time, we can straightforwardly establish that rebound effects would play a central role in dissecting the causal processes that link energy and growth.

Lighting is an important phenomenon also for the reason that this directly ties up with the size and the growth of population, so also overcomes the problematic partitioning between the two aspects of growth. In other words, we can envisage to measure economic growth by means of analyzing the expansion of human energetics, hence including technology not in the sense of production, but in the sense of extensions of the human phenotype, along the lines of recent theorizing in biology about the inclusion of external artefacts in the notion of biological organism [35,39,69]. Extensions are, among others, artefacts such as clothing or technologies for food preparation, but most importantly the entire technology of human dwelling, of which lighting is one aspect. Remarkably, energy consumed by human dwellings, *i.e.*, buildings with the accompanying infrastructure, represents the bulk of human energy consumption, far surpassing energy consumption by industry or transport [70]. From this follows that a possible measure of economic activity in thermodynamic terms is the growth of the stock of capital that makes up the human extended phenotype, in the aggregate.

This argument can be streamlined methodologically in the constitutive explanations framework. The central point is how we conceive, identify, circumscribe and characterize the system which displays rebound effects in general and also with special reference to aspects of human life on Earth, namely the artificial environments in which humans live today, of which lighting is one essential aspect (another essential one is heating and cooling). This methodological focus can be now grounded in general evolutionary theory, hence in the discipline of biology, thus mediating between physical (thermodynamic) and social and cultural phenomena. In this view, what matters are the means by which humans improve their biological functions by technological artefacts, thus evolving new structural and behavioral features of adaptation, a perspective that has also been explored in the Philosophy of Technology [71].

We can now give a more precise description of the systems in question which can be approached in terms of mechanistic explanations. The specific process in question is "urbanization", and the systems are human urban settlements. In economics, urbanization is mainly seen as a source of GDP growth, and in fact its driving force, as has been especially emphasized in the so-called "New Economic Geography" [72]. In a thermodynamic perspective, however, urbanization is the primary expression of economic activity, apart from agriculture, resulting in vast extensions of the human phenotype into complex urban technological systems and infrastructure that intensifies the flow of resources and energy: To mention England *vs.* China again, the extraordinary growth of London was a crucial factor in driving the demand for coal as a supplier of energy [41]. Economic growth is manifest in the expansion of urbanization, where a large number of complex self-reinforcing mechanisms and economies of scale (or, in another term, superlinear interactions) work together in further propelling economic growth [73–75]. This is driven by growing absolute amounts of energetic throughputs, though at higher levels of efficiency and productivity.

In order to understand these phenomena, it is again important approaching urban systems as a complex structure of operating mechanisms, in particular, firstly, as systems that organize the flow of resources and ultimately, energy, and secondly, as dynamic networks of interacting people [76]. These systems can be analyzed by a large array of analytical approaches which so far have been only marginally employed in economics, such as network analysis, and which allow to make the mechanisms of urban growth explicit [77]. Most importantly, this is also a research area where physical research and social science increasingly converge in similar methods and even theoretical hypotheses [78]. So, we would no longer approach economic growth at the aggregate level as expressed in GDP data, but as a complex evolving system of mechanisms dubbed "urbanization" (for a congenial in historical sciences, see [79]). Then, coming back to the issue of rebound effects, we would not investigate aggregate interdependencies between energy and growth, but aim at understanding how mechanisms of urbanization result in those effects, as discussed in the example of lighting. This also opens up the possibility to achieve substantial generalizations. Most significantly, as Bettencourt [75] has recently shown, for both the energetics of urban flows and the productivity of social networks, superlinearity seems to apply, resulting in a stable relationship between inputs, throughputs and outputs (in other words, technological innovations of urbanization would not result into absolute reductions of energy consumption). Theoretical relationships like this would provide a systematic foundation for the more detailed mechanistic analysis of particular rebound effects. At the same time, the pivotal role of rebound effects in understanding the energy–growth link would be confirmed.

Based on these considerations, I conclude with sketching an alternative approach to measuring economic activity and growth. This approach would be firmly embedded in evolutionary theory in focusing on the human organism, hence including population growth as an essential parameter. However, economic growth would be also seen as relating to the qualitative growth of the population, which boils down to the evolution of the human extended phenotype. This extended phenotype is defined via all artefacts that further enhance or enable human organismic functions, hence, in most general terms, enhance adaptive functions of the human organism (for a pertinent extension of measures of adaptation, see [80]). In arguing this way, we also need to consider the fact that human adaptation is "social", if not "ultrasocial", in the sense that even without considering technological artefacts, the human appropriation of natural resources is based on a social division of labor [20]. However, we can also assert that this division of labor as a collective phenomenon is only enabled by the technological infrastructures, as is most salient in the phenomenon of urbanization. Therefore, we can envisage a measure of economic growth that directly builds on the measurement of urban infrastructure, including all supporting structures which are necessary to maintain it. As I have shown, this is, for example, the capital stock of urban buildings and the flows that maintain living in buildings, such as lighting (this compares with related approaches in the literature which refer to accumulated GDP as a measure of thermodynamically relevant output [24,25]).

Measuring this capital stock as an aggregate quantity, however, would eventually also involve the use of monetary prices. However, the difficulties differ from using GDP data, as the capital stock would include both private and public stocks, and as there are many approaches and databases that allow assigning economic value to this stock. However, we can also, as a first approximation, refer back to population numbers: After all, the entire urban infrastructure serves to maintain a living for people. Therefore, I propose to regard the absolute and relative growth of the urban population as a measure for economic growth in an integrated framework of thermodynamics and economics. This is a most parsimonious way to include the two modes of growth in one measure that is directly compatible with a thermodynamic perspective: We treat the expansion of the extended phenotype by means of artefacts as the expansion of human energetics from considering the human metabolism only towards the inclusion of the urban technological metabolism that maintains the growing share of urban population as a part of the expanding total population.

Interestingly, this perspective also ties up with measuring the ecological impact of human activity by means of HANPP as this also includes the use of land for infrastructure as a form of land use [22]. We can infer also normative and design conclusions from this observation, thus establishing connections to the discourse of Ecological Economics as well. One simple ecological imperative is that land utilization by urban growth should be kept as small as possible, thus favoring expansion of urban infrastructure into the "third dimension", *i.e.*, high-rise buildings with high degrees of energetic efficiency in cooling and heating; this speaks against the global trend of suburbanization [81].

Coming back to my example of China, again, the two aforementioned modes of growth are directly reflected in the pattern of urbanization that was dominant until the mid-20th century. China had achieved a comparatively high level of urbanization in the Middle Ages, reflecting the mediaeval revolutions in agriculture and market organization. However, later, the growth of large cities was stalled, in favor of the spread of small-scale semi-urban settlements which remained deeply integrated with the rural areas [82]. This agrarian regime was sustainable over centuries, achieving high levels of efficiency without investing ever growing energetic resources into the expansion of urban structures. In Western countries, the accessibility and activation of huge amounts of fossil resources allowed for investing into the build-up of urban physical structures (for a related theoretical argument on the relationship between resource abundance and fixed costs of urbanization *vs.* agrarian structures, see [83]). China's recent explosive economic growth is accompanied by the rapid expansion of urban and metropolitan areas, so that we can directly approach this expansion, reflecting the extremely high rate of investment into urban infrastructures, as a measure of economic growth. Interestingly, China is also unique in achieving growth with extremely high rates of savings and investment: A considerable share of these investments is devoted to real estate, meaning urbanization. So, the distinct population dynamics of China past and present, corresponding to distinct patterns of growth in terms of GDP, can be directly interpreted as a measure of growth, with the exploding share of the urban population in total population, with now low rates of total population growth, indicating the switch between the two modes of growth. We can also directly apply the aforementioned design considerations, as one conspicuous feature of current Chinese urbanization are urban sprawl and the inefficient use of land [84].

4. Conclusions

The methodology of constitutive explanations offers a solution to the dilemma of combining thermodynamics and economics within one single explanatory paradigm. This reflects the fundamental philosophical quandary behind this dilemma, namely the widespread belief that human action is not determined by laws of nature, but only constrained by them. This view goes hand in hand with the idea that ultimately humans have the power to design the evolution of the technological and social systems they live in.

In the constitutive explanations framework, human action is part and parcel of the larger systems into which it is embedded. These systems are multi-level, hence include physical mechanisms, as well as biological or cultural ones. Approaching them in the mechanism view recognizes the fact that the evolution of these systems may be partly caused by human action, but is not fully designed by humans. The mechanism view does not imply, however, that natural laws directly determine human action; but it favors a naturalistic view on human action in the sense that its causes and effects are approached as phenomena in the material world.

The practical implications of this methodological view have been explored in this paper. I argue against the idea that it is sufficient to approach the thermodynamics–economics link in terms of highly aggregate regularities, such as the direct impact of energy on growth as measured by GDP. Beyond that, the constitutive explanations view aims at identifying the architecture of a larger number of mechanisms that play together in generating certain economic phenomena. For single mechanisms, such as technological mechanisms, physical laws may apply directly, but they cannot cover the complex interplay across ontological levels that is characteristic of human techno-economic systems. I have argued that approaching growth from this perspective means identifying core mechanisms of growth, and that this is urbanization. There are many implications for research strategies here, such as integrating analytical methods used in understanding technological systems with those applied to human social phenomena, and also for measurement strategies.

In conclusion, I think that the constitutive explanations framework defines the appropriate methodology for the "Economics of the Anthropocene", as it allows for a frictionless integration of the natural and the social sciences. Economists need to recognize the complex interplay of evolutionary processes on different ontological levels of the Earth system, and, in particular, need to approach technology as an independent force in explaining economic processes, beyond the conventional view that technology is a means to overcome constraints of economic actions.

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