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Energy, urbanization, and complexity: Towards a multi-scale ecological economic theory of innovation

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ABSTRACT

The concept of innovation is at the core of any attempt to draft a meaningful theory of economic change. Whether by reducing innovations to the "myth of the sole inventor" or by adopting technological determinism, dominant narratives ignore the complexity of the socio-ecological relations underpinning patterns of societal transformation. This article proposes a framework grounded in critical realism and ecological economics to characterise innovations as elements endogenous to historical patterns of socio-ecological reproduction. Departing from Schumpeter's definition of creative response and Georgescu-Roegen's concept of exosomatic evolution, I discuss three main arguments: first, the relation between innovations and socio-economic change is impredicative, because the direction of causality cannot be clearly established; second, the emergence of innovations is bounded by declining marginal returns to economic complexity. Third, economic change has to be contextualised in relation to historical cycles of energy use and economic complexification. These arguments corroborate the hypothesis that a long-lasting S-shaped wave of innovation took place in capitalist economies over the past two centuries. This article has several implications for the study of both innovation waves and economic growth, in particular, by proposing a new framework to conceptualise productivity, energy, and labour as cornerstones of a multi-scale theory of innovation.

1. Introduction

The myth of the sole inventor is the belief that groundbreaking ideas sprout in the minds of those ahead of their time - the visionaries, the pioneers, the dreamers. Yet, reducing innovation to the realm of ambitious entrepreneurs or brilliant scientists acting alone is a gross oversimplification. This oversimplification undermines any genuine effort to understand the intricate dynamics of technological, and therefore economic, change. As Lemley (2012), p. 736) eloquently puts it, clinging to the myth of the solitary inventor only feeds into "theories divorced from history," rendering their application merely rhetorical. History and historiography, however, can also be contested spaces of confrontation, where inference is often drawn from biassed views and preconceptions (Paavola and Fraser, 2011). For instance, the widely accepted historical interpretation of the industrial revolution as a trajectory of continuous economic growth and social progress perpetuates a simplistic rhetoric of "[t]echnological and institutional ingenuity […] as the two interrelated keys to the 'rise of the West' in the modern era" (Barca, 2011, p. 1310).

Such a partial interpretation of technological progress and market equilibrium has been recently criticised by heterodox scholars, and in particular ecological economists, for being inappropriately used to justify those political and research agendas based on the 'ecological modernization' paradigm (Jackson, 2019), the idea of 'circular economy' (Giampietro and Funtowicz, 2020), or the 'climate smart agriculture' narrative (Clapp et al., 2018). Historical analysis is therefore a key-element to define categories and elaborate theories but it requires a careful treatment of the notion of causality. Indeed, any meaningful analysis of socio-ecological change requires a systemic account of the means by which innovation emerges, and the goals that innovation serves. Following Alf Hornborg's (2016) argument, to interpret historical patterns of innovation it is necessary to deal with both the materiality (the means) and the morality (the goals) of the underlying socio-economic system.

This article provides a framework oriented to reconnect innovation theory and socio-economic and environmental history. To such an extent, I propose to re-interpret the role that innovations play in human societies by adopting a complexity-driven approach. I develop a four-step argument: first, I assess the implications of a critical realist view of innovation theory; second, I recollect the seminal ideas and concepts that have been developed so far in relation to the relationship between

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innovation and social complexity, in particular the definition of declining marginal returns to complexity and the great wave hypothesis; third, I propose three principles for the elaboration of an ecological economic theory of innovation; fourth, I show how those principles interoperate with the concept of declining marginal returns to complexity, and how the great wave hypothesis can be revisited accordingly.

2. A critical realist account of innovations – materially-dependent, temporally-situated, socially-constructed

Ecological economists began to elaborate on Critical Realist premises at the beginning of the twenty-first century (Spash, 2008, 2012, 2013; Holt et al., 2009), as they saw Critical Realism as an opportunity "[…] to clarify how natural and social sciences can cooperate and the extent to which they can combine in a way which meaningfully advances knowledge" (Spash, 2012, p. 37). The Critical Realist school of thought proposes an "approach that captures both realism and the inadequacy of our ability to know" (ibid., p. 42), acknowledging that a reality exists but is composed by different ontological strata, which emerge one from the other and are irreducible.

In the economic domain, Critical Realism asserts that events (e.g., products exchanged on markets) are the empirical manifestation of underlying causal mechanisms and generative structures. Looking at Fig. 1 from the top down, for instance, it is possible to classify two events (the black dots) as belonging to the ontological realm called "empirical." The two events can be directly observed as the quantity (Q2) and the price (P2) of a new commodity entering the market space. Of course, the two events are interrelated in some way, as they are probably intertwined with pre-existing exchanges of other commodities. Whereas neoclassical economics adopts a positivist interpretation of Humean causation, stemming from the formulation of general laws deduced from the observation of constant conjunctions of events of the type "whenever x then y" (Lawson, 1995), Critical Realism asserts that the analysis of regularities, patterns, and correlations in the empirical domain is not sufficient to explain how novelty emerges.

To explore causality it is therefore necessary to dig deep inside the "actual" domain, where observable (black dots) and unobservable (white dots) events take place and shape reality, but tend to escape from empirical investigation. These events might be the product of cultural, institutional, or social interactions. Fig. 1 shows how a new commodity emerges as an economic event thanks to its relationship to the other commodities sold within a physical, institutional, and cultural space, e.g., the "market." In turn, both the commodity and the market space emerge from an underlying "real" ontological layer, which comprises the fundamental causal mechanisms escaping empirical observation ("M1," "M2," "M3") that makes it possible for events to exist. These mechanisms are relations unfolding from particular generative structures ("S1" and "S2") that exist and have the power to enact (or to not enact) processes and relations from which events eventually result. Hence, the set of causes bringing an economic phenomenon (i.e., a new commodity) to emerge has to be thought as a complex process of broader change taking place through historical time in socio-technical systems embedded within specific configurations of socio-ecological relations.

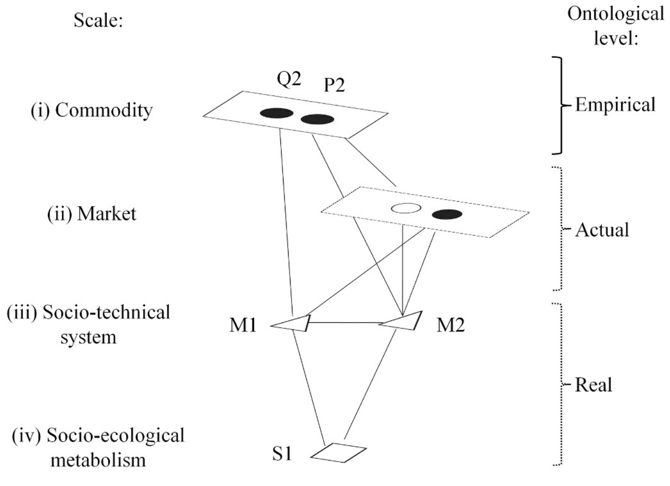

Fig. 1. A Critical Realist representation of a creative response generating a new commodity.

In Critical Realist terms, a socio-technical system is composed of:

> […] Multiple, lower-level entities (e.g. firms, technologies, infrastructures, norm circles) that are necessarily related in particular ways. [..] The relations and interactions between these constituent entities allow the system to function effectively as a whole and provide it with causal properties that would not exist in the absence of those relations and interactions. A sociotechnical system therefore has properties and capabilities that cannot be predicted from the individual behaviour of its constituent entities, including both the stability of the system and the processes by which it maintains that stability and resists change. Hence, explanations of both stability and change that do not refer to the emergent properties of the system are necessarily incomplete (Sorrell, 2018, p. 1276).

I individuate in the "socio-ecological metabolism" the generative structure - the set of physiological and dialectical relations that characterise a society within a specific biophysical environment- making possible for specific socio-technical systems to emerge. The word "metabolism" refers to Rosen's theory of the modelling relation, according to which social systems can be seen as systems constantly evolving by coordinating their structures and creating new functions in response to *anticipated* future states (Menegat, 2022). The process of anticipation is possible because the very social system produces models of the reality (norms, institutions, narratives, and ontologies) providing the agents with information about possible constraints and opportunities. The socio-ecological metabolism can therefore be conceptualized as a set of functions and relations unfolding in response to some sort of futured present.

In Critical Realism, therefore, ideas are not only socially constructed but also materially-dependent insofar as one "sees society as arising from creative action, [… which] can never be separated from its concrete, material medium" (Graeber, 2001, p. 54). Any new technology (e.g., a new tractor) can be defined through a set of relations bridging the technology's empirical manifestation (e.g., the new tractor sold to a farmer), its conception within a physical and social space (e.g., a market for agricultural equipment, a computer or a pencil to design it), the network of socio-technical relations necessary to achieve it (e.g., patent laws, factories, workers, entrepreneurs), and the underlying socio-ecological configurations (e.g., the availability of fuel and raw materials, food for factory workers, technical knowledge, and so on). This multi-layered view suggests that innovations emerge from causal mechanisms and generative structures through complex patterns of societal reproduction transforming both social relations and their material infrastructure (Tyfield, 2013, pp. 109–110).

3. From Schumpeter to Georgescu Roegen: evolution, energy, and promethean technologies

The Critical Realist lens adopted has two fundamental implications: first, material and social processes are unavoidably intertwined, and therefore innovations are both socially-constructed and materially-bounded; second, causality runs across multiple layers of reality and manifest itself throughout historical time, therefore innovations emerge from social relationships situated in both time and space. During the nineteenth century, two economists elaborated their theories of innovation departing from similar premises: Schumpeter and Georgescu-Roegen.

The father of innovation studies in economics, Joseph Schumpeter, coined the term "creative response" (Schumpeter, 1947, pp. 150–151) to characterise a process that introduces innovation to the economy, an industry, or a firm, and that is unpredictable, determines future outcomes, and is socially-constructed. By recalling the Critical Realist standpoint presented in the previous section, it can be said that, according to Schumpeter, creative responses manifest themselves at the empirical level as forms of process or product-innovation following events and causal mechanisms taking place in the actual and real domains, such as changes in tastes, culture, quantity or quality of factors of production. However, these events and causal mechanisms explain only a tiny portion of the great variety of innovations emerging in capitalist societies characterized by entrepreneurial activity (ibid.). In fact, the generative structure, or the initial cause, of most innovations in Schumpeter's view is represented by the social class of profit-seeking entrepreneurs (9Schumpeter, 1939, p. 100).[1] In turn, entrepreneurs' propensity to innovate depends on two additional causal forces: competition and declining physical returns. On the one hand, competition reduces firms' rate of profit by forcing prices downwards, thus pushing entrepreneurs to innovate in order to open new markets with lower competition or to cut production costs; on the other hand, the physical marginal returns of every factor of production tend to decline over time, thus limiting firms' capability to increase profits by expanding production without innovating (ibid., pp. 84–85).

The interaction between the socially-constructed (law of competition) and the materially-bounded (law of physical returns) nature of entrepreneurs' agency regulates the evolutionary pattern of capitalist economies through business cycles that constantly re-shape the methods of supplying commodities, thus determining the inherent instability of the economic process (ibid., p. 83). Schumpeter's theory is intrinsically associated with a temporal dimension, emphasizing the crucial role of change and evolution in its conceptual framework. These elements are foundational for an ecological economic approach to innovation theory.

Schumpeter's seminal contribution, however, has a critical limitation which is tied to the deductivist standpoint that characterizes the epistemology of his own time (de Graça Moura, 2004, pp. 280–282); in particular, in his work, he could not address innovations within a broader system of social reproduction and a deeper understanding of the materiality of the economic process, elements that are essential to understand how the class of entrepreneurs emerges as a distinct generative structure and how declining physical returns appear as causal forces. Some of these criticisms were evident in Paul Sweezy's observation that, in Schumpeter's theory of capitalist evolution, there is no place for capitalists at all, for if they were included, the "[…] Ordering of cause and effect may […] be reversed.*"* (Sweezy, 1943, pp. 95–96). Nikolai Kondratiev (another father of innovation studies) underlined a very similar point in his writings, namely that innovations should be understood as being at the same time creative responses to the endogenous forces of capitalist reproduction and one of their main drivers (Rosenberg and Frischtak, 1984, p. 9). This complex acceptation of causality entails that new technologies and new modes of production might appear as "creatively destructive" forces only for some agents and processes within a larger system of social reproduction. Indeed, if innovations on the one hand disrupt markets, ruin firms, and cause unemployment, on the other hand they also reinforce the very identity of the capitalist system, by expanding its technical infrastructure, by increasing its rate of accumulation, and by consolidating its power relations. Positive feedback loops and lock-ins therefore allow for the expansion of the system in place, while constraining the emergence of alternative patterns through "long-waves" of techno-economic evolution (Dewick et al., 2004).

In the 1930s, Georgescu-Roegen and Schumpeter met at Harvard. It was at this time that Schumpeter turned the young mathematician into an economist (Georgescu-Roegen, 1992, p. 130 quoted in Heinzel, 2013, p. 252). From then on, Georgescu-Roegen developed a theory of innovations that was close to Schumpeter's idea that creative responses are irreversible and qualitative leaps (Maneschi, 2006). However, he went further, arguing that declining physical returns are determined by a fundamental law of modern physics: the second law of thermodynamics. By introducing the thermodynamic lens, Georgescu-Roegen concluded that the emergence of certain types of innovations in a particular time and space, is tied to specific patterns of biological and economic (bioeconomic) evolution (Mayumi, 2009, pp. 1237–1238). In keeping with Georgescu-Roegen's argument (1984, p. 29), innovations (e.g., from the economic organization of a factory system to thermonuclear reactors) cannot violate the basic requirement of any physical process: the need to convert energy carriers (e.g., food for workers or fuel for a thermonuclear reactor) into useful work. Since "[…] no technology can produce its own fuel […]" (ibid.), different technologies require specific types of energy carriers, the availability of which depends on both the biophysical context (e.g., availability of forests for firewood) and the organization of the socio-economic system (e.g., availability of paid or unpaid workers). In this sense, innovations impact the way social organizations harass, transform, and distribute both human and extra-human energy to social agents. Georgescu-Roegen set the stage for overcoming the limitations of Schumpeter's theory by providing a rationale to understand how the entrepreneurs' social class reproduces itself, and how declining physical returns emerge as a force driving innovation. In other words, by introducing the concept of energy and the second law of thermodynamics he found convincing arguments supporting the idea that innovations are endogenous to underlying systems of social and biophysical reproduction.

The first argument (social reproduction) has to do with humans' capability to use tools. Indeed, Georgescu-Roegen understood the increasing reliance on "exosomatic organs" (i.e., tools to increase the range of -endosomatic- human activity) as being the characteristic trait of the evolutionary pattern of our species (Gowdy and Mesner, 1998, p. 149). Following his reasoning, this reliance became an addiction that eventually brought humanity to transcend the "[…] slow endosomatic improvement of its mode of existence" and to undertake a steady and unprecedented path of exosomatic evolution (Georgescu-Roegen, 1977, p. 363). One can easily imagine how the process of exosomatic evolution impacts the ordinary life of human societies. Exosomatic tools decrease the effort required to carry out ordinary tasks, they free up precious time that can be invested in other activities, and sometimes those activities produce new exosomatic tools that eventually can set up a self-reinforcing feedback loop (hence, Georgescu-Roegen's definition of "exosomatic addiction"). The comfort that people enjoy can possibly increase, but this process also triggers the emergence (or imposition) of asymmetric fluxes of biophysical exchange between societies (Hornborg, 2016) as well as within societies (depending on the distribution of exosomatic tools among different social classes). On the one hand, as in a positive feedback loop, the unequal distribution of tools sustains and reinforces those very power relations from which innovations eventually emerge to consolidate the unequal distribution of resources and wealth. On the other hand, innovations can change the distribution of exosomatic tools among social classes thus favouring functional differentiation (division of labour) of the system, as well as its expansion.

The second argument (biophysical reproduction) is directly tied to the second law of thermodynamics through the concept of promethean technologies. In Georgescu-Roegen's view, not all innovations are the same. A promethean technology is a tool, or a technique, that is capable of transforming energy into useful work through a chain reaction, thus generating a great amount of energy surplus. Exosomatic evolution therefore entails that great flows of easily accessible energy are invested by humans in order to produce (and reproduce) a limited set of

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[1] Schumpeter's point of view has changed on this subject, as shifts from his early to later works have shown. In his later texts, the author shifted the focus of his model from the entrepreneurs to the "large corporations." For a complete account of this subject, see Frank (1998).

technologies and techniques. Technologies and techniques that are not compatible with the existing flows of energy available in a society cannot exist as "innovations," because they simply are unviable. As Georgescu-Roegen explained:

> […] Surprising though it may seem, only two inventions have led to viable technologies. Perhaps even more surprising is that the first crucial invention consisted of what is now a most ordinary phenomenon: the mastery of fire. […] We may refer to the technology opened by Prometheus I (as he should be called) as the Wood Age. […] For centuries wood served as the only source of caloric power, so that, with industrial development growing continuously, forests began disappearing with increasing speed. […] The impending crisis was entirely analogous to the present impasse: the technology based on wood was running out of its supporting fuel. It was solved in time by the second crucial invention, the ingenious, unpredictable gift of another Prometheus -Prometheus II- actually, two mortals, Thomas Savery and Thomas Newcomen: the heat engine. […] The gift of Prometheus II enabled us to derive motor power from a new and more intensive source, the fire fed by mineral fuels. We still live mainly with that viable technology by obtaining work from heat (Georgescu-Roegen, 1984, p. 30).

Similarly to Schumpeter's physical returns, promethean technologies are also subject to declining returns. However, in Georgescu-Roegen's view, the cause of declining physical returns is the second law of thermodynamics. Therefore, in the long run, a trajectory of ongoing exosomatic evolution requires the discovery of new promethean technologies to compensate for the declining phase of the previous ones. Such an interpretation implies a fundamental consequence: exosomatic evolution is bounded by the availability of a promethean technology, and ordinary innovations cannot overcome the thermodynamic limits posed by the former. This means that, in the long run, the full exploitation of the possibilities opened by a promethean technology is expected to both deliver decreasing returns and to reduce the "option space" for the emergence of new innovations.

To sum up, both Schumpeter and Georgescu-Roegen recognized the process of economic change as a dynamic, evolutionary one. The key-driver of economic change is the emergence of innovations. However, innovations are tied to particular patterns of social change (distribution of tools, wealth, and power) and biophysical transformation (promethean technologies). The two dimensions are bounded together by, but not reduced to, the notion of energy, a concept encompassing both extra-human (i.e., energy sources) and human (i.e., labour) nature.

4. Recent developments: social complexity, urbanization, and the great wave hypothesis

An ecological economic view based on the premises presented in the previous sections has a crucial implication for the study of innovation processes: if energy matters in shaping the organization of human societies, then it is necessary to adopt a framework grounded in the thermodynamics of complex adaptive systems to properly discuss the process of innovation. While entropy increases at the overall level, complex adaptive systems can locally organize by harnessing external energy flows and information processing, creating a unique interplay between thermodynamic constraints and adaptive behaviour. In other words, these systems maintain their organization by dissipating external energy, not violating the second law but using it strategically. Complex adaptive systems therefore operate far from thermodynamic equilibrium, using positive feedback and self-organization to maintain their structure and adapt to changing environments.

Human societies and economies work as complex adaptive systems, increasing in complexity by processing increasing fluxes of available energy (Mayumi, 2001, pp. 99–100). In Tainter's (1988) definition, a socio-economic system can be considered more or less complex depending on its size and the quantity of specialised social roles necessary to its functioning (ibid., 23).[2] In Tainter's view, creative responses (technological or organizational innovations) arise as problem-solving strategies. Differently from Schumpeter, Tainter argues that the engine of change is not to be found in a particular social class interested in pursuing its interests (i.e., the entrepreneur innovating to make a profit), but in the whole society struggling to increase (or at least to maintain) its own complexity. However, such an endless search for increasing complexity sometimes destabilizes the entire system, bringing it towards a collapse (ibid., p. 37; Manheim, 2020). The argument runs as follows: growing economic and social complexity entails additional mechanisms of control and adaptation (e.g., institutions, bureaucracy, law enforcement institutions, armies). The growth of these activities increases the adaptive capacity of the entire society, but, in turn, it absorbs increasing amounts of resources and labor. Therefore, the society, and in particular those sectors providing it with flows of energy, materials and food, has to bear the "costs" of increased complexity. Once high levels of complexity are reached, further investments do not produce the same "benefits" that the previous ones delivered. Complex socio-economic systems are thus subject to decreasing marginal returns to their own complexity, meaning that "complexity as a strategy becomes increasingly costly, and yields decreasing marginal benefits" (Tainter, 1988, p. 93).

Tainter's ideas have been indirectly corroborated by numerous authors coming from different disciplines. On the one hand, Pastore et al. (2000) demonstrated how societies increasing their energy consumption and reducing the proportion of workforce employed in their productive sectors, such as energy, mining, and agriculture (Giampietro, 1997a, 1997b), achieve higher rates of functional specialization, economic growth, and higher material standards of living. On the other hand, various researchers, organizations, and economists have argued that the marginal "benefits" of GDP growth (and therefore of increasing social complexity), tend to decline at some point.

Certain scholars, for instance, have observed a decoupling between GDP growth and alternative indicators of well-being, such as the Index of Sustainable Economic Welfare (Daly and Cobb, 1994) or the Genuine Progress Indicator (Cobb et al., 1995). However, quantifying social "well-being" is intricate due to the complex, interconnected, and dynamic nature of socio-economic systems, diverse stakeholder perspectives, time lags, subjective valuation, global interconnectedness, and the challenge of assessing long-term and intangible impacts. Well-being indicators therefore rely on arbitrary assumptions which can undermine the fundamental definition of the assumed "benefits" and "costs" of economic growth (Neumayer, 1999).

Others have even suggested that structural shifts in the economy, such as demographic changes, slowing productivity growth, and persistent demand deficiencies, have lead to a chronic state of sluggish economic expansion, also called "secular stagnation" (Summers, 2016). Key factors driving this phenomenon may include an aging population, rising inequalities, and declining quality of energy (in particular oil) resources (Jackson, 2019). In addition, several scholars have underlined how the "secular stagnation" could be the consequence of declining marginal returns to innovation. For instance, both Robert Robert Gordon (2017) and Tyler Cowen (2011) emphasize the idea that low-hanging fruits of innovation have already been plucked, and therefore future innovations may be more difficult to achieve, while their returns in terms of productivity and economic growth will be declining over time. The notion of declining marginal returns to innovation suggests that as a society invests more in research and development, the incremental benefits or improvements gained from each additional unit of innovation diminish over time. This concept is rooted in the idea that easy and obvious innovations are typically adopted first, while subsequent advancements become progressively more challenging and resource-intensive. A classic example is Moore's Law in the semiconductor

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[2] For a critical assessment of this definition, see Allen et al. (2018).

industry. Initially, doubling the number of transistors on a microchip led to significant performance improvements, but as the industry has progressed, achieving further doublings has become increasingly complex and costly. Another illustration is the pharmaceutical sector, where the discovery of new drugs has become more difficult as researchers address more intricate medical challenges.

By focusing on innovation and by applying Tainter's (1988) analytical framework to contemporary societies, Bonaiuti (2014, 2018) argues that Western countries have already entered a phase of declining marginal returns to complexity somewhere between the late 1960s and the 1970s. Building on Georgescu-Roegen's idea of exosomatic evolution, Bonaiuti notes how declining marginal returns to complexity tend to emerge once the low-hanging fruit of a promethean innovation have been picked. According to Bonaiuti, a technology of this type represents a powerful entropic watershed capable of producing a "[…] leap in scale in social complexity" (2014, p. 26). Through waves of innovation, societies progressively expand and adapt themselves to the new conditions. However, once the low-hanging fruit derived from the widespread adoption of the promethean technology have been picked, declining marginal returns to complexity appear as a driving force of dynamic change. With his great wave hypothesis, Bonaiuti (2018) argues that after the introduction of a promethean technology, a first phase of increasing complexity marks the expansion of the system; when declining marginal returns emerge, a second wave of expansion can unfold, but if the promethean technology fails to deliver increasing returns in terms of energy surpluses, phases of increasing complexity bring about a rise in costs and deliver decreasing benefits, as observed by Tainter (1988). Although innovation is still taking place, the whole system enters the plateau stage, appearing as an S-shaped curve that Bonaiuti calls the "great wave." This is the most critical and unstable part of the entire cycle, as growing complexity results in higher costs and lower benefits for the entire society (Giampietro et al., 2013, pp. 241–242). In other words, this stage entails that the economy has jeopardised its own stability and resilience by further investing in its own complexification (Manheim, 2020). In Tainter's (1988) words:

> Technological innovation […] is subject to the law of diminishing returns, and this tends to reduce (but not eliminate) its long-term potential for resolving economic weakness […]. For human societies, the best key to continued socioeconomic growth, and to avoiding or circumventing (or at least financing) declines in marginal productivity, is to obtain a new energy subsidy when it becomes apparent that marginal productivity is beginning to drop (p.124).

In his analysis of UK and US returns to complexity, Bonaiuti (2018) focuses on the level that I called "empirical," where monetary productivity growth (total factor productivity, TFP) across different economic sectors (excluding agriculture) has been used as an approximation of the gains associated with increasing complexity (economic growth).

If, on the one hand, the approaches mentioned in this paragraph add new evidence to the hypothesis of declining marginal returns to complexity, on the other hand they do not address in a systemic way the relationship between innovation and social complexity, limiting their focus to the constant conjunction of empirical events (i.e., innovations and productivity growth). By contrast, a systemic approach should individuate possible causal mechanisms and generative structures at play. Similarly to Tainter's anthropological argument, system thinkers have convincingly shown how urbanization might be an important causal mechanism to take into account. Urbanization is a fundamental catalyst of complexity growth, because it enhances economies of scale in energy use and information processing capacity (Bettencourt et al., 2007). As Lane et al. (2009) aptly remark:

> Not only does this relatively high information processing capacity ensure that [cities] are able to maintain control over the channels through which goods and people flow on a daily basis, but their cultural (and, thus, information-processing) diversity also makes them into preferred loci of invention and innovation. The super–-linear scaling of innovation with city size enables cities to ensure the long-term maintenance of the information gradient that structures the whole system. It is due to a positive feedback loop between two of any city's roles. One the one hand, most flows of goods and people go through towns and cities. That confronts them most intensely with information about what is happening elsewhere, and this – again – enhances their potential for invention and innovation. But the same connections enable them to export these innovations most effectively – exchanging some part of their information processing superiority for material wealth. Cities are demographic centers, administrative centers, foci of road systems, but above all they are the nodes in the system where the most information processing goes on. As such, they are the backbone of any large-scale social system. (ibid, p. 3).

The factor linking together social complexity and innovation is therefore the constant exchange between material wealth (generated in the productive sectors of the economy located outside of urban centers like energy, mining, and agriculture activities) and information processing capacity of the cities (fundamental to innovate). This observation entails that, as in every complex adaptive system, also in human societies the growth of the system and its relative benefits are tied to the availability of energy surpluses. The arguments developed by Mauro Bonaiuti and David Lane therefore pave the way for a deeper analysis of Tainter's theory of declining marginal returns to complexity, which represents the basis for the development of an ecological economic theory of innovation.

5. Biophysical foundations for innovation studies

The energy-urbanization-complexity nexus determines three fundamental behaviors that characterise innovation processes in human societies: (i) a forced metabolic interplay between energy flows and the structure of socio-economic organizations; (ii) the multi-scalarity of the relationships between agents and processes located in non-equivalent, and therefore not-reducible, levels of the system; (iii) the dialectical tension, or even the trade-off, between the efficiency and the productivity of the socio-economic system. The following paragraphs discuss each of these arguments in detail and provide a general framework for the analysis of innovation dynamics through an ecological economic lens.

5.1. Forced metabolic interplays

Consider a socio-ecological system operating according to its own purpose within a specific biophysical context. The system enjoys some degree of freedom, meaning that it can organize itself in terms of the activities, functions, and structures necessary to pursue its goals. However, the system is also bounded by two categories of constraints: (i) first, external conditions constrain the evolution of the system insofar as it needs energy and materials to exist; (ii) at the same time, the relationship between the system's components (e.g., social classes, cultural norms, division of labour) defines the identity of the whole (e.g., an agrarian-feudal society or an industrial-capitalist one) and is constrained by it. Innovations are strategies for overcoming the first type of constraints and to make the adverse effects of the second ones at least bearable.

External pressures impact human organizations in various ways, particularly in those activities that involve interactions between social and ecological systems, like food, energy, and raw materials provisioning. Agriculture, energy, mining, and, to some extent, building and manufacturing are also productive sectors where part of the output must be re-invested in production to make flows of energy and materials available to the whole of society. Hence, they are called hypercyclic, in contrast with the dissipative sectors that only consume flows of resources to reproduce the structure of a society and increase its adaptability (Giampietro et al., 2014, p. 13). Innovations capable of increasing labour productivity in the hypercyclic sectors provide the economy with commodities and workforce, elements necessary to further increase the scale and the complexity of the social organization. For instance, growing productivity in the agricultural sector allow for the allocation of parts of the rural workforce to industry and services located in urban areas, boosting specialization, trade and, possibly, economic growth (Gomiero, 2018). Hence, growing flows of food and fibres produced by a diminishing rural population are typically associated with growing flows of human activity towards the town (Brandt, 1961, p. 87).

Innovations in the hypercyclic sectors may allow societies to increase the rate at which they extract and use both energy and materials. Innovations boosting labour productivity in the hypercycle are therefore necessary to increase urbanization and achieve both economic growth and functional differentiation. At the same time, these innovations are inevitably subject to shifting boundary conditions, such as declining soil fertility or mineral concentration. In turn, the boundary conditions are perceived as increasingly constraining as the effects of declining marginal returns to complexity begin to materialise. In this sense, boundaries to farming (e.g., lack of land or labour) are not perceived as constraints if a society can overcome them through further complexification (Tainter, 1988). During a stage of increasing marginal returns to complexity, for instance, the lack of land can be solved by investing resources in the appropriation of land from other contexts (e.g., through territorial expansion or international trade) or by developing new fertilizers or high-yield crops. The lack of labour can also be solved by appropriating it elsewhere (e.g., forced migration or slavery) or by introducing labour-saving innovations. However, all these strategies are at the same time expensive and temporary, insofar as a society needs to invest important amounts of resources in military expeditions, basic and applied research, long-distance transportation, and so on. In a context of declining marginal returns to complexity, when such investments fail to deliver the surplus necessary to maintain viable the strategies that have been implemented to temporarily expand the boundary conditions, a period of "involuntary degrowth" (Bonaiuti, 2018) or even a collapse can take place.

5.2. Multi-scale interactions across non-equivalent domains

The idea that socio-economic systems can be conceptualized as metabolic entities is certainly not new in sociology, and since the 1990s it has become relatively central to ecological economics (de Molina and Toledo, 2014; Padovan, 2000). In ecological economics, the term has been used mainly in two broad contexts: (i) in the tradition of Marxist political economy, the definition has been functionally articulated as an ontological and epistemological tension between humans and nature[3]; (ii) stemming from a technical-engineering approach, the notion has also been adopted to indicate the empirical dimensions of the exchanges between society and ecosystems.[4] Here I partially adopt the second definition, by including the argument developed by Giampietro and Lomas (2014), who argued that any meaningful representation of a metabolic system requires its characterization across multiple scales. With the term "scale" the authors mean at least three epistemic (relational) levels that are non-equivalent and therefore non-reducible:

> [..] 1) the small scale, where we can observe and describe the operation of the individual parts; 2) the medium scale, where we can observe and describe the interaction among the parts within the system boundaries that results in the expression of emergent properties of the whole; and 3) the large scale, where we can observe and describe the processes influencing the boundary conditions that determine the survival of the system as a whole (ibid., pp. 33–34).

The hierarchically-nested structure of metabolic processes implies that innovations are phenomena manifesting themselves throughout the different scales of a social organization as a consequence of different, although connected, causal mechanisms. The non-equivalent nature of the scales hinders the possibility to infer the direction of causality, meaning that the relationships between levels are fundamentally impredicative. For instance, following Giampietro et al. (2011), it is not possible to assert if it is technology that, by driving up food production, determines population growth (Malthus' position), or if it is population growth and a rising food demand that determine changes in technology (Boserup's theory). Defining in a clear, generalized way what "returns" to innovation or to increasing complexity are, is therefore challenging, if not impossible. But the hierarchical view also provides a rationale to interpret both urbanization (medium scale) and social complexity (large scale) as properties that emerge when substantial energy surpluses are available at the small scale, in the productive, hypercyclic, sectors of the economy. The concept of metabolism has therefore the potential to explain how the energy-urbanization-complexity nexus evolves by both driving and being driven by innovations, and especially promethean technologies.

5.3. Efficiency, productivity, and capitalization

To fully grasp the theoretical implications of the adoption of an energy-focused, multi-scale approach to innovation, it is necessary to introduce two different definitions of the word "efficiency" (Giampietro and Mayumi, 2018, p. 9): (i) efficiency of type 1 (EFT1) has to do with the principle of minimum entropy production. The principle states that the efficiency of a particular process in transforming energy fluxes is given by the ratio of input and output; (ii) efficiency of type 2 (EFT2) refers to the principle of maximum energy flux, representing the pace at which the energy transformation is performed. The intimate relationship between the two concepts lies in the fact that:

> […] The minimization of the flow of energy throughput (by reducing the input required to obtain the same output) can reduce the option space of behaviors. Such [sic] limit in the diversity of behaviors can become a liability when boundary conditions change or for a society willing to improve its living standards by expanding its set of functions. Expanding the ability to produce more in order to consume more—maximizing the energy flux—is a common attractor for socioeconomic systems. This explains why in both economic and biophysical analyses the idea that the maximization of EFT2 drives evolution has always been very popular. The principle of maximum energy flux in economics has been formalized in terms of the maximization of profit and welfare (ibid., p. 10).

One could simply denote EFT1 as "efficiency" and EFT2 as "productivity." Although existing functions tend to increase their efficiency (EFT1) through innovation, a society's drive for increasing complexity brings a constant pressure to increase the productivity (EFT2) among the same functions. Since the first industrial revolution, capitalist societies have relied on exponentially-increasing rates of mechanical transformation and transportation (Mayumi, 2001). Such an exponential

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[3] Martínez-Alier (2004) explains how Marx's adoption of the term "metabolism" had two different meanings: "First, as a biological analogy or metaphor to describe the circulation of commodities. Second […] he used the expression 'metabolism between man and earth, or between society and nature' to refer specifically to the cycles of plant nutrients" (p. 826).

[4] This approach has been mostly developed by a group of researchers based in Vienna at the Institute of Social Ecology, following the pioneering work of Robert Ayres in industrial ecology (e.g., Ayres et al., 1996). Fridolin Kraussman, one of the leading researchers at the institution defines social metabolism as "a concept that addresses these biophysical exchange processes, between society and Nature, and the related sustainability problems. It studies the biophysical basis of the economy and provides a framework to investigate patterns and dynamics of social economic material and energy flows and their drivers" (Kraussman, 2017, p. 108).

increase has been achieved through innovations that harassed the energy surplus generated by the exploitation of the last promethean technology, through the extraction and combustion of fossil fuels. However, as Mayumi notes:

> Raising EFT2 beyond a certain limit during the transformation process of matter and energy results in a smaller EFT1. For example, to raise the speed of a car beyond an economical speed, gas must be consumed at a higher rate, but even though most drivers know this fact, they prefer to drive fast. Such drivers prefer EFT2 in terms of speed of the car to EFT1 in terms of gas consumption (Mayumi, 2001, p. 80).

Within a hierarchically-nested framework, innovations increasing productivity in the productive sectors of the economy (hypercycle) and requiring small investments in terms of fuels and energy, allow urbanization and complexity to increase. This is the typical pattern generated by promethean technologies that allow the development of other innovations capable of substituting a relevant portion of workers' labour power with machineries and tools using exosomatic energy. In other words, capitalization in the productive sectors of the economy increases, driving up both exosomatic energy consumption and output per worker. However, when declining marginal returns to a promethean technology begin to manifest through declining efficiency, it becomes difficult to increase capitalization while also increasing -or even maintaining- labour productivity.

Consider, for instance, oil fields. During the first stages of exploitation easily accessible oil fields deliver high returns in terms of barrels of oil extracted per barrel of oil burned to generate the power necessary to increase production per worker. After the exhaustion of the most accessible oil fields, the exploitation of the remaining ones requires the investment of higher shares of output to extract the same amount of product, and even additional shares if one wants to increase output per worker. This results in rising capitalization and exosomatic energy consumption in the productive sectors of the economy. At some point, the entire process becomes unviable, thus compromising the profitability of firms at the small scale, but also the viability of further urbanization and complexity growth at the medium and large scales. This is either because it becomes no longer possible to increase output and provide the rest of society with abundant energy, or because productivity declines and it is no longer possible to displace labour power from the hypercycle to the dissipative sectors of the economy. Of course, incremental innovations can temporarily extend the time-window available for the exploitation of both efficiency and productivity gains, but in the long run, when a promethean technology enters a phase of declining marginal returns, the benefits of increasing productivity, urbanization and complexity come with increasing costs.

The three principles presented in this section therefore operate as general "rules" of innovation systems embedded in their biophysical context. In the next paragraph I briefly discuss what this entails in practical terms, especially in relation to Bonaiuti's view of declining marginal returns to innovation and his great wave hypothesis, which states that if a promethean technology fails to deliver increasing returns in terms of energy surpluses, the entire society may enter a phase of involuntary degrowth.

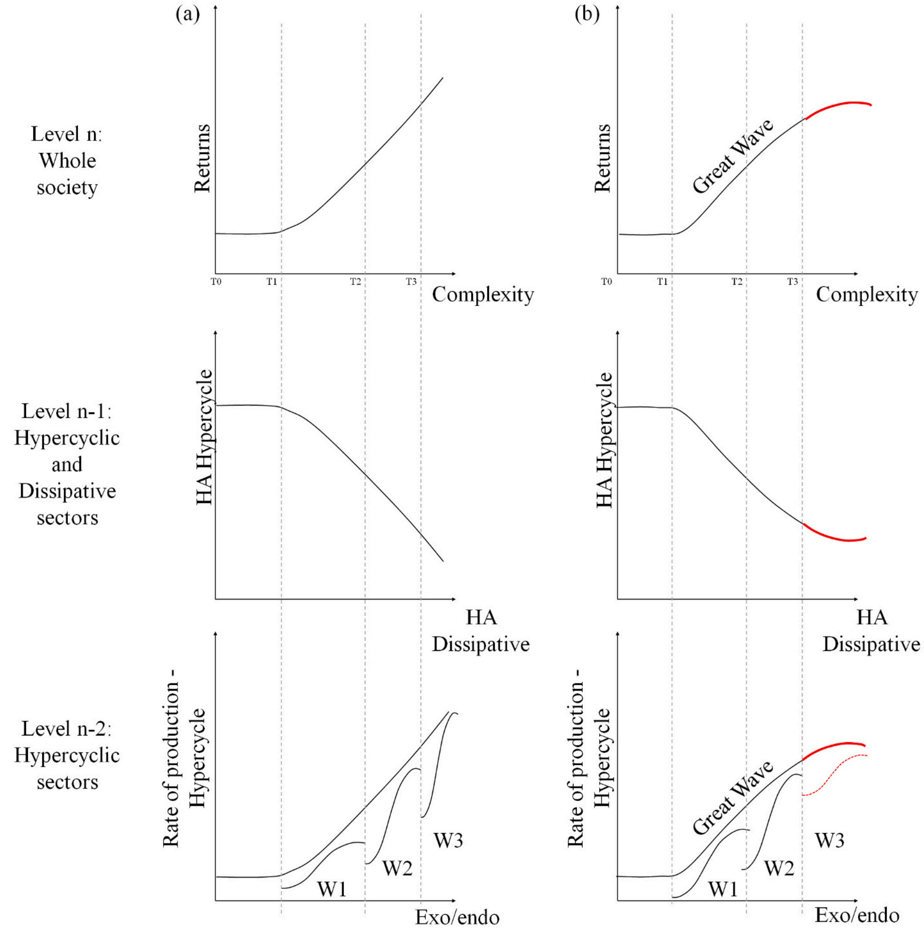

Fig. 2. Multi-scale representation of the effects of increasing economic complexity in a conventional view (a) and in the great wave hypothesis view (b).

6. Declining marginal returns to innovation and the great wave hypothesis revisited

Departing from Bonaiuti's argument, it is possible to further elaborate on the multi-scale implications of the great wave hypothesis (Fig. 2). As discussed above, in fact, the landmark innovations enabled by the promethean technology sustain a reinforcing feedback loop between the productivity of labour in the production of food, energy and mineral commodities, and the growing set of functions (e.g., basic research, corporate R&D) and infrastructures (e.g., universities, markets, legal frameworks) expressed by the society.

The multi-scale view of this process is based on the forced relation between the behaviour of the whole system (level n, whole society) in relation to its components. First, consider the case shown in Fig. 2a, which corresponds to the dominant "technology" and "markets" rhetoric of continuous innovation and unlimited economic growth: before the introduction of a promethean technology (interval between T0 and T1), complexity (approximated by the monetary measure of the size of the economy, i.e. the gross domestic product) can grow but it cannot deliver substantial benefits ("Returns," that might be approximated by the monetary evaluation of the economy's performance, i.e. total factor productivity). In dynamic terms, a society stuck within T0 and T1 can try different organizational configurations to increase capitalization and production in the hypercycle, for instance by introducing innovations exploiting animal labour power that allow the system to expand its dissipative activities and achieve higher social complexity, but only in a temporary way. Indeed, increasing capitalization in the hypercycle is a costly strategy, and if the returns to complexity growth are not

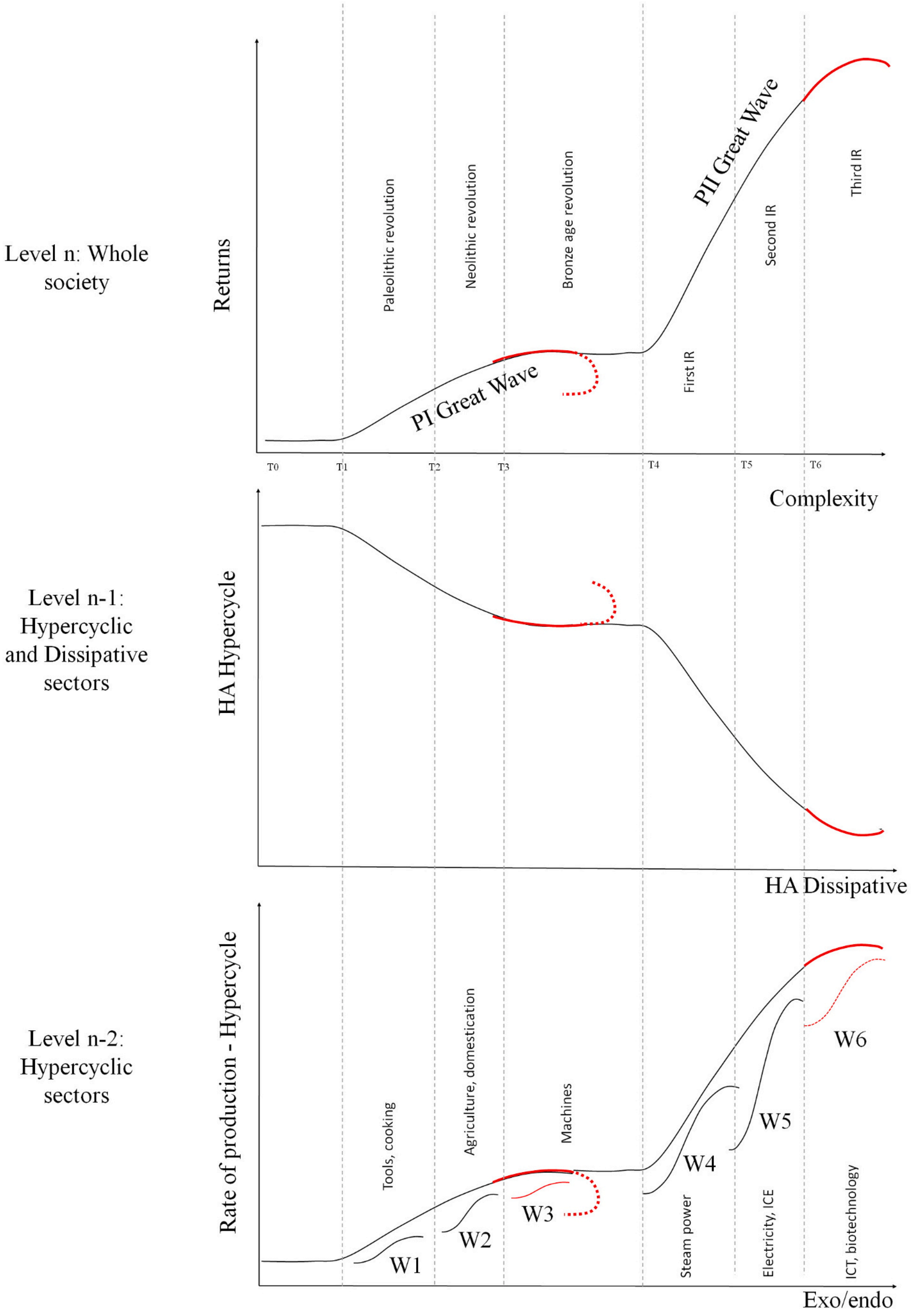

Fig. 3. Multi-scale representation of technological revolutions. Red lines are periods marked by declining marginal returns to complexity and innovation. Red arrows are possible trajectories of "involuntary degrowth" or "collapse". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

substantial, the costs are likely to be higher than the benefits. A promethean technology introduced after T1 liberates energy surpluses that can be invested in the hypercyclic sectors ("capitalization" expressing the ratio between exosomatic and endosomatic energy throughputs at level n-2) to increase productivity of energy, food, and raw materials (measured in physical output per hour of work invested in production). A first wave of innovations (W1) allows for the investment of human activity in the dissipative sectors (measured in hours of work, level n-1), which may further increase the capitalization of the hypercycle in order to reiterate and reinforce the whole process between T2 and T3. In Schumpeter's theory of business cycles, waves of innovation, or "creative destruction," (W1, W2, W3) characterise the growth of the system from T1 to T3. Each wave thus "solves" the issues posed by marginal returns declining to the previous socio-technical mixes.

Fig. 2b shows how the process unfolds when it is subject to declining marginal returns to complexity, according to the great wave hypothesis. This means that after a certain period (i.e., T3), the promethean technology fails to provide the energy surplus necessary to further increase productivity growth at the level "n-2," and therefore the marginal benefit of investing exosomatic energy in the productive sectors of the economy declines. Consequently, the trajectory of increasing urbanization observed between T1 and T3 approaches a plateau after T3, and the benefits that come with growing complexity decline. The third wave of innovation (W3) at the level of the hypercycle shows how the investment of further resources (exosomatic energy per unit of labour) in production delivers lower gains in terms of labour productivity.

Innovation in sectors other than the hypercycle can and does occur, often strengthening the behaviour of the system as a whole, but only promethean technologies have the potential to allow the system to make further leaps in scale and complexity (Bonaiuti, 2014).

A tentative representation of the great wave hypothesis is provided in Fig. 3, where the historical sequence of technological revolutions is divided into two great waves enhanced by those technologies that Georgecu-Roegen defined as promethean: the first wave ("PI great wave") represents the long-lasting wood age, during which human societies acquired their mastery of fire and exploited it to invent those tools, machines, and practices necessary to boost the productivity of the hypercyclic sectors of the economy and to sustain a growing population. The second wave ("PII great wave") begins with the first industrial revolution (IR) and the development of the fossil fuel age.

The time-intervals indicated by the letters "T*n*" are not proportional to their historical length but to the magnitude of socio-technical changes occurred during each period. The red lines show how declining marginal returns manifest throughout the different scales of the energy-urbanization-complexity nexus. Following the adaptive cycle metaphor (Menegat, 2022), these are stages of *conservation,* which bring the system into a lock-in situation, where the accumulated "wealth" (potential) is very high but it must be entirely invested to maintain the relations already in place; this kind of situation, in Holling's words, represents "[…] an accident waiting to happen" (Holling, 2001, p. 394). Indeed, the increased connectedness of the system entails rigidity and therefore vulnerability to possible disturbances. Following a shock, the system may enter a new stage, which Holling calls *release*, for the resources accumulated by the system are quickly liberated and connectedness declines steadily. The red arrows in Fig. 3 show a possible pattern of release, or "involuntary degrowth" to use Bonaiuti's (2018) words, or "collapse" as in Tainter's (1988) definition. According to Bonaiuti, in the period between the exhaustion of a great wave and the beginning of the following one (from "T3" to "T4" and after T6) a society is more vulnerable because of the emergence of declining marginal returns to its own complexity. On the one hand, complexity might still increase but it will deliver declining returns, because in the productive sectors of the economy an ever increasing use of exosomatic energy per worker will necessarily translate in a growing overhead (additional animals, technical investments, or fuel for machineries). During this stage, the "cost" of increasing a society's size and economic complexity might become unbearable. On the other hand, if innovations fail to further increase the productivity in the hyercycle because of ecological or social limitations, the society might enter a critical stage, where economic complexity declines, the amount of dissipative activities carried out shrinks, and productivity in the hypercycle cannot be maintained without investing increasing amounts of energy in production. Time, in these terms, is irreversible, but the process is also recursive. Societies may enter a declining marginal returns stage in different periods, thus generating geographical patterns of hegemonic control, conflict, expansion, decline, or collapse. As Tainter (1988) discusses, during the long-lasting period of the wood-age many civilizations found strategies to increase their own complexity, often at the expenses of other societies, in Asia, South America, and Europe, but only temporarily. Bonaiuti (2014) underlines how, in the fossil fuel age, societies entering a stage of declining marginal returns will have to face rising political instability and social conflict, thus they will be forced to choose between different future scenarios including collapse (involuntary degrowth), authoritarian involution (repressive degrowth), new expansion (not viable without a new promethean technology), or systematic simplification (voluntary degrowth).

7. Discussion and conclusions

In this paper I argued that a realist and critical innovation theory must consider technological change as a phenomenon endogenous to specific patterns of societal reproduction. I discussed three main principles that should be taken into account in the analysis of such patterns: first, the forced metabolic interplay between energy flows and the structure of socio-economic organizations entails the clear definition of human societies as systems of social systems, where certain activities are carried out in certain ways because the metabolic pattern that the society as a whole has undertaken requires so. It is expected that the productive (hypercyclic) part of a society will sustain the collective strive to increase complexity over time, as well as it is expected that the dissipative part will reinforce this trajectory by expanding its functions of innovation, adaptation, and control. Second, these processes take place throughout different scales of socio-ecological organization, in a way that is not reducible. Hence, declining marginal returns to complexity are not expected to produce the same effects at each level of social organization, and most of their impacts may not be empirically observable at the largest scale (the society as a whole). To explore how the energy-urbanization-complexity nexus evolves over time it might be useful to focus on the productive sectors of the economy, where the impact of declining marginal returns to promethean technologies is expected to produce relevant insights. Third, the efficiency of social systems in processing energy tends to increase thanks to investments of resources and labour in the dissipative sectors of the economy. However, increasing efficiency is not the main goal of a social system aiming at increasing its scale and complexity. Its primary goal is, instead, to boost the productivity of labour in the productive sectors of the economy, by substituting human workforce with technology fueled by exosomatic energy. This inevitably implies economic, social, environmental, as well as many other types of costs.

According to Georgescu-Roegen, humanity has found an addiction to the exosomatic mode of evolution—in its comforts and its potential plentiful possibilities. But exosomatic evolution requires energy, and energy transformation is bounded by the laws of thermodynamics. Moreover, the trajectory of exosomatic evolution under capitalism has generated physically and morally-unbearable inequalities, both within and between societies, that are increasingly fueling social conflicts and tensions (Hornborg, 2016). There are limits to technological change, as well as to the quantity of exosomatic devices that humanity can invent, produce, and reproduce. But there is no way to know precisely where those limits lie. Joseph Tainter states that falling energy surpluses hinder the possibility of increasing economic complexity indefinitely and it is the society itself that has to interpret, anticipate and adapt to possible emerging constraints (Menegat, 2022). Innovations serve this purpose, and innovations in the hypercyclic sectors of the economy are of fundamental importance to keep the system viable over time.

Western societies' exosomatic addiction has been growing at a steadily rapid pace during the past two centuries, leading to extraordinary windfalls in the form of increasing production and consumption rates of both services and commodities throughout a trajectory of exponential economic growth. However, according to Bonaiuti (2018), the limits of this process are becoming increasingly visible, to the point that western economies might already have entered an age of "involuntary degrowth." Ecological degradation and climate change are obviously important limits, but, from a broader socio-ecological perspective, the difficulty of reproducing what has been done in the past signals that the "end of plenty" may also depends on limits to further economic growth that are internal to contemporary societies. To test Bonaiuti's great wave hypothesis it is therefore necessary to better explore the biophysical dimensions of the productive sectors of the economy, trying to understand if, how, and possibly when declining marginal returns to the promethean technology appeared as a major force affecting the behaviour of the system.

In the future, even if a promethean technology could emerge in response to innovations arising in sectors like energy production, information technology, biotechnology, and nanotechnology (Dewick et al., 2004, p. 273), the sustainability timescale, both from an ecological and social perspective, would shrink even further if current processes of extraction and appropriation will expand to sustain larger and more complex economies, to the point that the future of the human species would be increasingly put in jeopardy (Gowdy, 2020; Handoh and Hidaka, 2010). In these terms, eco-innovation, or EFT1 growth, cannot be considered as a viable panacea as often evoked by the advocates of the "green growth" or the "ecological modernization" narratives. On the one hand, under capitalism, EFT1 gains obtained through energy-efficient are systematically offsetted by the growth in the provision or the production of the same service or good because of lower production costs (rebound effect). On the other hand, improving resource-efficiency also liberates energy surpluses that the capitalist system needs to invent processes, products, and markets to boost firms' profitability, thus resulting in further economic complexification, expansion, and overall increased resource consumption (Jevon's paradox).

To summarise, the framework discussed in this article doesn't allow for relying on the unconditional belief that technological innovation will be sufficient to cope with the currently ongoing environmental and social crises. On the contrary, the arguments presented above show how history (and in particular environmental history) can and does have a great potential to help us to interpret the present and project the future, but it also compels us to ask what kind of comprehensive theory offers sufficient tools to deal with the complexity of socio-ecological relations unfolding throughout historical time, geographical space, and ontological scales.

CRediT authorship contribution statement

Stefano Menegat: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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