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Methodological and Ideological Options

On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth

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A R T I C L E I N F O

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A B S T R A C T

This paper explores the existing confusion around the conceptual definitions and interpretations of the term circular bioeconomy. The co-existence of diametrically opposite interpretations of the concept indicates lack of a serious discussion of its theoretical foundations. Two narratives on circular bioeconomy are explored in depth: (i) the new economic paradigm based on technological progress (the economics of technological promises) that seeks perpetual economic growth; (ii) an entropic (thermodynamic) narrative that reflects on the limits on economic growth imposed by nature. The latter narrative makes a distinction between primary, secondary and tertiary resource flows and helps to identify what can and cannot be re-circulated within the metabolic pattern of social-ecological systems. Adopting the biophysical view, it becomes clear that the industrial revolution represented a linearization of material and energy flows with the goal to overcome the low pace and density of biological transformations. The required level of productivity of production factors in contemporary developed economies (flows per hour of labor and per hectare of land use) is orders of magnitude larger than the pace and density of supply and sink capacity of natural processes. Relying on nature to 'close the loop' will simply slow down the economic process.

1. Introduction

Many visions for the circular economy are currently being debated and developed in both the EU and other parts of the world (Kirchherr et al., 2017; Lazarevic and Valve, 2017; Winans et al., 2017; Korhonen et al., 2018). The unprecedented success of the term circular economy probably lies in the high expectations it raises about environmental, social and economic benefits. Particularly attractive to policy makers is the possibility to kill two birds with one stone: "*The transition to a more circular economy … is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy. It is an opportunity to transform our economy, create jobs and generate new and sustainable competitive advantages for Europe*" (European Commission, 2015). What is desperately needed is a panacea capable of lifting us out of the present economic stagnation and restart a pattern of perpetual economic growth by overcoming biophysical limits both on the input (depletion of non-renewable resources) and sink side (pollution and GHG emissions). This panacea goes under different names, such as green economy, bioeconomy, circular economy (D'Amato et al., 2017) and recently circular bioeconomy.

Lazarevic and Valve (Lazarevic and Valve, 2017) observed that "the emergence and mobilization of expectation that are shaping the EU transition … framed as a reassuring discourse and the necessary transition from the current linear economy by its prominent promoters" (p. 60). Generating expectations can be seen as a political activity with the goal of mobilizing resources and 'colonizing' the future (Brown and Michael, 2003). Jasanoff and Kim (Jasanoff and Kim, 2015) proposed the term 'economics of technological promises' for this strategy.

However, experience teaches us that hypes are often followed by disappointments (Brown and Michael, 2003; Bakker and Budde, 2012; Konrad, 2006). In the 1950s, we were promised that nuclear energy would produce electricity 'too cheap to meter'. In the 1970's, genetically modified crops were supposed to eradicate hunger from our vocabulary. In the 1980's, the hydrogen economy was going to solve our dependence on fossil energy. Having failed to do so, the same result was promised for the first generation of agro-biofuels in the 90s.

Given that the coherency of narratives used to define policies is extremely important to anticipate success or failure, this paper seeks to clarify the existing confusion about the meaning and normative implications associated with the use of the two terms 'circular economy' and 'bioeconomy' and their combination into 'circular bioeconomy'. To this purpose, the paper provides a critical appraisal of the "conventional

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narrative" underlying the EU view, using a theoretical resource perspective, and then proposes an alternative narrative based on non-equilibrium thermodynamics ("entropic or metabolic narrative").

The text is organized as follows. Section 2 discusses the origin of the different definitions and interpretations of the terms circular economy and bioeconomy. Circular economy is the "what" – the result to be achieved (the desirable outcome capable of decoupling the use of resources from natural resources), whereas, bioeconomy is the "how" (what type of biophysical processes should be enhanced to achieve the expected result). Section 3 compares the theoretical basis of the concept of circularity of 'resources' in the narrative of neoclassic economics and in the metabolic narrative of complex systems science (state-pressure framework). In the former the 'resources' considered are only the flows of materials and products under human control, whereas in the latter the analysis includes the entire set of flows (water, energy and materials) required to provide the primary sources and primary sinks associated with the metabolic pattern of modern economies. Section 4 adopts the entropic or metabolic narrative to introduce the distinction between primary, secondary and tertiary resource flows in the metabolic pattern of social-ecological systems and the implications for a definition of sustainable growth. This distinction requires making another distinction between processes going on inside the technosphere (those seen by economic narratives) and processes going on inside the biosphere (those ignored by economic narratives). Finally, Section 5 provides the conclusions.

2. Definitions and interpretations of the circular economy and bioeconomy

2.1. Circular economy

Definitions of the term 'circular economy' abound, as is evident from the title of a recent review by Kirchherr et al. (Kirchherr et al., 2017): "Conceptualizing the circular economy: an analysis of 114 definitions". All the same, Kirchherr et al. report substantial agreement on the general message associated with the definitions scrutinized and provide a synthesis (rather than providing their own): "*A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively re-using, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, national and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*" (Kirchherr et al., 2017).

We selectively highlight also the definition provided by the Ellen MacArthur Foundation (EMF) (Ellen MacArthur Foundation (EMF), 2015) as it has been highly influential in promoting the idea of a circular economy: "A circular economy is one that is regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. *This new economic model seeks to ultimately decouple global economic development from finite resource consumption*" (italics added for emphasis).

Note that both the EMF and Kirchherr et al. refer to circular economy as a *model*—"a new economic model" (Ellen MacArthur Foundation (EMF), 2015) or "a new generation of business models" (Kirchherr et al., 2017)—rather than an actual realization of a biophysical economic process of production and consumption of goods and services. Therefore, their definition or interpretation of the circular economy refers to a *desired* outcome (to the 'what') without reference or support as to whether or not that outcome is possible (no reference to the 'how'), and the association between circular economy and sustainability remains ambiguous (Geissdoerfer et al., 2017). A business model provides a 'how' to the system of control, but it does not guarantee the establishment of an effective 'how' in the biophysical realm of the economy. Indeed, the achievement of the desired outcome entirely relies on the assumption that implementation of the 'new economic and business models' will be possible and have the desired result. However, the initiatives towards achieving this goal are still incoherent (Kalmykova et al., 2018) and the progress obtained limited: "circular economy is a niche discussion among sustainable development professionals at this stage" (Kirchherr et al., 2018). In other words, these definitions of the circular economy are perfectly consistent with the description of the strategy of "raising expectations in order to mobilize resources and 'colonize' the future" (Brown and Michael, 2003) and with the narrative that Jasanoff and Kim (Jasanoff and Kim, 2015) call 'the economics of technological promises'.

The story is quite different with older references to the idea of circularity of the economy. Rather than referring to 'what' would be desirable to achieve (an aspiration), in the past older works used to focus on 'how' to preserve something (the 'what') that was existing. "*When we look back Edo (the present-day Tokyo), which sustained the population of 3 million under a moderately prosperous state within the condition of national isolation, we find there a typical case of the eco-cycle activated by human economy in various forms which we have heretofore described*" (Tsuchida and Murota, 1985) (p. 36). The thermodynamic analysis referred to by the authors focuses on the factors that made it possible to close the loop of consumption and production and maintain the circularity of Edo's economy in face of the existence of harsh external limits (Tamanoi et al., 1984). The concept of 'eco-cycle', a precursor of circular economy, is used here to identify the conditions under which the result was achieved and the concomitant consequences for society's prosperity. Similar conceptualizations and interpretations can be traced back to centuries ago, such as the treatise on sustainable agriculture *De Agri Cultura* of Cato the Elder.

The problematic aspect of the 'how' of the circular economy persisted until the late twentieth century. Notably, in the 1970–90s, neoMalthusians (discussed in detail in Section 3) confronted the idea of recirculating the actual throughput of material and energy flows in the economy against basic thermodynamic principles (Georgescu-Roegen, 1971). That is, they questioned whether the desired model of a full recirculation could be realized, especially in face of a growing population and increasing resource consumption per capita (Boulding, 1966). Even recognizing that the internal recycling of flows inside the economy is a commendable task, they argued that a continuous increase in the level of recycling may result first costly and then impossible. The storytelling of the neoMalthusians was not focused on 'what future we want', but on whether or not that desired future is possible.

2.2. Bioeconomy

Definitions and interpretations of the term 'bioeconomy' are surrounded by similar confusion (Bauer, 2018; Bugge et al., 2016; McCormick and Kautto, 2013). Two widely quoted definitions are those of the EU and the German Bioeconomy Council, which resonate well with each other:

> "The bioeconomy comprises those parts of the economy that use *renewable biological resources* from land and sea – such crops, forest, fish, animals and micro-organisms – to produce food, materials and energy" (European Commission Research and Innovation, n.d.)

> "All industrial and economic sectors and their associated services which produce process or in any way use biological resources (plants, animals, micro-organisms). These sectors include: agriculture and forestry, the food industry, fisheries, aquaculture, parts of the chemical, pharmaceutical, cosmetic, paper and textile industries, as well as the energy industry" (Bioökonomierat (German Bio-economy Research and Technology), 2009)

Vivien et al. (Vivien et al., 2019) flag the co-existence of three main interpretations of the term: one referring to the entropic narrative of the economic process (a theoretical framework proposed by Georgescu-Roegen to discuss the relation between 'the what' and 'the how' of sustainability), a second referring to the industrial promises offered by the biotechnology revolution, and a third referring to the bio-based carbon economy. I focus here on the first of these three interpretations –called more properly 'bioeconomics'– which dates back to 1918. The term bioeconomics was coined by Baranoff, a Russian marine biologist, to flag a systemic problem inherent in the exploitation of renewable resources. "*T. I. Baranoff referred to his work as "bionomics" or "bio-economics" although he made little explicit reference to economic factors*" (Gordon, 1954) (p. 125). Baranoff coupled the terms 'bio' and 'economy' to indicate that the economic management of fisheries needs to simultaneously consider two relevant issues: (i) the economic return on the investment (typical of the economic narrative) – an information relevant for the economic system of control; and (ii) the risk that overexploitation of the supply capacity of the aquatic ecosystem may cause depletion of the fish stock thereby reducing the long-term productivity of the economic activity (an ecological problem) – an information referring to the biophysical processes taking place in the environment. Baranoff's work is important in that it proposed a new term to flag that the economic exploitation of a renewable resource must respect the external limits imposed by the characteristics of the exploited ecosystem (i.e., 'the how' limiting 'the what'). Indeed, growth of an economic activity exploiting renewable resources is limited by the rate and density at which the resources are re-generated by ecological processes.

The idea of 'bioeconomics' remained dormant until the 1970s, when the economist Georgescu-Roegen published "Energy and Economic Myths" (Georgescu-Roegen, 1975) and "Bioeconomics: a new look at the nature of economic activity" (Georgescu-Roegen, 1977). Bioeconomics was "a term intended to make us bear in mind continuously the biological origin of the economic process and thus spotlight the problem of mankind's existence with a limited store of *accessible* resources unevenly located and unequally appropriated" (p. 79 in (Gowdy, 2015)).

2.3. The combination of the two concepts into the circular bioeconomy

At this point, we can better understand the nature of the problem with the term circular bioeconomy. According to the different interpretations of the term bioeconomy, the idea of implementing a circular bioeconomy to stimulate the economic growth of developed economies can be considered either a good solution combining a desirable 'what' (circular economy) with a feasible, viable and desirable 'how' (bioeconomy), or an oxymoron suggesting to combine two things that will not produce the expected result.

The EU Bioeconomy Strategy endorses the first interpretation. It first identified the bioeconomy as a way to boost 'sustainable economic growth':

> "It is meant to reduce the dependence on natural resources, transform manufacturing, promote sustainable production of renewable resources from land, fisheries and aquaculture and their conversion into food, feed, fibre, bio-based products and bio-energy, while growing new jobs and industries"
>
> (European Commission, n.d.)

Then, in its recent 2018 update of the Bioeconomy Strategy the European Commission (European Commission, 2018) makes explicit reference to a sustainable, *circular* bioeconomy:

> "Action Plan: Leading the way towards a sustainable, circular bioeconomy"
>
> (p. 10)

Thus combining the two messages of *what should be done* (the circular economy) and *how it can be done* (bioeconomy) into a single package (Aguilar et al., 2018; Staffas et al., 2013). Ironically, one of the three tiers of this updated action plan refers to the limits described by Baranoff and Georegescu-Roegen: "*understand the ecological boundaries of the bioeconomy*", although this acknowledgment that it might be wise to check whether sustainable growth with bio-economy is possible is preceded by two tiers that presume an absolute certainty it is.

In conclusion, the current EU interpretation of the bioeconomy is diametrically opposite to the original narrative of Baranoff and Georgescu-Roegen that told us that expanding the share of activities based on renewable resources in the economy would slow down economic growth and set strict limits on the overall expansion of the economy.

3. On circularity and linearity

3.1. Circularity in neoclassical economic theory

Neoclassical economics portrays the economic process as a self-sustaining merry-go-round between production and consumption, in which the crucial role of ecological processes in recycling is simply not considered. Natural capital is not among the production factors (Daly, 2017). This point of view reduces the economic process to the circulation of monetary flows, products and production factors entirely inside the technosphere. This is exemplified in Fig. 1.

The representation of 'circular flows' within the economy shown in Fig. 1 neatly reflects Pigou's (Pigou, 1935) stationary state: "In a stationary state factors of production are stocks, unchanging in amount, out of which emerges a continuous flow, also unchanging in amount, of real income." Note that Pigou's use of the term 'stocks' assumes that the *size* of production factors inside the technosphere is independent from the interactions with the embedding environment (the biosphere; the ecological processes providing inputs of natural resources and absorbing wastes). Note that the message illustrated in Fig. 1 is still instilled to students by modern economic textbooks: "We can picture the circular flow of economic life in Fig. 2-1*. The diagram provides an overview of how consumers and producers interact to determine prices and quantities for both inputs and outputs" (Samuelson and Nordhaus, 2010) (p. 34, * referring to Fig. 1).

In his Principles of Economics, Marshall (Marshall, 1920) acknowledged the limitations of this simplistic view of the economy: "The Mecca of the economist lies in economic biology rather than in economic dynamics. But biological conceptions are more complex than those of mechanics; a volume on Foundations must therefore give a relatively large place to mechanical analogies; and frequent use is made of the term "equilibrium," which suggests something of statical analogy" (p. xiv).

Similarly, in the EMF definition of the circular economy, the concept of circularity refers only to 'products, components and materials', that is, flows under human control inside the technosphere. However, it does not explain how these flows can be recycled without using ecological processes from the biosphere (energy, water, land, biomass, minerals). Nor does it mention the natural resources embodied in the goods and services imported from abroad. Furthermore, in order to achieve the mentioned 'decoupling' of the internal recycling of 'products, components and materials' from the use of finite natural resources, the circular process presumably takes place entirely inside the technosphere without exchanging natural resources with the biosphere. We therefore cannot but assume that the proposed business model is based on the neoclassical economic narrative illustrated in Fig. 1. Circularity of flows without using any services from the biosphere is illustrated in Fig. 2. It shows that in this narrative there is no place for studying the role of (embodied) ecological processes in the stabilization of the recycling. As observed by Cullen (Cullen, 2017) (p. 483): "A Circular Economy future is one in which waste no longer exists, one where material loops are closed, and where products are recycled indefinitely— an economy that perpetually gyrates without any input of

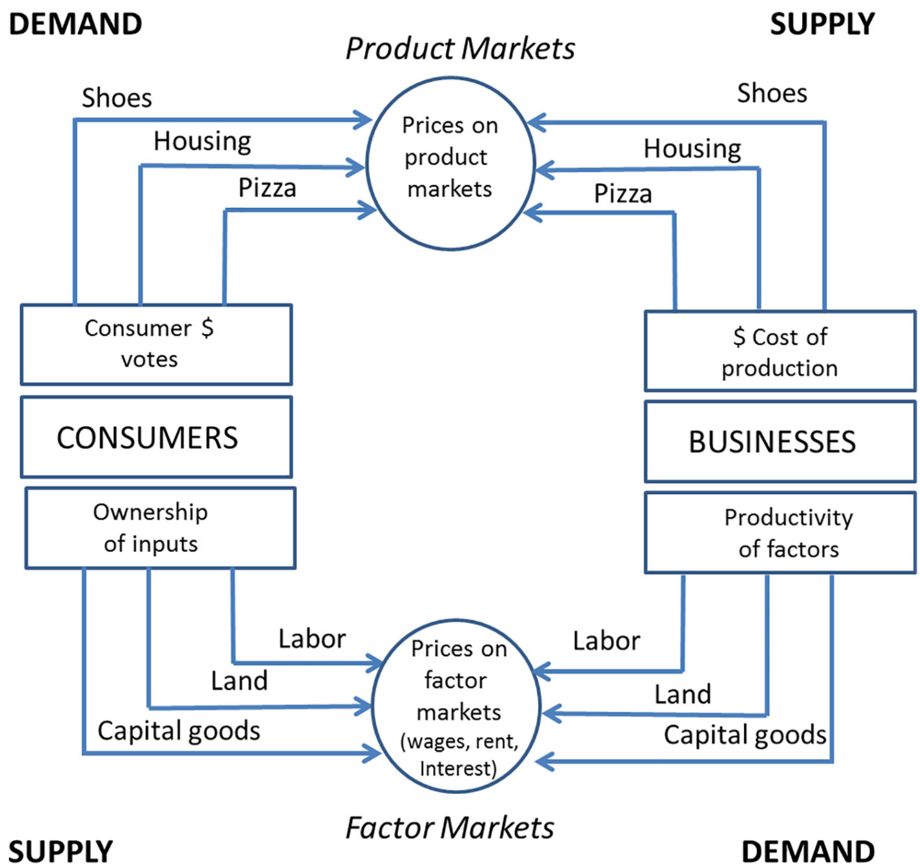

Fig. 1. The double circularity of flows: goods and services versus monetary flows in the economy (after Fig. 2-1, Samuelson and Nordhaus, 2010, p. 35).

depletable resources. For real materials and processes, this is, in any practical sense, impossible. Every loop around the circle creates dissipation and entropy, attributed to losses in quantity (physical material losses, by-products) and quality (mixing, downgrading). New materials and energy must be injected into any circular material loop, to overcome these dissipative losses". Therefore, this narrative of circular economy does not have any power of discrimination or anticipation with regard to sustainability. It cannot provide any answer to the question what would happen if the existing pattern of interaction between the economy and the surrounding environment would change because of an excess of economic growth or limitations to natural resources.

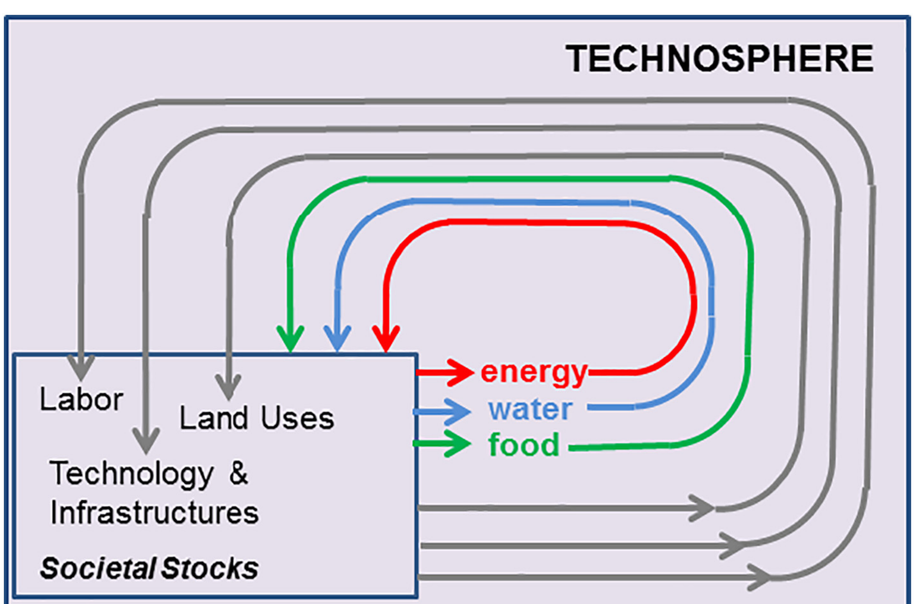

Fig. 2. The biophysical reading of the circular economy in conventional economics.

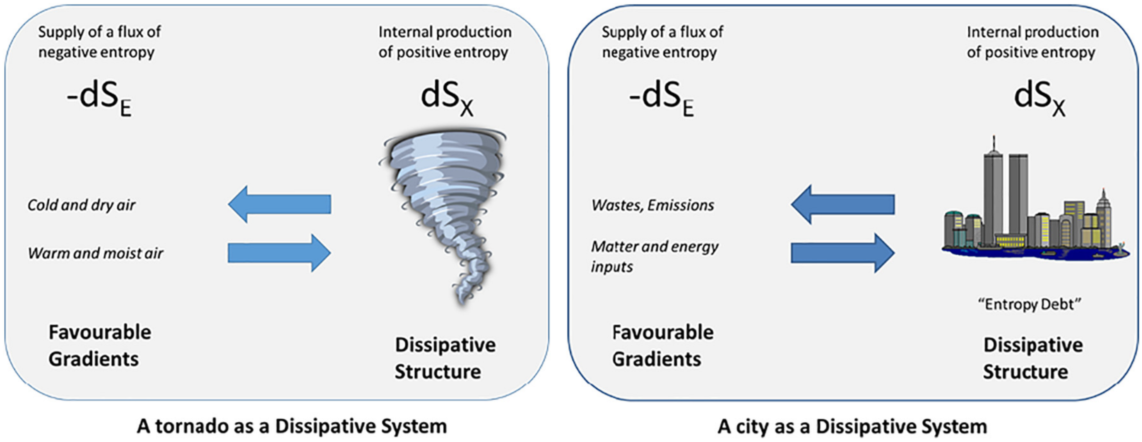

Fig. 3. The relation between a dissipative structure producing positive entropy ($+dS_X$) and its system of support in the environment producing the corresponding negative entropy ($-dS_E$).

3.2. *Circularity from a complex systems perspective*

In his seminal book "*What is life?*" Schrödinger (Schrödinger, 1967) proposed a revolutionary explanation for the extraordinary capacity of living systems to self-organize. To this purpose, he introduced the concept of negative entropy and thereby paved to way to the development of non-equilibrium thermodynamics. The school of non-equilibrium thermodynamics (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977) postulated that the property of self-organization is unique to *open systems*—they have to gather inputs from their environment and dispose wastes into it. This property carries with it an existential predicament for all self-organizing systems: in order to survive they must 'stress' the admissible environment they operate in. This predicament can become fatal for complex metabolic systems, such as human societies, that can grow both in size and in pace of activity per unit of size (e.g., economic growth). For these complex metabolic systems to survive they must learn and adapt to changes in their boundary conditions and notably *anticipate* potential future troubles (Poli, 2017). Rosen (1985) aptly called them 'anticipatory systems' and Prigogine (1980) 'becoming systems'. The revolutionary findings in non-equilibrium thermodynamics have shaped several scientific fields studying the process of self-organization, namely:

- The field of complexity theory dealing with self-organizing open systems in general terms (evolved from general systems theory). This includes complex adaptive systems (Holland, 2006; Gell-Mann, 1994), autopoietic systems (Maturana and Varela, 1980; Maturana and Varela, 1992), self-modifying systems (Kampis, 1991), and metabolic-repair (M-R) systems that can operate as anticipatory systems (Rosen, 1958; Rosen, 1991);
- The field of theoretical ecology specifically dealing with ecosystems (Lotka, 1956; Odum, 1971a; Odum, 1971b; Ulanowicz, 1986; Holling, 1973);
- A variety of fields dealing with social systems, including "energetics" (Lotka, 1956; Ostwald, 1907; Hall et al., 1986; Hall and Klitgaard, 2012; Leach, 1976; Pimentel and Pimentel, 2008; Slesser, 1978; Smil, 1991; Smil, 2003; Smil, 2015; Smil, 2017; Smil, 2013; Ostwald, 1911; Soddy, 1926; Vernadsky, 1986; Cottrell, 1955; Debeir et al., 1991; Gever et al., 1991; Giampietro et al., 2012; Giampietro et al., 2013), the work of White (White, 1943) and Zipf (Zipf, 1941) in the disciplines of anthropology and sociology, respectively, and the recently-developed field of social ecology (Broto et al., 2012; Daniels, 2002; Fischer-Kowalski and Hüttler, 1998; Martínez Alier and Schlüpmann, 1987; Swyngedouw, 2006; Tainter, 1988; Wolman, 1965).

The narratives developed in these fields suggest a strong analogy between the processes of self-organization of ecological systems and social systems: both require the existence of favorable boundary conditions and the capacity to exploit them (Odum, 1971b; Ulanowicz, 1986; Margalef, 1968; Gunderson and Holling, 2002). Indeed, they have converged into the concept of social-ecological system, thanks to the seminal work of, among others, Holling (1998, 2001), Berkes et al. (2003, 1998), Gunderson and Holling (2002).

A social-ecological system can be defined as the complex of functional and structural components operating within a prescribed boundary that is controlled in an integrated way by the activities expressed by a given set of ecosystems (in the biosphere) and a given set of social actors and institutions (in the technosphere) (Giampietro, 2018a). Thus, social-ecological systems are open systems (they must exchange input and waste flows with their context), depend on their context for maintaining their current level of activity and size of production factor and must be adaptive and anticipatory in order to survive in time because of their option space being constrained by processes beyond control. In other words, in a social-ecological system the process of maintenance and reproduction of the components of the technosphere should not interfere too much with the processes of maintenance and reproduction of the components of the biosphere. This forced relation is illustrated in Fig. 3, using the original conceptualization given in non-equilibrium thermodynamics.

The conditions for the survival of a dissipative system, such as a city, an economy or a tornado, have been explained in detail by Prigogine (1980). In short, a dissipative system (W) is determined by an expected pattern of interaction between two components: (i) a dissipative structure (X) generating a positive entropy flux needed to express its structures and functions; (ii) an environment (E) providing a flux of negative entropy compensating the continuous destruction of favorable gradients by the dissipative structure X. In analytical terms, the relation can be written as follows:

$$dS_W = dS_X - dS_E \tag{1}$$

Kay (2003) provided a technical explanation of this set of relations. Relation (1) aptly describes the conditions under which any metabolic system operates, whether this system is a tornado, a living system, a city or an economy (Fig. 3).

Integrating the vision of a circular economy with the rationale of non-equilibrium thermodynamics, we obtain Fig. 4. The continuous production and use of secondary inputs (products and materials) in the technosphere (labelled as $+dS_X$)—which in neoclassical economics (Fig. 2) is described as a closed loop—is now consistent with thermodynamic constraints. The entropic process of production and consumption of goods and services is compensated by the activity of

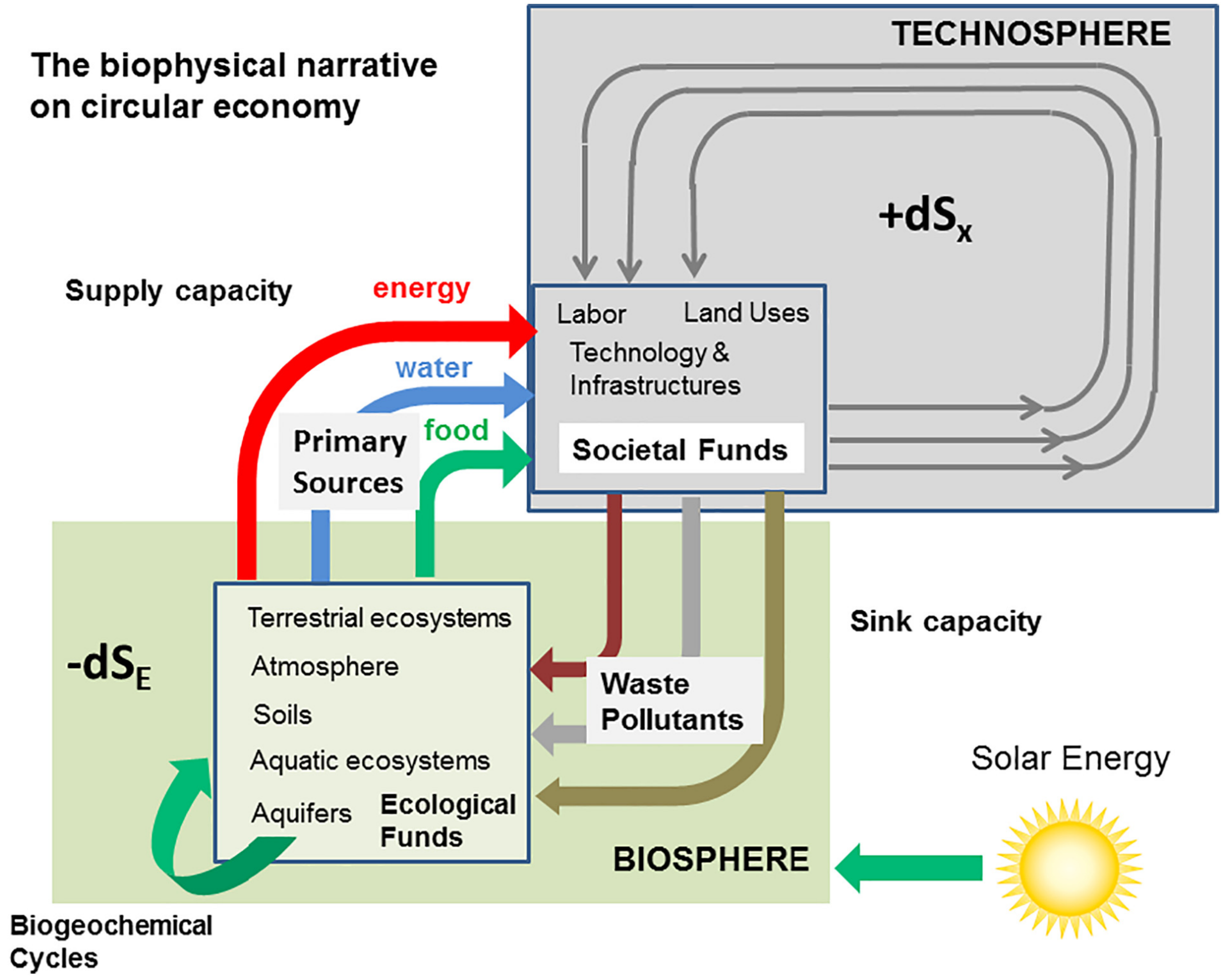

Fig. 4. The entropic narrative of the circular economy: the relations between ecological funds and societal funds closing the circle of material flows in the economy.

ecological funds (labelled as $-dS_E$) regenerating favorable gradients. The representation shown in Fig. 4 fulfills the condition that all metabolic (dissipative) systems, including human societies, must be open and depend on the existence of favorable boundary conditions determined by processes beyond human control.

The rationale of dissipative systems resonates well with the distinction between flows, stocks and funds proposed by Georgescu-Roegen (1971) in his bioeconomics for describing the process of interaction between the technosphere and the biosphere:

1. *Flows* are quantities disappearing or appearing over the duration of analysis. They can be further divided into (i) primary flows, requiring primary sources and primary sinks beyond human control and crossing the border between technosphere and biosphere, and (ii) secondary flows that are produced and consumed inside the technosphere and transformed under human control.
2. *Stocks* are quantities of accumulated flows that change their identity through the duration of the analysis because of outflows (stock depletion) and/or inflows (sink filling). Hence, in contrast to its use in economic jargon, in Georgescu-Roegen's analytical framework a stock is not a constituent component of the system, but an accumulated flow that changes its size in time.
3. *Funds* are agents capable of both producing and consuming flows inside the metabolic pattern of the social-ecological system. Funds do preserve their original identity throughout the duration of the analysis (e.g., the human population, the work force, technological capital, land use). Therefore, fund elements are the external referents that define what the system is made of. A *sustainable* economy is necessarily based on 'renewable' flows coming from fund-flow relations that respect and maintain the identity of the funds.

Note that the biophysical representation based on the rationale of metabolic systems thus describes the 'production factors' as fund elements, contrary to the economic representation in which they are considered stocks. In the view of Georgescu-Roegen, the sustainability of the economic process is not about stabilizing the flows of goods and services produced and consumed in the economy, but about reproducing the fund elements that are associated with the stabilization of the metabolized flows.

3.3. The question of size entailed by the entropic perspective

When adopting the metabolic view of the economic process, the issue of circularity not only requires us to study the material flows handled inside the technosphere, but also the associated primary flows (requiring primary sources) and the associated wastes and emissions (requiring primary sinks) in the biosphere. In this view, the issue of sustainability boils down to the compatibility between: (i) the size and the metabolic pace of the fund elements operating in the technosphere and determining the flux of +dSX, and (ii) the size and the metabolic pace of the fund elements operating in the biosphere and determining the flux of –dSE (Fig. 4). Put in another way, the identity of the fund elements entails a constraint on the pace and density of the flow throughput both in biosphere and technosphere. For example, a cow cannot produce 500 l of milk per day, a person cannot eat 200,000 kcal

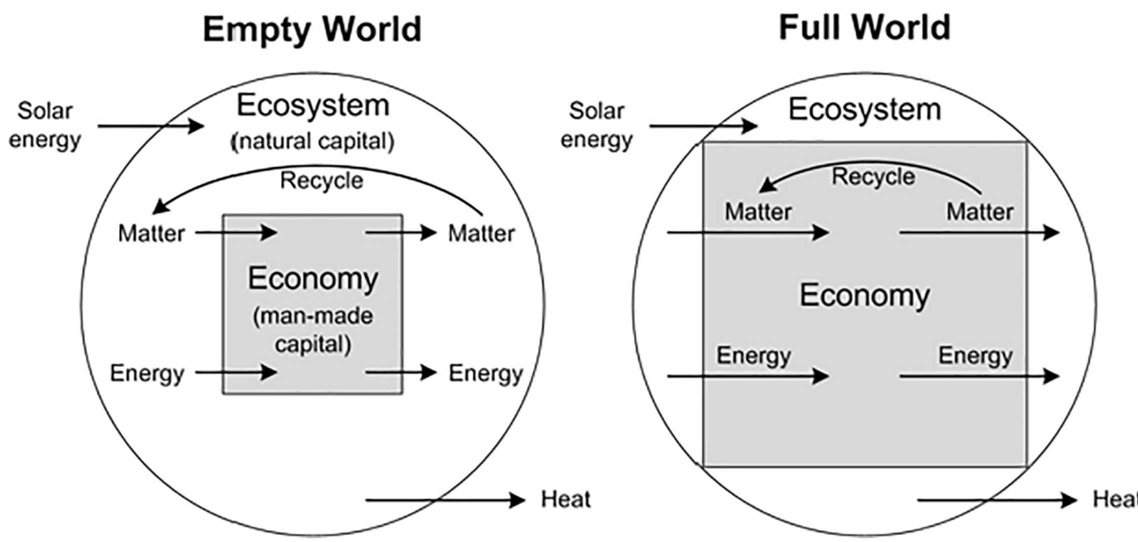

Fig. 5. Implications of moving from an empty to a full world for the feasibility of a circular economy (Goodland and Daly, 1996).

of food per day, and a healthy soil cannot restore 10 t of nitrogen per hectare per year.

Daly (1990) and Goodland and Daly (1990, 1996) used the narrative of moving from an 'empty world' to a 'full world' to explain the predicament of sustainability experienced in the third millennium. Their explanation of the concept of external (ecological) limits to the economic process is shown in Fig. 5. They neatly illustrate that when considering the interaction of the economic process (technosphere) with its environmental context (biosphere), what really matters in relation to the potential of recycling is *the size* of the required input flows and the waste flows generated by the economy (technosphere) compared to *the size* of the primary sources and primary sinks made available by ecological processes (biosphere).

In *an empty world*, the supply and sink capacity associated with the activity of natural processes (ecosystems) is larger than the supply and sink capacity required for sustaining the activity of the economy. In this situation, the ecosystem takes care of recycling and provides the socio-economic system with the energy and material flows needed by the economic process to sustain and reproduce it-self.

In *a full world*, the size and pace of the economy would require a much larger supply and sink capacity than available from the natural processes in terms of a renewable supply of required inputs (availability of primary sources) and a renewable absorption of the unavoidable wastes (availability of primary sink capacity). In this situation, natural ecosystems can no longer produce all that is required and absorb and recycle all that is produced by the socio-economic system. In a full world, some of the recycling needs to be internalized into the economic process (Fig. 5).

The internalization of recycling flows—i.e., the changes required to make the economy more circular—increases the cost for the economy and reduces its performance. Production factors must be invested in generating services (recycling of flows) that would otherwise have been provided for free by nature. This solution implies investing resources to provide services and goods to nature rather than to people and hence represents an opportunity cost for the economy.

3.4. Industrial revolution: the great linearization

Biophysical analyses of the metabolic pattern of contemporary social-ecological systems show that inside the technosphere both the densities and paces of flows per unit of societal funds (flow/fund ratios) are much larger than those of the natural flows per unit of ecological funds (flow/fund ratios) in the biosphere (Giampietro et al., 2012). Human society (in the technosphere) gathers and concentrates material and energy forms required for its maintenance and reproduction from the context, and to achieve this result it heavily relies on non-renewable energy sources (linearization of flows) (Giampietro et al., 2012). The current level of productivity of production factors (labor, capital, land) is obtained by altering the pace and density of the flows naturally occurring in the biosphere in managed ecosystems (human land-uses). In doing so, society can express structures and functions (associated with a given rate of positive entropy generation) that would otherwise not be possible (if relying on the negative flux generated by natural processes) (Smil, 2015).

For example, the yield of grain per hectare from a crop field is at least an order of magnitude larger than the available quantity of biomass from unmanaged land. The pace and density of the natural deposition of nitrogen in soil (the fund-flow supply given by nature) does not permit yields of 7–10 t/ha of grain typical of modern agriculture. Maintaining such yields require heavy doses of artificial fertilizer. In the same way, irrigation in agriculture boosts the supply of water (blue water) whenever the natural availability of water in the soil (green water) would limit yields. Rather than relying on ecological processes of natural pest control, modern agriculture uses pesticides. Indeed, with the event of the industrial revolution the agricultural sector moved from low external input to high external input agriculture (Giampietro, 1997; Arizpe et al., 2011). While the former relied on nutrient recycling through a complex network of interactions among ecological fund elements (thus guaranteeing soil health, biodiversity, healthy aquifers, etc.), the latter is based on linearization of flows through the use of fossil energy (stressing ecological fund elements). This continuous human struggle to boost the pace and density of natural flows has resulted in a tremendous increase in agricultural productivity inside the technosphere: from less than 1 t/ha of grain in pre-industrial agriculture to more than 10 t/ha in industrial agriculture. An even more impressive improvement has been achieved in labor productivity—from about 1 kg of grain per hour of labor in pre-industrial agriculture to around 1000 kg/h in industrial agriculture. The price to pay for this increased agricultural productivity has been a progressive liquidation of ecological funds (which would slow down productivity because of their low flow/fund ratio).

A similar linearization took place in relation to energy security. The energy supply of modern society predominantly consists of a linear exploitation of non-renewable stocks of fossil energy allowing a density and pace of flows that are orders of magnitude higher than those of circular renewable fund flows, such as biomass (Smil, 2003; Smil, 2015; Giampietro and Mayumi, 2009). The density of typical energy uses in developed countries (shown in the left graph of Fig. 6) is order of

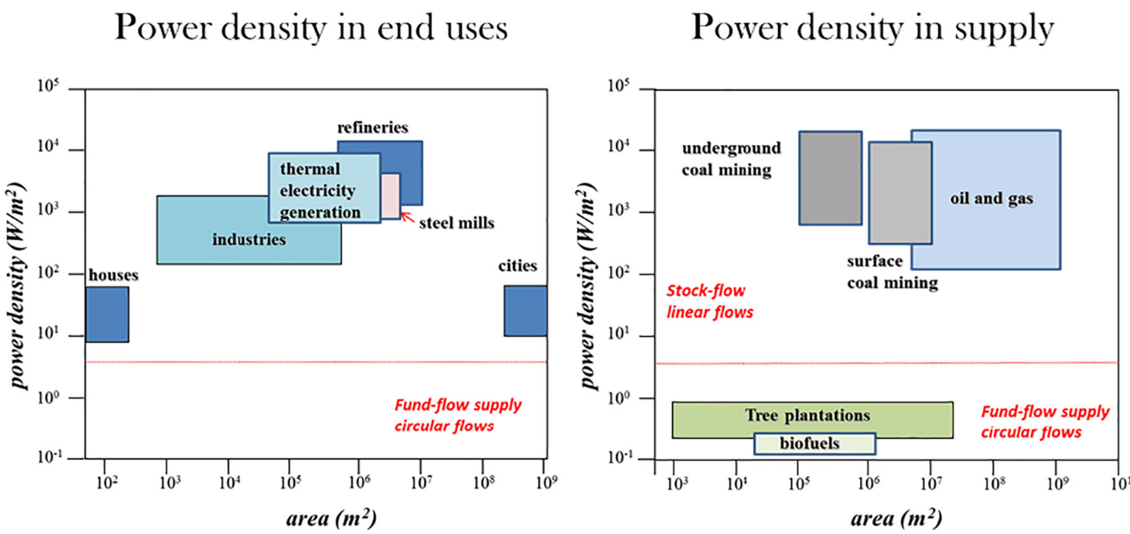

Fig. 6. The power density gap: energy supply from biomass (renewable) and from fossil energy (non-renewable) and energy density of consumption (urban land uses) (after Smil (2015), Figs. 7.3 and 7.5).

magnitude larger than the density of energy supply provided by natural occurring biomass (in Fig. 6, lower part of right graph). The two graphs in Fig. 6 explain the progressive increase of urban populations on our planet: the massive use of fossil energy guarantees a high spatial density in the supply of energy inputs that enables a high spatial density in the supply and consumption of food, goods and services.

The combined effect of the changes that took place during the past two centuries in the agricultural and the energy sector of modern economies is shown in Fig. 7. This figure clearly illustrates the essence of the industrial revolution that shaped contemporary society. The mode of energy and food production changed dramatically from being almost entirely based on circular fund-flows (inputs produced and wastes absorbed by ecological funds) to almost complete dependence on linear stock flows (inputs extracted from stocks and wastes overwhelming environmental sink capacity).

4. Conceptualizing resource flows in social-ecological systems

4.1. Primary, secondary and tertiary flows in the metabolic pattern

The narrative of metabolism is very important because it flags the existence of a systemic feature of this class of systems: metabolic systems define expected characteristics on their inside (e.g., temperature of the human body) that are partially independent of the characteristics of their context (e.g., ambient temperature). This implies a bifurcation in the type of information required for describing their functioning (Giampietro et al., 2012): what is perceived as “the expected pattern” from agents operating inside the system (the black-box), and what is perceived as the interaction of the black-box with its context (a view that can only be obtained from the outside). This bifurcation explains the different views about the circularity of the economy described in

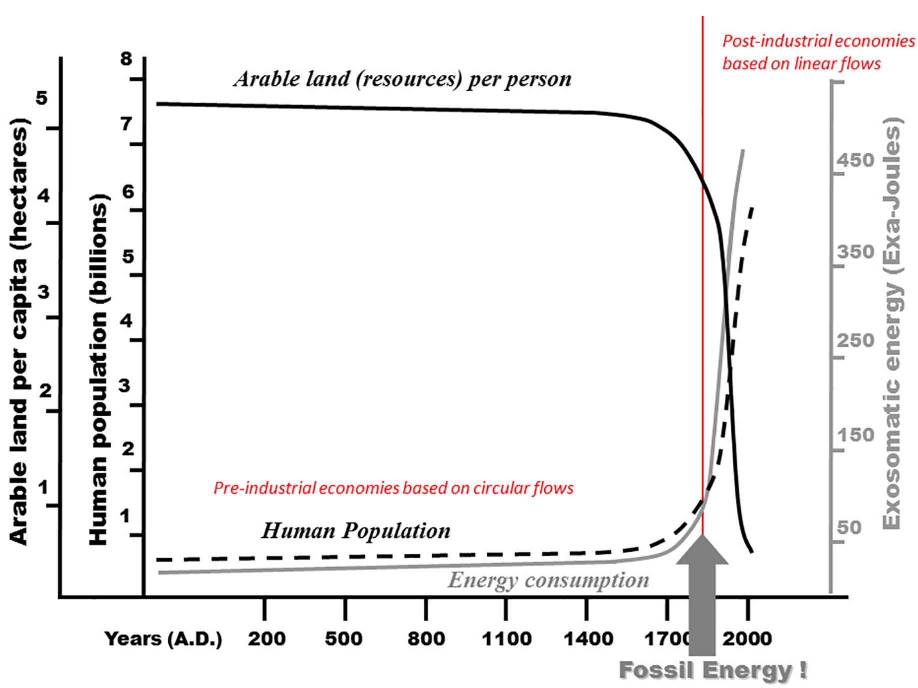

Fig. 7. The world economy moving from exploitation of circular flows to dependence on linear stock flows—a phenomenon also known as the industrial revolution (after Giampietro and Mayumi (2009)).

Section 3: The neoclassical economics view reflects the perspective of economic agents operating inside the economy. This perception is based on the assumption that the situation of moderate scarcity (required to guarantee the expression of prices) will be guaranteed, no matter what. The entropic narrative, on the other hand, is based on the assumption that the stabilization of the flows under human control inside the black box depends on the stabilization of flows in the context, determined by processes outside human control. Using this rationale, a distinction can be made over the different types of flows that should be considered when dealing with the circularity of the economy:

1. Flows observed from within the technosphere—this representation sees what goes into and out the various functional parts of the technosphere, but only what remains inside the black-box (the narrative of conventional economics represented in Fig. 2).
2. Flows observed from outside of the technosphere—this representation focuses on what gets into and out (water, energy, food, mineral, emissions) of the technosphere (seen as a black box) into the context (biosphere) (the narrative represented in Fig. 4).

The combination of these two views and the corresponding interlinkage of metabolic flows across the techno- and biosphere in a complex metabolic pattern is illustrated in Fig. 8.

An effective integrated system of accounting of metabolic flows should use make a distinction between: (i) *primary flows* - flows crossing the interface between the technosphere and biosphere as defined in Fig. 8 as That is, primary flows enter from the biosphere into the technosphere (extracted from primary sources, such as coalmines, aquifers) and exit from the technosphere into the biosphere (into primary sinks, such as the atmosphere, water table, dumpsites); (ii) *secondary flows* - flows derived from the exploitation of primary flows. For example, in energy statistics secondary energy is represented by energy carriers, such as electricity or gasoline, which are produced from primary energy sources (e.g., wind, fossil energy). Note that secondary flows are at the same time *inputs and outputs* produced and consumed within the technosphere; (iii) *tertiary flows* - flows derived from the recycling of secondary flows.

Inside the technosphere, secondary and tertiary flows are used as inputs to express useful tasks. This transformation can be associated with the concept of *end-uses*. Any end-use entails both the expression of a useful task (production of a secondary or tertiary useful ouput, evapotranspiration of water for biomass production, consumption of electricity in manufacturing goods, eating potatoes to remain alive—all examples of dissipative structures $+dS_X$) and the unwanted generation of waste and emissions that sooner or later are dumped into the biosphere. When the flows metabolized inside the technosphere cross the border to return into the biosphere, they again become primary flows, more precisely primary outputs, such as water vapor, heat, greenhouse gas emissions, excreta, degraded materials. They are called primary flows because they need the existence of *primary sinks* operating in the biosphere. Primary sinks comprise all the environmental funds that are used/required to dispose of solid, liquid, gaseous or thermal emissions. Note that the entropic narrative dictates that the metabolism of secondary or tertiary flows always requires availability of corresponding primary flows in the biosphere both on the supply and sink side. ‘Free lunches’ or ‘perpetual motion machines’ do not exist. The conversion of metabolic flows belonging to these three categories is schematized in Fig. 8.

This distinction between the different categories of flows is essential to understand the confusion about the accounting of water, energy, mineral and food flows in the circular economy. Note that the terms ‘water’, ‘energy’, ‘mineral’ and ‘food’ are mere semantic labels in the narrative of metabolic flows and cannot be used as such to carry out a quantitative study of circularity. The nature of these flows has to be further specified in relation to the particular metabolic step to which they refer and the corresponding status of primary, secondary or

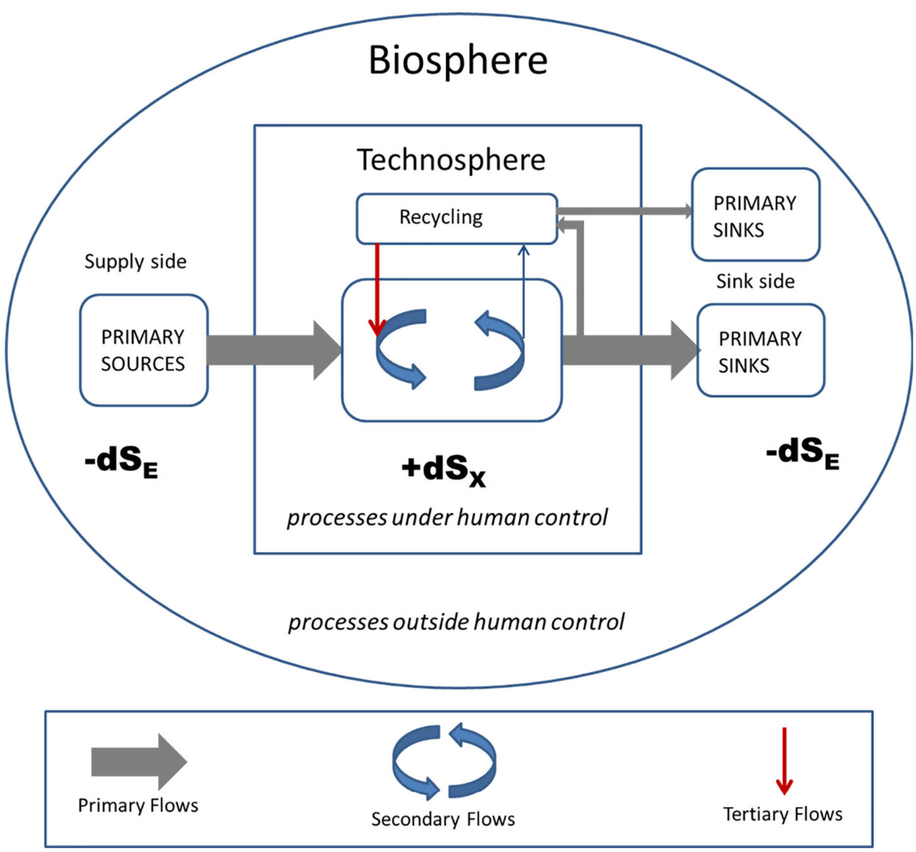

Fig. 8. Three different typologies of flows inside the metabolic pattern of human society connecting the techno-and biosphere.

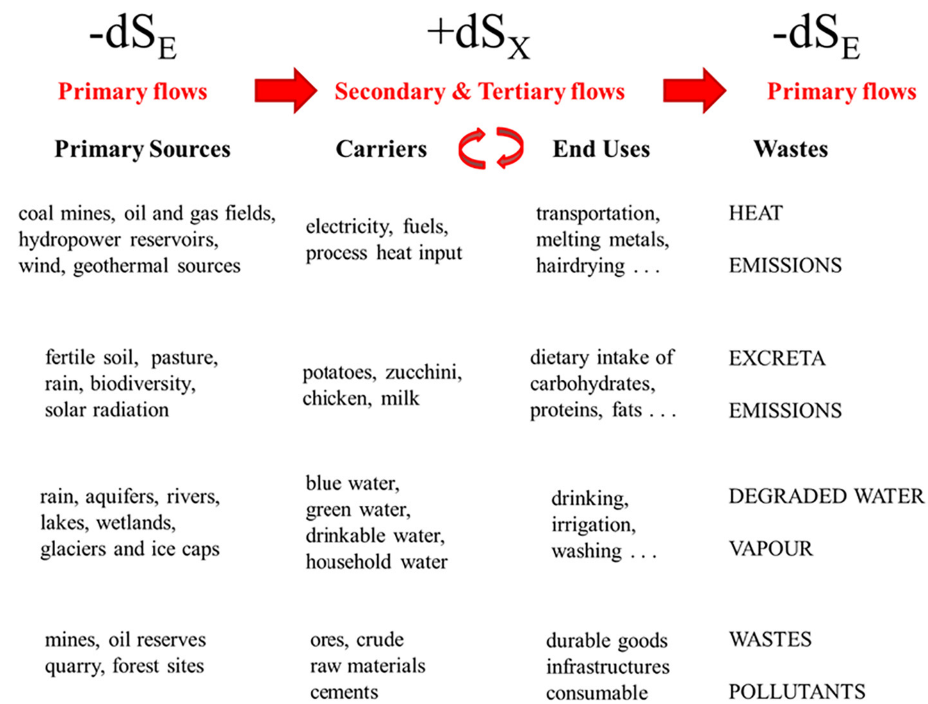

Fig. 9. Examples of conversion of energy, food and water across the interface of the technosphere and biosphere.

tertiary flow. As illustrated in Fig. 9, they can be quantified only after defining, in a pre-analytical phase, a taxonomy of different accounting categories for the different forms they can take on (Giampietro et al., 2012; Giampietro et al., 2014).

An important aspect of the metabolic pattern with regard to circularity is the distinction between the anabolic and catabolic compartments inside the technosphere:

1) The catabolic part of the metabolic process (the one destroying gradients provided for free by nature) comprises the processes taking place in the primary production sectors of the economy (agriculture, energy and mining). This part is called catabolic because, in analogy with biochemical processes, primary sources (the free flux -dS_E in Figs. 3, 4 and 8) are degraded to produce secondary inputs (commodities, goods and services) for use inside the technosphere.
2) The anabolic part of the metabolic process comprises the processes taking place in the remaining sectors of the economy (residential, manufacturing and construction, service and government). This part is called anabolic because like in biochemical processes, secondary and tertiary inputs are used to generate products and material needed to build and maintain the activity of society and reproduce its structures (+dS_X in Figs. 3, 4 and 8).

In the anabolic compartment secondary inputs are *both produced and consumed in the economic process*. The *secondary outputs* of a given primary sector (e.g., the supply of electricity, food, minerals or products) become *secondary inputs* to other sectors in the catabolic part but also in the anabolic part itself (e.g., all consumption of electricity, food, mineral or products in the economy). The production of secondary outputs is conditional on their being useful as input by some other metabolic elements otherwise they would not be produced in the first place. This may explain the idea of full circularity of the economy in the neoclassical narrative. However, looking at Fig. 9 it is clear that there is no recycling of primary flows in the technosphere.

4.2. Using the fund-flow model to explain the economic problem of recycling

Looking at Fig. 8, the question is how much can we increase the size of tertiary flows (i.e., the level of recycling)? Rather than providing an analytical discussion we can use a metaphor - the evolution of diapers – to illustrate (some of) the problems with recycling. Reusable diapers have done their job for centuries. Nonetheless, in the twentieth century society massively switched to the use of disposable diapers. Why?

Reusable diapers are fund elements that can be used over and over again (a renewable resource). They remain in the household and guarantee the processing of a flow (the 'outputs' of the baby) for an extended period. Disposable diapers, on the other hand, are flow elements derived from a non-renewable stock of disposable diapers depleted by usage. After usage, disposable diapers disappear from the household together with the output of the baby. The characteristics of the two solutions are illustrated in Fig. 10.

The diaper example is relevant because it shows that circularity implies two types of costs: (i) direct cost because the maintenance of fund elements requires labor, capital (infrastructures), technical inputs, energy, water, space, etc.; and (ii) an indirect cost because circularity, when guaranteed by natural funds, entails an overall reduction of the productivity of societal funds. In fact, the larger requirement of labor and space inherent in the use of reusable diapers represents an opportunity cost preventing the expression of other functions by the household.

Indeed, there are limits to recycling and technological fixes in the technosphere for two basic reasons:

1. According to the first principle of thermodynamics energy cannot be produced. We cannot increase the size of primary energy sources, but only learn how to use them better.
2. According to the second principle of thermodynamics irreversible processes alter the qualitative characteristics of material flows. Recycling can be done, but only to a certain extent and at a certain cost, and only if the corresponding primary resources are available. Hence, the amount of primary waste outflows of an economy can be reduced by recycling (provided the inputs required by the recycling process itself do not exceed the waste outflow recycled), but a

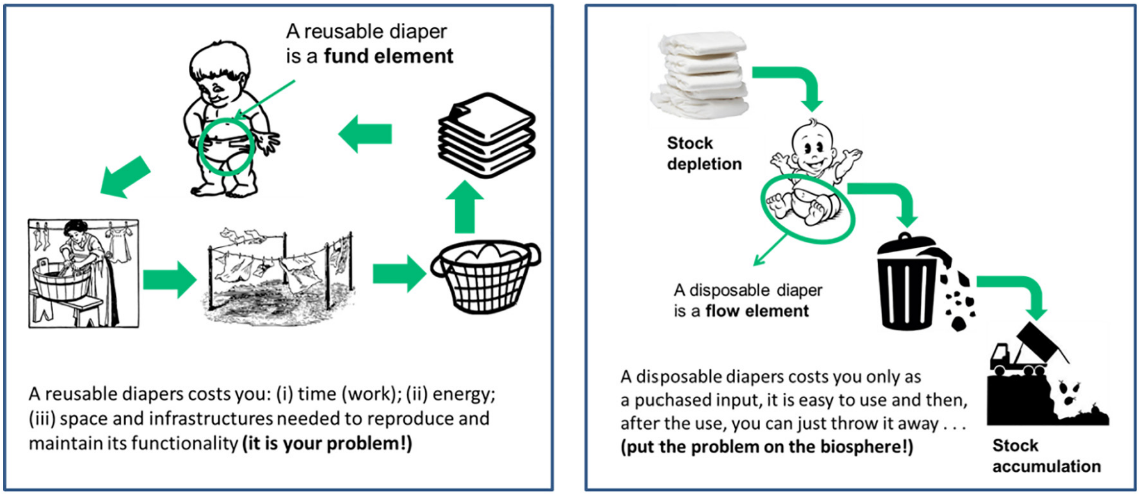

Fig. 10. Comparison of the advantages and disadvantages of fund and flow elements.

continuous production of wastes is unavoidable.

For example, the biogas from manure or the electricity produced by burning solid urban waste are both tertiary flows obtained from the recycling of wastes generated by the previous use of secondary flows. While the input from tertiary flows is certainly a welcome contribution for a more effective use of resources, their very existence depends on the previous use of secondary flows, which in turn depends on prior availability of primary energy sources. In the case of biogas, primary resources were used to produce the animal feed converted into manure for producing biogas. In the case of electricity produced from waste, primary resources were consumed to produce the discarded products ended up in solid wastes converted in electricity. In addition, as discussed in the example of the reusable diapers, production factors are required to transform secondary output in tertiary inputs. Internal recycling is important, but when analyzing the pressure on the environment exerted by the metabolic pattern of a social-ecological system, what really matters is the relation between the size of the primary flows *required* by the technosphere and the size of the primary sources and primary sinks made available by the biosphere. As shown in Fig. 8, changes in the internal loops within the technosphere may alter the internal requirement of secondary flows, but its relevance for the resulting environmental pressure depends only on the effect on the requirement of primary input and resulting primary output flows. This is especially important in the analysis of the resource nexus because the metabolism of water, energy and food entirely depends on the availability of primary sources and primary sinks determined by processes beyond human control.

4.3. Implications for sustainable growth

In the 1960s and 70s, the exponential nature of growth in population and energy consumption (Bartlett, 2004; Steffen et al., 2015) caused concern about scarcity of exhaustible natural resources in the United States, which cumulated in the publication of The Limits to Growth by Meadows et al. in 1972 (Meadows et al., 1972). Many other scholars expressed their concern about the (un)sustainability of perpetual economic growth (Boulding, 1966; Carson, 1962; Ehrlich, 1971; Hardin, 1985) and an intense debate between 'cornucopians' and 'neoMalthusians' followed. Cornucopians, confiding in the power of the economic market and human ingenuity, dismissed concerns about biophysical limits to perpetual economic growth. The neoMalthusians, on the other hand, challenged the idea of perpetual economic growth based on the finiteness of the non-renewable resources used to power this pattern of economic growth. Recently the discussion between cornucopians (neoclassical economists) and neoMalthusians has rekindled, fueled by the concern for climate change and the emergence of the concept of the water-energy-food-environment nexus (Giampietro, 2018b). Indeed, acknowledging the key role of the interlinkages between (embodied) water, energy, food and land-uses in stabilizing the functioning of social-ecological systems (including climatic conditions), it becomes evident that external limits to the expansion of economic activity do exist (Hoff, 2011; Bazilian et al., 2011; Ringler et al., 2013; Gulati et al., 2013; Endo et al., 2017; Hák et al., 2016; Khan et al., 2017). Note that the concept of resource nexus is closely related to that of circular economy and bioeconomy. A circular (bio)economy implies the ability to stabilize in time the recycling of the mix of nutrients and water required for a renewable supply of biomass for food and energy security in a coordinated way.

Indeed, the flow-fund model is helpful to analyze the tension between economic growth and sustainability. Sustainability would require respect for the natural paces and densities of flow throughput associated with the identity of ecological fund elements (aquifers, soil, biodiversity conservation, etc.). On the other hand, economic growth requires a boost in pace and density of the flows entering and existing the economic process (flows getting in and out of the technosphere) to meet the demanding flow throughput of societal funds. As noted earlier, societal flows have paces and densities that exceed the metabolic characteristics of ecological fund element (Lomas and Giampietro, 2017). This tension is the very predicament faced by the 'bioeconomy', and the origin of the bifurcation in perceptions about the role of the bioeconomy in sustainable growth. The economic narrative defines acceptable benchmarks for economic performance from "within the technosphere" based on the existing pace and density of secondary resource flows transformed inside the economic process. The ecological narrative, on the other hand, defines acceptable benchmarks for ecological compatibility based on the pace and density of the primary flows transformed in the biosphere (i.e., the renewable primary supply capacity and the regeneration capacity of primary sinks) a view obtained when looking at the economic process "from outside the technosphere". In the last two centuries the huge gap between the density and pace of flows inside the technosphere and the density and pace associated with ecological processes in the biosphere has been filled by non-renewable stock exploitation (stock-flow supply), rather than by sustainably managing useful ecological funds (fund-flow supply). Indeed, at present, the loop is far from being closed for most primary flows (notably energy and food) and the mismatch is 'solved' by depleting stocks of primary resources (fossil energy, minerals) and filling sinks (GHG in the atmosphere, pollutants and wastes in the hydro and geospheres).

Economic activities that respect the integrity of natural cycles translate into a burden for the economy as a whole because the throughputs in the exploitation of renewable resources is too slow and too disperse compared to those achieved in other economic sectors based on linear stock-flow exploitation (Giampietro et al., 2012; Giampietro et al., 2013). Indeed, for this reason, economic sectors dealing with fund-flow supply of energy and food (the bioeconomy) currently require huge economic subsidies to be economically viable as well as major injections of fossil energy based inputs. In fact, the agricultural sector continues to shrink in modern economies—in terms of both work force and sectoral GDP (Giampietro et al., 2012; Giampietro and Mayumi, 2009). The idea that the 'bioeconomy' can contribute to sustainable economic growth within the existing economic pattern based on a massive linearization of flows is simply impractical.

5. Conclusions

This paper has shown that the solution consisting in a new *business model* proposed by the advocates of a circular bioeconomy does not address any of the problems pointed out by the neoMalthusians in the 1970s and 80s. On the contrary, the solution of the circular bioeconomy *seeking to ultimately decouple global economic development from finite resource consumption* is just a re-emergence of the mantra of cornucopians. By presenting different narratives and associated resource models, the paper has revealed that the current EU narratives explicitly support the claim of the neoclassical economists that any limiting production factor can be substituted by technological innovation: "the world can, in effect, get along without natural resources" (Solow, 1974) (p. 11). The paper has illustrated how the narratives of EU and bioeconomy as presented in (global) politics and by important interest groups have a theoretical basis in neoclassic models that endorse a strategy of top-down planning of technological fixes typical of the neoliberal ideology (Ramcilovic-Suominen and Pülzl, 2018; Kleinschmit et al., 2017). The narrative put forward by the Ellen Mac Arthur Foundation *assumes* that it is possible to increase the economic productivity of our contemporary post-industrial economy without increasing the consumption of natural resources, such as energy, water or minerals, simply by recycling of products and components. However, the list of failed grand technological promises discussed in the introduction suggests a more sobering attitude in relation to the potentiality of market and human ingenuity. It is very doubtful that it will be possible to expand the complete recycling of products and components at zero biophysical cost.

On the contrary, the bioeconomics of Georgescu-Roegen emphasizes that the economic process is entropic and that therefore it entails a continuous consumption of resources that must be counterbalanced by the work of nature to remain stable. In this original narrative, the industrial revolution is considered a unique event that made it possible to break away from the external ecological constraints associated with the limited pace and density of flow throughput found in pre-industrial economies. This breaking away was only possible because of the plundering of non-renewable fossil energy resources that enabled a dramatic acceleration of the pace and density of economic throughputs through a linearization of previously circular processes. Primary economic activities relying on biological transformations, such as agriculture and energy supply from biomass, were subsequently marginalized in the overall formation of value added in the Gross Domestic Product of developed economies because of their low biophysical productivity. For this reason, according to Georgescu-Roegen's bio-economic narrative, a massive increase in the weight of biological processes in the economy will slow down the pace of growth of the contemporary economy.

Finally, as regards the identification of indicators, the circular economy 'business model' provides no theoretical framework to identify targets and indicators for its implementation. Which flows should be accounted for and how (in relation to which transformations) when generating an integrated set of targets monitoring the implementation of the circularity of "the economy"? The claimed decoupling of economic growth from natural resource use is only related to targets for increasing the level of 'reusing and recycling'. It is unclear why estimates of the quantities of recycled wastes and the amount of material recycled from products arrived at their end-of-life should be useful indicators to study green economic growth. Why should an economy grow by shifting resource investments from producing and consuming goods and services to recycling wastes and used materials? The new business model proposed for the circular economy does not provide a credible theoretical discussion of the growth issue. On the contrary, the entropic narrative based on non-equilibrium thermodynamics, allows us to distinguish between primary flows (coming from primary sources and going into primary sinks in the biosphere), secondary flows (used to produce inputs and outputs inside the technosphere associated with the production and use of goods and service), tertiary flows (obtained from recycling the output of secondary flows that no longer useful). This distinction helps us to better define the trade-offs allowing the study of the limits of recycling and the effects of an increased reliance of the economic process on biological transformations.

This paper suggests that the entropic narrative can provide the necessary theoretical foundation for an informed discussion of the relation between circular economy and bioeconomy. This narrative helps to solve the existing confusion over these terms by allowing a distinction between what is seen by economic narratives – i.e. information useful for operating the economic system of control (business models) - and what is addressed by the thermodynamic narratives – i.e. information useful to explore the option space of economic activity (biophysical constraints).

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