**Chapter N**

**Entropic Limits of Circular Economy**

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**Abstract.** The world has become enchanted with the idea of the Circular Economy as it is seen as a remedy to solve most ecological problems. Re-introduction processes, such as recycling or refurbishment, undoubtedly support the objectives of a circular economy, but inevitably result in material wastes or the production of undesirable by-products. Initially, the Circular Economy descriptions completely ignored the relationship between natural and economic systems, which are the most important problem in ecological economics. Circular Economy is criticized, inter alia, for not taking into account the physical limits of recycling. In each recycling cycle, some materials are lost or degraded (down-cycling), which leads to an increase in entropy. When recycling on an industrial scale, more and more materials are scattered and lost with each cycle, leading to waste and emissions. Achieving closed material cycles will therefore require the segregation and treatment of high entropy waste for recycling and reuse as a low entropy resource. Application of Statistical Entropy Analysis extended to complex products, revealed to be useful to minimize waste production and to make people aware that the zero waste strategy is a utopia.

**Keywords.** Entropy, circular economy, zero waste strategy, relative statistical entropy, material flow analysis



# Introduction

Conventional economy is characterized by the “buy, use, throw-away” concept whereas circular economy is intended as the transformation of fluxes of input materials (and of both wastes and emissions into environment, as output), into cycles that minimize material use, energy flows and environmental impacts, without compromising economic, social and technical progress (Stahel W.R., 2022). Ellen MacArthur renewed the definition of circular economy (MacArthur E., 2015) stating that it “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”. On the promise of this suggested decoupling, Stephan (Stephan G. et al., 2022) advises on the presence of physical limits to decoupling, pointing out that if basic principles of thermodynamics are taken seriously into account, such an idea of a circular economy, remains an illusion. In fact, if we considered a Material Flow Analysis (MFA) approach, which in its simplest version says that fluxes of materials in input equal that of both wastes and emissions into environment, as output, it will induce to think that recycling will allow a complete decoupling of economic activities from nature. This material and energy balance approach is the application of the first law of thermodynamics in the economic environment, which states that in an isolated system, the energy sum always remains constant and energy can only change its state form. Georgescu-Roegen clearly stated that production and consumption are accompanied by an irreversible change in the quality of energy and raw materials, introducing entropy, a concept from thermodynamics, in economic theory (Georgescu-Roegen, N., 1971). This represents the application of the second law of thermodynamics as isolated thermodynamic systems strive in the long run towards a state of maximum entropy and thus minimum structure and order. In other terms once the energy is transformed into heat completely, the opposite transformation is not entirely possible. Transformation of the existing economy into a more sustainable one requires minimizing the rise of entropy, realizing the only realistic sustainable circular economy (Stephan, 2022). With the development of more energy efficient technologies, this rise in entropy may slowly decrease, but never be eliminated. According to the second law of thermodynamics recovery and recycling of materials, waste and end-of-life product disposal, require energy and resources, which increase in a nonlinear manner as the percentage of recycled material rises. Consequently, in this works to the authors will investigate the new analytical tools which could represent the best approach to quantitatively apply the second law of thermodynamics to economy. Moreover, as the subject is attracting the attention not only of scholars but also of policy makers, in this paper the recent trends of the scientific literature on this intriguing issue will be depicted, in the aim to reveal actual practical application and future developments.

# Relationships between thermodynamics and economics

Circular economy (CE) is recognized as a movement for over 10 years promoting the decoupling of economic development from the unsustainable consumption of natural resources (Kirchherr et al., 2017; Muradin et al., 2019). There is a general agreement to end the linear economy, but not necessarily what to apply instead: eco-design, recycling, short cycles, resource efficiency, etc. Reintroduction processes, such as recycling or refurbishment, undoubtedly support the objectives of a circular economy, but inevitably result in material waste or the production of undesirable by-products. Basically relations between thermodynamics and economics are relationships between natural and economic systems and represent the most important problem in ecological economics (Ciegis, 2008; Hammond et al., 2009). Georgescu-Roegen was the first economist to recognize the importance of thermodynamic constraints in economic theory (Georgescu-Roegen, 1971), whereas Solow and Stiglitz recognized the existence of the laws of thermodynamics but argued that they had no significant consequences for economic analyses and could therefore be safely ignored (Daly H.E. et al., 1997; Germain M. et al., 2019). The increase in entropy on Earth (as a whole) is only reversible because there is a complex biosphere powered mainly by solar radiation, which is the main source of exergy influx. Most of this energy is returned back to extraterrestrial space, however some of it is converted by plants and living organisms to chemical energy and some of it becomes a backup carbon source (hard coal, oil, natural gas) with low entropy. The energy flowing on Earth is part of open cycles: solar energy is provided, and heat is expelled. Flows of energy and matter from the ecosphere to the economy (technosphere) and back to ecological reservoirs are called “throughput”. The distinction between natural (ecosphere) and technical (technosphere) systems does not mean that the former are purely cyclical and waste-free, while the latter are purely linear and waste-generating. Many industries rely on the recycling of matter and energy from production processes and consumer waste. At the same time, the biosphere gets rid of “carbon” in natural landfills. In natural systems, cycles are local, decentralized and developed towards more and more closed cycles with the consequent reduction of emissions and waste. In technical systems, cycles are increasingly global, reliant on transport and developed to be open, with the consequent increase in emissions and waste. The green economy and movements for sustainable development assume that the technosphere will contribute to resolve the conflict between economic growth and environmental protection. Different approaches exist: Cradle to cradle; Industrial ecology, Natural capitalism, Circular economy. Will these approaches enable sustainable economic growth in an environmentally friendly manner in the long term? Do they correctly interpret, appreciate / ignore the biophysical limits set by the dynamics of systems and thermodynamics ? The potential contribution of industrial symbiosis and the circular economy to sustainable development and to the Sustainable Development Goals set in the United Nations Agenda 2030 is under discussion by scholars (Cecchin A. et al., 2021). Ecodesign and "cradle to grave" see the possibility of ensuring continuous economic growth in an environmentally friendly way, considering the entire life cycle of the product. They are criticized for not taking into account the physical limitations of recycling. When recycling, for example plastics, on an industrial scale, we disperse and lose more and more materials with each cycle, leading to waste and emissions (Foltynowicz et al., 2020). Achieving closed material cycles will therefore require the segregation and treatment of high entropy waste for recycling and reuse as a low entropy resource.

* 1. **The Statistical Entropy Analysis**

SEA quantifies the changes in the substance concentration or distribution throughout a MFA, which instead assesses flows and stocks of materials within a system. In other words a process can concentrate, dilute, or leave unaltered a substance concentration/distribution. MFA is an invaluable tool for evaluating the most important processes and flows in an industrial metabolism useful for optimization, but the analysis does not cover qualitative changes of material flows that occur during all the processes that transform input-flows into output-flows. The processes should be clustered into steps to calculate the degree of dilution of substances and SEA that decreases in processes like mining, refining, separate waste collection, mechanical sorting and recycling whereas raise in all that processes that dilutes a substance, e.g. mixing, or emission into an environmental compartment such as the atmosphere. A single substance MFA represents the lowest SEA equal to zero (pure and most concentrated) the more uniformly a substance is distributed, the closer the statistical entropy value will reach the maximum. The method has recently successfully extended for considering, both various separate substances and materials at the component level and the combination of components at the level of the product. The method has been successfully applied in several case studies: 1) on the recycling and reuse of components of a simplified car (Parchomenko A., et al., 2020); 2) to reliably assess the recyclability of plastics (Nimmegeers P, et al., 2021); 3) for the optimization of separation and purification processes like a sieving process for waste lithium-ion batteries (Velázquez Martínez O et al., 2019); 4) to measure the recyclability of municipal solid wastes with a slightly different approach using the EWRI index (Tong X, et al., 2021); 5) to evaluate the best recycling process of thermoelectric devices, solid-state devices capable of converting a temperature gradient into electric power (Velázquez-Martinez O et al., 2020).

* 1. **Conclusions and future perspectives**

Thermodynamic limits of the Circular Economy are emerging issues in the scientific literature posing serious problems in realizing zero-waste strategies. MFA assesses flows and stocks of materials within a system assuming the quality of the flows remain constant, whereas SEA calculates qualitative changes of material flows during transformation of input into output flows. SEA is the analog of entropy in thermodynamic systems and fixes insurmountable limits to the application of circular economy paradigms. Recycling or refurbishment, the reintroduction processes, foster the objectives of a circular economy, but inevitably, material waste or undesirable by-products are generated. Research efforts are directed towards application of SEA in different production and recycling areas, to make the approach useful to minimize waste production and to choose the best strategy to apply for a recycling process. Another interesting and useful perspective of this approach will be to use this tool and its scientific approach, to make stakeholders aware that the zero waste strategy is a utopia.

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