detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

USING EXERGY TO ADDRESS A CIRCULAR ECONOMY

Marc A. Rosen *

Faculty of Engineering and Applied Science, Ontario Tech University, Oshawa, Ontario, Canada

Article Info:
Received:
19 April 2024
Revised:
17 July 2024
Accepted:
28 August 2024
Available online:
6 October 2024

Keywords:
Circular economy
Exergy
Energy
Environment
Ecology

ABSTRACT

The use of exergy is described as a tool for addressing a circular economy so the benefits can be appreciated and attained. Exergy can be used to understand circular economy measures and to assess and improve energy systems, and can help better understand the benefits of utilizing sustainable energy by providing more useful and meaningful information than energy provides. Exergy clearly identifies efficiency improvements and reductions in wastes and environmental impacts attributable to sustainable energy. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. Exergy should be applied in addressing a circular economy.

1. INTRODUCTION

The concept of a circular economy has been investigated by many, from various perspectives and in many domains. These investigations include contributions by the present author in the fields of business and engineering (Alvarez-Risco et al., 2022), the plastic industry (Alvarez-Risco et al., 2020), the food industry (Del-Aguila-Arcentales et al., 2022), and companies in pandemic times (Alvarez-Risco et al., 2021).

The use of energy as a tool for addressing a circular economy and measuring the benefits of sustainable energy systems can be misleading and confusing. However, the thermodynamic quantity exergy, which can be used to help address a circular economy and to enhance energy systems, can help better understand the potential benefits of relevant measures.

Exergy can clearly identify efficiency improvements and reductions in wastes and environmental impacts. Exergy can also identify better than energy ways to improve environmental benefits and economics. Hence, many researchers suggest that the impact of energy use on the environment, the achievement of increased efficiency, and the economics of energy systems are best addressed by considering exergy (Dincer and Rosen, 2021; Demirel and Rosen, 2023). Thus, many exergy methods have been developed, e.g., exergy analysis for efficiency improvement, and exergoeconomics for improving the economics of energy systems. Thus, exergy has an important role to play in addressing a circular economy.

This article discusses these points with the objective of demonstrating how exergy can help improve understanding and applying exergy methods for addressing a circular economy.

2. USES OF EXERGY

2.1 Efficiency improvement and emissions reduction

The primary use of exergy analysis is as a methodology for understanding the behavior of and improving the efficiency of energy systems. The exergy method is useful for improving efficiency because more meaningful efficiencies are evaluated with exergy rather compared to energy, since exergy efficiencies are always a measure of the approach to the ideal.

2.2 Government and public policy

Facets of exergy relate to government policies, strategies and priorities in areas such as environment, energy, natural resources, industry and economic development. Governments can use exergy methods in establishing public policies in such areas to increase the benefits. Some of these follow:

- Environment policies. In recent decades, various exergy-environment methods have evolved, which can be integrated with government environmental policy.text text text
- Energy and natural resources policies. Exergy can provide a useful perspective for governments to establish natural resource and energy security, for a country or societies within it.

* Corresponding author:
Marc A. Rosen
email: marc.rosen@ontariotechu.ca

https://doi.org/10.31025/2611-4135/2024.19431

- Economic and industry policies. Exergy methods can be integrated with economics to address financial and economic problems in industry.
- Global, national and regional policies. Evaluations have been carried out of exergy flows through the world, countries and regions, and help in understanding the true efficiency of energy and resource use in these jurisdictions.

3. EXERGY AND ECONOMICS

Economic issues are important in assessing systems. In designing systems, technical disciplines (especially thermodynamics) are combined with economics to achieve preferred and optimal systems. For energy system, costs are usually based on energy, although many suggest costs are better distributed among outputs based on exergy.

Numerous exergy-economic methods have been developed, e.g., exergoeconomics, thermoeconomics and second-law costing. Some researchers have critically reviewed costing methods using exergy, while others describe thermoeconomic optimization. Some even use exergy in describing price-driven economic order systems from a thermodynamic perspective. One reason costs are better distributed among outputs when based on exergy is that exergy often is a consistent measure of economic value, while this is true only sometimes for energy.

4. EXERGY, ENVIRONMENT AND SUSTAINABILITY

Although energy and resources help meet human needs and improve living standards and quality of life, they generally lead to environment impacts. The UN Sustainable Development Goals (2015-2030) reinforce and expand on these ideas (UN, 2015; Rosen, 2021b). In particular, carbon dioxide emissions mitigation can be achieved by introducing sustainable and renewable energy sources, reducing the fossil fuel portion of the energy mix and increasing efficiency.

4.1 Exergy and the environment

Environmental actions can reduce impacts like climate change by lowering resource and energy losses. This raises exergy efficiency and reduces exergy losses. One link between environmental impact and exergy stems from the latter being a measure of the departure of the state of a system from the environment (Rosen, 2021a). The exergy of a system, which depends on the states of both the system and the environment, is zero only when the system and its environment are in equilibrium.

Recently, activity regarding improving understanding of the relation between exergy and the environment has expanded (Nižetić and Papadopoulos, 2018). Kılkış and Kılkış (2017) propose exergy metrics for energy, the environment, and the economy. Exergoeconoenvironmental analysis is considered for improving understanding of systems and for developing thermodynamically, economically, and environmentally sound energy conversion systems (Esmaeilion et al., 2024; Moharamian et al., 2023). Also, Nwodo et al. (2020) have recently reviewed exergetic life cycle assessment.

Research on the relation between exergy and ecology has also increased in recent years. Valero et al. (2018) describe the theory of exergy cost and thermo-ecological cost, and assess the exergy degradation of natural capital. Some consider thermo-ecological cost for quantifying the exergy and ecology connection. Sciubba (2019) has reviewed exergy-based ecological indicators. Some consider eco-exergy as an indicator of ecosystem complexity, and Hothersuse exergy as an index for system-level ecological risk assessment of contaminates. Issues have also been examined, e.g., Nielsen (2019) discusses issues arising when shifting the concept of exergy among ecological levels and domains.

Some studies have focused on climate change. For example, some examine limits imposed by the second law of thermodynamics on reducing greenhouse gas emissions, while Hernandez and Cullen (2019) describe exergy as a universal metric for measuring resource efficiency to address industrial decarbonisation. Veiga and Romanelli (2020) examine the mitigation of greenhouse gas emissions using exergy, and Zhang and Reistad (1998) analyze energy conversion systems with exergy methods, including material and global warming aspects. Khajehpour et al. (2019) consider responsibility allocation of climate change based on exergy. Arango-Miranda et al. (2018) investigate the role of exergy in carbon dioxide emissions, energy consumption and economic growth, while Wu and Wang (2020) explore avoidable carbon emissions by reducing exergy destruction based on advanced exergy analysis.

4.2 Exergy and sustainability

The United Nations Sustainable Development Goals for 2015-2030 (UN, 2015) spell out a broad view for moving the world towards sustainability, and energy is a key aspect of many of the 17 goals. Sustainability requires sustainable energy resources be used, both cleanly and efficiently (Rosen, 2021b). Exergy methods aid in improving efficiency, thereby enhancing the benefits derived from resources while mitigating problems like environmental impact and lengthening the lifetimes of finite resources. When striving for sustainability, one seeks energy resources that cause no environmental impact. This probably involves using energy resources that lead to no environmental waste emissions or only waste emissions having no environmental impact, the latter relevant when environmental emissions are inert or in equilibrium with the environment. In actuality, resource use entails some environmental impact, and increased efficiency can offset some of the limitations imposed on sustainability by environmental emissions. Even if inexpensive and widely available, it will be advantageous to use energy resources efficiently to reduce the corresponding resource needs (energy, material, etc.) to build the relevant systems and environmental impacts.

Others have examined exergy and sustainability relations. Nielsen (2020) describes an exergy-based approach to sustainable development indicators, while Lucia and Grisolia (2019) consider exergy inefficiency as an indicator for sustainable development. Whiting et al. (2017) describe the use of exergy to evaluate the sustainability of fossil fuels and non-fuel mineral depletion and Zhang et al. (2018)

improve understanding of fuel sustainability from the exergy viewpoint. Stanek et al. (2019) describe exergy as a measure of sustainability through thermo-ecology. Exergy is used as an element of a method to assess the environmental impact and sustainability of energy systems (Kiehbadroudinezhad et al., 2023; Jalili et al., 2024).

5. EXERGY AND A CIRCULAR ECONOMY

5.1 Resources and resource depletion

Many investigations focusing on the application of exergy methods to resources, from the perspective of a circular economy have been reported. Many of these studies relate to energy resources, due to their widespread usage and the many concerns related to them, regarding environmental impacts, resource supplies, economics and other factors. Numerous studies have also been carried out on other resources such as metals and plastics.

An interesting general study is the one by Llamas et al. (2024), which examines the quantification of resource dissipation using an exergy approach, as a means of supporting a circular economy. They write, "exergy analysis highlights irreversibilities in circular economy systems, and it provides an appropriate and complementary resource efficiency indicator," and that through the irreversibilities obtained with exergy analysis, "their dissipative role in the circular economy can be quantified."

5.1.1 Energy resources

Energy resources have been examined using exergy methods for decades, and recently many have focused on a circular economy. The advantages of exergy in addressing energy issues as part of a circular economy have been examined by the present author (Rosen, 2022; Dincer and Rosen, 2021; Demirel and Rosen, 2023). For instance, Dincer and Rosen (2021) describe eco-industrial clusters that integrate circular economy with industrial ecology based on industrial symbiosis. Cooper et al. (2017) provide insights on a circular economy from a thermodynamic perspective focused on exergy. The study involves analyses of the impact of a range of circular economy approaches on energy use, which proves to be a particularly important application area for exergy methods with respect to circularity.

Waste to energy: Sharma et al. (2020) investigate the waste-to-energy nexus as part of a circular economy including environmental protection, including an exergy perspective. Their focus on the employment of biological methods for waste materials is a key part of their waste-to-energy approach, which helps in addressing concerns about waste management, energy demand and environmental impact.

de Almeida and Borsato (2020) extended the RIPEx exergy-based method, which quantifies energy and material flows in terms of exergy and considers environmental impact, efficiency and cost, yielding a method they claim may support waste to energy as part of a circular economy. The inclusion of exergy in the method is central to its advantages.

Energy conservation: Alvarez et al. (2022) propose a product innovation method based on exergy and knowledge management that they claim is essential for energy conservation and environmental protection. The method helps to raise exergy efficiencies by lowering exergy destruction rates, i.e., irreversibilities, to support the circular economy. Their approach is transdisciplinary and contributes to climate change mitigation, which is an important area in general as well as for circularity, and which benefits notably from applying exergy concepts.

Heating: North and Jentsch (2021) formulate an approach to heating processes supportive of a circular economy that focuses on exergy. The application of exergy analysis helps identify resource options that are efficient and conserve primary energy resources greatly. They focus on applications to buildings, although heating for other applications benefits similarly from the application of exergy methods.

Renewable energy: Much research has focused on renewable energy sources as alternatives to fossil fuels in support of a circular economy, often from exergy viewpoints. In a general manner, Alvarez et al. (2022) investigate the modeling product innovation from renewable energy based on an exergy methodology. Through energy conservation and environmental protection, the method helps to shift towards a circular economy.

Different types of renewable energy have received attention, given they all have applications where they can be advantageous. Cano et al. (2020) apply life cycle assessment based on exergy indicators to contrast the use of renewable and non-renewable resources in processes in a circular economy. Various renewable resources from nature are considered, including hydraulic, solar and wind, allowing for a reduction in consumption of non-renewable resources. Alvarez et al. (2022) consider the innovation of products utilizing renewable energy to satisfy environmental protection regulations. Their focus on exergy helps in climate change mitigation and achieving a circular economy. Novak (2017) focuses on a sustainable energy system based on renewable energy in support of a circular economy, following exergy methods. The author stresses how the circular economy necessitates exergy considerations in technology and economic patterns.

Solar energy has received much attention in recent years and applications have grown considerably, especially in the area of photovoltaic (PV) systems. Bartie et al. (2020) focus on the role of metallurgical infrastructure in their analysis of the resource efficiency of the circular economy, focusing on cadmium telluride PV technology and its life cycle. The work focuses on thermodynamic limits that are made clear with exergy methods. Bartie et al. (2021) assess solar resources from an exergy perspective through photovoltaic technology, and examine the opportunities it provides for a circular economy. The authors focus on opportunities for recovery of resources to sustain PV industry growth through consideration of the PV life cycle, and point out how the technical limits of circularity are highlighted via exergy methods.

Alternative fuels: Various fuels that are alternatives to fossil fuels have been considered from exergy perspectives, in support of a circular economy. These fuels facilitate the use of renewable energy sources in most cases, thus making energy systems more circular.

One important alternative fuel is hydrogen, which has received increasing interest in recent decades. Martínez-Rodríguez and Abánades (2020) assess and compare hydrogen production techniques (e.g., electrolysis and pyrolysis) with exergy methods. The work can support a hydrogen economy, in which the main energy carriers are electricity and hydrogen, which in turn can support a circular economy. Sharma et al. (2020) investigate hydrogen energy trends as part of a waste-to-energy nexus and thereby part of a circular economy. They focus on hydrogen yields, economics, research and development needs, commercial viability and sustainable development, all in support of a circular economy. They note the imperative need for a circular economy and sustainable development. Novak (2017), in considering exergy as sustainability measure for energy systems, proposes hydrogen production from solar and planetary energy at high exergy efficiency as a means to a circular economy that can support the development of societies. The work focuses on known chemical processes and existing infrastructure, with an aim of reducing the harm caused by fossil fuels and their resource limitations.

Another important alternative fuel is methanol. Vilardi et al. (2020) investigated methanol production with exergy methods via biogas upgrading routes. The authors claim these are key to a circular economy by permitting reuse of wastes. Novak (2017) proposes methanol from solar and planetary energy as part of a circular economy, partly in extension of work on hydrogen production. The work, based on exergy methods, incorporates carbon recycling.

Novak (2017) proposes synthetic methane produced from solar and planetary energy as part of a sustainable energy system in support of a circular economy. The work is founded on an exergy approach. The work provides an interesting focus, given methane is a key constituent of natural gas, but the synthetic nature of the product methane avoids issues associated with natural gas utilization.

Vilardi et al. (2020) focus on biogas production and treatment to generate alternative bio-derived fuels for a circular economy, drawing on waste sources and exergy methods. Following an exergy approach, Novak (2017) proposes using solar and planetary energy like biomass within a circular economy to produce gaseous and liquid fuels, via chemical processes.

5.1.2 Non-energy resources

Non-energy resources have been examined using exergy methods, sometimes focusing on a circular economy. North and Jentsch (2021) adopt a circular economy approach that involves decoupling resource consumption from resource depletion. Gai et al. (2021) examine the recycling of multiple resources, by considering materials recovery, exergy demand and economics as well as the trade-offs between them. They apply the work to industrial and urban processes. In support of sustainable production and consumption, Hernandez and Cullen (2019) propose exergy as a universal metric for increasing resource efficiency and reducing global carbon emissions. They work is developed under the rubric of material efficiency or circular economy, and has the potential for widespread application in many disciplines given its "universal" intent and approach.

Much work on non-energy resources relates to metallurgy and metals. Reuter et al. (2019) examine material and metallurgical issues from the viewpoint of product design, within a circular economy. They utilize a product (mineral)-centric approach and clarify limitations of material-focused considerations. Abadías Llamas et al. (2020) report an exergy analysis of zinc production for large circular economy systems. The exergy-based methodology demonstrates resource efficiency limits through exergy dissipation, in terms of material losses. Hannula et al. (2020) examine aluminum recycling and related processes with exergy, focusing on separation processes. Through the work, they demonstrate that recycling and process metallurgy are the main enablers of a circular economy. Cano et al. (2020) examine gold mining using exergy indicators within a life cycle assessment. They consider both open-pit and alluvial mining. Applying a circular economy focus, the helps in reducing resource consumption. Focusing on cadmium telluride production, Bartie et al. (2020) examine the roles of mineral processing, extractive metallurgy and metallurgical infrastructure in a circular economy, while considering thermodynamic limits via exergy methods. Making metal processes more circular is an important need in a circular economy, given the pervasiveness of the usage of metals. Finally, Llamas et al. (2024) use exergy to quantify resource dissipation for metallurgical processes and point out how it provides an appropriate and complementary resource efficiency indicator for them.

Other work on non-energy resources involves non-metal materials and, like metal processes, making them more circular is an important need in a circular economy given their extensive usage. Reuter et al. (2019) examine material factors, within a circular economy and identify limitations of material-focused considerations through exergy. Cano Londoño and Cabezas (2021) present their perspectives on a circular economy via a supply chain strategy, considering the thermodynamic limitations in terms of exergy factors. The work focuses on maintaining materials in a useful state in products, and avoiding losses and dissipation. Specific materials have also been examined. Textiles like cotton have been assessed by Popescu et al. (2022) for their exergy footprint in terms of recycling. Popescu et al. (2022) also examine polyethylene production in a related manner. The work involves the entire process chain of polyethylene synthesis by recycling cotton waste, and demonstrates how circular economy approaches tend to decrease the exergy footprint. Russo et al. (2021) examine the production and recycling of polymers and plastic based on exergy. The work is useful for developing recycling processes for plastics. Ortego et al. (2023) extend this work focusing on plastic car parts, highlighting the recycling challenges because of the wide variety of plastics used. Huysman et al. (2017) examine post-industrial plastic waste and relevant performance indicators for a circular economy, accounting for cumulative exergy extraction. Some of the indicators are observed to be useful for guiding how to use waste streams, based their quality and environmental considerations.

5.2 Chemical processes

Many investigations have been reported of chemical processes a circular economy, following exergy methods, and this is not surprising given the particular benefits of exergy to processing operations of a chemical nature in particular. Focusing on a chemical engineering context, Cano Londoño and Cabezas (2021) examine various views on a circular economy and sustainable development, considering the thermodynamic limitations through exergy. A wide range of diverse chemical processes have been considered. The benefits are demonstrated of efficient resource use and efficient technology. As well, the valorization and minimization of wastes is rationalized and quantified via exergy.

Many specific chemical processes have been investigated. Sharma et al. (2020) investigate hydrogen energy trends, in support of a circular economy, considering biological and chemical processes for wastes. They consider such processes as dark fermentation, photofermentation, and combined dark and photofermentation, as well as pretreatment methods including heat treatment, acid or base treatment, ultrasonication, aeration and electroporation. Vilardi et al. (2020) examine several processes for biogas upgrading to biomethane (amine scrubbing, water scrubbing and membrane separation) with exergy methods, consistent with the precepts of a circular economy. The upgraded biogas is developed to meet the standards for injection into a grid, and is also usable directly. Vilardi and Verdone (2022) also examine with exergy the processes involved in waste incineration, including oxy-combustion, air separation and flue gas recirculation. Waste reuse is confirmed through the results to be an important aspect of a circular economy. In examining with exergy methods the polymers and plastics production and recycling, Russo et al. (2021) consider the life cycle of nine commercial polymers and the resource consumption during all processes to generate the crude polymeric material. By considering such a variety of polymers, the generality of the exergy-based approach is demonstrated to have great breadth. In investigating polyethylene production via the exergy footprint, Popescu et al. (2022) consider all processes polyethylene synthesis by recycling waste, highlighting the advantages of a circular economy approach. Hannula et al. (2020) examine the production of alloys with exergy-based and LCA methods, focusing on physical separation (e.g., using an eddy current separator) and re-melting processes, illustrating how exergy methods support circularity through more efficient resource use.

5.3 Waste utilization, recycling and end-of-life processes

Much research has been reported on waste utilization, recycling and end-of-life processes, incorporating exergy methods. Such work is founded on the rationale values of the usefulness of wastes and inputs provided with exergy methods. de Almeida and Borsato (2020) investigate waste to energy processes and their contribution to a circular economy, following an exergy-based method that considers exergy flows. They obtain broad results in the areas of environmental impact, efficiency and economics, and consider the trade-offs involved in reuse, recycling and incineration.

Many specific waste utilization, recycling and end-of-life processes have been investigated in line with the concepts of a circular economy. In examining biogas upgrading processes, Vilardi et al. (2020) examine with exergy analysis the reuse of industrial by-products and agro-industrial wastes, for several energy intensive sectors. Vilardi and Verdone (2022) also examine by exergy methods the use of municipal solid waste to contribute to a circular economy, through incineration. Waste to energy processes have also been investigated from an exergy perspective as an important aspect of a circular economy by Sharma et al. (2020), providing an avenue for about waste management in a manner that supports a circular economy. Huysman et al. (2017) consider plastic waste processing for a circular economy, accounting for indicators to quantify the circular economy performance based on exergy.

Finally, many studies have focused on applications of recycling to contribute to the circular economy through exergy approaches. Gai et al. (2021) examine trade-offs in recycling multiple resources, as well as the advantages in terms of circularity. The criteria applied are derived from exergy through a circular exergy use rate, and these are straightforwardly contrasted with the results of more conventional approaches. In assessing via exergy methods resource recovery opportunities as a means of circularity, Bartie et al. (2021) use neural networks to investigate a system's response to variations in end-of-life processes and recycling. They consider primary resource and electricity use and environmental emissions. Popescu et al. (2022) assess with an exergy approach the use of recycling in textile production, drawing on a procedure for industrial chemical recycling. The widespread pervasiveness of textiles globally, in countries of greatly varying levels of wealth, make this application particularly impactful across the planet. de Almeida and Borsato (2020) study end of life processes in waste treatment of industrial products, considering reuse and recycling, via an exergy-based method, that supports a circular economy. Polymer and plastic recycling is examined based on exergy by Russo et al. (2021), via thermodynamic recycling indexes that are founded in exergy. Reuter et al. (2019) examine design for recycling with a product-centric approach using exergy to address circular economy challenges. The product-centric nature of this approach makes it different from many other methods, but it still is contingent on applying exergy concepts. Llamas et al. (2024) quantify resource dissipation using an exergy approach and indicate that it provides an appropriate and complementary resource efficiency indicator for recycling processes.

5.4 Advanced exergy-based methods for a circular economy

Many investigations have been reported focusing on the development of advanced exergy-based methods in support of a circular economy, and their applications in numerous areas. Many of these studies relate only to thermodynamic techniques, while others go beyond thermodynamics, covering such areas as the environment and economics and more broadly design and optimization. All of these can support a circular economy, either directly or indirectly.

5.4.1 Methods for resources and energy

Numerous studies have examined means of increasing efficiency. North and Jentsch (2021) apply exergy methods to buildings heating processes to identify efficient resource options and conserve energy resources in support of a circular economy. Hernandez and Cullen (2019) use exergy methods to increase resource efficiency in support of sustainable production and consumption via a circular economy. Cano et al. (2020) investigate means to increase efficiency through reducing exergy wastes by applying exergy methods and exergy life cycle assessment to support a circular economy, and apply them to mining processes. Although a unique type of operation, mining is nonetheless widespread globally, rendering the work described here important for more circular use of mined resources.

Hernandez and Cullen (2019) propose a resource efficiency metric based on exergy, in a sense as a universal metric. They find that such an exergy-based resource efficiency metric has high relevance and robustness, and can help raise awareness and understanding about exergy and its benefits for a circular economy. The benefit of a universal approach in this approach is quite significant, as one criticism of exergy methods can be that they have to be tailored to individual processes or operations. A universal approach once widely accepted could therefore advance the exergy-based resource efficiency metric rapidly.

Gai et al. (2021) propose a multi-resource integration map for processes (e.g., recycling) as a way of managing the trade-off between process circularity and the expenditure of resources (energy, economic, etc.). The technique considers multiple resources, and such activities as materials recovery.

Gai et al. (2021) also propose a total circularity index, developed by integrating circular exergy use rate and circular material use rate. The technique constitutes a way of providing guidance for the integration of multi-resource systems, and an understanding of economic and exergy performance of circular economy options. A good degree of practicality is reflected in this approach as well as the one described in the prior paragraph through their recognition of the necessary trade-offs when striving for circularity.

To focus on sustainability in a realistic manner, Huysman et al. (2017) propose a performance indicator for a circular economy based on cumulative exergy extraction from the natural environment, and apply it to waste streams and their treatment options for plastics. The indicator is useful for valorization of waste streams and attaining and comparing environmental benefits. The applicability of this approach is great, due to the broad use of plastics, providing significant potential in moving towards a circular economy.

5.4.2 Methods for the environment

To aid in environmental protection and energy conservation, Alvarez et al. (2022) propose eco-innovation, i.e., a technique involving product innovation focusing on renewable energy use. The transdisciplinary technique involves exergy methods and knowledge management, and bolsters a circular economy. This is particularly evident in the substitution it envisions of renewable energy for fossil fuels.

Popescu et al. (2022) develop and utilize the exergy footprint concept and apply it to recycling. The process stages are identified and examined, with subsequent efforts made to reduce or eliminate wastes and reduce exergy input, thereby decreasing the exergy footprint. Doing so enhances circularity directly.

Numerous researchers consider life cycle assessment and related techniques as key to a circular economy. Hannula et al. (2020) consider aluminum recycling using exergy and life cycle assessment, as a means to enabler a circular economy. Resource efficiency and environmental impacts are determined through exergy analysis and life cycle assessment, along with modeling and simulation. The significant benefits of assessing and addressing environmental issue via a life cycle assessment approach are notably enhanced by the incorporation into the approach of exergy concepts. Cano et al. (2020) apply exergy life cycle assessment and related indicators to investigate the mining sector.

Many researchers consider decarbonization as part of a circular economy, exploiting the advantages of exergy methods. North and Jentsch (2021) formulate an approach focusing on exergy to decarbonizing building heating. Xie et al. (2023) examine the nexus between low-carbon and circular economies. They show how low-carbon actions and circular practices can work together at various scales and dimensions, and suggest bio-waste management and renewable energy use, and adjusting the mix of circular actions to follow the transition to a low-carbon energy. Hernandez and Cullen (2019) propose exergy metrics for reducing global carbon emissions as well as increasing resource efficiency, and consider numerous efficiency metrics as a means of powering a low-carbon transition. Novak (2017) examine and promote industrial decarbonisation through the utilization of exergy as a universal metric for resource efficiency renewable energy in support of a circular economy, following exergy methods. The author emphasizes how renewable energy supports a circular economy. This approach, and the others noted in this paragraph, further point out the benefit of exergy methods in efforts for a circular economy.

In a somewhat related way, numerous researchers consider climate change using exergy methods, in support of a circular economy. In one example, Alvarez et al. (2022) apply eco-innovation along with renewable energy to mitigate climate change. This approach is extremely noteworthy, given the significance and urgency of challenges related to climate change.

5.4.3 Methods for economics, design and optimization

Abadías Llamas et al. (2020) report and apply a thermoeconomic technique that combines exergy methods (i.e., a thermodynamic perspective) with economics. The technique demonstrates resource efficiency limits, in terms of material losses and exergy dissipation and resource-efficient alternative to minimize wastes, and is shown to be useful for circular economy systems.

Reuter et al. (2019) examine challenges of a circular economy material from a product design perspective factors, including design for recycling following a product-centric approach and assisted by exergy considerations. The authors focus on using wastes as resources and extending product life cycles for maximizing resource efficiency, and apply the research to metallurgical processing.

Bartie et al. (2020) consider factors related to optimization within a circular economy and demonstrate how the true performance is related to thermodynamic limits established with exergy methods, and apply the work to photovoltaic systems.

Given the importance of design in engineering, and the great value of optimization, especially when accounting for economics, these methods are potentially very important to the engineering community.

5.5 Broader applications of exergy methods for a circular economy

Studies have been undertaken on broader applications of exergy methods for a circular economy, often focusing on the large scale, including research in support of policy making and sustainability. These broader applications are significant, as broader and larger applications of exergy approaches to a circular economy, can have a multiplier effect compared to applications to single processes or systems.

North and Jentsch (2021) examine the use of exergy in policy making related to a circular economy, in particular to prioritise the reuse of these freely available heat sources from wastes and renewable sources. The approach helps in decoupling resource consumption from depletion. The authors consider building heating along with heat networks, and examine the use of exergy methods in city energy planning to identify and prioritize resource efficiency and energy resource conservation.

The topics of sustainability and sustainable development, which are attracting increasing attention in recent years, are in line with a circular economy and can be enhanced with exergy methods. Cano Londoño and Cabezas (2021) identify and investigate perspectives on a circular economy in the context of and sustainable development. The work aims to materialize the environmental sustainability of supply chains, considering exergy to acknowledge thermodynamic limitations, and seeks to make production processes more sustainable, especially in the domain of chemical engineering. In examining hydrogen production options with exergy methods, Martínez-Rodríguez and Abánades (2020), point out the importance of a hydrogen economy and how hydrogen is produced affects the sustainability of a hydrogen economy. Xie et al. (2023) demonstrate how a circular economy and low-carbon economy can be viewed as pillars of sustainable development. They show how practices in these areas can be mutually beneficial and support sustainable development of various entities of many sizes. They go beyond economic and environmental sustainability by pointing out the importance of considering social sustainability. In examining challenges to a circular economy, Reuter et al. (2019) show how integrating product-centric considerations in various domains (e.g., energy, water, industry, transport) can help in improving or maximizing the resource efficiency and make cities sustainable in the future, thereby contributing to the Sustainable Development Goals of the United Nations. Since humanity is now more than half way through the 2015-2030 time frame set for the Sustainable Development Goals, and most experts suggest there is significant effort still needed since progress notably lags what was expected, the impact of this method may be high and widespread.

5.6 Fields of application of exergy methods for a circular economy

Many fields have been the focus of investigations on the application of exergy methods to support a circular economy, particularly in industry and regions. A selection of these is shown in Figure 1, and details are provided below.

Industries have been examined with exergy methods to enhance how they can support a circular economy, both at the general level and for specific industries. Industrial processes in general are examined from an exergy viewpoint by Hernandez and Cullen (2019), particularly regarding decarbonisation and resource efficiency. The show that, to reduce carbon emissions, industry needs to increase both energy efficiency and material efficiency. In discussing the need for exergy in design education, Dincer and Rosen (2021) describe a circular economy and education model incorporating exergy for a dairy facility.

Cano Londoño and Cabezas (2021) examine the chemicals sector and its industries to identify circularity factors and opportunities, using exergy methods. These industries are primarily involved in transforming raw materials into products.

North and Jentsch (2021) focus on buildings and the building sector in developing an exergy approach supportive of a circular economy. They point out the importance of the building sector by pointing out that building heating accounts a significant portion of the energy consumption and greenhouse gas emissions in many countries.

Russo et al. (2021) and Ortego et al. (2023) apply exergy-based assessments to automobiles and the automotive sector. The work has implications for the material content of vehicles and their components, recycling, efficiency and decarbonization. That work also demonstrates the importance of car part materials on design and end-of-life management to promote circularity.

The electricity generation sector has been the subject of numerous studies using exergy methods, in line with its role in a circular economy. North and Jentsch (2021) describe the burdens on electricity infrastructures if heating processes becomes electrified in the future and if renewable energy is increasingly used to provide electricity, hydrogen and heating. Xie et al. (2023) investigate low-carbon and circular economies, focusing issues affecting a circular economy in relation to carbon-intensive electricity. Novak (2017) presents a vision for a sustainable energy sys-

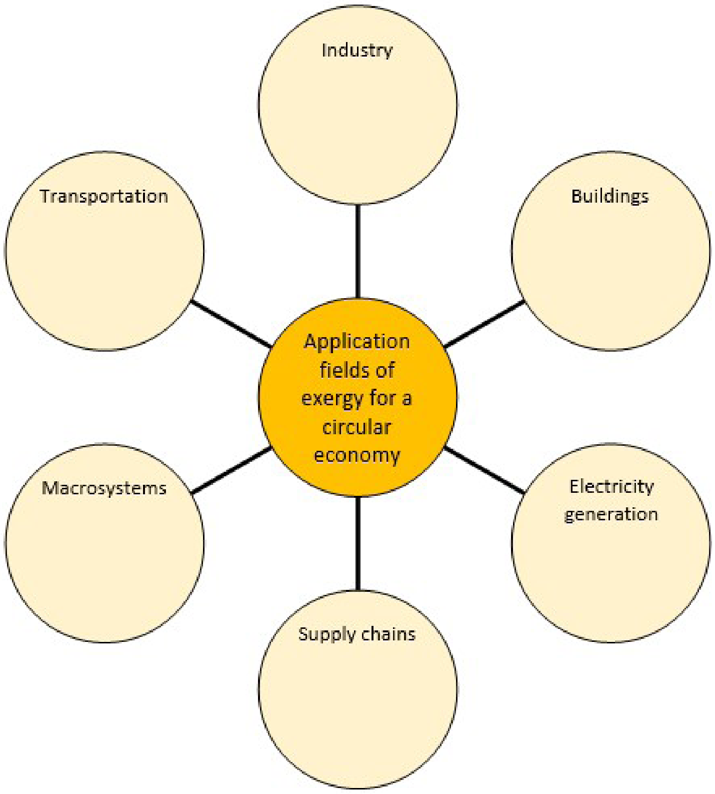

FIGURE 1: Selected fields of application of exergy methods to support a circular economy.

tem premised on solar and other natural energy being used to produce renewable electricity and where appropriate hydrogen. The vision is consistent with a circular economy and is developed using exergy methods. Bartie et al. (2020) and Bartie et al. (2021) examine photovoltaic technology over its life cycle, utilizing exergy methods, and how such technology is a key component of a circular economy.

Supply chains have received attention, as applied to various industries. In examining energy use and its relation to a circular economy, Cooper et al. (2017) identity supply chain impacts through input-output analyses. This work enables prioritization of the areas in which circular economy approaches have the strongest potential for supply chains. Cano Londoño and Cabezas (2021) propose a supply chain strategy that includes limitations identified through exergy methods, as a means of supporting a circular economy. The strategy allows for the materialization of the environmental sustainability of supply chains. While examining low-carbon and circular economies, Xie et al. (2023) describe the need for regional supply structure and circular economy chains to address the trade-offs arising from carbon-intensive energy and raw material scarcity.

Regions have also been studied using exergy methods to enhance their contribution to a circular economy. As pointed out earlier, such broader applications of exergy approaches to a circular economy can have a much more widespread impact compared to applications to single processes or systems, making the activity for regions notable. Xie et al. (2023) investigate with exergy methods the benefits of urban-industrial symbiosis and the need to address urban-industrial planning and challenges. They demonstrate the importance for decision-makers to minimize trade-offs while maximizing synergies to support a circular economy. Gai et al. (2021) develop a method involving urban symbiosis where product demands are satisfied by a set of waste resources, with or without processing. Applicable to industrial and urban processes, the method can help guide the integration of multi-resource systems by determining economic and exergy performance of circular economy measures. Cooper et al. (2017) provide insights on a circular economy for macrosystems like countries and regions, from an exergy perspective. Although focused on energy use, the implications are broader and permit prioritizing areas where circular economy measures can have noteworthy impacts.

6. GUIDELINES FOR EXERGY ANALYSES RELEVANT TO A CIRCULAR ECONOMY

As a consequence of the critical review presented in this article, guidelines for exergy analysis can be developed relevant to a circular economy. This is done in this section, first by presenting steps for exergy analyses for a circular economy, and then by comparing exergy analysis with conventional approaches.

6.1 Steps for exergy analyses for a circular economy

Exergy analysis uses these concepts to specify quantitatively limitations by expressing losses in terms of exergy. As only a portion of the input exergy to a system or process can be recovered, exergy analysis provides theoretical limitations for a system. Exergy analysis always indicates that exergy cannot conserved is conserved by a real system, but is conserved in the limiting case of a reversible or an ideal system. All of these ideas pertain to a circular economy.

A procedure for performing energy and exergy analyses of a process or system in the context of a circular economy can be developed. It involves the following steps:

- Subdivide the process or system into sections to match level of detail and information desired in the context of assessing circularity for a circular economy.
- Perform conventional mass and energy balances, and determine relevant quantities (e.g., work, heat, mass) and properties (e.g., temperature, pressure), ensuring all needed values to assess a circular economy are accounted for, both for the system or process being examined and modified versions to improve circularity.
- Select a reference-environment model, accounting for characteristics of process/system, information sought, accuracy required and analysis complexity for assessing contribution to a circular economy.
- Determine energy and exergy values, relative to selected reference-environment model.
- Develop exergy balances, including determination of exergy consumptions, to allow the circularity to be assessed for existing and modified versions of the system or process.
- Select and evaluate appropriate measures of merit (e.g., exergy efficiencies or indices) that assess level of circularity attained and the contribution to a circular economy.
- Interpret results, draw appropriate conclusions and make recommendations in the context of improving the system or process through the principles associated with a circular economy.

Some of these steps are common with exergy analyses in general, while others are unique for a circular economy.

A breakdown of the steps in the procedure for performing energy and exergy analyses of a process or system, in the context of a circular economy with emphasis on those aspects, is presented in Table 1.

Note that it is important to recall the definition of exergy at all times, and to differentiate it from energy. Exergy is a measure of the ability to perform work. This can be applied to exergy a flow or commodity. Either way, exergy is the maximum work can be obtained from it as it passes reversibly to the environmental state, exchanging materials and heat only with the surroundings.

6.2 Comparison of exergy analysis with conventional approaches

A comparison of exergy analysis with conventional approaches for assessing and improving circularity can be useful and instructive. Hence one is provided here, through the following points:

- Exergy analysis allows true measures of thermodynamic efficiency and loss to be attained, whereas energy analysis does not. This making assessments regarding the advantages of circularity based on energy can lead to erroneous or skewed results. Assessments based on exergy values avoid such problems and are always based on efficiencies that measure approach to ideality and losses that measure deviations from ideality.
- System improvements based on enhanced circularity are more meaningfully developed and assessed based on exergy, as the true values of losses are identified in terms of their exergy. This allows rational decisions about which losses are worth recovering at all, and what the priority should be for recovering and reusing separate loss quantities or flows. Also, the true advantage of the circularity efforts in terms of modified systems are clearly assessed in this manner.
- Circularity improvements are quantified in all respects when exergy analysis is applied, since exergy losses are identified in all respects (e.g., causes, locations, quantities). Thus, more comprehensive information is provided and enhanced decisions can be correspondingly made.

7. ILLUSTRATIVE EXAMPLE OF EXERGY ANALYSES FOR A CIRCULAR ECONOMY: TRIGENERATION

An illustrative example based on a trigeneration process is presented to help explain the method of exergy

TABLE 1: Procedure for exergy analysis of a process or system in the context of a circular economy.

Step	Actions	Circularity aspects
1	Subdivide process or system into appropriate sections	Select sections to provide information desired for assessing circularity
2	Perform conventional mass and energy balances, and determine relevant quantities and properties	Ensure values for assessing a circular economy are evaluated, for existing system or process and modified versions to improve circularity
3	Select a reference-environment model for evaluating exergy	Account for characteristics of process or system and information sought for assessing contribution to a circular economy
4	Determine energy and exergy values, relative to selected reference-environment model	Ensure all values necessary to evaluate circularity are attained.
5	Develop exergy balances, including exergy consumptions	Obtain accurate balances for all system or process parts that affect circularity and its assessment for existing and modified versions
6	Select and evaluate appropriate measures of merit (e.g., efficiencies)	Select appropriate measures for assessing level of circularity attained and the contribution to a circular economy
7	Interpret results, draw appropriate conclusions and make recommendations	Carry out interpretation steps from the perspective of improving the system or process through circular economy principles

analyses for a circular economy, and the benefits it can provide.

7.1 Trigeneration

Trigeneration is a process that produces three products simultaneously from an input, rather than in separate processes for each product. Often the products are electricity, useful heat and useful cooling.

A general trigeneration system is shown in Figure 2, where three distinct products are generated from a single input in a single process.

A specific trigeneration process in which the three products are electricity, useful heat and useful cooling is presented in Figure 3.

To avoid confusion and provide clarity, it is noted that cogeneration is a simplified and more common form of trigeneration. Cogeneration is the generation of two products, typically electricity and useful heat, in a single process rather than in separate electricity generation and heating processes. Trigeneration can thus be seen to be an expanded form of cogeneration, which typically yields useful cooling as a third product in addition to electricity and useful heat.

Interest in both cogeneration and trigeneration has expanded as concerns grew about energy supplies, costs and environmental impacts have grown, as such systems can be more efficient than separate systems for each product.

7.2 Trigeneration to improve circularity

The manner by which trigeneration contributes to a circular economy can be seen most readily by considering the conventional alternative to it, which is three separate processes (one for electricity generation, one for heating and one for cooling). Three such processes are shown in Figure 4.

When these three processes are integrated in a manner to enhance circularity, several options become possible:

- The loss from the electricity generator (waste heat) can be redirected to provide the product heat, thereby avoiding the loss and eliminating the need for a resource input to the heater.
- The loss from the electricity generator (waste heat) can be redirected to be the input to the chiller (if am absorption chiller, which is a heat-driven device is used, thereby avoiding the loss and eliminating the need for a resource input to the chiller.
- Some of the product electricity from the electricity generator can be redirected to be the input to the heater, thereby eliminating the need for a resource input to the heater (although at the sacrifice of some of the electrical product from the electricity generator).
- Some of the product electricity from the electricity generator can be redirected to be the input to the chiller (if a vapor compression chiller, which is typically electrically driven), thereby eliminating the need for a resource input to the chiller (although at the sacrifice of some of the electrical product from the electricity generator).

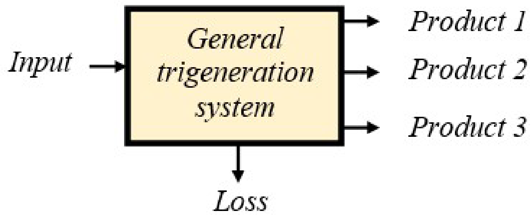

FIGURE 2: A general trigeneration system.

Any of the four options listed above can improve circularity compared to separate processes for electricity generation, heating and cooling. Also, various combinations of the above four options can also help improve circularity. The best option depends on the characteristics of the inputs, wastes and products, including their values, and these are often best determined using exergy methods, rather than the more conventional energy methods.

It is pointed out that this illustrative example is not just theoretical, but quite practical. In many locations across the globe, power plants driven by on fossil fuels are replaced or modified so that waste heat from these power plants is no longer wasted, but instead utilized to produce heating and/or cooling. The benefit of trigeneration can be reduced input fuel use and wastes, in line with the circularity improvements. That is, trigeneration is able to mitigate environmental impact by facilitating the use of waste heat for cooling and/or heating, thereby offsetting either burning fossil fuel or consuming electricity. The production of three products from a single input via trigeneration boosts efficiency notably. In addition, there can also be a reduction in operating costs, and when carbon taxes are applied, trigeneration can lower the carbon tax paid by recovering waste heat and converting it to additional products.

8. PERSPECTIVE AND LONG-TERM VIEW OF EXERGY ANALYSES RELEVANT TO A CIRCULAR ECONOMY

Based on the findings in the literature presented in this article, a perspective and long-term view can be developed

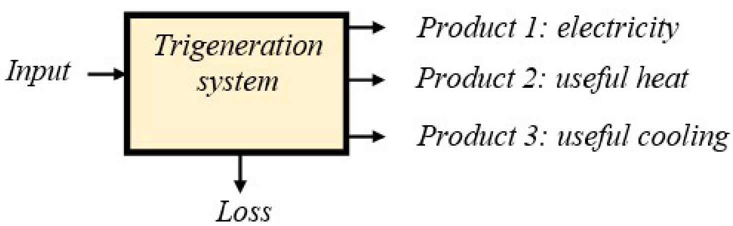

FIGURE 3: A trigeneration system for electricity, useful heat and useful cooling.

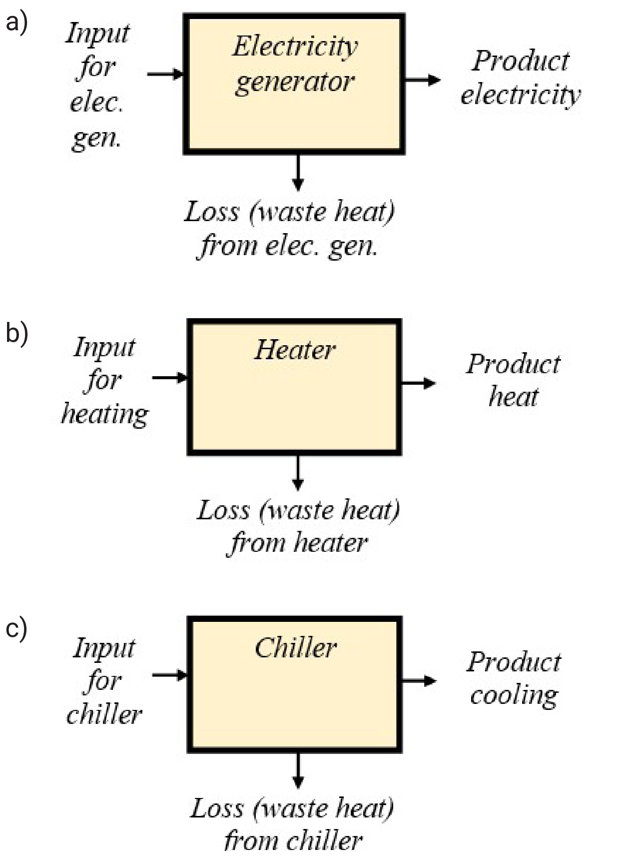

FIGURE 4: Separate systems for electricity (a), useful heat (b) and useful cooling (c).

of the topic of exergy analyses relevant to a circular economy. This is done in this section.

The following points cover several key aspects of such a perspective and long-term view the topic of exergy analyses relevant to a circular economy:

- First, exergy methods are important in general for understanding thermodynamic efficiencies and losses for processes and systems, and for making decisions on system improvements. When exergy methods are not employed, and more conventional methods like energy analysis are used, the results can be misleading and sometimes erroneous.
- Second, given the importance of exergy methods, as raised in the last point, it is perhaps not surprising that exergy is proving to be important and relevant to a circular economy. The same reasoning on why exergy methods are important in general, also apply to methods to improve circularity of systems and processes.
- Third, elaborating on the last point, it is emphasized that based on the literature review decisions regarding improving the circularity of processes and systems are made in terms of meaningful efficiencies and meaningful loss avoidance when such decisions are based on exergy, through the application of relevant exergy methods.
- Finally, it is anticipated, based on the review presented here and the numerous benefits pointed out by applying exergy methods, that applications of exergy methods to enhance circularity of systems and processes, and thereby contribute to a circular economy, will grow in number and expand in disciplines reflected and regional areas of employment.

9. CONCLUSIONS

The benefits of using exergy as a tool for addressing a circular economy, in particular by identifying and explaining the benefits of sustainable energy, has been demonstrated. It is concluded that the concepts encompassing exergy have a significant role to play in addressing a circular economy and increasing sustainable energy use. Exergy clearly identifies efficiency improvements and reductions in wastes and environmental impacts attributable to sustainable energy, and enhances understanding of environmental benefits and economics. Exergy should prove useful in such activities to engineers and scientists, as well as decision and policy makers in addressing a circular economy.

ACKNOWLEDGEMENTS

The support for this work provided by the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

REFERENCES

Abadías Llamas, A., Bartie, N.J., Heibeck, M., Stelter, M., Reuter, M.A. 2020. Simulation-based exergy analysis of large circular economy systems: Zinc production coupled to CdTe photovoltaic module life cycle. Journal of Sustainable Metallurgy 6:34–67.

Alvarez, J.C., Hatakeyama, K., Carvalho, M., Marçal, R.C., Inche, J., de Melo, N. 2022. A model for renewable energy-based product innovation based on TRIZ methodology, exergy analysis and knowledge management: Case study. Energy Reports 8(Supplement 9):1107-1114.

Alvarez-Risco, A., Estrada-Merino, A., Rosen, M.A., Vargas-Herrera, A., and Del-Aguila-Arcentales, S. 2021. Factors for Implementation of Circular Economy in Firms in COVID-19 Pandemic Times: The Case of Peru. Environments 8(9):95.

Alvarez-Risco, A., Rosen, M.A. and Del-Aguila-Arcentales, S. 2020. A New Regulation for Supporting a Circular Economy in the Plastic Industry: The Case of Peru. Journal of Landscape Ecology 13(1):1-3.

Alvarez-Risco, A., Rosen, M.A. and Del-Aguila-Arcentales, S. (Eds.). 2022. Towards a Circular Economy: Transdisciplinary Approach for Business. Springer, Cham, Switzerland.

Arango-Miranda, R., Hausler, R., Romero-Lopez, R., Glaus, M., Ibarra-Zavaleta, S.P. 2018. Carbon dioxide emissions, energy consumption and economic growth: A comparative empirical study of selected developed and developing countries. "The role of exergy". Energies 11:2668.

Bartie, N.J., Abadías Llamas, A., Heibeck, M., Fröhling, M., Volkova, O. Reuter, M.A. 2020. The simulation-based analysis of the resource efficiency of the circular economy: The enabling role of metallurgical infrastructure. Mineral Processing and Extractive Metallurgy 129(2):229-249.

Bartie, N.J., Cobos-Becerra, Y.L., Fröhling, M., Schlatmann, R., Reuter, M.A. 2021. The resources, exergetic and environmental footprint of the silicon photovoltaic circular economy: Assessment and opportunities. Resources, Conservation and Recycling 169:105516.

Cano, N.A., Hasenstab, C., Velasquez, H.I. 2020. Exergy life cycle assessment indicators in Colombian gold mining sector. Journal of Sustainable Mining 19(3):2.

Cano Londoño, N.A., Cabezas, H. 2021. Perspectives on circular economy in the context of chemical engineering and sustainable development. Current Opinion in Chemical Engineering 34:100738.

Cooper, S.J.G., Giesekam, J., Hammond, G.P., Norman, J.B., Owen, A., Rogers, J.G., Scott, K. 2017. Thermodynamic insights and assessment of the 'circular economy'. Journal of Cleaner Production 162:1356-1367.

de Almeida, S.T., Borsato, M. 2020. Extending the RIPEx exergy-based method for selecting End of Life strategy. Resources, Conservation and Recycling 152:104536.

Del-Aguila-Arcentales, S., Alvarez-Risco, A., Carvache-Franco, M., Rosen, M.A. and Yáñez, J.A. 2022. Bibliometric Analysis of Current Status of Circular Economy during 2012–2021: Case of Foods. Processes 10(9):1810.

Demirel, Y., Rosen, M.A. 2023. Sustainable Engineering: Process Intensification, Energy Analysis, Artificial Intelligence. CRC Press/Taylor and Francis, Boca Raton, FL, U.S.

Dincer, I., Rosen, M.A. 2021. Exergy: Energy, Environment and Sustainable Development, 3d ed., Elsevier, Oxford, UK.

Esmaeilion, F., Soltani, M., Nathwani, J., Al-Haq, A., Dusseault, M.B., Rosen, M.A. 2024. Exergoeconomic assessment of a high-efficiency compressed air energy storage system. Renewable and Sustainable Energy Reviews 191:114143.

Gai, L., Sabev Varbanov, P., Van Fan, Y., Klemeš, J.J., Vladimirovich Romanenko, S. 2021. Trade-offs between the recovery, exergy demand and economy in the recycling of multiple resources. Resources, Conservation and Recycling 167:105428.

Hannula, J., Godinho, J.R.A., Abadías Llamas, A., Luukkanen, S., Reuter, M.A. 2020. Simulation-based exergy and LCA analysis of aluminum recycling: Linking predictive physical separation and remelting process models with specific alloy production. Journal of Sustainable Metallurgy 6:174–189.

Hernandez, A.G., Cullen, J.M. 2019. Exergy: A universal metric for measuring resource efficiency to address industrial decarbonization. Sustainable Production and Consumption 20:151-164.

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., De Meester, S. 2017. Performance indicators for a circular economy: A case study on post-industrial plastic waste. Resources, Conservation and Recycling 120:46-54.

Jalili, M., Beyrami, J., Ziyaei, M., Chitsaz, A., Rosen, M.A. 2024. Innovative synthetic natural gas production from biomass and renewable hydrogen: Evaluation and optimization with sustainability perspective. Process Safety and Environmental Protection 182:139-153.

Khajehpour, H., Saboohi, Y., Tsatsaronis, G. 2019. Exergy-based responsibility allocation of climate change. In: Leal Filho, W., Leal-Arcas, R. (Eds), University Initiatives in Climate Change Mitigation and Adaptation, Springer, Cham, Switzerland.

Kiehbadroudinezhad, M., Hosseinzadeh-Bandbafha, H., Rosen, M.A., Kumar Gupta, V., Peng, W., Tabatabaei, M., Aghbashlo, M. 2023. The role of energy security and resilience in the sustainability of green microgrids: Paving the way to sustainable and clean production. Sustainable Energy Technologies and Assessments 60:103485.

Kılkış, B., Kılkış, Ş. 2017. New exergy metrics for energy, environment, and economy nexus and optimum design model for nearly-zero exergy airport (nZEXAP) systems. Energy 140(Part 2):1329-1349.

Abadías Llamas, A., Bartie, N.J., Meskers, C., Reuter, M.A. 2024. Exergy—Quantification of resource dissipation. Chapter 45 in Meskers, C., Worrell, E., Reuter, M.A. (Editors), Handbook of Recycling, 2nd ed., Elsevier, pp. 675-684.Lucia, U., Grisolia, G. 2019. Exergy inefficiency: An indicator for sustainable development analysis. Energy Reports 5:62-69.

Martínez-Rodríguez, A., Abánades, A. 2020. Comparative analysis of energy and exergy performance of hydrogen production methods. Entropy 22(11):1286.

Moharamian, A., Adibi, T., Ghahremani, M.A., Soltani, S., Rosen, M.A., Mahmoudi, S.M.S. 2023. Thermodynamic and exergoeconomic analyses of a novel solar-based externally fired biomass combined cycle with hydrogen production. International Journal of Ambient Energy 44(1):668-685.

Nielsen, S.N. 2019. Reductions in ecology and thermodynamics. On the problems arising when shifting the concept of exergy to other hierarchical levels and domains. Ecological Indicators 100:118-134.

Nielsen, S.N. 2020. Sustainable Development Indicators: An Exergy-Based Approach. CRC Press, Boca Raton, FL.

Nižetić, S., Papadopoulos, A. (Eds.). 2018. The Role of Exergy in Energy and the Environment, Springer, Cham, Switzerland.

North, P., Jentsch, A. 2021. A circular economy approach to building heating: The role of exergy in policymaking. Energy Reports 7(Supplement 4):334-342.

Novak, P. 2017. Exergy as measure of sustainability of energy system, International Journal of Earth & Environmental Sciences 2:139.

Nwodo, M.N., Anumba, C.J. 2020. Exergetic life cycle assessment: A review. Energies 13:2684.

Ortego, A., Russo, S., Iglesias-Émbil, M., Valero, A., Magdalena, R. 2023. Exergy assessment of plastic car parts. Vehicles 5(3):1211-1226.

Popescu, A.P., Cheah, Y.K., Sabev Varbanov, P., Klemeš, J.J., Kabli, M.R., Shahzad, K. 2022. Exergy footprint assessment of cotton textile recycling to polyethylene. Energies 15(1):205.

Reuter, M.A., van Schaik, A., Gutzmer, J., Bartie, N.J., Abadías Llamas, A. 2019. Challenges of the circular economy: A material, metallurgical, and product design perspective. Annual Review of Materials Research 49:253-274.

Rosen, M.A. 2021a. Energy sustainability with a focus on environmental perspectives. Earth Systems and Environment 5(2):217–230.

Rosen, M.A. 2021b. Exergy analysis as a tool for addressing climate change. European Journal of Sustainable Development Research 5(2):em0148.

Rosen, M.A. 2022. The Circular Economy and Energy. Chapter 7 in Alvarez-Risco, A., Rosen, M.A. and Del-Aguila-Arcentales, S. (Eds.). 2022. Towards a Circular Economy: Transdisciplinary Approach for Business. Springer, Cham, Switzerland, pp. 133-149.

Russo, S., Valero, A., Valero, A., Iglesias-Émbil, M. 2021. Exergy-based assessment of polymers production and recycling: An application to the automotive sector. Energies 14(2):363.

Sciubba, E. 2019. Exergy-based ecological indicators: From Thermo-Economics to cumulative exergy consumption to Thermo-Ecological Cost and Extended Exergy Accounting. Energy 168:462-476.

Sharma, S., Basu, S., Shetti, N.P., Aminabhavi, T.M. 2020. Waste-to-energy nexus for circular economy and environmental protection: Recent trends in hydrogen energy. Science of The Total Environment 713:136633.

Stanek, W., Gladysz, P., Czarnowska, L., Simla, T. 2019. Thermo-ecology: Exergy as a Measure of Sustainability. Elsevier, Oxford, UK,

UN. 2015. Transforming our World: The 2030 Agenda for Sustainable Development. Report A/RES/70/1, United Nations, 2015. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication

Valero, A., Valero, A., Stanek, W. 2018. Assessing the exergy degradation of the natural capital: From Szargut's updated reference environment to the new thermoecological-cost methodology. Energy 163:1140-1149.

Veiga, J.P.S., Romanelli, T.L. 2020. Mitigation of greenhouse gas emissions using exergy. Journal of Cleaner Production 260:121092.

Vilardi, G., Bassano, C., Deiana, P., Verdone, N. 2020. Exergy and energy analysis of three biogas upgrading processes. Energy Conversion and Management 224:113323.

Vilardi, G., Verdone, N. 2022. Exergy analysis of municipal solid waste incineration processes: The use of O2-enriched air and the oxy-combustion process. Energy 239(Part B):122147.

Whiting, K., Carmona, L.G., Sousa, T. 2017. A review of the use of exergy to evaluate the sustainability of fossil fuels and non-fuel mineral depletion. Renewable and Sustainable Energy Reviews 76:202-211.

Wu, J., Wang, N. 2020. Exploring avoidable carbon emissions by reducing exergy destruction based on advanced exergy analysis: A case study. Energy 206:118246.

Xie, J., Xia, Z., Tian, X., Liu, Y. 2023. Nexus and synergy between the low-carbon economy and circular economy: A systematic and critical review. Environmental Impact Assessment Review 100:107077.

Zhang, M., Reistad, G.M. 1998. Analysis of energy conversion systems, including material and global warming aspects. Int. J. Heating, Ventilating, Air-Cond. and Refrigerating Research 1:45-65.

Zhang, Y., Zhao, W., Li, B., Li, H. 2018. Understanding the sustainability of fuel from the viewpoint of exergy. European Journal of Sustainable Development Research 2(1):09.