Circular Economy and Sustainability
https://doi.org/10.1007/s43615-023-00297-8

ORIGINAL PAPER

On the Economics of the Transition to a Circular Economy

Ahmed Chennak[1] · **Konstantinos Giannakas**[1] · **Tala Awada**[2]

Received: 8 May 2023 / Accepted: 26 July 2023

Abstract
Humanity is facing complex challenges posed by population growth, climate change, and the need to increase food, feed, fiber, and bioenergy production while confronting the scarcity of natural resources. The transition to a circular economy, characterized by reduced resource use and waste, is being increasingly recognized in academic, business, and policy making circles as essential to meeting these challenges, with the emphasis being on the development of methods and processes that enable and facilitate the transition from a linear to a circular economy. This paper argues the need for an increased emphasis on the economics of the circular economy and presents a general framework that illustrates the transition from a linear to a circular economic system. In addition, the paper highlights the economic issues that arise during the transition to increased circularity and the policy options available to facilitate the successful transition to a more circular economic system.

Keywords Circular economy · Economic analysis · Economic issues · Optimal policy response

Abbreviations

3R	reduce, recycle, and reuse
4R	reduce, recycle, reuse, and recover
b_i'	byproduct under circular supply chain
b_i	byproduct under linear supply chain
CE	circular economy
CR_1	circularity rate at stage one
CSC	circular supply chain
DFR	design for recycling
EDM_1	environmental damage mitigation at stage one
EMF	Ellen MacArthur Foundation
EU	European Union
GHGs	greenhouse gases
IPPC	Intergovernmental Panel on Climate Change
k_i^m	manufactured capital

✉ Konstantinos Giannakas
kgiannakas@unl.edu

1 Department of Agricultural Economics, University of Nebraska-Lincoln, Lincoln, NE, USA

2 Agricultural Research Division, University of Nebraska-Lincoln, Lincoln, NE, USA

Published online: 05 August 2023

k_i^n	natural capital
k_i^o	recovered capital in a different supply chain
k_i^r	recycled capital
LCA	life cycle assessment
LSC	linear supply chain
PLE	product life extension
RPO	retain product ownership
SDGs	sustainable development goals
UN	United Nations
w_i'	waste under circular supply chain
w_i	waste under linear supply chain
WTP	willingness-to-pay
y	desirable output
y^{u^*}	environmentally damaging output under circular supply chain
y^u	environmentally damaging output under linear supply chain
z_i	non recoverable waste/byproduct

Introduction

In recent years, the concept of circular economy (CE), characterized by reduced resource use, waste, and their environmental impacts by closing the loops of energy and materials and extending the lifecycle of products circulating in the economy [1–4], has received significant attention from scholars, practitioners, and policy makers as an alternative paradigm to replace the dominant use-and-dispose linear economy, and facilitate a more sustainable development [5–10]. CE is viewed as an essential feature of sustainability, with sustainable production and consumption — core principles of CE — being critical in every framing of the concept of sustainability included in the Sustainable Development Goals (SDGs) of the United Nations [11, 12]. Several countries have developed national goals and policies for transitioning to a CE. China adopted a nation-wide strategy for implementing circularity and passed *The Circular Economy Promotion Law* in 2009, and *Circular Development Leading Action Plan* in 2017 with the objective of economic growth and environmental sustainability [13]. Similarly, the European Commission introduced the *Circular Economy Package* in 2014 which was later revised under the *Closing the Loop — An EU plan for the Circular Economy.* As suggested by the European Commission [14], scaling up CE to be the center of business models for mainstream economic players is key to not only decoupling economic growth from resource use and achieving decarbonization and climate neutrality by 2050 but also to ensuring the long-term competitiveness of businesses. However, circular supply chains are relatively rare [15]. According to Haas et al. [16], only 6% of all materials processed by the global economy are recycled and contribute to "closing the loop." Despite this, there is growing recognition within the business and policy circles of the need for CE practices in supply chains and across various sectors of the economy [13].

Circular business models that have been developed to implement the principles of CE include four main strategies: (1) closing resource loops, (2) slowing resource loops, (3) narrowing resource loops, and (4) regenerative resource flow [2, 5, 7]. Closing resource loops involves redirecting post-consumption materials and waste away from disposal and back into closed loops, resulting in a circular flow of resources. Slowing resource loops consists of prolonging and extending the lifespan of a product in use. Narrowing resource loops aims to minimize the use of resources and negative environmental impacts per unit of output produced, resulting in increased efficiency. Finally, regenerative resource flows aim at preserving and enhancing natural capital.

These circular business models can be implemented through various strategies including retain product ownership (RPO), product life extension (PLE), design for recycling (DFR), and industrial symbiosis [2, 17, 18]. Under the RPO strategy, the producer is responsible for products after the consumption stage. Rather than delivering ownership, producers offer rent or lease of their product to consumers. Car sharing, leased printers and photocopies, and document management systems are examples of this strategy. PLE, on the other hand, prioritizes durability, the design of products that last longer, and the creation of value in residuals and product components. Examples of this strategy include remanufactured and refurbished products, and assigning reward points and cash for recycled products. DFR refers to design strategies that maximize recoverability of the products' components (e.g., design for disassembly and reassembly).[1] Industrial symbiosis, also known as eco-symbiosis, focuses on redirecting waste and byproducts from one process and industry to be used as inputs in a different process and industry [19, 20]. The Kalundborg model in Denmark is an example of such supply chain. This model consists of six manufacturing facilities with the wastes and byproducts from a facility being used as inputs in other facilities. For instance, waste steam from a coal-fired electrical power generating station is used by a pharmaceutical plant and an oil refinery, and wastewater from an oil refinery is used by a power plant [18]. It is important to note that these circular business strategies overlap and have blurred boundaries. Atasu et al. [17] suggested that these business models provide a framework for corporations to develop circular supply chains that create economic value and reduce their environmental footprints through the recovery and the recycling of the resources used to produce their products.

Recognizing the importance of the transition to a more CE, the relevant literature to date has focused primarily on methods and processes that facilitate circularity, approaching it as a technical and engineering challenge (i.e., system of processes) that prioritizes the production side of the economy [21]. In particular, the core principles of the CE models are based on materials and energy flows aimed at reducing primary production, extending the life of materials and products already in circulation, and minimizing waste, while maximizing environmental benefits [1, 5, 22]. This is achieved mainly through closing the loop and using waste from one process as an input in another process, creating new flows of inputs and outputs known as secondary production, such as recovered and recycled materials, waste, and byproducts [2, 23, 24].

However, while the development of effective processes is certainly *necessary* for increased circularity, it is *not sufficient* in ensuring the successful transition to a more circular economic system. Unless the adoption of these processes is viewed as beneficial/profitable for the interest groups involved, they may not be adopted in practice. Factors such as high costs, adverse impacts on quantity or/and quality of production, specialized knowledge or skill needs, uncertainty, and/or a negative consumer response may hinder the adoption of these processes and derail the transition to increased circularity.

In essence, a circular economic system is as much a system of markets as it is a system of material and energy flows. That is, for every secondary production associated with or resulting from circularity (e.g., recovered wastes and byproducts), there is a market with

[1] Bocken et al. [2] provide a detailed treatment of strategies used to implement circular business models

supply and demand conditions affecting the producers and consumers of the recovered secondary product in question, as well as other participants in the supply chain of interest and the economy at large. In this context, an understanding of the system-wide market and welfare impacts of circular economic processes, the economic costs and benefits associated with these processes, and other socioeconomic factors affecting their adoption and market acceptance and success is of paramount significance for (a) assessing their market potential and economic viability, (b) identifying areas where the potential for a market failure exists (i.e., areas where an incomplete internalization of the benefits of the increased circularity facilitated by the processes in question might result in the market forces failing to generate the socially desirable outcome/circularity[2]), and (c) designing policies and strategies that can induce the socially desirable market outcomes/level of circularity.

In addition to highlighting the need for an increased emphasis on the economics of the CE, this paper has two additional objectives. The first objective is to develop a general framework that illustrates the transition from a linear to a circular economic system and the key areas involved in or affected by this transition. The second objective is to highlight the economic issues that arise during the transition to increased circularity and the policy options available to facilitate the successful transition to a more circular economic system.

The rest of the paper is organized as follows. "Review of Literature on the Circular Economy" section provides a review of some key literature highlighting the developments that have shaped our understanding of the CE concept. "Transitioning from a Linear to a Circular Economic System" section introduces a general framework that captures the fundamental transformations and technological changes at the different stages of the supply chain when transitioning from a linear to a circular economic system. "Key Economic Issues Associated with the Transition to a Circular Economy" section highlights some key economic issues that arise from the transition to a circular economic system. Policies that can address potential market failures and induce the socially desirable transition to a CE are discussed in the "Policy Implications" section. "Summary and Concluding Remarks" section summarizes and concludes the paper.

Review of Literature on the Circular Economy

The concept of the CE has roots in both economics and the industrial ecology fields.[3] Boulding [25] discussed the difference between open and closed systems in relation to materials, energy, and information, and identified the key difference between an open (linear) and a closed economy. In the open economy, also termed by the author as a "cowboy economy," earth has unlimited resources and reservoirs of raw materials. On the other hand, in the closed economy, termed as a "spacemen economy," earth has limited resources and reservoirs of raw materials. In this case, to maintain the capital stocks, the author advocated for the necessity of adopting cyclical systems in which all the outputs from consumptions (i.e., waste) need to be constantly recycled and become inputs in the production process. Building on these ideas, Stahel [23] formulated the concept of the closed-loop economy [9]. A key contribution in the field of industrial ecology, which focuses primarily on the

[2] The implicit assumption in this article is that the transition to a circular economic system results in social benefits that outweigh the social costs of this transition

[3] For a comprehensive review of the literature on the historical development of the concept of CE see Blomsma and Brennan [1].

flow of material, is the work of Frosh and Gallopoulos [20]. They suggested that the linear industrial activity should be transformed into an industrial ecosystem in which material and energy consumption are optimized, waste is minimized, and effluents of one process are reused raw materials for another process. They advocated for the adoption of sustainable industrial ecosystems by the creation of closed cycles and a design for recycling.

The term CE was introduced first by Pearce and Turner [26] who addressed the relationship between CE and the four functions of the environment and provided a simple diagram for CE.[4] Building on this work, Anderson [27] highlighted the role of environmental economists in addressing the environmental externalities caused by economic activity. He suggested that, when accounting for the four functions of the environment, unpriced or underpriced services and disservices should be internalized using life cycle assessment (LCA) and consumer valuation of environmental goods. Note that both Pearce and Turner [26] and Anderson [27] viewed recycling as the key component of CE.

Following the publication of the EMF's report on CE in 2013, the concept of CE gained increasing attention by scholars, practitioners, and policymakers, while the development of national policies in Sweden, Germany, Japan, China, and the European Union has contributed to the wider spread of circularity [1]. The number of peer-reviewed articles on CE increased from 14 articles on 2014 to more than 100 articles in 2016 [11], while a recent Scopus search containing the term "circular economy" by Kirchherr et al. [8] resulted in more than 13,000 documents. Rejeb et al. [28] conducted co-occurrence network and main path analyses on the entire domain of CE research and identified the following research themes: CE and sustainability, bioeconomy, CE practices, LCA and industrial symbiosis, construction activities, waste management, and the drivers and barriers of implementing CE.

Kirchherr et al. [3] analyzed 114 definitions of CE and found that CE and recycling are used interchangeably, the 3R framework (i.e., reduce, recycle, and reuse) is the most common conceptualization of CE in the literature, and that some of the definitions fail to highlight the necessity for a systemic shift. This study was revised recently to include 221 definitions of CE and noted an increased attention to the 4R framework (i.e., reduce, recycle, reuse, and recover) and to business models and consumers [8]. Indeed, there has been a growing interest in circular supply chains (CSC) and circularity indicators. Montag [4] provided a comprehensive study of CSC and identified the core properties of CSC as (1) regeneration, (2) open loops and cascading flows, (3) value creation focus, and (4) paradigm shift, while Pascale et al. [29], Saidani et al. [30], Moraga et al. [31], and Kulakovskaya et al. [32] provided systematic reviews of the literature on circularity metrics and indicators. As noted by Kulakovskaya et al. [32], however, studies on economic CE indicators are rare.

Related to our paper is the work of Zink and Geyer [21] and Fullerton et al. [33]. Zink & Geyer [21] pointed out that CE research has been focusing on engineering and technological solutions, while neglecting economic incentives and behaviors. Fullerton et al. [33] noted that the concept of CE started among architects and engineers and has received little interest among economists. They introduced key notions of circularity to economists and identified potential areas for future transdisciplinary research. We contribute to this emerging literature by arguing the need for an increased emphasis on the economics of the CE. We present a general framework that illustrates the transition from a linear to a circular

[4] According to Pearce and Turner [26], the four functions of the environment are (1) provision of amenities, (2) resource base for economic activities, (3) sink for economic activities, and (4) fundamental life-support

economic system and highlight the economic issues that arise and policy options available to facilitate the successful, effective, and efficient transition to increased circularity.

Transitioning from a Linear to a Circular Economic System

In this section, we present a general framework that captures the fundamental transformations and technological changes taking place at different stages of a supply chain when transitioning from a linear to a circular system. In Fig. 1, we distinguish between the linear supply chain (LSC, drawn in black), the circular supply chain (CSC, drawn in blue), and their relationship with the environment (drawn in green). The LSC is presented first, followed by the required changes associated with circularity at each stage of this general supply chain.

A Linear Supply Chain

An LSC has four distinct stages from upstream to downstream: producers/input suppliers, processors, retailers, and final consumers. Agri-food supply chains are examples of such a supply chain and are directly involved with the grand societal challenges addressed through increased circularity. Producers 1 and 2 use two inputs, natural capital k_1^n and k_2^n and manufactured capital k_1^m and k_2^m, to produce outputs y_1 and y_2, respectively. In addition to outputs y_1 and y_2, this stage often entails the generation of environmentally damaging outputs y_1^u and y_2^u, byproducts b_1 and b_2, and wastes w_1 and w_2. Under the LSC, wastes and byproducts are discarded in the environment.[5] For an agri-food supply chain, producer 1 could refer to crop producers, while producer 2 could refer to livestock production units. In this case, the natural capital would include inputs like land, water, and organic fertilizer, while the manufactured capital would include inputs like transportation and machinery. The environmentally damaging, and thus undesirable outputs, would include the release of greenhouse gases (GHGs) and water acidification due to nutrients (e.g., nitrogen) loss associated with agricultural and livestock production. In fact, agriculture is estimated to be responsible for 25% of total global emissions of GHGs [34, 35], 25% of global terrestrial acidification, and 74% of total freshwater and marine eutrophication [36]. Waste would include animal waste (e.g., manure) and crop residues (e.g., wasted biomass) at the farm level.

At the processing stage, in addition to natural capital k_3^n and k_4^n and manufactured capital k_3^m and k_4^m, processors 1 and 2 use outputs y_1 and y_2 from the production stage as inputs to produce outputs y_3 and y_4, respectively. Environmentally damaging outputs y_3^u and y_4^u, byproducts b_3 and b_4, and wastes w_3 and w_4 are often generated and discarded in the environment at this stage of the LSC as well. Outputs y_3 and y_4 move to the retailer stage and are used, along with natural k_5^n and k_6^n and manufactured capital k_5^m and k_6^m as inputs for the final consumer products y_5 and y_6. Waste occurs at the retailer stage in the form of w_5 and w_6 and it is discarded in the environment. y_5^u and y_6^u represent the environmentally damaging output at this stage of the supply chain. At the final stage of the LSC, the consumption of the final products y_5 and y_6 generates waste w_7 and w_8 that is discarded in the

[5] While there are byproducts that are recovered and reintroduced into the supply chain, we focus on byproducts that are discarded in the environment

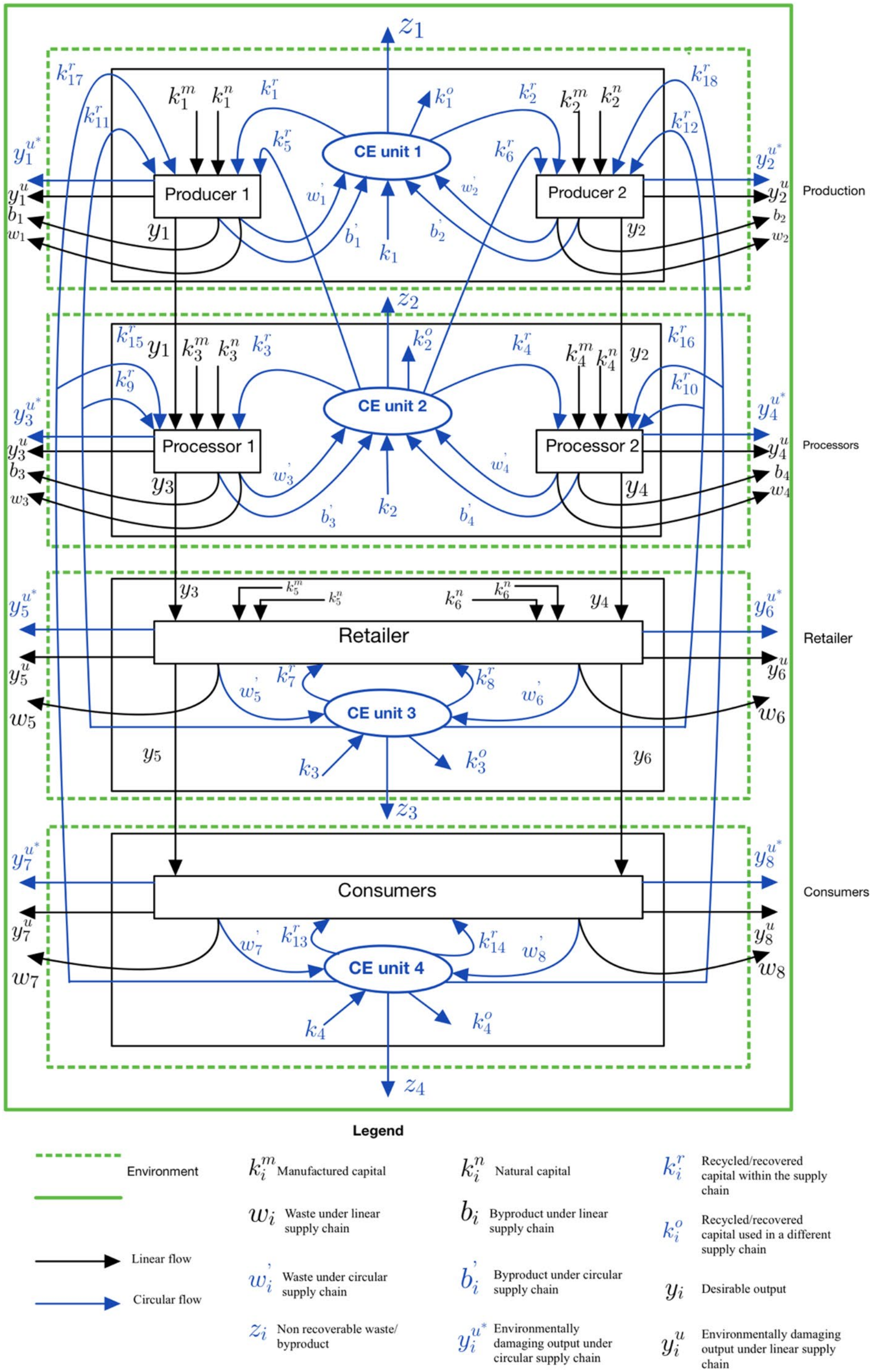

Fig. 1 Transitioning from a linear to a circular supply chain

environment, and the environmentally damaging outputs y_7^u and y_8^u. In the context of an agri-food supply chain, waste at this stage would translate primarily into food waste.

A Circular Supply Chain

Having determined the different stages of the LSC required to produce, process, and distribute the final products and its environmental impacts, we discuss next the fundamental transformations and changes required to establish a CSC. The transition to a CSC is achieved by closing the loop of materials and extending the lifecycle utility of wastes and byproducts with the objective of maximizing the value and minimizing the environmental impacts of production and consumption at the different stages of the supply chain. To implement circularity, a CE unit is introduced at each stage of the supply chain. Wastes and byproducts that are discarded in the environment under the LSC are now collected and recovered by these CE units and used as inputs at different stages of this and other supply chains.

At this point, it is important to note that there are two levels of circularity, the first is within each stage of the supply chain, and the second is the overall circularity, which refers to circularity of the (whole) supply chain. While wastes and byproducts are generated along the relevant LSC, implementing circularity is not costless and requires additional inputs denoted by capital k_i with $i = 1, 2, 3, 4$ referring to the relevant stage in the supply chain. This cost is associated with the collection, recovery, and treatment of wastes and byproducts.

At the production stage, in addition to input k_1 (i.e., the input capturing the cost of circularity at the production stage), CE unit 1 recovers and reuses wastes w_1 and w_2 and byproducts b_1 and b_2 generated at this stage of the supply chain as inputs to produce two types of outputs: recycled capital (i.e., secondary products) k_1^r and k_2^r, and other capital k_1^o. The recycled capital k_1^r and k_2^r are used as inputs by producer 1 and producer 2, respectively,[6] while the other capital k_1^o can be used in different supply chains. By extending the lifecycle of wastes and byproducts, circularity can reduce environmentally damaging outputs from y_1^u to $y_1^{u^*}$ for producer 1, and from y_2^u to $y_2^{u^*}$ for producer 2.[7] Finally, z_1 represents the amount of waste and byproducts that cannot be recycled back to the supply chain, and it is discarded in the environment. In the context of an agri-food supply chain, the CE unit 1 could collect animal waste (manure) and process it through a bio digestor to produce biofertilizer and biogas (mainly methane). The biofertilizer can, then, be used as input in crop production, and the biogas can be used as a source of electricity.

Similarly, at the processing stage, the objective of CE unit 2 is to create circularity at this stage of the supply chain by closing the loops. CE unit 2 uses input k_2 and byproducts b_3 and b_4, and recovers waste w_3 and w_4 to produce recycled capital k_3^r, k_4^r, k_5^r, k_6^r, and other capital k_2^o. The recycled capital k_3^r and k_4^r are used as inputs by processors 1 and 2, respectively, while the recycled capital k_5^r and k_6^r leave the processing stage and go back the production stage where they are used as inputs by producers 1 and 2, respectively. The other capital k_2^o can be used as an input in a different supply chain. As a result, the

[6] As shown in Fig. 1 and discussed below, the use of waste and/or byproducts from other stages of the supply chain as inputs in this stage is also possible

[7] This happens through two mechanisms: (1) when the produced recycled capital at the CE unit can substitute the use of manufactured and natural capitals, which mitigates the negative environmental impact associated with the production, extraction, and use of natural and manufactured capital, and (2) by extending the lifecycle of waste and byproducts

environmentally damaging outputs y_3^u and y_4^u are reduced to $y_3^{u^*}$and $y_4^{u^*}$, respectively. Finally, z_2 represents the non-recoverable waste and byproducts at the processing stage that is discarded in the environment.

At the retailer stage, CE unit 3 recovers and reuses waste w_5 and w_6 to produce, using input k_4, the recycled capital k_7^r, k_8^r, k_9^r, k_{10}^r, k_{11}^r, k_{12}^r, and other capital k_3^o. The recycled capital k_7^r and k_8^r are used as an input by the retailer at the same stage of supply chain; recycled capital k_9^r and k_{10}^r leave the retailer stage and go back to the processing stage and are used as inputs by processors 1 and 2, respectively; and the recycled capital k_{11}^r and k_{12}^r are used as inputs by producers 1 and 2, respectively. Because of circularity, the environmentally damaging outputs y_5^u and y_6^u are reduced to $y_5^{u^*}$and $y_6^{u^*}$, respectively. Finally, z_3 represents the non-recoverable waste at the retail stage. Note that the CE unit 3 enhances circularity both within the retail stage and along other stages of the supply chain.

Finally, at the consumer stage, CE unit 4 recovers and reuses waste w_7 and w_8 as inputs to produce, along with input k_4, the recycled capital k_{13}^r, k_{14}^r, k_{15}^r, k_{16}^r, k_{17}^r, k_{18}^r, and other capital k_4^o. The recycled capital k_{13}^r and k_{14}^r are used by consumers; the recycled capital k_{15}^r and k_{16}^r go back to the processing stage and are used as inputs by processors 1 and 2, respectively; while the recycled capital k_{17}^r and k_{18}^r are used as inputs by producers 1 and 2, respectively. The waste at the consumer stage that cannot be recovered, denoted by z_4, is discarded in the environment. Similar to CE unit 3, CE unit 4 enhances circularity both within the same stage and along other stages of the supply chain. Because of circularity, the environmentally damaging outputs y_7^u and y_8^u are reduced to $y_7^{u^*}$and $y_8^{u^*}$, respectively.

Before concluding this section, it is important to note that our framework is general, and it can be adapted to capture the idiosyncrasies of a wide range of supply chains. And, as indicated earlier, it can capture circularity at each stage of the supply chain as well as the circularity of the whole system. In addition, our framework can be applied to a variety of scales. For instance, producer 1 can refer to an individual producer or aggregate production of a product. Similarly, processor 1 can refer to a specific processor or all processors of a specific product within the supply chain. Obviously, the development of properly adjusted frameworks for each supply chain of a region/economy could provide a region-/economy-wide model of circularity, which is important when examining aggregate circularity in a region/economy [37]. Finally, the framework can be used to provide metrics and indicators of circularity in the economic system under study. These metrics can measure the progress towards circularity at each stage of the supply chain as well as at the supply chain as a whole. In fact, our framework can be used to construct environmental, technical, and economic metrics.[8] Environmental metrics measure the reduction and the mitigation of the environmental damages associated with the various stages of the supply chain when transitioning to a circular supply chain. For instance, metrics to assess the environmental damage mitigation (EDM_1) in stage 1 when transitioning from LSC to CSC are given by:

$$EDM_1 = \frac{\left(y_1^{u*} + z_1\right) - \left(y_1^u + b_1 + w_1 + b_2 + w_2\right)}{\left(y_1^u + b_1 + w_1 + b_2 + w_2\right)} \tag{1}$$

Technical (or physical) metrics focus on circularity associated with the physical flow of input and outputs, i.e., how much waste is recovered or circularity rate (CR_1) in stage 1 given by:

$$CR_1 = \frac{z_1}{b_1' + w_1' + b_2' + w_2'} \tag{2}$$

[8] As noted in the literature review section, economic metrics are rare

Finally, when prices and costs are available, economic metrics that reflect the revenues and the costs of circularity at each stage of the supply chains can be constructed. This can be done by constructing indexes using both economic data and physical flow of inputs and outputs. Economic metrics assign prices and costs to the circular flow of inputs and outputs, i.e., the economic value and the cost of recovered wastes and valorized byproducts.

Key Economic Issues Associated with the Transition to a Circular Economy

Having determined a general framework that encompasses relevant and significant transformations and technological changes required for transitioning from an LSC to a CSC, we discuss, next, some key economic issues that arise from the transition to increased circularity. As noted in the introduction, the CE is as much a system of markets as it is a system of material and energy flows. That is, for each secondary production resulting from the transition to a CE/increased circularity, there is a market involving costs and benefits that impact the direct participants in this market/economic activity, as well as participants in other stages of the supply chain and, when recovered or secondary products are used in other supply chains, they affect participants in these supply chains as well. Changes in production functions/production technologies[9] used; costs, quantity, and/or quality of production; consumer preferences; market structure, along with increased uncertainty and revenues from byproducts and waste utilized in a circular economic system; and benefits from corporate social responsibility are some of the economic issues associated with the transition from a linear to a CE. These economic issues are important as they can affect the expected impacts of circularity and, through this, the adoption of the methods and processes required for the transition from a linear to a circular economic system.

Changes in Production Functions/Production Technologies and Quantity of Output Produced

The changes needed to achieve circularity can have direct impacts on the production functions/technologies (i.e., the technical relationship between the output produced and the inputs used in its production, which captures the production technology and gives the maximum output that can be produced from a given level of inputs), at the different stages of the supply chain. At the primal/quantity space, redirecting wastes and byproducts away from disposal and back into closed loops that cycle materials back to the supply chain results in the creation of a new set of inputs (i.e., secondary products or recycled capital). As a result, the set of inputs available to producers increases, which can change the production functions/production technologies used. For instance, in Fig. 1, the production function of producer 1 under the LSC is given by $y_1 = f\left(k_1^m, k_1^n\right)$, while, under circularity, the production function can become $y_1 = g\left(k_1^m, k_1^n, k_1^r, k_5^r, k_{11}^r, k_{17}^r\right)$. Thus, not only does circularity result in additional inputs available to producers (i.e., recycled capital k_1^r, k_5^r, k_{11}^r, and k_{17}^r), it also changes the production technology from $f(.)$ to $g(.)$, and the maximum

[9] In economics, a production function depicts the technical/technological relationship between the quantities of the physical inputs used in the production process and the quantities of the output(s) produced — i.e., the way inputs are combined to produce the output. It reflects the production technology used/technology used in the production process, and specifies the maximum output that can be produced from a given set of inputs [44, 45]

output that can be produced in the two cases. The impacts of this change are determined by the relationship of the production technologies under the LSC and under the CSC, the technical relationship between the secondary products and the traditional inputs used in production, and the returns to scale under the different production technologies.

Changes in the Costs of Production

In addition to affecting the quantity of the product that can be produced with the available resources, the use of secondary products/recycled capital in the production process can also affect the costs of production along the supply chain. The cheaper are the secondary products relative to the traditional inputs used and/or the greater the substitutability of these inputs, the greater are the cost savings associated with the use of secondary products as inputs in the production processes involved, and the greater is the economic efficiency of the supply chain. The transition from a linear to a circular economic system can also result in adjustment costs associated with the change in the production practices necessitated by this transition. The greater are the changes in the production practices required under a circular economic system, the greater are the adjustment costs faced by the producers involved.

Costs of Establishing the CE Units and Producing the Secondary Products

While the use of secondary products as inputs in the relevant production processes can generate production cost savings in the different stages of the supply chain, the production of these secondary products through the CE units in each stage is costly. These circularity costs entail both fixed costs associated with the establishment of the CE units and variable costs associated with the operation of these units and the production of the secondary products through the recovery, recycling, and treatment of wastes and byproducts. It should be noted that the spatial context is a key attribute of circular business models [15]. The more local the secondary production, the more efficient and cost effective the recovery and the reuse of waste and byproducts.[10]

Changes in Market Structure

The fixed costs associated with the establishment of CE units at the different stages of the supply chain can affect the structure of the relevant markets. The greater are the fixed costs associated with the transition to circularity, the greater is the minimum efficient size of operation, and the more concentrated the relevant markets are expected to be. Changes in market structure are important as they affect both the size and the distribution of the economic surplus generated by an economic activity [38].

Changes in the Quality of the Products and Consumer Preferences

In addition to affecting the quantity and the costs of the products produced along the supply chain of interest, the use of secondary products as inputs in the production process

[10] While important, the spatial attribute poses a significant challenge for modern supply chains, like the increasingly industrialized agri-food sector [46, 47]. These supply chains rely on economies of scale, making it difficult to rely on locally sourced byproducts and waste

can also affect the actual or perceived quality of the products produced. Consumers can increase their valuation of, and willingness-to-pay (WTP) for products produced through circular economic processes when they value/care about the socioeconomic and environmental benefits associated with increased circularity [39]. Consumers can also perceive circular products as being of lower quality when the use of secondary products is viewed as detrimental to the quality of the final product [40]. Examples of such cases would be vegetables produced with recycled/reclaimed wastewater.

Rebound Effect

An increased consumer valuation of circular products can create economic incentives for increased production of byproducts and waste (used as inputs in the production of the secondary product utilized in the production process of the circular economic system). The result could be an increased primary production (resulting in increased extraction and processing of natural capitals), which could exacerbate environmental damages and create a rebound effect.[11] As noted by Zink and Geyer [21], CE activities can also lead to a rebound effect when CE production fails to compete effectively with primary production, resulting in increased primary production.

Uncertainty About the Economic Impacts of Increased Circularity

The novel nature of the circular economic system/supply chain, the quality of the secondary products as inputs in the production processes involved, the consumer response to circular products, and potential rebound effects can create uncertainty about the impacts of the transition to circularity, which results in costs for risk averse participants in the supply chain of interest. The more risk averse are the individual decision makers involved and/or the greater is the uncertainty surrounding a certain transition to increased circularity, the greater are the perceived costs associated with the specific transition.

Additional Revenues from Waste and Byproducts

The recycling and reuse of byproducts and waste in a circular economic system creates potential revenues for the producers of these byproducts and waste. The more significant these byproducts and waste become in the production of the secondary products, and the greater the value of the relevant secondary products in the production processes involved, the greater are the additional revenues generated by the transition to a circular economic system.

Benefits from Corporate Social Responsibility

Firms have been facing increased pressures and demands from their customers to be actively involved in addressing important current and emerging socioeconomic and

[11] In energy economics, the rebound effect refers to the phenomenon when increased efficiency reduces the costs and increases the consumption of energy goods, which can offset the environmental benefits of increased efficiency and lead to a backfire effect [48, 49]

environmental challenges even when these challenges are not relevant to the firm's business practices [41–43].[12] Given the ability of the CE to address a multitude of these challenges, the proper management of firms' involvement in this space can result in increased goodwill towards, and public valuation of these firms.

Policy Implications

The economic costs and benefits associated with the transition from a linear to a circular economic system are important as they will determine the economic incentives for the adoption of the methods and processes that this transition requires. While the relevance and significance of each of these costs and benefits will vary with the sector and the idiosyncrasies of the processes and the products involved, the relationship between the expected costs and benefits will determine the success of the transition to circularity. And since there is not only one way of transitioning to a circular economic system, the relevant costs and benefits will also determine the economically optimal path to circularity for those involved. While many participants in the supply channels of interest value the socioeconomic and environmental benefits associated with increased circularity (see below), the key objective of rational firms is the maximization of their profits. In this context, the relationship between the economic costs and benefits associated with the transition from a linear to a circular economic system is of paramount significance for the successful, effective, and efficient transition to increased circularity.

Apparently, when the expected benefits outweigh the expected costs of such transition for all relevant parties involved, rational decision makers can be expected to adopt the methods and processes required by the CE. No policy action is required in this case as the market forces facilitate the socially desirable transition to the CE.

The need for policy intervention will arise, however, when the balance of the expected costs and benefits is such that the methods and processes required for the transition to the socially desirable circular economic system are not adopted by the relevant supply chain participants. This can occur when the expected costs outweigh the expected benefits of those involved and/or when the supply chain participants do not consider or internalize the socioeconomic and environmental benefits of increased circularity, which creates a difference between the private and the social benefits of circularity and a market failure to generate the socially desirable outcome.

Effective policies, in this case, are those that address the source of the problem and change the relationship between the expected costs and benefits to induce the desired behavior of the relevant parties involved (adoption of the methods and processes that lead to the transition to a circular economic system, in our case). In this context, if the problem lied with high costs of establishing the CE units and producing the secondary products, the government could address it through the provision of subsidies designed to reduce these costs to a level where the transition to circularity would become profitable for the decision makers involved. Properly designed subsidies could also address issues with reduced production or/and reduced quality of output due to the use of secondary products, while issues with increased producer

[12] A recent Cone Communications report indicates that 7 in 10 Americans believe companies have an obligation to take action to improve issues that might not be relevant to everyday business operations. In the same report, 86% of Americans expect companies to address environmental and societal issues in addition to making profits

uncertainty and/or low consumer valuation of CE products could be addressed through the provision of relevant information on the methods, processes, and the benefits of increased circularity. Such information could also enhance the producer valuation of the circular economic system and reduce an existing discrepancy between the social and private benefits of increased circularity (and address the market failure that such discrepancy can create). While the policy tools for inducing the desired outcome(s) exist, a clear understanding of the economics of the transition to CE in a supply chain is essential for determining whether a policy intervention is needed and, if so, what form it should take.

Summary and Concluding Remarks

The transition to a CE is widely regarded as a critical approach to tackling the multifaceted challenges associated with population growth, climate change, and the need to increase production of food, feed, fiber, and bioenergy while confronting dwindling natural resources. This transition has been receiving increasing attention in academic and policy making circles with the main focus being on the development of methods and processes that enable reduced resource use and waste in economic activity.

While the development of such methods and processes is certainly necessary, it is not sufficient for facilitating the successful transition to a more circular economic system. Unless the interest groups involved find it optimal to adopt the methods and processes required for increased circularity, these methods and processes will not realize their potential. High costs, adverse impacts on quantity or/and quality of production, uncertainty and/or a negative consumer response may hinder the adoption of these processes and derail the transition to increased circularity.

In this context, an understanding of the economic impacts of circular economic processes is of paramount significance for the market acceptance and success of these processes. In addition to highlighting the need for an increased emphasis on the economics of the CE, this paper develops a general, scalable, and adaptable framework that illustrates the transition from a linear to a circular economic system and the key areas affected by this transition. The paper also highlights key economic issues that arise and policies that can be utilized to address these issues and to facilitate the successful, effective, and efficient transition to increased circularity.

Funding This study has been funded by a Grant Challenges Planning Grant from the University of Nebraska-Lincoln.

Declarations

Conflict of Interest The authors declare no competing interests.

References

1. Blomsma F, Brennan G (2017) The emergence of circular economy: a new framing around prolonging resource productivity. J Ind Ecol 21(3):603–614. https://doi.org/10.1111/jiec.12603
2. Bocken NM, De Pauw I, Bakker C, Van Der Grinten B (2016) Product design and business model strategies for a circular economy. J Ind Prod Eng 33(5):308–320. https://doi.org/10.1080/21681015.2016.1172124
3. Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
4. Montag L (2023) Circular economy and supply chains: definitions, conceptualizations, and research agenda of the circular supply chain framework. Circ Econ Sust 3(1):35–75. https://doi.org/10.1007/s43615-022-00172-y
5. Ellen MacArthur Foundation (2013) Towards the circular economy: opportunities for the consumer goods sector. https://emf.thirdlight.com/file/24/qzvD2i1qVnZjTMqzpI2qI32rGA/Towards%20the%20circular%20economy%20Vol.%202%3A%20opportunities%20for%20the%20consumer%20goods%20sector.pdf. Accessed 11 Mar 2023
6. Ellen MacArthur Foundation (2015) Towards a circular economy: business rationale for an accelerated transition. https://emf.thirdlight.com/file/24/_A-BkCs_h7gfln_Am1g_JKe2t9/Towards%20a%20circular%20economy%3A%20Business%20rationale%20for%20an%20accelerated%20transition.pdf. Accessed 11 Mar 2023
7. Ellen MacArthur Foundation (2019) Completing the picture: how the circular economy tackles climate change. https://emf.thirdlight.com/file/24/XoGiOySXvopGQ9Xo4d6XnKIvUh/Completing%20the%20picture%20-%20%20Executive%20summary.pdf. Accessed 11 Mar 2023
8. Kirchherr J, Yang NHN, Schulze-Spüntrup F, Heerink MJ, Hartley K (2023) Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour Conserv Recycl 194:107001. https://doi.org/10.1016/j.resconrec.2023.107001
9. Murray A, Skene K, Haynes K (2017) The circular economy: an interdisciplinary exploration of the concept and application in a global context. J Bus Ethics 140:369–380. https://doi.org/10.1007/s10551-015-2693-2
10. Schroeder P, Anggraeni K, Weber U (2019) The relevance of circular economy practices to the sustainable development goals. J Ind Ecol 23(1):77–95. https://doi.org/10.1111/jiec.12732
11. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2017) The circular economy – a new sustainability paradigm? J Clean Prod 143:757–768. https://doi.org/10.1016/j.jclepro.2016.12.048
12. United Nations (2015) Transforming our world: the 2030 agenda for sustainable development. https://sustainabledevelopment.un.org/post2015/transformingourworld/publication. Accessed 10 Mar 2023
13. Ekins P, Domenech T, Drummond P, Bleischwitz R, Hughes N, Lotti L (2019) The circular economy: what, why, how and where, background paper for an OECD/EC workshop on 5 July 2019 within the workshop series. In: Managing environmental and energy transitions for regions and cities. https://www.oecd.org/cfe/regionaldevelopment/Ekins-2019-Circular-Economy-What-Why-How-Where.pdf. Accessed 11 Mar 2023
14. European Commission (2020) Circular economy action plan: for a cleaner and more competitive Europe. European Union https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN. Accessed 12 Mar 2023
15. Soufani K, Loch C (2021) Circular supply chains are more sustainable. Why are they so rare? Harvard business review https://hbr.org/2021/05/circular-supply-chains-are-more-sustainable-why-are-they-so-rare. Accessed 15 Mar 2023
16. Haas W, Krausmann F, Wiedenhofer D, Heinz M (2015) How circular is the global economy?: an assessment of material flows, waste production, and recycling in the European Union and the world in 2005. J Ind Ecol 19(5):765–777. https://doi.org/10.1111/jiec.12244
17. Atasu A, Dumas C, Van Wassenhove LN (2021) The circular business model. Harv Bus Rev 99(4):72–81
18. Basile A, Centi G, De Falco M, Iaquaniello G (2020) The vision of future sustainable energy, catalyst, and chemistry: opportunities for innovation and business. In: In Studies in Surface Science and Catalysis, vol 179. Elsevier, pp 7–20. https://doi.org/10.1016/B978-0-444-64337-7.00001-X
19. Chertow MR (2007) Uncovering industrial symbiosis. J Ind Ecol 11(1):11–30. https://doi.org/10.1162/jiec.2007.1110
20. Frosch RA, Gallopoulos NE (1989) Strategies for manufacturing. Sci Am 261(3):144–153
21. Zink T, Geyer R (2017) Circular economy rebound. J Ind Ecol 21(3):593–602. https://doi.org/10.1111/jiec.12545

22. Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J Clean Prod 114:11–32. https://doi.org/10.1016/j.jclepro.2015.09.007
23. Stahel W (1994) The utilization-focused service economy: resource efficiency and product-life extension. In: The Greening of Industrial Ecosystems. National Academy Press, Washington. DC, pp 178–190
24. Stahel WR (2016) The circular economy. Nature 531(7595):435–443. https://doi.org/10.1038/531435a
25. Boulding KE (1966) The economics of the coming spaceship earth. In: Jarrett H (ed) Environmental quality in a growing economy. John Hopkins University Press, pp 3–14
26. Pearce DW, Turner RK (1989) Economics of natural resources and the environment. Johns Hopkins University Press
27. Andersen MS (2007) An introductory note on the environmental economics of the circular economy. Sustain Sci 2(1):133–140
28. Rejeb A, Rejeb K, Zailani S, Kayikci Y, Keogh JG (2023) Examining knowledge diffusion in the circular economy domain: a main path analysis. Circ Econ Sust 3(1):125–166. https://doi.org/10.1007/s43615-022-00189-3
29. De Pascale A, Arbolino R, Szopik-Depczyńska K, Limosani M, Ioppolo G (2021) A systematic review for measuring circular economy: the 61 indicators. J Clean Prod 281:124942. https://doi.org/10.1016/j.jclepro.2020.124942
30. Saidani M, Yannou B, Leroy Y, Cluzel F, Kendall A (2019) A taxonomy of circular economy indicators. J Clean Prod 207:542–559. https://doi.org/10.1016/j.jclepro.2018.10.014
31. Moraga G, Huysveld S, Mathieux F, Blengini GA, Alaerts L, Van Acker K, Demeester S, Dewulf J (2019) Circular economy indicators: what do they measure? Resour Conserv Recycl 146:452–461. https://doi.org/10.1016/j.resconrec.2019.03.045
32. Kulakovskaya A, Knoeri C, Radke F, Blum NU (2022) Measuring the economic impacts of a circular economy: an evaluation of indicators. Circ Econ Sust 3(2):657–692. https://doi.org/10.1007/s43615-022-00190-w
33. Fullerton D, Babbitt CW, Bilec MM, He S, Isenhour C, Khanna V, Lee E, Theis TL (2022) Introducing the circular economy to economists. Ann Rev Resour Econ 14:493–514. https://doi.org/10.1146/annurev-resource-101321-053659
34. Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2(3):198–209. https://doi.org/10.1038/s43016-021-00225-9
35. IPCC Report (2022) Climate change: impacts, adaptation and vulnerability. https://www.ipcc.ch/report/ar6/wg2/. Accessed 21 Mar 2023
36. Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science 360(6392):987–992. https://doi.org/10.1126/science.aaq0216
37. Mayer A, Haas W, Wiedenhofer D, Krausmann F, Nuss P, Blengini GA (2019) Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. J Ind Ecol 23(1):62–76. https://doi.org/10.1111/jiec.12809
38. Alston JM, Sexton RJ, Zhang M (1997) The effects of imperfect competition on the size and distribution of research benefits. Am J Agric Econ 79(4):1252–1265. https://doi.org/10.2307/1244282
39. Pretner G, Darnall N, Testa F, Iraldo F (2021) Are consumers willing to pay for circular products? The role of recycled and second-hand attributes, messaging, and third-party certification. Resour Conserv Recycl 175:105888. https://doi.org/10.1016/j.resconrec.2021.105888
40. Hamzaoui Essoussi L, Linton JD (2010) New or recycled products: how much are consumers willing to pay? J Consum Mark 27(5):458–468. https://doi.org/10.1108/07363761011063358
41. Cone C (2017) Cone communications CSR study. Available at: https://conecomm.com/2017-csr-study/#download-the-research. Accessed 28 Mar 2023
42. Falck O, Heblich S (2007) Corporate social responsibility: doing well by doing good. Bus Horiz 50(3):247–254. https://doi.org/10.1016/j.bushor.2006.12.002
43. Frooman J (1999) Stakeholder influence strategies. Acad Manag Rev 24(2):191–205
44. Färe R (1988) Fundamentals of production theory, Lecture Notes in Economics and Mathematical Systems. Springer-Verlag, Heidelberg
45. Shephard RW (2015) Theory of cost and production functions. Princeton University Press
46. Boehlje M (1996) Industrialization of agriculture: what are the implications? Choices 11:316-2016-6650. https://doi.org/10.22004/ag.econ.131950

47. Sexton RJ (2000) Industrialization and consolidation in the US food sector: implications for competition and welfare. Am J Agric Econ 82(5):1087–1104
48. Berkhout PH, Muskens JC, Velthuijsen JW (2000) Defining the rebound effect. Energy Polic 28(6-7):425–432. https://doi.org/10.1016/S0301-4215(00)00022-7
49. Sorrell S, Dimitropoulos J (2008) The rebound effect: microeconomic definitions, limitations and extensions. Ecol Econ 65(3):636–649. https://doi.org/10.1016/j.ecolecon.2007.08.013