MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, Jan-June 2026, Pages: 1275-1280

Quantifying the Impacts of Sustainability-Oriented Innovation on the Linear Economy

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Abstract
Sustainability-oriented innovation is widely promoted, yet rarely quantified in ways that allow meaningful economic, labour, and environmental comparison. Without formal measurement, sustainability transitions risk remaining aspirational rather than actionable. This paper addresses that gap by translating sustainability-oriented innovation into a set of transparent equations designed to evaluate its impacts within a linear economic system.

Introduction:
Sustainability-oriented innovation (SOI) is increasingly promoted as a mechanism for improving economic performance, employment outcomes, and environmental efficiency within traditionally linear economic systems. However, despite extensive conceptual discussion, there remains a lack of unified frameworks that translate SOI into measurable and comparable economic, labour, and environmental impacts.

Methods:
This study adopts a conceptual and analytical approach to develop a formalised model for quantifying the impacts of SOI within a linear economy. Drawing on innovation economics, sustainability science, and systems analysis, the paper constructs an integrated modelling framework based on four interrelated equations. These equations explicitly link SOI investment, technology adoption, labour productivity, and emissions intensity to changes in GDP, employment levels, and environmental outcomes. The model is designed for scenario-based simulation rather than empirical estimation, allowing users to compare outcomes under varying levels of SOI adoption and policy intensity.

Results:
The proposed equations demonstrate how SOI can generate positive economic returns through investment and cost-efficiency channels, influence employment through productivity gains and workforce transition dynamics, and reduce environmental pressure via technological efficiency and market penetration of sustainable products and processes. By incorporating baseline conditions and adjustment parameters, the framework highlights potential trade-offs between short-term transition costs and long-term sustainability gains. The model further enables sensitivity analysis to identify the variables that exert the greatest influence on economic growth, labour restructuring, and emission reduction within a linear economy.

Discussion:
By prioritising formal equations and transparent assumptions, this study advances sustainability research beyond descriptive narratives toward structured quantification. The proposed framework offers policymakers, researchers, and practitioners a practical tool for benchmarking SOI strategies, designing simulation scenarios, and guiding future empirical testing. In doing so, the paper contributes a foundational measurement logic that supports evidence-based transitions toward sustainability within linear economic systems.

Keywords: Linear economy; sustainability-oriented innovation; conceptual modelling; employment change; GDP impact; emissions reduction.

1. Introduction

The current global economy in terms of manufacturing and sales is using a linear model commonly referred to as 'take-make-dispose(Madžar, 2021; Turner et al., 2019).' Extraction, transformation, and disposal of materials cause emissions of greenhouse gases, destruction of the ecosystem, and depletion of resources. This calls for change in relation to more sustainable forms of economy. (Zhang et al., 2022).

Sustainable business model innovation (SBMI) has been deemed a valuable one with the application of sustainability-oriented innovation (SOI), including renewable energy, circular material flows, energy efficiency, and sustainable production and consumption. (Kaup, 2015; Sun et al., 2022). By adopting SOI into the economic system, it is unlikely to equate economic growth with the destruction of the environment and instead move towards a circular economy.(Mead et al., 2022). However, the highly entrenched linear economy remains the global production and consumption paradigm of choice with broader environmental and economic impacts. (Kara et al., 2022).

This paper's objective is to establish an analytical framework that can be used to estimate the economic disruptions of SOI on the linear economy and the relative values of GDP, employment opportunities, and the degree of emissions reduction. The results can help to decisions, critical practices, and necessary policies in order to enhance positive frameworks.

2. Literature Review

There is abundant literature that addresses the warranted theorization of the innovation-sustainability relationship. However, empirical research evidence of sustainability-oriented innovation (SOI) applications and effects is limited and inconclusive. The Schumpeterian view of innovation as a process that leads to economic growth does not envisage the environmental and social costs of some innovations. (Harsanto et al., 2022) . Therefore, scholars have aptly called for a more comprehensive approach where sustainability principles are integrated into the innovation cycle. (Boons & Lüdeke-Freund, 2013; Carrillo-Hermosilla et al., 2010a).

Nonetheless, the components that influence SOI are still ambiguous, and the implementation of this principle still has many challenges. (Bernstein & Rohrer, 2007). The dominant 'white' linear economy paradigms are well embedded while aiming

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for more circular and regenerative forms presents significant institutional as well as technological and behavioral challenges. (Schulz et al., 2019).

Further, the assessments of SOI in economic models are mostly welfare optimistic, fully capturing the indicators such as GDP and employment growth but disregarding distributional consequences and doubling-back effects. (Hellström, 2007; Kalimeris et al., 2020). The idea that, with the help of SOI, economic growth can be 'unlinked' from environmental pollution has been receiving more critical views, thus implying the need to engage in critical thinking about the role of innovation for sustainability and economic change. (Calábria et al., 2018).

Overall, it can be seen that there are still many research gaps when it comes to the overall understanding of SOI and its effectiveness, as well as the social consequences involved. To understand the social dynamics and issues surrounding change to a sustainable innovation model, there is a need for a more skeptical and realistic outlook.

3. Method

The development of conceptual models for sustainability-oriented innovation (SOI) requires more than descriptive alignment with sustainability goals; it demands structured assumptions, transparent logic, and internally coherent quantification mechanisms. Previous work has demonstrated that while SOI is widely acknowledged as a driver of economic, labour, and environmental transformation, its measurement has often remained fragmented, sector-specific, or methodologically inconsistent. In particular, existing studies tend to prioritise either empirical correlations without formalised structure or conceptual discussions without explicit operational logic.

Building on this gap, prior research by Al Owais (2024a) and Alowais (2024b) provided important groundwork by identifying the internal and external pressures shaping SOI measurement and by compiling quantification techniques used within circular and sustainability-focused economic models. However, these contributions also highlight a critical limitation in the current literature: the absence of an integrated and generalisable modelling framework capable of linking SOI inputs to economic, labour, and environmental outcomes within a conventional linear economy. While earlier studies advanced the discussion on *what* should be measured, they left open the question of *how* such impacts can be coherently modelled across multiple dimensions and policy scenarios.

In response, the present study adopts a structured conceptual modelling approach that formalises SOI impacts through a set of interrelated equations grounded in innovation economics, sustainability science, and systems analysis. Model construction follows a transparent logic of variable selection, relationship specification, and assumption articulation, allowing for scenario-based simulation and sensitivity assessment. Rather than seeking empirical validation at this stage, the model is evaluated through internal consistency, theoretical alignment, and analytical plausibility, ensuring that it can serve as a robust foundation for future empirical testing and policy application. In doing so, this study advances SOI research from fragmented measurement practices toward a unified and analytically rigorous framework suitable for comparative and forward-looking sustainability analysis.

3.1. Conceptual Model Development

The evaluation of the following works from the related literature concerning the linear economy and sustainability-oriented innovation will form the basis of the analysis of the formation of the conceptual model. (Blomsma & Brennan, 2017; Geissdoerfer et al., 2017). The model is built around variables that help to outline the economic, environmental, and social impacts of the movement toward higher sustainability in the innovation paradigms. Studies have pointed towards it from Blomsma & Brennan (2017) and Geissdoerfer et al. (2017). These indicators will include GDP, resource utilization, emission levels, and employment statistics (Kirchherr et al., 2017; Klewitz & Hansen, 2014).

3. 2. Model Construction and Validation

The conceptual model will be transformed into a set of equations and mathematical relations based on the theories of innovation economics, sustainability science, and systems analysis. (Carrillo-Hermosilla et al., 2010b). Furthermore, the proposed model will be subjected to validation and calibration to establish logical and empirical validity and to examine sensitivity measures of drivers and trade-offs. (Boons & Lüdeke-Freund, 2013).

The proposed model consists of a set of equations and mathematical inferences based on the existing corpus of innovation economics, sustainability sciences, and system analysis. (Carrillo-Hermosilla et al., 2010b). Additionally, in terms of application, the proposed model needs to be validated and calibrated to achieve local and empirical validity and also warrants sensitivity measures of different economic drivers and trade-offs.

3.3 Limitations of Existing Approaches to Quantifying Sustainability-Oriented Innovation

Earlier research examining sustainability challenges has underscored a persistent gap between environmental policy objectives and their effective economic implementation, particularly in contexts where regulatory enforcement and financial allocation mechanisms remain weak (AlOwais & AlHudaithi, 2023). While such studies provide valuable diagnostic insights, they stop short of offering formalised tools capable of translating sustainability-oriented innovation into quantifiable economic, labour, and environmental impacts. As a result, sustainability discussions often remain descriptive rather than analytically operational. Addressing this gap, the present paper develops a structured conceptual model that formalises sustainability-oriented innovation through explicit equations, enabling systematic comparison, simulation, and future empirical testing within a linear economic framework.

3.4 Conceptual Nature, Perceptual Foundations, and Analytical Boundaries of the Model

The equations presented in this study are conceptual representations intended to illustrate how the impacts of sustainability-oriented innovation may be structured and assessed within a linear economic framework. The model does not claim to provide precise empirical estimates; rather, it reflects a perception-informed analytical logic derived from established theories in innovation economics, sustainability science, and systems analysis. As such, the formulation of each component

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is influenced by assumptions commonly discussed in the literature, including investment-driven growth, productivity-based employment dynamics, and technology-led emissions reduction.

It is acknowledged that conceptual models of this nature are inherently subject to simplification and may not fully capture the complexity of real-world economic systems. The coefficients and functional relationships proposed should therefore be interpreted as illustrative rather than definitive, and their values may vary across sectors, institutional settings, and policy environments. This limitation is intentionally recognised to ensure analytical transparency and to avoid overstating the predictive capacity of the framework.

Importantly, the model does not reproduce or replicate any single existing framework. Each equation is independently constructed and grounded in insights synthesised from prior academic literature, with all conceptual influences appropriately cited. The purpose of the framework is not to appropriate existing models, but to consolidate dispersed theoretical insights into a coherent structure that demonstrates how sustainability-oriented innovation *could* be quantified in principle.Accordingly, this study should be viewed as offering a conceptual guide for how economic, labour, and environmental impacts of sustainability-oriented innovation may be calculated and compared, rather than as a validated measurement tool. The framework is designed to support scenario analysis, policy discussion, and future empirical testing, providing a transparent foundation upon which subsequent quantitative research can build.

4. Proposed Model/Results

To address the growing need for structured and comparable methods to evaluate sustainability-oriented innovation, this study proposes a conceptual model that quantifies the economic, labour, and environmental impacts of SOI within a linear economic system. Prior research has highlighted that while sustainability-oriented innovation is widely discussed, its measurement often remains fragmented, context-specific, or limited to single outcome dimensions (Al Owais, 2024a; Alowais, 2024b). Building on these insights, the proposed model translates abstract sustainability concepts into a set of interrelated equations that capture how SOI investment, technological adoption, labour productivity, and emissions interact within a conventional linear economy. The model is designed to provide a transparent and adaptable framework that can support scenario analysis, policy evaluation, and future empirical testing across different economic contexts.

4.1. Model Assumptions

The proposed conceptual model is built on a small number of realistic and widely accepted assumptions about how economies operate and how innovation influences them.

First, the model assumes that the linear economy (also referred to as the industrial economy) operates in a temporary equilibrium, where production, employment, and emissions follow relatively stable patterns. However, this equilibrium is not fixed. When sustainability-oriented innovation (SOI) is introduced, it disrupts existing production methods, cost structures, and labour arrangements. As a result, economic, employment, and environmental outcomes begin to change.

Second, the model assumes that technological progress occurs gradually over time. As firms invest more in SOI, technologies become cheaper, more efficient, and easier to adopt. This reflects real-world innovation dynamics, where early adoption is costly, but efficiency improves as learning, scale, and diffusion increase.

Third, the model recognises that policies and regulations matter. Government legislation, incentives, and environmental regulations influence firms' willingness and ability to adopt SOI. Institutional pressure can accelerate adoption, while weak policy frameworks may slow it. Including policy-related assumptions ensures that the model reflects real economic and political conditions rather than a purely technical transition.

Together, these assumptions justify treating SOI not as a one-time change, but as a dynamic process that gradually reshapes the linear economy.

4.2. Key Equations and Relationships

The conceptual framework uses three equations, each representing one core dimension of sustainability:
economic performance, employment, and environmental impact.
Each equation answers a simple question.

4.2.1. Economic Impact Equation: GDP Impact

Question answered: How does investing in sustainability-oriented innovation affect economic growth?
Equation

$$\Delta GDP = I_{SOI} \times \alpha + C_{SOI} \times \beta + T_{adopt} \times \gamma$$

Simple explanation

This equation states that economic growth changes for three main reasons when SOI is introduced:

Investment in SOI (ISOI): When firms invest in sustainable technologies, processes, and innovation, they stimulate economic activity. This includes spending on equipment, R&D, and infrastructure, which contributes positively to GDP.

Cost savings from SOI (CSOI): Sustainability-oriented innovation often reduces costs in the long run through lower energy use, reduced waste, and more efficient resource use. These savings improve firm profitability and overall economic output.

Technology adoption rate (Tadopt): The faster sustainable technologies are adopted, the greater their economic impact. Widespread adoption improves productivity and competitiveness across industries.

The coefficients (α, β, γ) simply represent how strongly each factor affects GDP. Their values depend on economic conditions, sectoral structure, and policy environments.

Why this model makes sense? Economic theory consistently identifies investment, efficiency gains, and technological change as core drivers of GDP growth. This equation adapts those traditional drivers specifically to the context of sustainability-oriented innovation.

4.2.2. Employment Impact Equation: Employment Change
Question answered: Does sustainability-oriented innovation create or destroy jobs?
Equation

$$\Delta E = I_{SOI} \times \delta + \lambda_{SOI} \times \varepsilon - L_{retrain} \times \zeta$$

Simple explanation
This equation recognises that SOI has both positive and negative employment effects.
Investment in SOI (ISOI): New investments create jobs in areas such as renewable energy, sustainable manufacturing, environmental services, and innovation management.
Labour productivity improvements (λSOI): SOI often improves how efficiently workers produce goods and services. Higher productivity can support job creation by making firms more competitive and financially stable.
Labour retraining and reskilling (Lretrain): Transitioning to sustainable technologies can displace workers in traditional industries. During this transition, employment may temporarily decline as workers require retraining.
The equation therefore captures a net employment effect, balancing job creation against short-term disruption.
Why this model makes sense? Sustainability transitions are rarely job-neutral. This equation reflects the widely observed reality that innovation creates new jobs, but also requires workforce adaptation, especially in economies shifting away from carbon-intensive activities.

4.2.3. Environmental Impact Equation: Emissions Reduction
Question answered: How much can sustainability-oriented innovation reduce environmental damage in a linear economy?
Equation

$$\Delta Emissions = T_{eff} \times \eta + P_{SOI} \times \theta - E_{baseline} \times \kappa$$

Simple explanation
This equation explains emissions reduction through three mechanisms:
Technological efficiency improvements (Teff): More efficient technologies use less energy and fewer materials, directly reducing emissions per unit of output.
Penetration of SOI products and processes (PSOI): As sustainable products and processes replace conventional ones, emissions decline across the economy.
Baseline emissions (Ebaseline): The linear economy starts with high emissions. Reductions are measured relative to this baseline, allowing the model to estimate how far sustainability efforts shift the system away from its original environmental footprint.
The coefficients reflect how responsive emissions are to each factor.
Why this model makes sense? Environmental improvement depends not only on technology efficiency but also on how widely sustainable solutions are adopted. Measuring change relative to a baseline ensures that progress is evaluated realistically rather than in isolation.

4.3. Simulation Scenarios
The model is not designed to predict exact outcomes but to compare scenarios.

4.3.1. Baseline Scenario (Linear Economy):
This scenario assumes no SOI adoption, where production, employment, and emissions follow existing linear patterns. It serves as a reference point.

4.3.2. Alternative Scenario (SOI Integration):
This scenario simulates different levels of SOI adoption, from low to high. By adjusting inputs such as investment, adoption rates, and efficiency, the model shows how outcomes change across economic, labour, and environmental indicators.
The general function:

$$\Delta Indicator = f(I_{SOI}, C_{SOI}, T_{adopt}, \lambda_{SOI}, L_{retrain}, T_{eff}, P_{SOI})$$

allows users to observe how changes in SOI intensity translate into different outcomes.

4.4. Conceptual Sensitivity Analysis
The sensitivity analysis examines which variables matter most in shaping results. By changing one input at a time (such as investment or technology adoption), the model identifies:
Key drivers of economic growth
Trade-offs between employment gains and retraining costs
Thresholds where environmental benefits accelerate
This step strengthens the model by showing that results are not arbitrary, but depend on identifiable economic and technological conditions. Overall, the proposed conceptual model provides a simple, transparent, and adaptable framework for understanding how sustainability-oriented innovation reshapes economic growth, employment structures, and environmental performance within a linear economy.

5. Discussion
The model developed is underpinned by theories from innovation economics, sustainability science, and systems analysis (Adams et al., 2016; Carrillo-Hermosilla et al., 2010a). It involves parameters such as Sustainable Innovation Investment (SII), technology adoption, labor productivity, and emissions reduction; besides, the sensitivity analysis part provides key insights into the organizational relationships and offsets when it comes to SOI strategies. (Blomsma & Brennan, 2017; Geissdoerfer et al., 2017).

However, the model requires parameters, such as MSE, market equilibrium, and linear relationship, which are restrictive and may not fully capture the nature of the data. (Bansal et al., 1995; Martin & Nagel, 2022). The modulation of measures' impact or the consideration of other factors, such as rebound effects, distributional consequences, and institutional constraints, are all absent from the model. The issues arising from parameterization revolve around the availability and reliability of data, which must be validated and calibrated for its practical application and policy implication. (Bellocchi et al., 2010; Van Vliet et al., 2016).

However, it is crucial to recognize that, given these limitations, the conceptual model remains a major advancement in the effort to better estimate the complex consequences of moving towards a more sustainable model of economic growth. The application of the model in providing clear and integrated information about the costs/benefits of economic, employment, and environmental effects of SOI provides a clear base for policymaking towards the promotion of the use of SOI.

6. Conclusion and Implications

The proposed conceptual model contains substantial improvements in measuring SOI and other transitional effects of shifting a nation's economy toward a more sustainable, SOI-based approach. The model synthesizes economic, employment, and environmental indices as a tool for analysis that would help in decision-making and policy formulation and implementation for sustainability-based innovation. However, the actual success of the model will depend on overcoming these limitations by undertaking a more stringent validation, calibration, and empirical examination of the results.

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