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The role of dematerialization in promoting sustainable development

Ranshi Fang

Sino-Canada Concord School of Hefei High Tech Zone, Hefei, Anhui, 230001, China

skyfrs@outlook.com

Abstract. In light of the escalating global environmental issues, including climate change, biodiversity decline, and diverse pollutant types, researchers have introduced the notion of dematerialization. This idea primarily emphasizes minimizing material use and optimizing resource utilization to mitigate environmental impacts. This paper, through a literature review and case studies, will discuss the fundamental concept of dematerialization, its relationship with the Sustainable Development Goals (SDGs), and its role in different aspects of modern society. The paper will also examine how various innovations and policies reflect dematerialization and how this process contributes to achieving the SDGs. Research and studies indicate that dematerialization is an essential trajectory for humanity. Numerous rich nations and certain emerging ones are actively promoting this process. However, significant benefits may not be visible in the short term, and further technological and political supports are needed globally to ensure its development and effectiveness.

Keywords: Sustainable Development, Environment, Dematerialization, Technology, Politics.

1. Introduction

Sustainability refers to the practice of fulfilling the needs of the present human beings without damaging the development of the future ones' generations. The concept encompasses the targets of balancing economic growth, environmental protection, and social well-being. The idea of sustainability germinates since the realization of the finite resources and the need for long-term development.

Dematerialization refers to the process of minimizing the amount of materials necessary for the production of goods or services. The notion entails enhancing resource efficiency through technical innovation or optimizing distribution while decreasing waste [1]. Dematerialization will promote sustainability by conserving resources for future generations, driving technological innovation, and reducing negative impacts.

In 1988, Robert Herman, Siamak Ardekani, and Jesse Ausubel began investigating whether human societies were experiencing "dematerialization." Dematerialization was primarily defined as a decrease over time in the weight of materials used in industrial end products or in the "embedded energy" within those products. Dematerialization broadly denotes the complete or relative decrease in the quantity of materials required to perform economic operations [2]. Currently, with economic expansion, consumerism dominates, leading to a significant increase in resource consumption, which in turn exacerbates waste and pollution at an unparalleled rate.

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The SDGs, which refer to the sustainable development goals, contain 17 goals in total , which include zero hunger, clean water and sanitation, affordable and clean energy, industry, innovation and infrastructure, and climate action, which is strongly related to the dematerialization [3-4].

This paper will examine the dematerialization scheme through a literature review and case studies, highlighting notable examples and providing a generalization of dematerialization. This will provide a fundamental understanding of our global circumstances and the initiatives we have undertaken, as well as those we must pursue.

2. Dematerialization Strategies

Various sectors are contributing to the attainment of the Sustainable Development Goals through the ongoing dematerialization initiative. This part, by explaining concept and cases associated with dematerialization will show the process of dematerialization.

2.1. Industry

Industrial Ecosystem (IE) gives a counter-intuitive assumption that an industrial system is a kind of ecosystem since it resembles other ecosystems by presenting a specific distribution of energy, materials, and information flows, and depends on the finite resources provided by the natural system of the earth [5]. The term "dematerialization" is increasingly linked to environmental concerns and the Sustainable Development Goals (SDGs) due to the depletion of natural resources. Industrial ecology addresses the crucial question raised at major UN conferences, such as the Rio Summit's report in June 1992: How can sustainable development *be practically and economically implemented by treating the industrial system as an ecosystem* [4]? Several successful examples illustrate the application of this concept: the Kalundborg industrial park in Denmark facilitates the reuse of waste materials among companies; Toyota Motor Company repurposes greenhouse gas emissions for thermal energy; the Darling Quarter Commonwealth Bank Place in Sydney reuses wastewater; and the Hellisheiði geothermal power station injects carbon byproducts back into the Earth, achieving net zero carbon emissions [5-8].

The Kalundborg industrial park, as stated in their official report, conserves 4 million m^3 of groundwater, reduces CO_2 emissions by 586 tons, and prevents 62 tons of residual material from being discarded [5]. The Toyota Motor Company recovers 8600 tons of thermal energy from the wasted gases. These measures assist industries in diminishing the extraction of natural resources from the environment. The percentage of waste gas reuse reaches 98.9% [6].

2.2. Economy

Circular Economy (CE, or circularity) is an economic model focused on resource production and consumption, where existing materials and products are shared, leased, reused, repaired, refurbished, and recycled for as long as possible [9-10].

The modern interpretation of the Circular Economy and its practical applications to economic systems and industrial processes has evolved by incorporating various features and ideas from multiple concepts that emphasize closed-loop systems. Some of the most significant theoretical influences include cradle-to-cradle, proposed by McDonough and Braungart in 2002 and the laws of ecology proposed by Commoner in 1971.

The Circular Economy plays a crucial role in promoting material reduction. Stahel proposed the Looped and Performance Economy in 2010, while Pauli proposed the Blue Economy in 2010 [11]. Despite their differences, these ideas aim to reduce the new resource input from the environment, thereby slowing down the rate of material depletion for human use today and in the future.

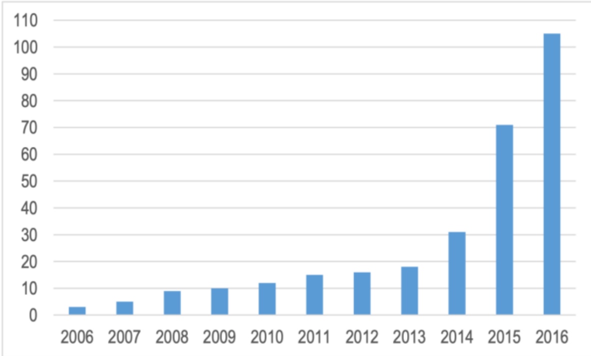

Figure 1. Number of reviews and articles per year with the topic circular economy on Web-of-Science [12]

As shown in Figure 1, the topic of circularity has prevailed more and more as time moves on. The growing focus on environmental issues necessitates dematerialization and sustainable development.

This underscores the significance of circularity. It demonstrates the recognition of utilizing less resources to achieve the same economic function, indicative of dematerialization.

The Tapio decoupling index (TDI) serves as a visible model to demonstrate the effect of the CE. This model analyzes the correlation between GDP and the materials utilized in industrial production during a specific timeframe to demonstrate the degree of circularity in a country's economy. The TDI is calculated using the formula:

$$\mathrm{TDI} = \%\Delta\mathrm{MR}/\%\Delta\mathrm{GDP} = \frac{(\mathrm{MRt}-\mathrm{MRt}_0)}{\mathrm{MRt}_0} \Big/ \frac{(\mathrm{GDPt}-\mathrm{GDPt}_0)}{\mathrm{DPt}_0} \tag{1}$$

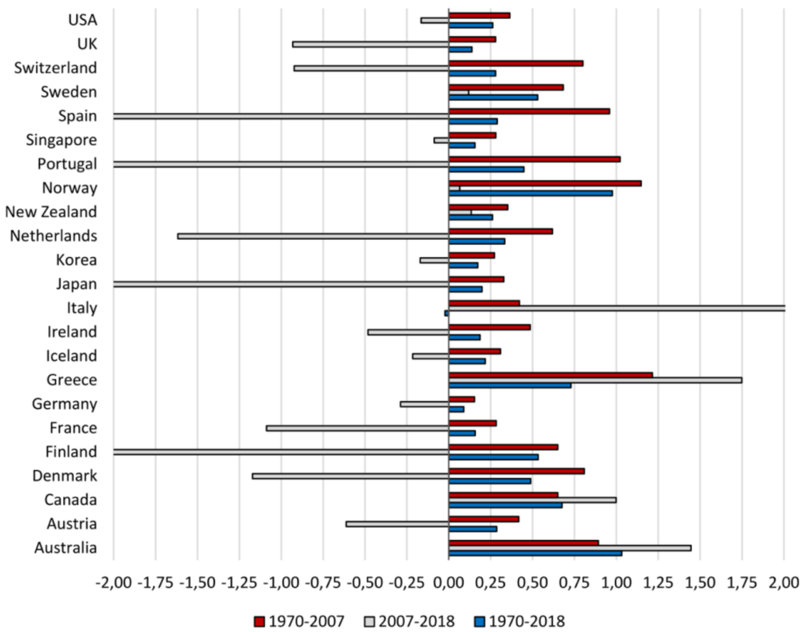

Figure 2. The TDI of Countries in different periods

Figure 2 shows the TDI situation of all countries included in a 2022 analysis. he data indicates that while several countries excessively utilized resources for GDP development during the economic crisis from 2007 to 2018, all industrialized nations demonstrated a consistent trend of dematerialization from

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1970 to 2018, as evidenced by their TDI remaining above 0 throughout this period. Consequently, those countries currently possess a favorable CE state. [13].

2.3. Technological Innovation

Internet services represent another significant form of dematerialization. Online services significantly reduce resource consumption, whereas offline services do not. For instance, online shopping not only minimizes the need for physical retail space but also cuts down on the electricity used by brick-and-mortar stores and decreases emissions associated with customers traveling to these locations.

In addition to Internet services, several innovative technologies also contribute to dematerialization. Industries like automotive and aerospace are increasingly adopting lightweight materials such as carbon fiber, aluminum alloys, and composites. These materials not only reduce the amount of raw material required but also enhance energy efficiency, lower fuel consumption, and decrease carbon emissions.

Technologies like waste-to-resource processes, the development of biodegradable materials, and chemical recycling are at the forefront of reducing the demand for new raw materials. By converting waste into reusable resources, these technologies play a critical role in promoting a circular economy and mitigating environmental impact.

3D printing, or additive manufacturing, enables on-demand production, which significantly reduces material waste. Additionally, it allows for the use of recyclable materials, making it a key player in sustainable manufacturing practices. This technology is increasingly being applied across various industries, including manufacturing, construction, and medical devices.

Among these examples, lightweight materials have been effectively utilized by companies like Tesla. For instance, the Tesla Model S incorporates aluminum in its body structure, resulting in a material savings of over 30% compared to similarly sized steel vehicles. Similarly, Agilyx is a company that focuses on recycling difficult-to-recycle plastics, such as polystyrene and mixed plastics. Agilyx's technology breaks down these materials into their chemical components, allowing for their reuse in the production of new plastic products. Notably, Agilyx's process expands the range of recyclable materials by handling contaminated and mixed plastic streams that are traditionally considered non-recyclable.

These innovative technologies not only reflect the ongoing trend of dematerialization but also highlight the industry's commitment to sustainability by reducing resource consumption and waste.

2.4. Policy and Regulation

Globally, countries are paying more attention to sustainable developments, thus putting more effort into dematerialization actions. These countries are making more policies and regulations about dematerialization. The European Union (EU) made policies of the green tax reform (GTR) scheme, aiming to promote the dematerialization process by putting more tax on virgin materials or resources exploited in the environment and utilizing the revenue of the green taxes to innovate technologies that related to environmental protections, such as renewable materials like PBAT; renewable energy makes like solar panels; and more resource-efficient technologies that use fewer resources and add less pollution to the environment. Additionally, the EU mandated that its companies and factories train their employees to adopt resource-efficient production processes and establish guidelines for using virgin materials in each production, thereby preventing overuse of finite resources [12]. As another example, Japan implements the 3R policy (Reduce, Reuse, Recycle), which involves shifting from resource-consuming industries like steel and cement towards less power-consuming sectors, reusing valuable waste to make products or energy, and recycling energies to create district heating or cooling systems in each community instead of continuing to use AC systems. By reducing the energy consumption per unit and altering the industrial structure, Japan successfully separates the GNP growth and energy demand [14]. As one of the representatives of the developing countries, China also has the regulation to promote dematerialization. In 2020, China proclaimed the plastic limitation regulation. In 2022, the regulation mandates that all prefecture-level cities, food delivery services, and the hotel industry refrain from using single-use non-degradable plastic products, instead substituting them with new renewable and recyclable materials. Plastic materials are replaced by new renewable and recyclable materials. For

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example, PHA (a biologically degradable material) is one of the main materials used for replacing it but the price is as high as 35000 RMB per ton. Pushing by the dematerialization, which is represented by the plastic limitation regulation, the researchers at Tsinghua University state that they will let the price lower down to 12000 RMB per ton within 5 years. According to a 2020 report, this regulation has resulted in a 66% reduction in plastic production compared to the production of the same material in 2008 [15].

3. Benefits and Challenges of Dematerialization

3.1. Benefits

The main goal of dematerialization action is to reduce the use of resources, leaving more usable materials for future generations to develop, thus helping to achieve the SDGs. Publicizing that resources are unable to sustain human ‘development without altering our current production methods, countries, enterprises, and individuals are using their actions to implement dematerialization. Admittedly, resource use is still increasing yearly, but the trend of using resources is actually slowing down: According to the United Nations Global Resources Outlook 2019 report, the global average material productivity (the ratio of GDP to material consumption) increased from $0.8 per kilogram in 2000 to $1.1 per kilogram in 2017. This increase indicates an improvement in resource usage efficiency, meaning more economic output is being generated per unit of resource consumed [16].

As production resources are reduced and some emissions are reused, global GHG emissions are decreasing. Despite the fact that global carbon emissions continue to rise, the growth rate has slowed. According to data from the Global Carbon Project, the average annual growth rate of global CO2 emissions was 1.5% from 2010 to 2019, compared to 2.4% during the period from 2000 to 2009 [17].

More and more technologies that could help us increase energy and production efficiency are emerging under dematerialization. These technologies will help to decouple economic growth with the utilization of virgin resources.

3.2. Challenges

Dematerialization would force technological advancements. However, the implementation of dematerialization would face limitations due to the infancy of these technologies, as well as the instability of the market and their inherent characteristics [18]. Ensuring the advancement of these dematerialization-related technologies is a crucial prerequisite to guarantee the formal progression of dematerialization. Moreover, high-performance materials like rare metals and composites are difficult to replace due to their unique properties. For instance, lithium and cobalt used in lithium-ion batteries are essential for their high energy density and conductivity. According to the International Energy Agency (IEA), global lithium demand grew by 91% in 2021, while alternative materials are still in the early development stages.

Economic limitations could also be a big problem. Implementing material reduction often requires a significant initial investment. For instance, lightweight materials like carbon fiber composites are much more expensive than traditional materials. According to MarketsandMarkets, the average price of carbon fiber composites in 2022 was $16 per kilogram, compared to around $0.5 per kilogram for steel [19].

People may not fully embrace the new lifestyles brought about by dematerialization, as they may need to adjust their daily routines to accommodate these changes. On the other hand, consumerism has the potential to further impact the dematerialization process. Consumers’ demand for new products and technologies continues to rise, particularly in electronics and fashion, exacerbating resource consumption. According to the International Telecommunication Union (ITU), global smartphone shipments increased from around 300 million units in 2010 to approximately 1.4 billion units in 2021. This could pose a significant threat to dematerialization, particularly if countries fail to take action to improve education in schools and society.

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4. Conclusion

Dematerialization is essential for attaining the United Nations Sustainable Development Goals (SDGs), especially those concerning resource efficiency, climate action, and the responsible usage of finite resources. Industries can decrease waste, reduce greenhouse gas (GHG) emissions, and foster sustainable resource utilization by optimizing material usage and decreasing physical materials. The adoption of dematerialization is increasingly gaining momentum globally from industrial, economic, and policy viewpoints. Industrial Ecology (IE) frameworks and Circular Economy (CE) models, in conjunction with national sustainability legislation and technical breakthroughs, are being utilized globally to facilitate this shift. These projects prioritize minimizing material consumption and improving resource efficiency, yielding environmental advantages while sustaining conventional economic growth.

The benefits of dematerialization extend beyond mere resource conservation and emission mitigation. Technological innovation is driven by the demand for more efficient, durable, and eco-friendly materials, facilitating advancements across several sectors. Nonetheless, considerable obstacles remain, such as technology constraints, substantial initial expenditures necessary for the implementation of dematerialization initiatives, and market reluctance to embrace new practices. The shift to a dematerialized economy necessitates robust regulatory support and international collaboration to overcome these challenges.

To fully harness the promise of dematerialization and connect with the Sustainable Development Goals, sustained efforts from governments, corporations, and individuals are needed. Cooperative initiatives are essential to surmount obstacles and realize the enduring advantages of sustainable development. Consequently, dematerialization can act as a vital catalyst for innovation and environmental responsibility, steering us towards a more sustainable and fair future.

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