Article

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Circular economy and energy transition: A nexus focusing on the non-energy use of fuels

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Abstract

Given emerging concerns about climate change, low-carbon energy transition is advocated and promoted. Non-energy use of fossil fuels accounted for 8.9% of the world's total final energy consumption in 2015. Non-energy use intensity does not show an evident reduction, while energy intensity as fuel per dollar of gross domestic product has decreased thanks to energy transition efforts such as energy efficiency promotion and renewable energy expansion.

This study conducted an extensive review of the circular economy and energy transition frameworks, and found that the energy transition framework has a critical gap, so it cannot provide a foundation for investigating non-energy use. This study suggests that the energy transition discourse needs to be extended to incorporate the transition of non-energy use and the achievement of a closed loop of non-energy use, which is part of the circular economy framework. The coordinated circular economy–energy transition approach could bring in synergistic effects, such as promoting circular economy activities among industries, reducing energy demand, and attaining additional greenhouse gas mitigation potential.

Keywords

Circular economy, energy transition, low carbon, non-energy use of fuels

Introduction

Both circular economy (CE) and energy transition (ET) concern the environment as well as the economy and promote reaching a sustainable future. *CE* aims to optimize the use of

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resources by eliminating waste in the life cycle of a good or a service;[1] while the aim of contemporary *ET* is the changes to a sustainable energy system consisting of diverse and low-carbon resources.[2] While the concepts of CE and low-carbon ET have emerged in the 21st century, little conversation has been established between them. This study proposes to use the *non-energy use* (NEU) of fossil fuels as the connecting link between the CE and ET literature.

NEU covers products used as raw materials for industrial production or for direct use, such as bitumen to waterproof roads, rather than being used as a fuel or transformed into another fuel[a].[3] NEU have rarely been spotlighted in ET literature despite being a main component of energy consumption, comprising 8.9% of worldwide total final energy consumption (TFEC) in 2015. The NEU of fossil fuels as raw materials plays a significant role in the inputs to a CE, particularly in the petrochemical industry, even though these raw materials are not called NEU. The objective of this study is to extend the current discussion of ET to include NEU resources and find linkages between research into the CE and ET.

This study statistically examines global NEU and reviews how NEU is discussed in the CE and ET literatures. The research objective is to establish a bridge between CE and ET by focusing on NEU. To achieve the research goal, this study surveys global NEU and examines the changing pattern of NEU of fossil fuels. This study also reviews the CE and ET literature to answer the following questions: (1) How do CE literature/studies approach NEU of fuels? (2) How do ET literature/studies approach NEU of fuels? (3) Does a shared value exist between the fields of CE and ET? (4) Could NEU of fuels act as a connecting point between these two fields of research?

This study first defines NEU and introduces the significant role of NEU of fuels in modern life by reviewing statistics and literature. This study then discusses two important corresponding frameworks, CE and ET, investigating how NEU is discussed in each. The fourth section provides an integrated framework that can capture NEU issues for future ET studies. Contributions and directions for future study are identified as closing remarks.

Background: The definition and status of NEU

Definition of NEU

NEU is a key portion of final consumption in energy surveys and statistics. Most international organizations that collect global energy statistics provide definitions for NEU. The International Energy Agency (IEA) defines NEU as "those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel."[4] The European Commission states that "Final non-energy consumption includes fuels that are used as raw materials and are not consumed as fuel or transformed into another fuel (for example, chemical reactions or bitumen for road construction)."[5] In short, NEU covers products used as feedstock or raw materials in final consumption sectors rather than being consumed as fuel or transformed into another fuel.

Although NEU is classified as an energy consumption sector in energy statistics, usually along with the residential, industrial, transportation, and agriculture sectors, NEU is more of an activity, the usage of energy raw material to produce other non-energy products, than a final consumption sector.[6] Therefore, NEU can occur in any sector, and is most common in the industrial sector. For example, natural gas feedstocks are used to produce agricultural chemicals. Petroleum products (such as naphtha) and natural gas liquids are used for,

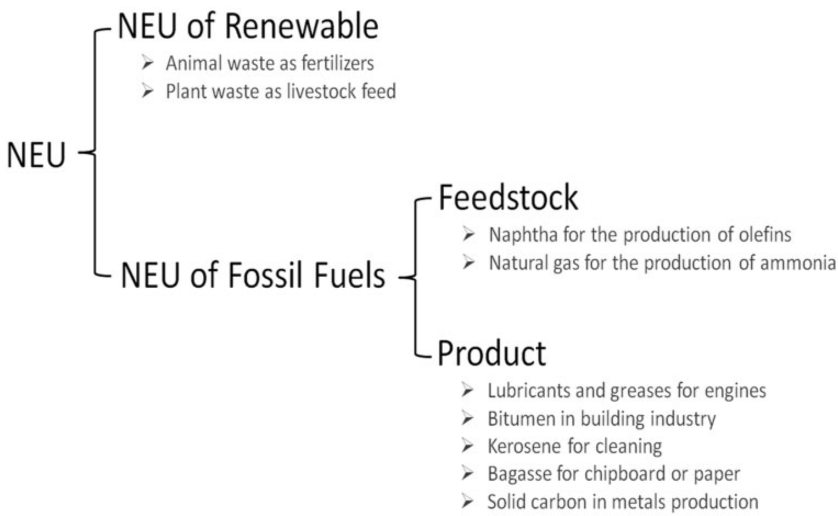

Figure 1. Categories and examples of NEU.

among other things, organic chemical manufacture and plastics. In addition to industrial production, NEU can also occur in other sectors, such as animal waste as fertilizers and plant residue as livestock feed in the agricultural sector and lubricants and grease for engines in the transportation sector.[6,7] Figure 1 categorizes NEU and lists some applications.

Statistics and trends in NEU

Figure 2 illustrates the world's TFEC, which includes the consumption of fossil fuels, renewable energy, and NEU consumption, between 1973 and 2015. In 2015, world TFEC was 9,383 million tons of oil equivalent (Mtoe), approximately double what it was in 1973 (4,661 Mtoe). Over the same period, renewable consumption increased from 609 Mtoe in 1973 to 1,052 in 2015, a 173% growth. Significantly, NEU consumption increased from 286 Mtoe in 1973 to 836 Mtoe in 2015, which is a 292% growth. NEU went from 6.1% of TFEC in 1973 to 8.9% in 2015. The increasing proportion of NEU is expected to continue because it is the primary source for fertilizers, polymers, automobiles, and metals, all of which continue to be widely used in modern economies.[8]

Table 1 shows the 2015 configuration of world NEU in more detail. Oil products[b] are the largest share of NEU (72.4%). Almost all (795 Mtoe, or 95.1%) of NEU is consumed in the industrial sector of the economy. The chemical and petrochemical industries are the largest NEU user, accounting for 74.4% (590.93 Mtoe) of total NEU consumption in the industrial sector[9,c].

In addition to the fuels mentioned in Table 1, biomass is also part of NEU, but it is not included in mainstream energy statistics databases. An exception is the FAOSTAT (Food and Agriculture Organization Corporate Statistical Database). The FAO forestry database accounts for wood as wood fuel (energy use) and wood for other usages, such as industrial roundwood (NEU). In 2016, global wood fuel production was 1,863 million m^3, and other wood usage was 3,618 million m^3. In other words, about 34% of wood was used as fuel while 66% was used as NEU.[11]

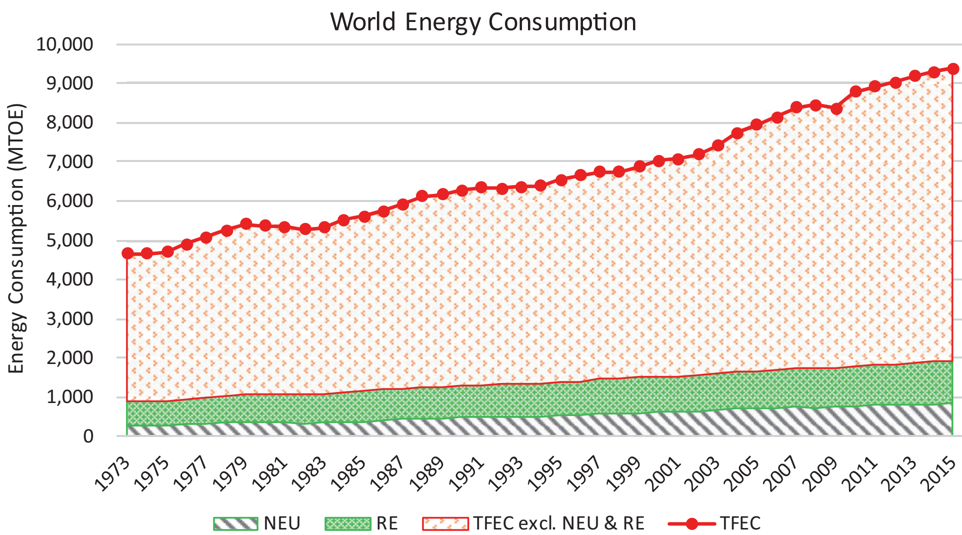

Figure 2. World energy consumption (1973–2015). *Source*: The authors constructed this figure, using data from IEA database.[9] Note: NEU, RE, and TFEC excl. NEU and RE stand for non-energy use, renewable energy, and total fossil fuel energy consumption excluding NEU and RE.

Table 1. Non-energy use consumption by fuel and by sector in 2015.

	Mtoe	Percentage
By Fuel		
Oil	10	1.2%
Oil products	605	72.4%
Coal	61	7.3%
Natural gas	160	19.1%
Total	836	100.0%
By sector		
Industry	795	95.1%
Transport	10	1.2%
Other	31	3.7%
Total	836	100.0%

Source: The authors constructed this table using data from the IEA database.

Figure 3 presents world energy intensities between 1973 and 2015. This chart implies a decoupling between fuel consumption (TFEC excl. NEU) and economic growth—energy intensity (energy consumption per unit of gross domestic product [GDP]) generally decreased over the period, except in 2010. However, no decoupling between GDP and NEU consumption can be found. The non-energy intensity (NEU/GDP) shows different patterns. NEU intensity fluctuates between positive and negative changes. This implies that a transition in energy as fuel has occurred, but a transition in energy as material has not yet been implemented.

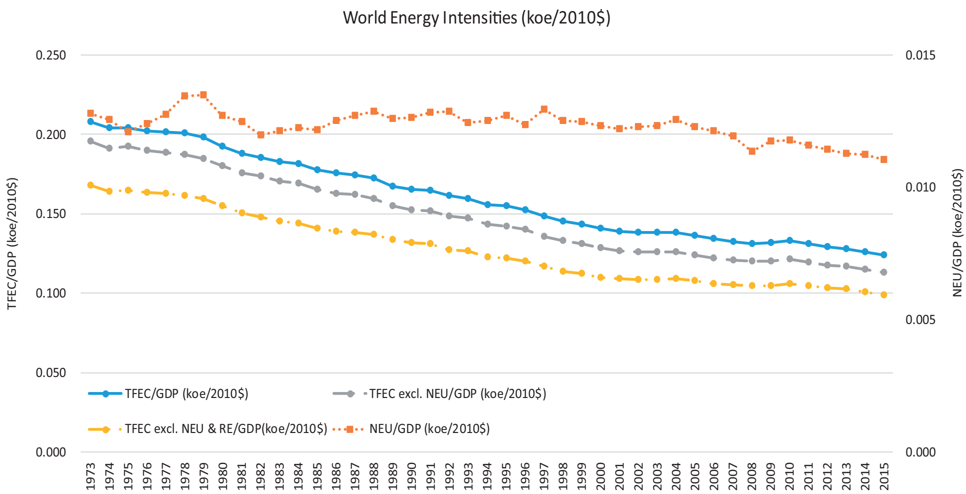

Figure 3. World energy intensities (1973–2015). *Source*: The authors constructed this chart using data from IEA database and World Bank database.[9,12]

The importance of the NEU of fossil fuels is revealed by its significant and steady use. However, this has attracted limited attention in the academy. This paper identifies NEU as a crucial piece for completing the puzzle of energy management as well as fostering a CE.

Literature review

Circular economy

Pearce and Turner (1990) first used the term CE to describe the resources and waste flow in an economic system.[13] They argued that material flows are circular, based on the first and second laws of thermodynamics. As described by Kenneth Boulding in 1966, the Earth is like a spaceship.[14] Within this spaceship, resources input into an economic system equal to the waste output. Economic and environmental interactions are not characterized by linear linkages, but by a circular relationship. Some material could reenter the economic system through recycling, but it is impossible to reuse all energy and material even in this circular system because some energy and material disappear entropically according to the second law of thermodynamics. Because a certain amount of waste cannot be recycled, sustainability requires ensuring that waste is within the capacity for environmental tolerance.

CE is advocated in both developed and developing countries. The European Union (EU) adopted a new CE Package in 2018 to help European businesses and consumers make a transition to a "stronger and more circular economy."[15] The Chinese government set CE as a national goal in the 11th Five-Year Plan (2006–2010), and its Circular Economy Promotion Law of 2009 included nationally focused CE indicators.[16] CE has, therefore, become widely used by politicians, practitioners, and scholars in multiple disciplines. However, definitions of CE have become diverse and vague. Therefore, many researchers have reviewed the current understanding and application of CE to enhance the transparency of this concept and move toward a consensus on terminology.[17–22]

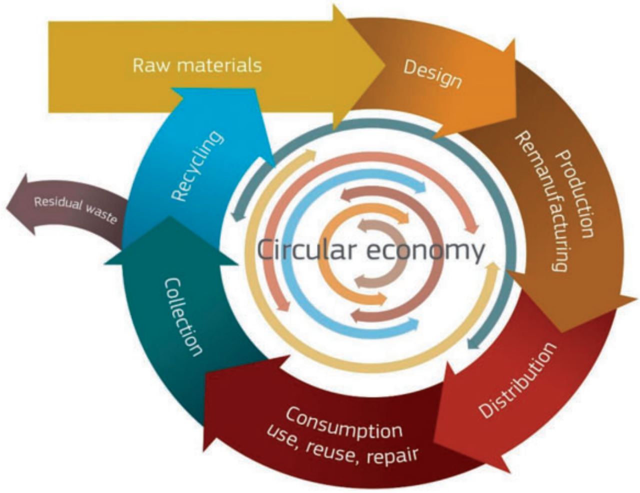

Figure 4. Conceptual and simplified diagram of circular economy. *Source*: European Commission.[25]

Although diverse CE definitions and applications exist (see Appendix A in Homrich et al.[17] and table 5 in Kirchherr et al.[42]) the "closed and circular loop" is still a basic CE concept and the "3R" (reduce–reuse–recycling) and life-cycle assessment principles are widely adopted as CE actions. For example, Geng and Doberstein (2018) stated that the CE is "closed loop material flow in the whole economic system." [1,23] Geissdoerfer et al. described CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling."(see Figure 4)[24]

The CE concept was formulated to discuss the interaction between economies and the environment. Its aim is decoupling economic growth from the growth of raw material and energy use. Today, CE is applied in response to the challenges of resource scarcity, environmental impact, and economic benefits.[21] CE research from the resource scarcity perspective detects material and energy flow during production and consumption. CE researchers oriented toward environmental impact study solid waste, landfill, emissions, or pollution issues. CE researchers focused on economic benefits examine cost savings, revenue increases, or GDP. By far, most CE research is within the resource scarcity or environmental impact perspectives.[21] Pan et al. explored increasing the waste-to-energy rate,[26] Li et al. promoted energy conservation,[27] and Waqas et al. increased the recovery rates of wasted fuels.[28]

Energy transition

ET is a structural change in the energy system, related to the collection, conversion, transport, consumption, and management of energy resources. Traditionally, ET studies have focused on major changes in energy usage from a historical perspective (Figure 5). Scholars such as Vaclav Smil identified energy usage patterns, the timing of the primary energy shifts,

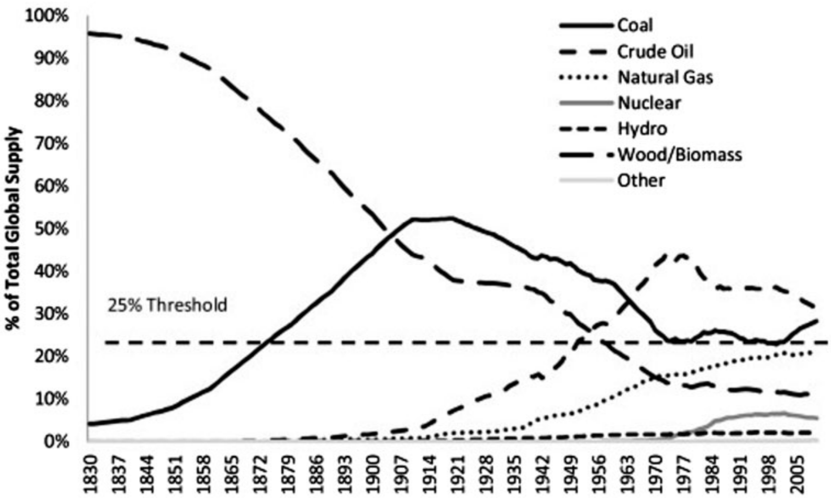

Figure 5. Global primary energy supplies by fuel source.[30]

and factors that accelerate changes. Today, ET studies have moved from historical analysis toward the outlook for future energy generation components and usage.[29,30]

Contemporary ET is also called low-carbon or sustainable ET. Unlike historical ETs, which were primarily driven by technical innovation and new resource adoption, low carbon transition is driven by a new global challenge: climate change.[4,32] Therefore, the most recent ET is led by national policies with the purpose of reducing greenhouse gases (GHGs) emissions and limiting the rise of global temperature to >2°C, as set in the Paris Agreement. The central approaches to reach this goal are renewable energy development and energy efficiency improvement.[33] They include various technical and policy innovations, such as electric vehicles, smart meters, carbon pricing, and emissions trading.

The pillars of low-carbon transition studies are parallel to the three dimensions of sustainable development: environment, economics, and society. As mentioned above, global environmental change has triggered the new ET. How the energy sector can transition to a decarbonized, reliable, and secure energy sector at reasonable costs is a key question. The policy goal is always facilitating economic development while promoting renewable energy and energy efficiency as found in one of the objectives of IEA, "promote sustainable energy policies that spur economic growth and environmental protection in a global context—particularly in terms of reducing GHG emissions that contribute to climate change."

Social considerations are widely included in low-carbon transition studies. As O'Connor[34] highlighted, the ET is a "particularly significant set of changes to the patterns of energy use in a society" (p. 8). Social dimension issues such as energy equity and stakeholder participation attract enormous attention. Energy equity deals with the accessibility and affordability of energy supply across the population.[35] Stakeholder participation policies encourage citizens to join community energy initiatives or projects (e.g., Kim[33] and Mundaca et al.[36]). To successfully reach a low-carbon future, innovations are necessary for both policies and technologies.[37]

The analytical concepts and approaches for ET are diverse and multidimensional. Scholars advocate adopting a multilevel analysis model to comprehensively examine questions about the recent low-carbon transition, including what it is and when, why, and how it occurs.[38,39] Sovacool proposed four major academic theories that could be used to understand ET, including sociotechnical transitions, ecological modernization theory, sociology and social practice theory, and political economy. Among practical approaches, the IEA established the World Energy Model and developed global energy statistics and accounting system as a basis for energy analysis. Many other international organizations and private companies, such as the World Bank and BP, also publish energy statistics and design new analytical methodologies. Because low-carbon ET is surging and dynamically changing, more academic and practical approaches are under development.

The comparison of CE and ET

Table 2 compares the goals and principles of CE and ET frameworks. It also categorizes the CE and ET literature, presenting the scope of studies and the main methodologies used. Each framework originates from a specific area: CE from industrial ecology and contemporary ET from energy, environment, and climate change studies. These two overarching frameworks provide theoretical foundations for different disciplines, and they have different definitions, goals, underlying principles, and implementing strategies.

The ET framework primarily focuses on energy, as seen in its definition, while CE covers materials as well as energy. The dimensions of CE goals are generally parallel to those of ET. CE spans resource, environment, and economy dimensions; ET incorporates social aspects related to energy use in addition to energy security (resource) and environmental sustainability (environment).

The differences in principles and implementing strategies are more distinct. Under CE, effective resource management such as 3R is pursued; these activities are evaluated and applied based on a lifecycle assessment. ET principles emphasize the conditions that enable low-carbon transition: shifting energy sources together with reduced energy consumption. In addition, the transition needs to allow more people to receive modern energy. Despite these differences, both ET and transition to CE need various stakeholders' participation and economic feasibility.[19]

Implementing strategies for CE generally focus on industries or product life cycles, such as closed-loop supply chains, while ET strategies focus more on energy systems, such as renewable energy deployment, and behavioral changes in the society or people surrounding the system.

There are barriers or lock-ins that hinder the transition to a CE or a low-carbon/sustainable energy system. Low-carbon ET is hindered by the resistance of existing sociotechnical systems, vested interests such as coal-power related stakeholders including investors and workers,[40] and policies that hamper innovation.[41] The core barriers to the CE are cultural, according to Kirchherr et al.'s EU study;[42] they include hesitant company culture and lack of consumer awareness and interest. Therefore, the CE concept is a niche discussion among sustainable development professionals instead of one that sees widespread practical implementation.

Table 2. Circular economy and low-carbon energy transition comparison.

	Circular economy	Low-carbon energy transition
Definition	Circulating the material and energy flows in an economic system as a closed loop	Transforming energy use into a low-carbon and sustainable pattern
Goals	• Environmental quality • Resource management • Economic prosperity	• Environmental sustainability (especially, climate mitigation) • Energy equity enhancement • Energy security guarantee • Economic prosperity
Principles	• 3R (reduction, reuse, and recycling) • 4R (3R plus recover) • 6R (4R plus redesign and remanufacture) • Life cycle assessment • Stakeholder participation • Economic feasibility	• Energy efficiency and conservation • Low-carbon energy (e.g., renewable energy) • Energy equity • Stakeholder participation (particularly, citizens) • Economic feasibility
Strategies (examples)	• Novel business model • Eco-industrial park • Closed-loop supply chains • Value chains • Sustainable design strategies (SDS) • Systematic change in society	• Renewable energy deployment • Innovative business models (e.g., energy cooperative initiatives) • Energy demand management (e.g., behavioral changes) • Energy efficiency enhancement (e.g., building retrofit)
Research disciplines (examples)	• Industrial ecology • Material science • Chemical engineering • Environmental policy • Waste management • Economics • Mechanical engineering • Chemical engineering	• Environmental/resource economics • Energy policy • Electronic engineering • Sociology • Geography • Engineering
Barriers	• Technology • Lack of consumer interest/awareness • Hesitant company culture	• Lock-in

Imperative nexus: CE and low-carbon ET

Non-energy use: The connection of CE and low-carbon ET

CE and low-carbon ET share common characteristics even though they were promoted by different disciplines. Both concepts concern the environment as well as the economy and aim to reach a sustainable future. To expand the scope of research for both CE and low-carbon ET, this study identifies the NEU as a crucial connection nexus that deserves more attention.

The NEU has attracted limited discussion in the ET literature. Most ET studies have focused on power generation from fossil fuels, i.e., the energy use of fossil fuels. However, fossil fuels are used not only as fuels but also as raw materials to produce various products. Although the energy system is gradually transforming toward a low-carbon paradigm,[43] the

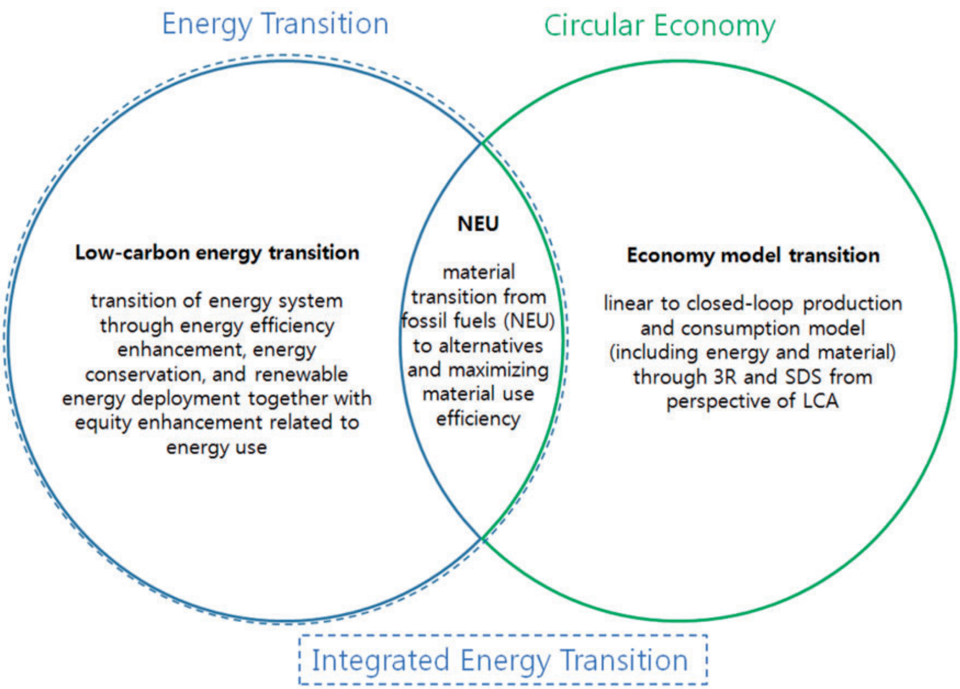

Figure 6. Schematic diagram of an integrated energy transition model.

high dependency on the NEU of fossil fuels has been rarely discussed. Vaclav Smil[29] indicated that in an era of emerging renewable energy, most alternative energy resources contribute to electricity generation. However, readily available alternatives for NEU have not been found and NEU is a large segment of modern energy consumption.[29] No practical solutions have been proposed in the field of ET. This critical missing part could be covered by the field of CE.

In CE studies, NEU is treated as feedstock for production and is categorized as material flow. Many CE–NEU studies have measured the practical and technical levels of the actual physical flows of materials in production-consumption systems[20] or have investigated approaches to reduce materials usage. For example, CE researchers investigated how to utilize biowaste to reduce dependence on NEU and promote production efficiency. The CE research into NEU could make ET studies more comprehensive. Figure 6 shows the interconnection of CE and ET studies, with the nexus of NEU. The reduction of NEU and using environmentally friendly alternatives to NEU in production can promote a CE. At the same time, a low-carbon ET could be promoted by relieving the dependence on fossil fuel NEU.

The integration of CE and ET with the nexus of NEU could contribute to climate change policies as well. CE activities are estimated to reduce up to 12.7% of global primary energy extraction,[44] which could efficiently cut greenhouse emissions. In addition, a pioneering study by the Finnish Innovation Fund, Sitra, and the European Climate Foundation showed that CE can play a vital role in reaching the goals of the Paris Climate Agreement.[45] Their report analyzed carbon emissions from plastics production and use and calculated that as much as 287 billion tonnes of emissions will come from plastic by

2100.[45] This analysis of plastics is a good example of integrating CE and ET concepts to consider NEU and achieve climate change goals. A contrasting example is the CE policy measures to reduce the waste generation in South Korea, which are carried out separately from ET policies. In turn, ET policies incorporate a very limited part of CE policies, only waste-to-energy, and miss other opportunities that could flow from this integrated approach.[46] The coordinated CE–ET approach could bring in synergistic effects, such as promoting CE activities among industries, reducing energy demand, and attaining additional GHG mitigation potential.

Integrated research direction

Low-carbon ET is imperative due to the contemporary ecological challenge of climate change. In fact, climate change provides a stage on which NEU can demonstrate the benefit of integrating CE and low-carbon ET concepts. Intergovernmental Panel on Climate Change (IPCC) working group III's sixth assessment report on various mitigation options, which is being currently prepared, will assess CE in its chapter 5 because it could affect energy demand (including NEU), and in turn affect GHG emissions.[47] This interdisciplinary group of researchers is looking into the potential of nexus of CE and ET. Still, the opportunities are not often recognized by decision makers or researchers in different disciplines.

Carbon accounting is an emerging methodology that acknowledges the significant role of NEU in energy consumption. The purpose of carbon accounting is to calculate the carbon emissions from energy production and consumption. Most countries use the IPCC Reference Approach (IPCC-RA) to estimate national carbon emissions from NEU of fossil fuels. However, uncertainties exist because of inconsistent definitions of NEU across countries, the complexity of energy and material flow in the chemical and petrochemical industries, and the different definitions of storage fractions in the IPCC- RA.[48]

Therefore, the Non-Energy Use Emission Accounting Tables (NEAT) was established in response to uncertainties about the NEU carbon emissions estimated by the IPCC-RA. The NEAT model estimates carbon emissions and storage from NEU based on material flow analysis (MFA).[49] Although the NEAT model was introduced in a special 2005 issue of the *Journal of Resources, Conservation and Recycling*, the material flow concept for carbon calculation is much older. Patel calculated the carbon emissions from NEU of fossil fuels in Italy using MFA from cradle to final consumer products.[50]

Researchers have applied the NEAT model to many countries, including Italy, Japan, Korea, the Netherlands and the USA. Motta et al. applied the NEAT model to Italy and compared the results estimated by NEAT and the IPCC-RA.[51] Park used Korea as an example to demonstrate the different estimates by NEAT and by IPCC-RA.[52] Both cases showed that the NEAT model provides a more accurate estimation of carbon emission and storage from NEU than the IPCC model.

It is possible to go from the NEAT model to a practical application of ET and CE integration. The MFA of NEAT shows a way to connect ET and CE through the nexus of NEU. This model provides the foundation for GHG accounting of NEU, together with material flow (e.g., carbon contents in each material and lifespan and lifecycle of the material). The potential of GHG mitigation from CE activities such as increasing resource use efficiency by achieving a closed loop and shifting the material source from fossil fuels to bio-waste could be estimated using the NEAT model, as could the GHG mitigation potential of ET policies.

Conclusion and further study

Low-carbon ET is advocated and promoted to mitigate climate change and reach a sustainable future. Fuels can be used as energy or as raw materials. The latter is also called NEU, which accounts for 8.9% of the world TFEC as of 2015. Although the significant proportion of NEU in total energy consumption and low-carbon transition has been noted in recent decades, few carbon reduction efforts have been made in the NEU sector. Furthermore, NEU intensity does not show an evident enhancement, while energy use as fuel per dollar of GDP has decreased thanks to ET efforts such as energy efficiency enhancement and renewable energy expansion. Most ET discourse discusses transition of energy as fuels and energy use patterns. The NEU became an underemphasized gap within ET studies. Consequently, the ET discourse could not provide the foundations that enable experts to look into issues regarding fossil fuel-oriented materials that significantly account for the TFEC, which are furthermore essential for modern life because they are used as raw materials for products such as plastics, pharmaceuticals, and fertilizers.

To fill in the NEU gap in the ET literature, this study proposes that the CE framework could complement the ET framework. This study compared the CE and ET literature and found that the current ET framework has a gap. To incorporate NEU issues, the ET framework needs to be expanded.

This study provided an integrated framework for ET that incorporates NEU. This will contribute to promoting NEU studies as part of ET studies. Also, this study exemplified a methodology, the NEAT model. In short, the practical opportunities from the collaboration between ET policies and CE policies in terms of NEU, and the energy saving potential from CE activities, need to be explored. The opportunities for maximizing material and resource use efficiency and investigating alternatives to NEU are missed by existing ET policies.

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Notes

a. This definition is adopted by the European Commission (Eurostat), the International Energy Agency (IEA), the Organization of Petroleum Exporting Countries (OPEC), and the United Nations Economic Commission for Europe (UNECE).
b. Oil products are oil-based products obtained by distillation. Oil products are typically used outside the refining industry. Examples include ethane, liquefied petroleum gas (LPG), aviation gasoline, and many more. The IEA provides detailed information at www.iea.org/statistics/resources/balancedefinitions/

c. However, the NEU data in international energy statistics are subject to uncertainty because of inconsistent system boundaries for NEU data among countries. Proposed solutions include the bottom-up methodology established by Weiss et al.[10]

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