Journal of Sustainable Development of Natural Resources Management

http://www.sdewes.org/jsdnarema

Year 2025, Volume 1, Issue 4, 1010636

Review Article

Energy Implications of Circular Economy Solutions and Renewable Energy Integration

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Cite as: Boldyryev, S., Wan Alwi, S. R., Varbanov, P. S., Nowak-Ocłoń, M., Pan, T., Yu, H., Energy Implications of Circular Economy Solutions and Renewable Energy Integration, J. Sustain. Dev. Nat. Res. Man., 1(4), 1010636, 2025, https://doi.org/10.13044/j.sdnarema.d1.0636

ABSTRACT

The global transition towards sustainable development necessitates the integration of renewable energy systems with circular resource management to mitigate environmental impacts and enhance efficiency. This review emphasises the urgent need to assess how circular economy strategies interact with the deployment of renewable energy in practical settings. It is posited that a synergistic integration of these two approaches can significantly improve sustainability outcomes. The study utilises a systems-level analysis that encompasses thermodynamic evaluations, spatial planning, and optimisation of energy flows through advanced process integration methodologies. Several groups of challenges have been identified – thermodynamic, spatial, and multiplicity challenges. The multiplicity challenge class is the most complex, encompassing topology, variability, and organisational subclasses. The review points to several possible tools to be applied – including Energy Quality Pinch for the thermodynamic challenges, P-graph framework and digital orchestration to address the multiplicity and organisational challenges. The review concludes that the strategic application of intelligent coordination mechanisms, transparent accounting frameworks, and emerging technologies has the potential to realise the benefits of sustainable circular energy systems fully.

KEYWORDS

Circular Economy; Sustainable Development; Renewable Energy; Process Integration; Waste-to-Energy; Material Recovery.

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INTRODUCTION

The Waste-to-Energy (WtE) principle has been implemented into policies and practices worldwide – starting with Germany [1]. The government of the Philippines has also followed this trend, as analysed by Anonas et al. [2]. The authors reported that the core of the Philippine WtE policy is the waste generation minimisation in the first place, which is also in line with the well-established Waste Hierarchy [3].

The drive to using renewable energy has been investigated at the continental scale with medium-term trend evaluation for Europe by Potrč and co-authors in 2021 [4]. Setting up the EU's climate targets by 2050, the authors forecast that it is possible to achieve them without compromising food production, based on the significant increase in the installations of wind and solar power generation capacities, as illustrated in Figure 1. This result implies further elaboration concerning the power system stability, the quality of service and ensuring sufficient freedom of choice to European energy users.

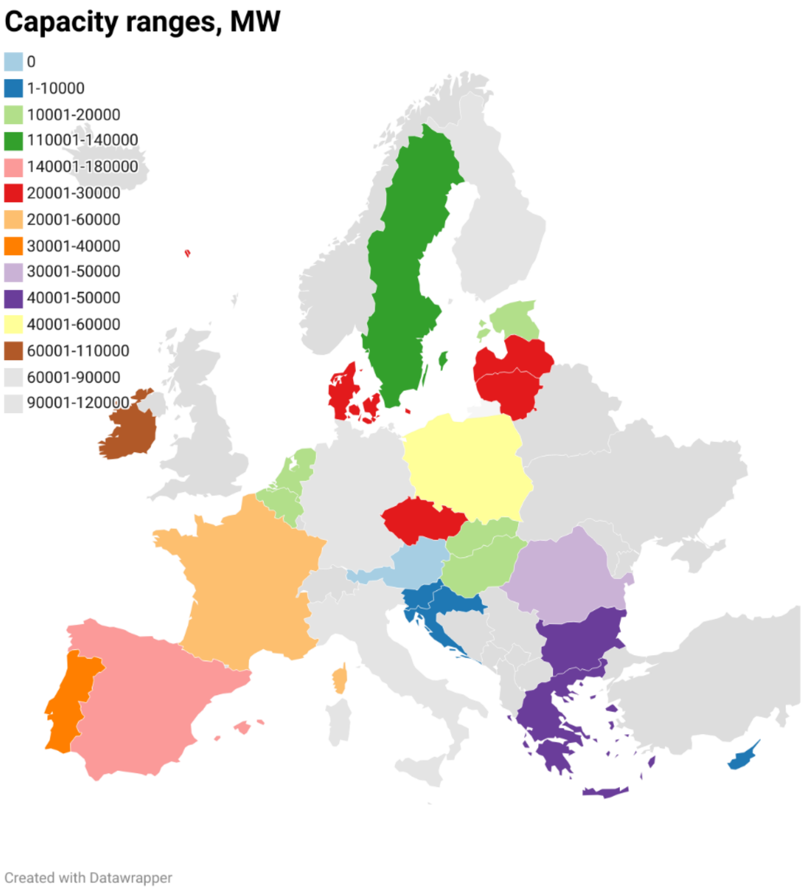

Figure 1. Forecast of the distribution of renewable electricity generation in 2040; summarised from [4] using Datawrapper [5]

Various industrial symbiosis implementation strategies can be devised in response to the resource scarcity and environmental pollution - the paramount challenges facing contemporary society. Traditionally, companies have adopted a linear model of production and sales, focusing on generating greater quantities of goods without aligning their output with society's actual demand. This approach not only leads to inefficiencies but also significantly escalates energy consumption during the manufacturing processes. Moreover, the prevalent patterns of consumption within society, characterised by unsustainable and energy-intensive habits, exacerbate the demand for energy resources necessary to sustain the modern economic framework. As a result, energy security has emerged as a critical priority on the agendas of governments worldwide [6].

The Circular Economy has been the subject of numerous studies, including the formulation of circularity indicators. Some examples of previous analyses include the evaluation of the recyclability of renewable energy technologies [7], an editorial presenting a special issue with bibliography annotations [8], an approach to using circularity for reducing the intensity of the energy-water-food nexus [9], an econometrics-based evaluation of the circularity efforts in Europe [10], and an editorial review paper [11] related to Process Integration for energy efficiency and utilisation of renewable energy.

It can be summarised that previous works and reviews have covered energy efficiency, energy integration and process circularity as separate issues and as potential nexuses. However, the systematic evaluation of energy implications, challenges, problem classes, and the necessary methods for minimising external energy input and environmental impact are not well covered. The current review targets this gap by first defining the problem and then analysing the problem and the potential solutions. The review proceeds to identify a set of key challenges and potential solution tools, supporting the points with specific references to previous research.

PROBLEM FORMULATION

The global transition toward a low-emission economy requires the simultaneous implementation of circular economy (CE) strategies and the integration of renewable energy sources (RES). Despite a growing number of publications highlighting the benefits of both CE and RES, there is still a lack of comprehensive analyses that consider their mutual interactions and integration in real-world systems. This omission is significant, as CE and RES systems influence each other through complex, non-linear, and multi-scalar material and energy flow interconnections.

The interdependence between CE and RES is not merely a technological issue but a systemic one, encompassing multidimensional challenges related to optimising flows, minimising environmental footprints, and ensuring economic viability. A lack of integrated approaches can lead to situations where seemingly green solutions become inefficient or even contradictory to sustainable development goals. For example, recycling processes may generate more emissions than would be avoided by reducing the need for primary production.

Therefore, it is essential to identify the key problem classes and potential tools that would allow the development of advanced analytical methods and planning tools. Those future tools should enable the identification of intersection points between CE and RES systems, the evaluation of the economic viability and energy efficiency of their integration, and the optimisation of these combined systems under real-world conditions, taking into account

The global patterns of material and energy flows

Energy supply to urban, rural, and industrial systems is strongly dependent on Thermodynamics [12]. This has been observed and analysed in the work on Thermodynamics-based sustainability evaluation of industrial and other processes [13]. The core property of material flows on Earth is that they always form closed loops with regard to the environment, including industrial and business processes (**Figure 2**). Within this circularity, there are two possible modes of operation. The first way involves a lack of or poor waste management [14], which results in varying degrees of pollution, causing environmental [15] and health impacts [16]. The alternative route is to purposely manage the waste streams via combinations of treatment, reuse, and recycling, which is expected to significantly reduce both environmental footprints and the demand for fresh natural resources [17].

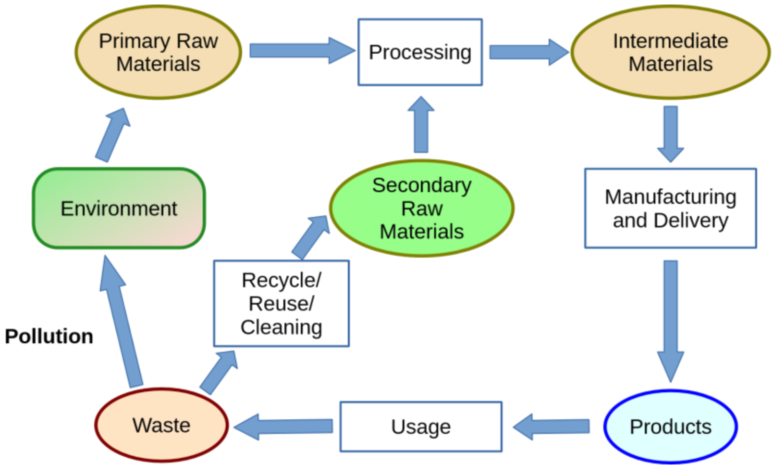

Figure 2. Circularity of terrestrial material flows, after [13]

There are technologies to recycle many types of waste, as can be seen by overviews from various perspectives – "zero waste" [18], water and wastewater management [19], targeted wastewater treatment methods analysis [20], as well as in food waste valorisation [21] and biofuel production from industrial and agricultural waste [22]. Further technologies can also be developed, and it can be assumed that waste streams can be successfully prevented or treated nearly completely from the viewpoint of mass balances. However, the energy demand and the associated emissions of the overall material resource life cycles need further evaluation to ensure that they are minimal and acceptable. This is why it is essential to pay attention to the patterns of the energy flows.

From the viewpoint of terrestrial systems (i.e., on the planet Earth), the net energy supply comes from the Sun [23]. This is reflected in the work by Varbanov et al. in 2020 [13] and demonstrated in Figure 3. The main observations from that work are the following:

- The Sun supplies primary energy, which, when captured, enters the terrestrial energy systems at certain quality levels and, by flowing through the systems, is cascaded, degraded, and dissipated.
- The energy supply options conventionally thought of as energy sources are, in fact, carriers of energy captured and stored at various locations on Earth.

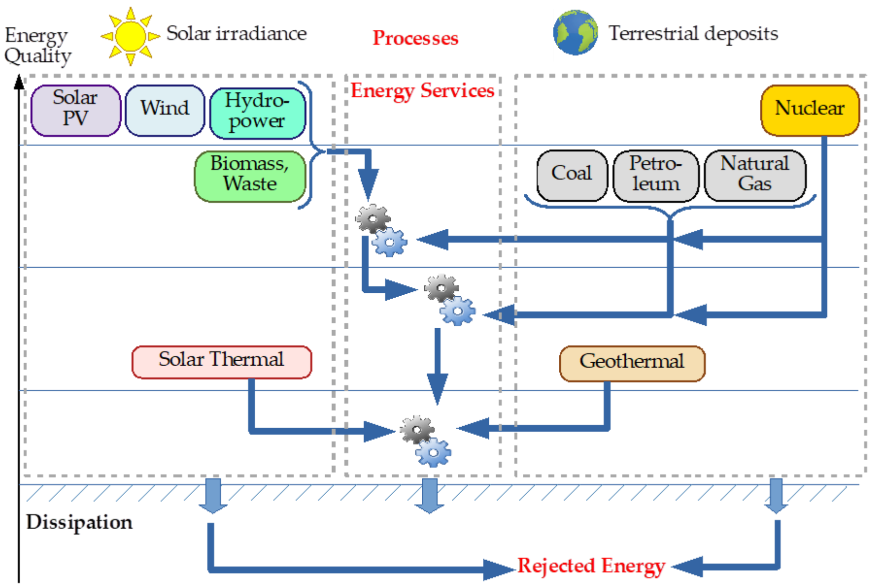

Figure 3.Terrestrial energy flow patterns, after [13]. The gear wheels represent industrial and business processes

Key challenges of energy supply, conversion and use

The main challenges faced in the supply, conversion, and utilisation of energy hinge on two critical dimensions: thermodynamics and spatial organisation. Thermodynamics is fundamental in determining how energy flows, transforms, and is employed [24]. The principles governing thermodynamics reveal the constraints of energy efficiency, exposing the significant losses that arise during conversion processes. For instance, converting fossil fuels into electricity through combustion not only leads to substantial heat losses, reducing the overall efficiency, but also results in environmental impacts [25]. Additionally, the unique thermodynamic characteristics of different energy sources influence their effectiveness for applications [26]. Renewable resources such as solar and wind energy face specific challenges, as their effectiveness relies on variable natural conditions [27]. The task at hand is to effectively capture these energy sources and convert them into a stable, usable supply while addressing the inherent thermodynamic inefficiencies that can emerge at various operational scales.

Conversely, spatial organisation encompasses the geographical and logistical elements of energy supply chains [28]. The location of energy sources, whether fossil fuel reserves, nuclear facilities, or renewable energy installations, has a crucial impact on energy accessibility and distribution. For example, while solar energy generation is optimal in sunny regions, these areas may not always align with high-demand centres [29]. This gap necessitates the development of robust transmission networks to distribute energy over large distances, introducing challenges related to infrastructure costs, grid reliability, and potential transmission losses [30]. Furthermore, urban planning and policymaking significantly shape how energy is consumed in any given locality [31]. Embracing energy-efficient technologies and smart grid solutions can enhance accessibility and usage, but this requires meticulous spatial planning and collaboration among diverse stakeholders.

To effectively tackle the challenges surrounding energy supply, conversion, and utilisation, a holistic approach that integrates the principles of thermodynamics [32] with the intricacies of spatial organisation [33] should be adopted. By paying attention to both dimensions, the way to a sustainable energy future that optimises efficiency while ensuring equitable access to energy resources can be paved.

Energy generation from fossil fuels

Fossil fuel-based energy generation presents a multifaceted array of scientific, environmental, economic, and geopolitical challenges that necessitate critical examination [34]. The combustion of fossil fuels, namely coal, oil, and natural gas, releases substantial quantities of CO_2, methane, and a variety of other greenhouse gases [35]. This release significantly exacerbates global warming and climate change, leading to a cascade of environmental consequences, including rising sea levels, extreme weather events, and biodiversity loss [36]. Additionally, the combustion process generates air pollutants, such as SO_2 and nitrogen oxides [37], which contribute to the formation of acid rain and smog [38]. These pollutants have direct and detrimental impacts on human health, resulting in respiratory diseases, cardiovascular issues, and increased mortality rates [39]. Environmental degradation extends beyond the atmosphere. Fossil fuel extraction and processing also affect aquatic ecosystems [40]. Water contamination from oil spills [41], runoff from coal mining activities [42], and chemicals used in hydraulic fracturing [43], pose severe threats to both ecosystems and the availability of safe drinking water for communities.

The limited availability of fossil fuel reserves raises long-term concerns regarding energy sustainability. Many easily accessible deposits are being depleted at an alarming rate [44], propelling the need for potentially environmentally damaging extraction methods such as deep-sea drilling [45] and tar sands processing [46]. These techniques not only pose ecological risks but also incur high economic costs, adding complexity to energy production. Energy security emerges as another critical issue; numerous countries heavily rely on imported fossil fuels [47].

This dependency exposes them to vulnerabilities associated with geopolitical instability, potential supply chain disruptions, and fluctuations in global markets. Furthermore, the existing fossil fuel infrastructure, including power plants and pipelines, demands ongoing maintenance, retrofitting, or complete replacement due to ageing facilities and increasingly stringent regulatory frameworks aimed at mitigating environmental impacts.

The inherent inefficiency of thermal power plants, which often dissipate significant amounts of energy as waste heat [48], diminishes their viability relative to advancing renewable energy technologies. The current paradigm also highlights occupational hazards associated with fossil fuel industries, such as coal mining and oil drilling. Workers frequently face exposure to toxic substances, risks of explosions, and long-term health complications, underscoring the societal costs tied to fossil fuel reliance [49]. In response to these multifarious challenges, global commitments to decarbonisation are intensifying. Policymakers are enacting stringent climate policies, including carbon pricing and emission caps, to incentivise a transition toward renewable energy sources such as solar, wind, and nuclear power [50]. These alternatives not only promise greater sustainability but also efficiency in energy production and distribution [51]. As the global energy landscape undergoes tectonic shifts, economies reliant on fossil fuels face significant financial and social restructuring challenges. The transition to a cleaner energy future demands substantial investments in innovative technologies, workforce retraining programs to assist those affected by the shift, and modernisation of the energy grid. Only through these concerted efforts can nations navigate towards a stable and resilient energy paradigm that prioritises environmental stewardship and sustainable growth.

Worldwide Virtual GHG Emission Flows

Much energy coming from fossil fuels is spent on manufacturing and shipping goods, which is associated with significant GHG footprints. The 2017 review analysis by Liu et al. [52] presented a mapping of the virtual GHG flows from international trade between continents (Figure 4). The study clearly illustrates the significant virtual GHG flows resulting from transcontinental supply chains. A substantial disparity between production-based and consumption-based accounting of the GHG emissions was identified by that work, pointing to the need for a more equitable accounting and balanced emission target setting.

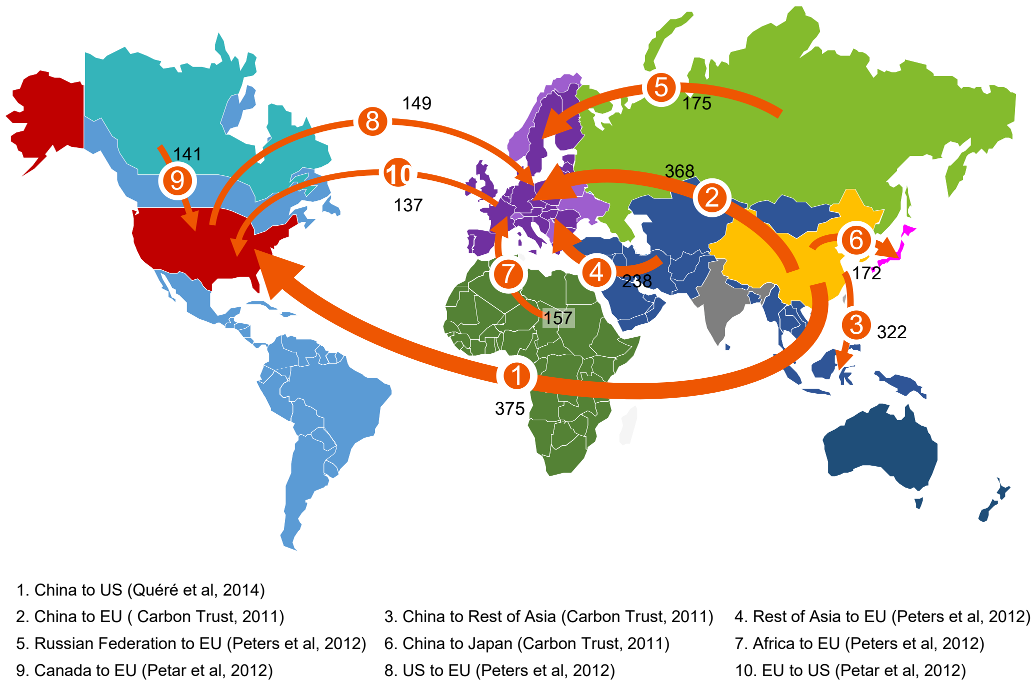

Figure 4. Virtual GHG Emissions Flows in International Trade, after the 2017 study by Liu et al. [52]. The numerical values in black font represent the magnitudes of the virtual GHG flows in $MtCO_{2eq}/y$

Another lesson can also be extracted from this work. The scale of the virtual flows (black-font values in **Figure 4**) is very substantial, indicating the need to work on the serious reduction of emissions. Although this study was published 8 years ago and reflects 10-year-old data, international trade and specific emissions have not decreased substantially since then, as indicated by a recent study by a UK-Chinese team of authors [53].

The environmental footprints of the main energy sources. Based on the European Commission's EU energy figures for 2024 [54], global energy production can be categorised into six primary sources:

- Petroleum and products
- Solid fuels
- Gas
- Renewables
- Nuclear
- Others

The total world energy production in 2022 was reported as 15,072 Mtoe (**Figure 5**), illustrating the contribution of different energy sources. The data highlights that petroleum, solid fuels, and gas remain the primary energy sources, with renewables following behind. This indicates that the global energy landscape is still largely dominated by fossil fuels [55]. As the world seeks to address climate change while ensuring sustainable growth, evaluating the environmental footprint of different energy sources is essential [56].

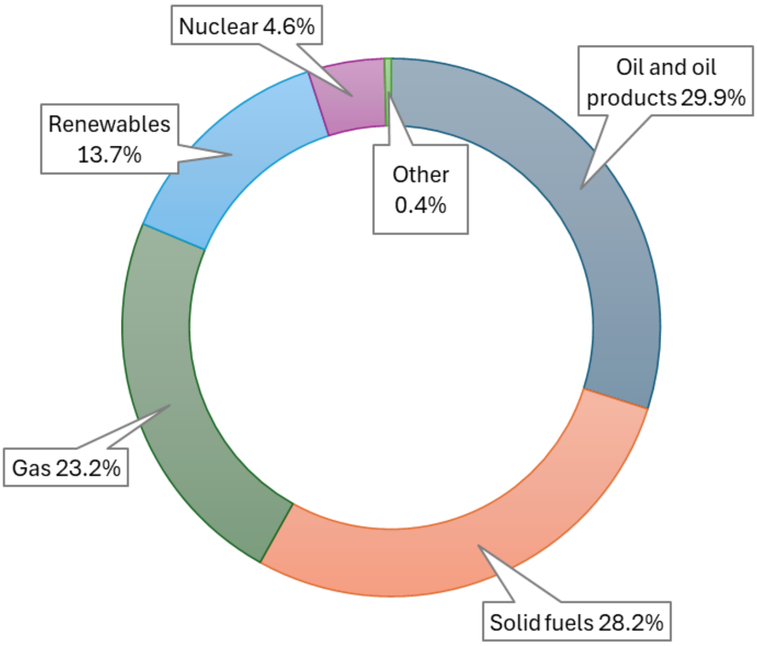

Figure 5 . The global contribution of different energy sources in 2022, developed based on [55]

Among renewables, solar energy, wind, and hydropower are the most widely adopted energy sources [57]. Solar photovoltaic (PV) systems have a relatively low environmental footprint, with land use, water consumption, and material recycling being key considerations. Innovative approaches such as floating PV systems and self-cleaning technologies can enhance efficiency while minimising land and water use [58]. Concentrated solar power (CSP) systems, on the other hand, have water consumption levels that depend on site conditions and system specifications, with non-water-based cleaning methods being the most effective for reducing the environmental footprint [59]. The land use will be at a reasonable level due to space-efficient designs. CSP power plants have an insignificant influence on wildlife or human health during their operation phase. However, during the construction stage, the CSP plant has a negative impact on the local environment [60]. Wind energy faces challenges related to land use due to turbine spacing requirements. Wind farms also impact wildlife, particularly bird populations, and generate noise and visual disturbances [61]. Hydropower plants have zero GHG emissions during operation, but during installation, maintenance and decommissioning, GHG emissions are released. However, the longer lifespan (50-100 y) makes the latter emissions negligible. The dams change the temperature and the flow of the water, as well as the chemical characteristics of the surroundings. The fish mortality from hydropower turbines ranges between 5 % to 10 % [62]. Fossil fuels have the potential for improved climate performance when integrated with carbon capture and storage (CCS). However, CCS poses challenges such as potential leakage, high costs, and societal concerns regarding storage site selection [63]. Figure 6 demonstrates the effects of various energy sources on the environment [64], emphasising the trade-offs between renewable and conventional energy technologies. It must be emphasised that the evaluation of the energy choices depends on selecting the context, and that some footprints can differ depending on the system setup. For instance, installing PV panels on building roofs would have much smaller land and ecosystem impacts than installing them in fields typically intended for crops.

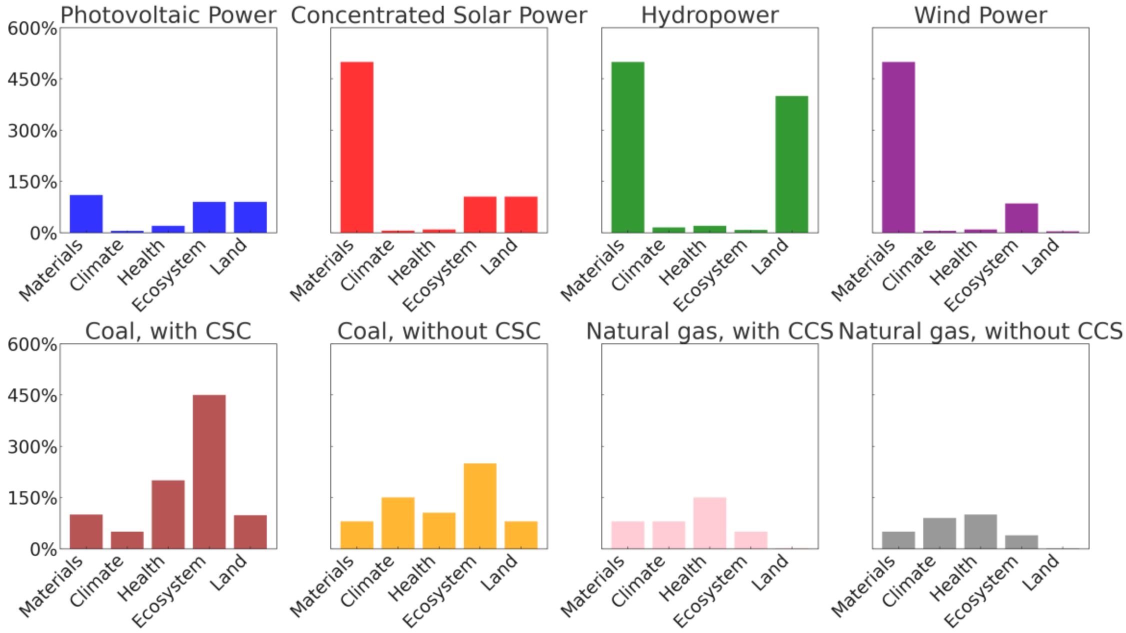

Figure 6. The environmental footprint of various energy sources (logarithmic scale), amended after [56]

Spatial organisation and logistics challenge of renewables

Waste collection for processing and the utilisation of renewable energy resources face a common challenge. While these activities have historically been based on different terminologies, the challenges and management patterns remain the same.

Municipal solid waste is collected from various households or neighbourhoods. In some cases, industrial waste must also be collected, concentrated and transported. In the terminology of supply chains, this is denoted as the "reverse logistics" problem [65]. It involves collecting varying amounts of waste (smaller or larger) from multiple disparate locations and transporting the collected batches to one or several processing hubs. This forms a network structure similar to a reverse tree (see Figure 7) as analysed in [66].

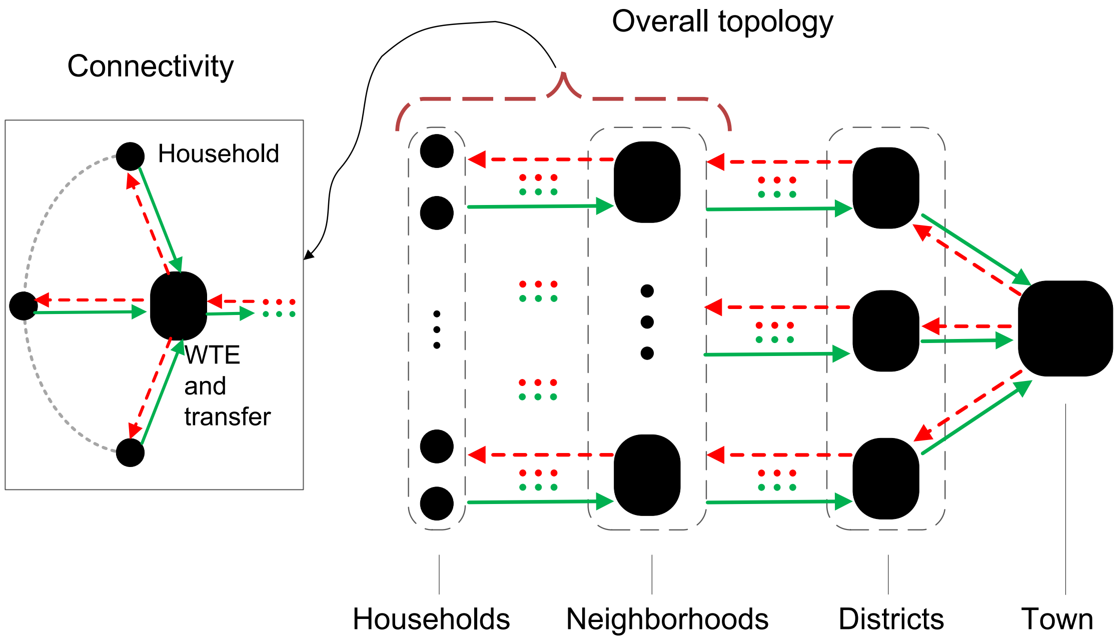

Figure 7. Reverse Logistics tree topology, modified after [66]

That processing topology was evaluated in the application area of Municipal Solid Waste (MSW) management in [67] to determine the optimal size of a collection area for energy recovery and GHG emission savings. The study clearly shows that while increasing the size of the collection area simultaneously increases

- The amount of waste that can be processed and valorised, together with the potential GHG emission savings;
- The overall area and distance to be served by the logistics network, along with the GHG emissions released from operating the logistics.

These two factors act in opposite directions with respect to GHG emission savings and energy recovery ratio from the system. According to that source [67], from the viewpoint of both criteria, collection zones of up to 20 km^2 seem most beneficial for lower population densities (up to 5000 inhabitants/km^2). The logistics factor tends to outweigh the potential benefits of waste valorisation for larger collection zones. In this context, the study is worth extending in terms of other environmental footprints (e.g., water footprint) and higher population densities, which are typical for highly urbanised cities, while in Europe, the urban population density usually is below 3000 inhabitants/km^2 [68], some cities worldwide exceed the range considered in [67], reaching 20000-30000 inhabitants/km^2 [69]. That processing topology was evaluated on the application area of MSW management to target how large a collection area can be viable from the viewpoint of energy recovery and GHG emission savings. The study clearly shows that, on the one hand, increasing the size of the collection area increases the waste collection amounts, making processing plants more efficient. On the other hand, that is also associated with the opposite trend of extending logistic routes, which results in unproductive emission overheads, and a reduction of the waste recycling benefits (see Figure 8). The lesson from this consideration is that distributed processing of waste streams must be contemplated, and any extended logistics have to be used only for the most valuable streams with high utility density – economic, material and other.

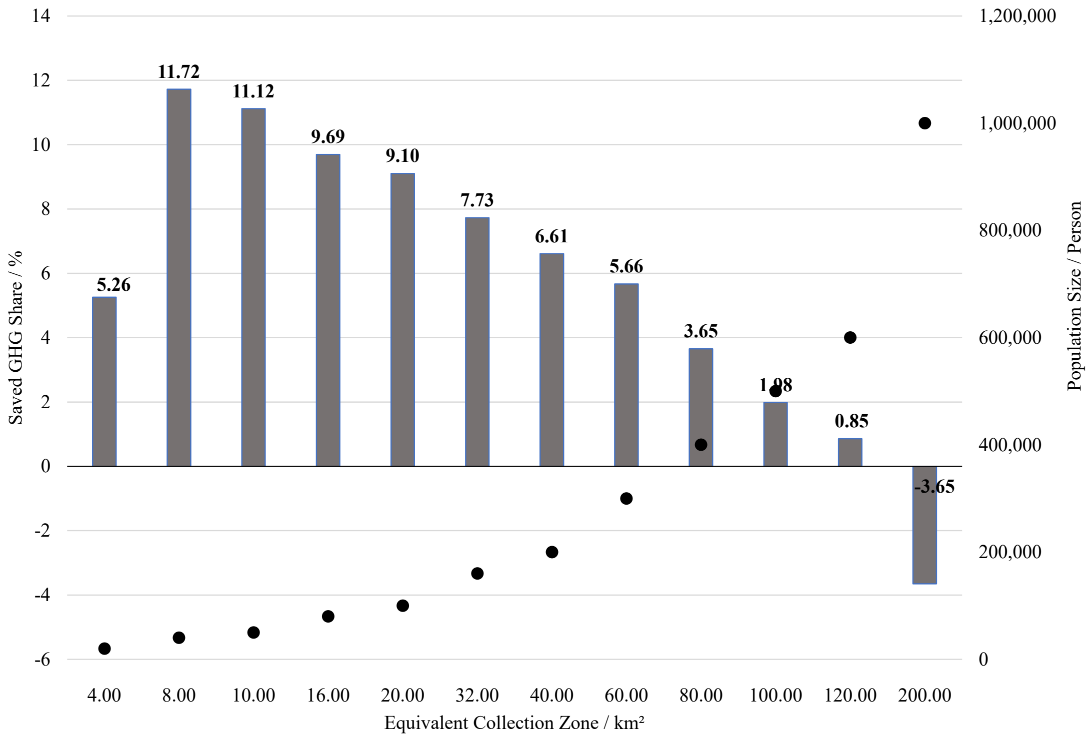

Figure 8. Waste supply chain trends. Legend: Bars denote GHG savings in % from replacement of fossil fuels; dots denote population size (inhabitants)

Biomass waste and biomass from energy crops, although not formally involving reverse logistics, are managed by operations that need spatial organisation. Crops are grown in fields of various sizes and at different locations within a region, then harvested and transported to processing hubs. This has led to the realisation of partitioning biomass-sourcing regions into zones [70] (Figure 9) and clustering those zones (Figure 10) for the collection and processing of biomass for energy [71]. The clustering models used GHG emissions as a minimisation objective function. That idea was further elaborated by Ng and Lam [72] to an extended method for clustering and supply network synthesis involving multiple sources of raw materials and multiple types of products beyond energy, essentially implementing the biorefinery concept.

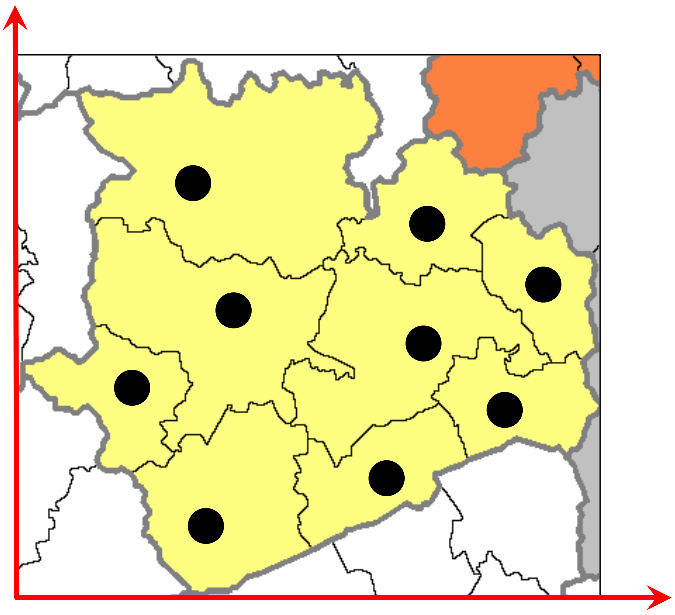

Figure 9. Region representation, partitioned into zones for exchanging secondary resources

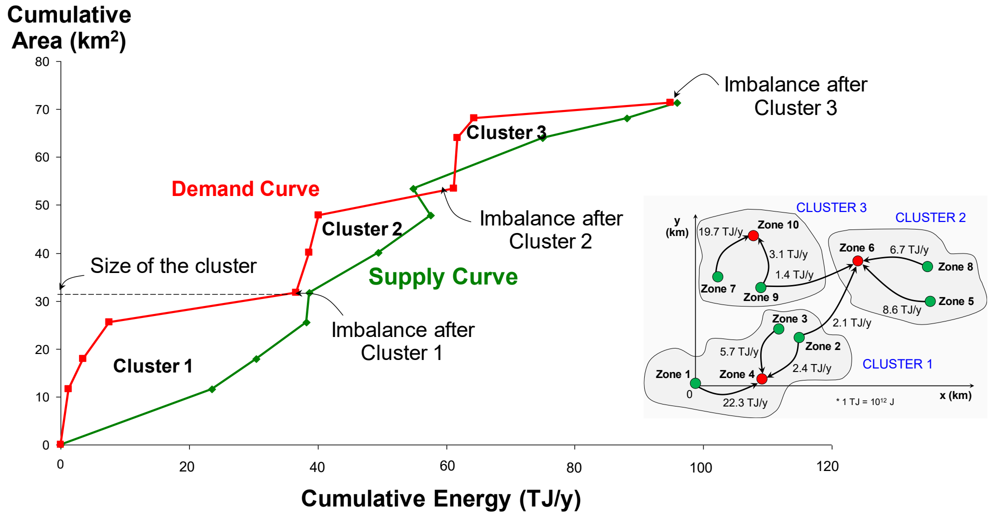

Figure 10. Regional Energy Supply Demand Curves for Regional Energy Clustering – target estimation for biomass utilisation in a region, amended after [71]

The other types of renewable energy sources are wind and solar energy, which are also collected over a certain area. This is followed by transportation operations that allow the concentration of the flows and their conversion into forms suitable for utility to users. Wind energy is typically directly converted to electrical power, while solar energy can be captured into thermal carriers or electricity, including combined devices, e.g., photovoltaic-thermal (PVT). The logistics challenge is apparent but much less pronounced when carriers with higher energy density are transported, such as petroleum, distilled fuels, and natural gas, including liquid natural gas (LNG) and synthetic natural gas (SNG). In summary, the logistics takes away a tangible part of the energy value of energy carriers, as presented in **Table 1**. By implication, the energy costs of logistics in symbiosis networks are also expected to be substantial.

Table 1. Energy expenditure of energy carrier logistics

Energy carrier/source	Energy expenditure/loss	Sources
Piped Natural Gas	Compressors along the pipeline route typically use 3-5 % of the gas; Up to 9 % of the gas is consumed by the delivery infrastructure in the United States.	Compressor consumption [73]; Overall facilities consumption in the USA [74].
LNG	6-20 % of the sourced natural gas (distances > 2000 km);	Flow analysis Pospíšil et al. [75].
MSW	MSW energy value outweighed by energy for transportation distance of ≈2 km (≈10 km^2 collection zone); GHG savings outweigh at ≈7 km	Varbanov et al. [67].
Biomass	Energy loss < 2 % for distances within 100 km. Cost of transport up to 28 % of the biomass price for 100 km transportation; GHG contribution of transportation up to 0.007 kg CO_2/kg biomass for 100 km transportation.	Energy loss, calculation based on logistical parameters [76] and fuel consumption [77]; For the cost, see Areias et al. [78]; GHG data [79].

The circularity challenges

There has been a strong and continued strive for a circular type of management of natural resources. This can be traced within official institutions, such as the United States Environmental Protection Agency [80], the European Union institutions [81], who have adopted the "Waste Hierarchy" concept into their regulations to foster a circular economy. There are also non-profit organisations, such as the Ellen MacArthur Foundation [82], who add research and training. Dedicated scientific conferences are organised annually by the University of Maribor, which provide a venue to present research and discuss ideas and practices on the Circular Economy [83].

There are two essential parts of the Waste Hierarchy concept. The first is to set up the priorities for business and social activities in a way that decomposes the waste management problem in an optimal way and simultaneously minimises two negative impact flows, waste disposal and resource consumption from nature. That philosophy can be traced in the Circular Integration concept formulated and discussed by Walmsley et al. [84]. The priorities are as follows:

- Reduce waste generation by preventing equipment failures and wear of assets and equipment, as well as reducing direct wastage of resources, such as energy or water.
- Reuse of products and assets, which represents circularity of user utility;
- Recycling of materials and material flows, representing circularity of materials
- Energy recovery by cascading and reuse, representing energy circularity, is typically implemented via energy integration or valorisation.

The second part of the Waste Hierarchy concept is related to the scope of the management of material flows and goods in the economy. This view of the concept is important for the identification of the key indicators, degrees of freedom and interactions in Process Systems that can bring about reduction of environmental footprints while ensuring thermodynamic and economic viability. This is illustrated in **Figure 11**. Starting with the demands for products and services and their use, these activities are served by product distribution, maintenance, and recovery. In turn, those are encompassed by activities on resource generation and conversion, resource delivery, resource harvesting and supply, ending with the natural resources (the environment) and the emissions, which have various negative impacts.

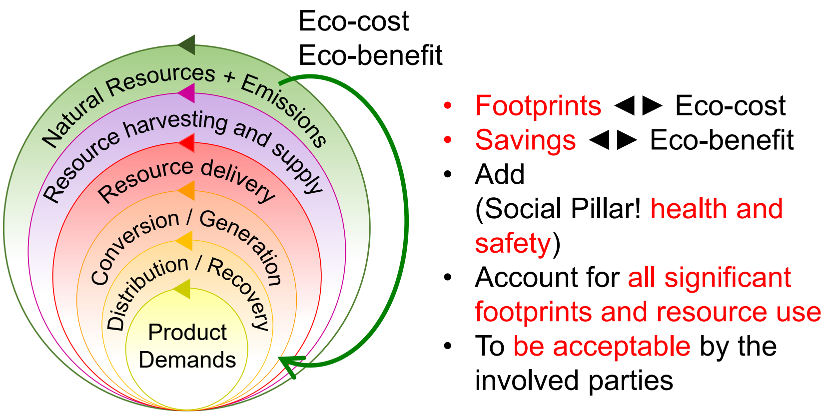

Figure 11. Process Systems from a control viewpoint

There are cases of recycling that result in net GHG footprint reduction. An example of this is presented by van der Hulst et al. [85] on the case of direct chemical recycling of plastic-rich post-consumer waste in the Netherlands. They investigated the chemical recycling of mixed plastic waste and evaluated the GHG emission balance on a Life-Cycle basis. The considered system boundary included feedstock transportation, processing to chemicals (olefins and other products), and energy generation from byproducts. The authors reported that the avoided GHG emissions exceeded the released ones by 0.04 kg CO_2-eq/kg recycled plastics. However, the result is highly dependent on the current GHG footprint of grid electricity. The reported positive figure is based on a given fuel mix with a relatively low share of renewables contributing to the grid.

The multiplicity challenges

Circular business patterns and renewable resource use systems inherit several classes of challenges from the linear business pattern based on fossil resources. They stem from the technologies to be considered, as well as the actors and types of actors who hold different viewpoints and interests. They intersect with the intermittent nature of renewable resources. The complication introduced by the circularity pattern is related to the need to retrieve secondary resources and feed them back to the processing and supply networks. As a result, the multiplicity challenge classes are

- The topology (combinatorial) challenge
- The need for reconciliation and orchestration of the behaviour of multiple system actors (stakeholders).
- Multiple operating modes of the energy capture and conversion facilities, as well as of industrial plants

ANALYSIS AND POTENTIAL DIRECTIONS

The analysis begins with examples of high recycling rates that have low energy or other footprints. The implementation of high-efficiency recycling methods with minimal energy consumption and environmental impact is essential for sustainable resource management. For instance, various recycling strategies substantially impact the German energy system. In the absence of recycling, energy demand is projected to exceed 300 TWh by 2050, and the costs associated with the transformation of the energy system are anticipated to increase by 85 % compared to a reference scenario reflecting current recycling rates [86]. To transition the concept of a Circular Economy from theory to practice, it is essential to capture and repurpose the residual value of plastic waste. This circular flow of secondary resources is facilitated by reverse logistics, which enhances the efficiency of recovery, reuse, and recycling processes [87]. Other authors developed a circular economy model for post-consumer expanded polystyrene waste by conducting a case study in collaboration with a local plastic manufacturer [88].

Minimising the energy intake of circular processes

Mineral resource limitations pose significant constraints on the sustainable development of green energy in the long term, leading to a plateau in low-carbon energy production [89]. A recent study intends to conduct a comprehensive and strategic evaluation of the recycling impacts associated with rare earth resources linked to renewable energy generation, focusing on environmental, economic, social, and governance dimensions [90]. To facilitate this analysis, a SWOT framework was developed, incorporating a management cycle alongside an intelligent text data mining technique. This approach enables a thorough exploration of the relevant issues from an ESG perspective.

Aluminium closed-loop recycling exemplifies this, requiring only approximately 5 % of the energy needed to produce primary aluminium, thereby significantly curtailing carbon emissions [91]. In Norway, Hydro Aluminium utilises hydropower in its operations, further decreasing the ecological footprint associated with secondary aluminium production [92].

The policy options and programmatic components of Extended Producer Responsibility (EPR) as implemented in the United States and Canada were examined. It traces the historical evolution of EPR in both countries and identifies the common characteristics that define EPR in each nation [93]. Paper recycling, particularly in eco-friendly paper mills that adopt enzymatic de-inking and closed-loop water systems, can achieve a reduction in energy consumption by up to 60 % compared to the production of virgin paper, in addition to minimising chemical usage [94].

Mechanical recycling of textiles, as practised in Italy's Prato district, allows for the recovery of wool and cotton fibres without the need for chemical processing. This method substantially mitigates the water and energy demands typically associated with textile manufacturing [95]. Moreover, composting organic waste through methods such as Bokashi fermentation and vermicomposting efficiently decomposes biomass without requiring industrial-scale energy inputs, promoting soil health and aiding in carbon sequestration [96].

Electronic waste recycling via bioleaching, employed by firms like Umicore, facilitates the extraction of precious metals such as gold and copper using microorganisms. This method notably reduces emissions and the generation of toxic byproducts when compared to conventional smelting processes [97]. Another research aims to fill significant gaps in the existing literature regarding gold recovery from electronic waste. It encompasses a variety of methodologies, including established techniques such as hydrometallurgy and pyrometallurgy, as well as less-explored approaches like mechanical processing and biotechnology for gold recovery, thereby addressing the disparity in attention given to these methods [98]. A comparative environmental and economic assessment of various recycling methods for plastic waste, including mechanical, physical, and chemical recycling, as well as energy recovery, utilising primary data alongside supplementary external information, was proposed. The results indicate that, for climate change mitigation, physical or chemical recycling represents a more advantageous alternative for processing plastic waste that is currently directed towards energy recovery or landfill disposal [99]. A comprehensive Recycling Potential Index has been developed to assess the recycling potential of high-tech metals utilised in low-carbon energy technologies in China for the period from 2020 to 2050. The findings reveal four distinct evolutionary trends in recycling potential: one trajectory indicates a rapid ascent to a high level, while another denotes a gradual increase to mid-range and mid-high levels [100].

The recycling strategy is widely investigated globally and may contribute significantly to the circularity concept. The application of recycled concrete powder and calcium carbide slag in the production of low-heat cement clinker was studied, with the objective of promoting waste recycling, conserving natural resources, and minimising the carbon footprint associated with cement manufacturing [101]. Investigations regarding treatment parameters, such as treatment temperature and duration, and the necessity for high production pressure (100 MPa) indicate practical challenges. The effectiveness of two novel treatment methods on compact materials, focusing on enhancing their strength and reducing their carbon footprint, was investigated in [102]. A comparative life cycle assessment was employed to evaluate the engineering material footprint and fossil fuel material footprint associated with the closed-loop recycling of three types of concrete: siliceous concrete, limestone concrete, and lightweight aggregate concrete [103]. Substituting diesel with synthetic diesel derived from electrolysis and coal for concrete recycling may potentially lead to an increase in the fossil fuel material footprint. In contrast, employing biodiesel produced from rapeseed and wood-based synthetic diesel can result in reductions of 47–51 % and 84–89 % in the fuel material footprint, respectively, when compared to a virgin diesel-based recycling system.

These methodologies illustrate that closed-loop and low-energy recycling systems can significantly diminish environmental footprints while maintaining material integrity, reinforcing the necessity of incorporating sustainable recycling technologies into global waste management frameworks. Energy flows have to be combined across different operations. This includes energy flows of different types and of different energy quality levels.

Basic examples. The interrelationship between wastewater treatment facilities and energy consumption emphasises their role as significant energy consumers and greenhouse gas emitters. In this context, the primary aim is to explore the potential utilisation of a wastewater treatment plant's internal chemical, potential, and kinetic energy, alongside the integration of external renewable technologies, to promote sustainable energy usage and decrease greenhouse gas emissions. The analysis focuses on the feasibility of implementing alternative technologies, such as anaerobic digestion, hydraulic turbines, wind turbines, and photovoltaic modules, to fulfil the energy requirements of the facility. The case study of the Jinamar plant, Canary Islands, Spain, demonstrates that a renewable energy production capacity of 3,396 MWh/year is achievable, which exceeds the energy consumption requirements of the plant. However, it also highlights the necessity for an energy storage system to address the seasonal variability in the availability of energy resources. In terms of mitigating climate change, this approach results in the avoidance of 2,754 t/y of greenhouse gas emissions **[104]**. Sewage sludge can be regarded as a renewable energy resource, as its incineration results in significantly lower greenhouse gas emissions compared to energy generation from fossil fuels. Specifically, when evaluated for equivalent energy output, the incineration of sewage sludge produces 58 % fewer emissions than natural gas and 80 % fewer emissions in comparison to hard coal and fuel oil. The study **[105]** demonstrated the feasibility of various sewage sludge disposal methods by examining three distinct scenarios: landfilling, co-incineration, and mono-incineration. The findings indicate that landfilling is the most cost-effective disposal method for approximately 60 % of the wastewater treatment plants assessed in Croatia, while co-incineration emerges as the preferred option for the remaining 40 %.

Another study investigated the continuous gasification of sewage sludge within an inert atmosphere. A systematic analysis was performed on a range of process parameters to assess their effects on the overall performance of the gasification system, with a specific focus on optimising syngas yield, increasing hydrogen concentration in the syngas, and maximising energy output. Drawing from the insights obtained, targeted recommendations have been developed to enhance the efficiency and output of the gasification process. These conditions culminate in a maximum syngas yield of 46 % (by mass) **[106]**. The energy valorised from waste can be effectively combined with various renewable energy sources to create a more sustainable and efficient energy system.

Energy Quality Pinch as a tool for large-scale energy integration

The essence of Energy Quality Pinch

This is a process energy assessment tool that determines the minimum energy requirements of a system was introduced based on the Energy Quality Factor, which measures the useful energy extractable from material and energy flows. Energy Quality Pinch Analysis identifies these minimum requirements while assessing the sustainability of circular systems. It evaluates energy cascades within recycling and symbiotic processes, considering high-quality energy inputs and waste energy outputs **[107]**. Applied to case studies, including Total Site Heat and Power Integration, chemical energy reuse in wastewater treatment, and MSW management, the methodology suggests practical energy conversion technologies. Results indicate that energy recovery rates can reach up to 60 % in utility systems and even higher in wastewater and municipal waste treatment contexts. The general procedure includes the following steps:

- Identify sources and sinks of material recycling (types, quantities, and compatibility).
- Determine the recycling processes and pathways (inputs and outputs of materials, energy balances, energy inflow and outflow, while accounting for energy quality).
- Categorise the pathways into energy sources and energy sinks.
- Establish the Energy Quality Cascade, along with the Energy Quality Profiles and Energy Quality Composite Curves.
- Implement targeting strategies.
- Conduct analysis and facilitate system evolution.

An example of a logistics-dominated problem

The preceding study examines a comprehensive MSW recycling supply chain, focusing on its larger-scale implications. MSW comprises various secondary materials that hold potential for reuse or reprocessing into valuable products, which can include both materials and energy. However, the recycling of MSW does not achieve complete circularity, primarily due to the energy-intensive nature of the recycling processes that necessitate external energy inputs. To optimise the sustainability of the MSW recycling system, it is imperative to investigate its maximum energy recycling potential and minimise the energy deficit within the system. This understanding will facilitate strategic system retrofitting, aimed at enhancing the sustainable circularity of MSW management practices [107].

Table 2 presents the full energy data of the processes used for this assessment analysis. In the context of the MSW study, energy sources are conceptualised as secondary products that can be transformed into energy, such as the outputs generated from incineration and pyrolysis processes. The energy demands are characterised as the energy necessities associated with each recycling pathway. The quality of this energy demand is evaluated based on two metrics: the fuel requirements and the electrical power requirements. It is important to recognise that both the energy sources and demands are influenced by the distribution of waste across the various recycling processes. To evaluate the maximum potential for energy recycling, taking into account this specific waste distribution, a corresponding Energy Quality Pinch Analysis is performed. This analysis facilitates the identification of opportunities for optimising energy recovery within the MSW recycling system.

This case study, shown in Figure 12, illustrates that the Pinch Point corresponds to an energy quality level of 1. The plastics recycling network requires a minimum of 209 MW of external energy. Approximately 78 MW of energy remains untapped. Under current quality conditions, around 28 % of energy can be recovered within the network, indicating a significant imbalance. To minimise energy losses and reduce energy input, modifications in processing may be warranted. Potential strategies include integrating additional energy users, minimising transportation needs, and altering processing pathways to transition from higher to lower temperature heat demands.

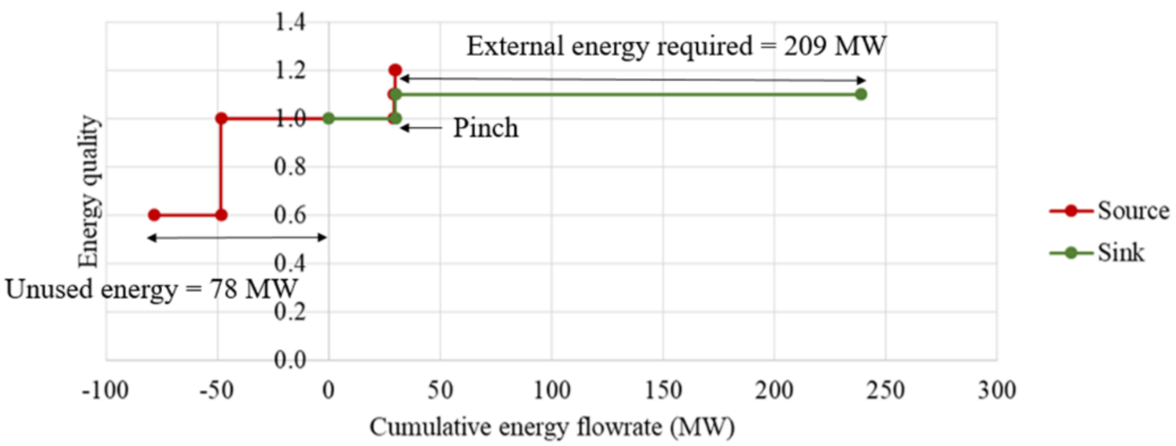

Figure 12. Waste management Energy Quality Composite Curve, reproduced based on [107]

It is possible to use Energy Quality Pinch for evaluating process combinations. The quality of energy in thermodynamic systems is significantly influenced by two primary factors: the temperature levels of fluid streams and their chemical composition. In many scenarios, chemical exergy measures the maximum useful work obtainable from a stream when it reaches equilibrium with its surroundings. It is notably higher in streams with a greater concentration of solutes. This increase in chemical exergy is attributed to the enhanced salinity gradient, which provides a stronger driving force for energy conversion processes. However, it is important to note that the relationship between temperature and composition is not always straightforward. There are instances where a stream may exhibit a low temperature yet possess a high chemical exergy due to its solute concentration, indicating a favourable energy quality. This phenomenon highlights the complex interplay between temperature and composition in determining the overall energy potential of a stream.

Table 2. Municipal solid waste data source [108]

Inputs	Process	Outputs	Heat/Power required	Waste input (t/y)	Conversion ratio [109] (t or kWh/t of input)
	Waste transport	-	Energy usage: 12.5 kWh/(t km), total distance travelled = 2,000 km (Diesel vehicles) [110]		
PE	Thermal recycling [111]	Gasoline	0.259 MWh/t; 0.018 t/t (diesel)	904.28	0.299 t/t
PE	Thermal recycling [111]	Diesel	0.259 MWh/t; 0.018 t/t (diesel)	3,037.94	0.068 t/t
PE	Thermal recycling [111]	Heavy oil	0.259 MWh/t; 0.018 t/t (diesel)	868,516.47	0.068 t/t
HDPE	Pyrolysis [112]	N-olefins	3.36 MWh/t 4.18 MWh/t (Thermal)	2,942.65	0.446 t/t
HDPE	Pyrolysis [112]	N-paraffins	3.36 MWh/t 4.18 MWh/t (Thermal)	3,136.48	0.432 t/t
PP	Pyrolysis [112]	Branch paraffins	3.36 MWh/t 4.18 MWh/t (Thermal)	3,038.08	0.333 t/t
PE	Incineration [111]	Heat	0.089 MWh/t	2,436.95	19.44 kWh/t
PP/PE/PET	Nanotubes 140 [13]	Nanotubes	Sorting + Smashing: 0.438 MWh/t	3,038.13	0.15 t/t
PE	Nanotubes 160 [13]	Nanotubes	Sorting + Smashing: 0.438 MWh/t	3,037.98	0.415 t/t
PE/PP	Nanotubes 252 [13]	Nanotubes	Sorting + Smashing: 0.438 MWh/t	3,038.04	0.672 t/t
PE/PS/PP	Material recycling [13]	Pellets	Sorting + Smashing: 0.438 MWh/t	3,037.99	0.299 t/t
Others	Landfill [113]	-		15,000	-

In practical applications, the effective exchange of energy between streams is often constrained by thermodynamic principles. Specifically, heat transfer is limited to the direction from higher to lower temperatures, which can impede thermal energy recovery from lower-temperature streams. Nonetheless, the conversion of chemical exergy to electrical energy can circumvent this limitation, enabling the use of processes such as heat pumps. These systems capitalise on the differences in chemical exergy to elevate the thermal energy of the lower-temperature stream, enhancing its ability to exchange energy with other streams and facilitating more efficient energy recovery and utilisation. Understanding the nuanced relationship between temperature and composition is essential for optimising energy systems, particularly in improving energy quality and achieving greater efficiency in energy conversion and transfer processes.

As demonstrated in **Figure 13**, in Process System 1, the energy source curve demonstrates a substantial excess relative to the energy demands. This surplus enables the assessment of a potential combination with a second process. By integrating the two processes without incurring additional energy costs, the classical principles of Pinch Analysis can be further expanded upon to determine optimal placement and efficiency.

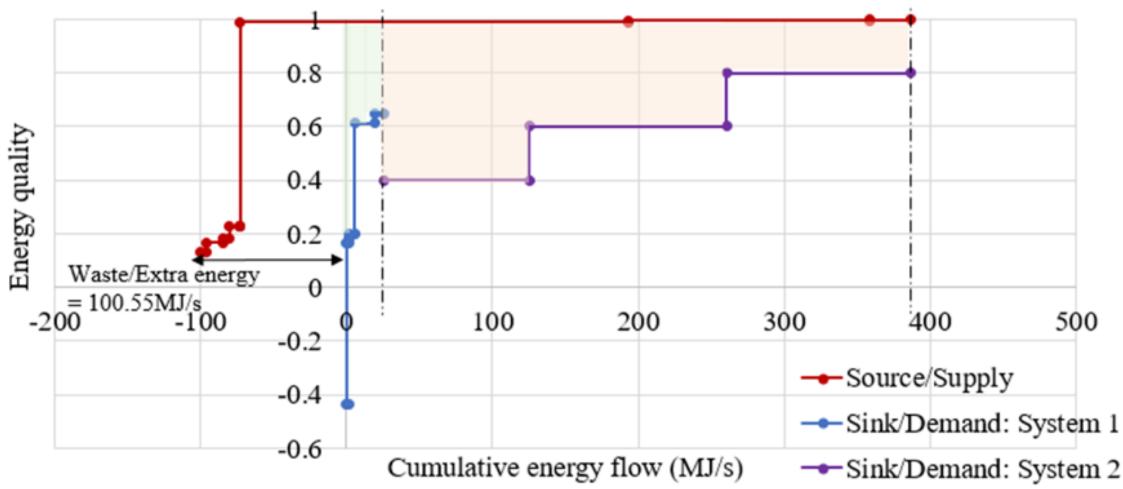

Figure 13. Energy Quality Composite Curves for two processes, reproduced based on **[107]**

<u>*A problem without logistics: building energy management*</u>

RESHeat is an advanced heating system for residential buildings that leverages renewable energy sources, primarily solar energy. Its core components include photovoltaic-thermal (PV/T) panels, rotating solar collectors, a heat pump, and an underground thermal energy storage unit (**Figure 14**). Through intelligent integration and management of these elements, RESHeat maximises energy efficiency and strives for complete building energy independence.

The system has been demonstrated in three distinct climatic regions: Limanowa (Poland), Kraków (Poland), and Palombara Sabina (Italy). In Limanowa, thermal energy storage relies on a non-insulated heat storage system. The heat pump's coefficient of performance (COP) was evaluated across various operating conditions, achieving values up to 5.5 when integrated with the heat storage and PV/T systems. Renewable energy accounts for over 70 % of the building's total energy demand. The system generates 29.63 MWh of electricity annually from PV and PV/T, while its electricity demand is 13.24 MWh/year, facilitating significant self-consumption of renewable energy **[114]**. In Kraków, the system features an insulated heat storage tank designed for seasonal thermal energy storage from PVT panels and solar collectors. Unlike the non-insulated tank in Limanowa, this setup prioritises heat retention to boost energy efficiency in urban settings. TRNSYS simulations predict a COP ranging from 4.34 to 4.80 **[115]**. The system achieves complete energy independence for heating and domestic hot water production, driven by advanced energy management and efficient thermal storage.

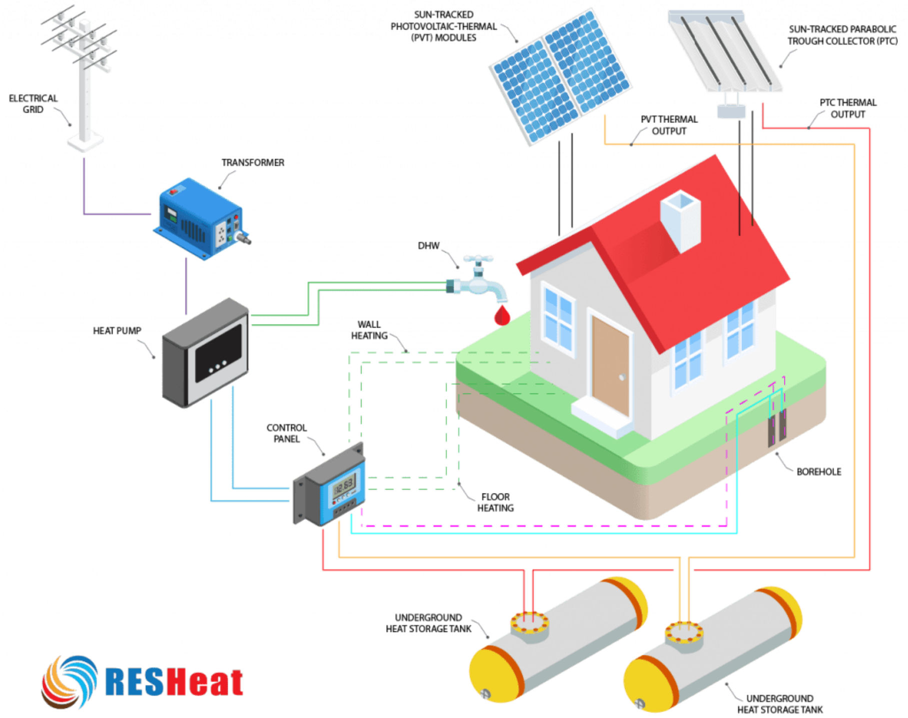

Figure 14. The schematic of the RESHeat system [116]

Optimised control strategies have stabilised operations and reduced the heat pump's electricity consumption. The latest demo case in Italy (Palombara Sabina), presented in Figure 15, was designed with different climatic conditions in mind, which is why it integrates RES not only with heating systems but also with cooling systems. The system includes PVT modules, an air-to-water heat pump, a buffer heat storage tank, a dry cooler, and fan coil units. Advanced control and efficient system management ensure high energy efficiency. The results of the energy efficiency analysis show that the average annual COP of the heat pump is approximately 5.4 [117]. Compared to other systems, high electricity production from PVT reduces grid energy demand, significantly improving the system's economic balance. Reduction in primary energy consumption: over 70 %, and the share of renewable energy in total heat demand is 94 %. The dry cooler enables optimal heat utilisation in summer, which is crucial for user comfort.

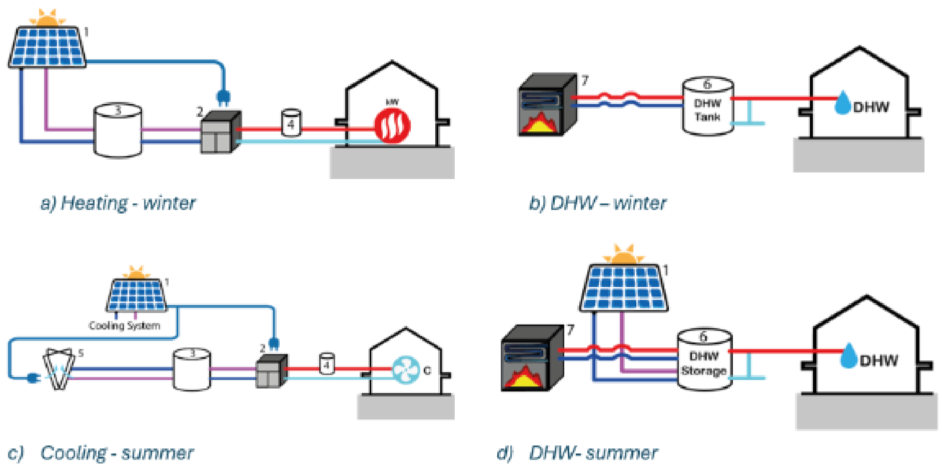

Figure 15. Schematic of the system in Italy, adapted after [117]

These results show that the RESHeat system effectively reduces primary energy consumption and significantly increases the share of renewable energy, contributing to the reduction of CO_2 emissions and the enhancement of buildings' energy independence.

Additionally, research and calculations have been conducted to enhance the performance and energy efficiency of the RESHeat system. In their study, Pan et al. [118] presented the operational optimisation of integrated renewable energy systems, incorporating Demand Response (DR) strategies and Ladder Carbon Trading (LCT) to improve energy management. The results indicate that the RESHeat system, when optimised using DR and LCT strategies, achieves a 57.8 % reduction in CO_2 emissions compared to its initial configuration. Furthermore, the study highlights the potential for AI-driven energy management, which could enable dynamic optimisation of RESHeat operations, further increasing system efficiency and sustainability. As demonstrated by the article [118], the RESHeat system and its implementations represent an innovative approach to integrating renewable energy sources. Proper energy management in buildings, without the need for extensive logistics, enables a significant reduction in primary energy consumption and the achievement of energy independence, thereby eliminating reliance on external energy sources. Additionally, the implementation of Demand Response (DR) strategies and Ladder Carbon Trading (LCT) could reduce CO_2 emissions by 57.79 % compared to the system's initial configuration, significantly enhancing its environmental and economic efficiency.

Tools for addressing the multiplicity and topology challenges

In terms of topology complexity, a prominent tool set is offered by the P-graph framework [119]. It is built around several key components:

- **P-graph topology representation based on set theory**. This is illustrated on the example of a Fuel Cell Combined Cycle (Figure 16) This allows performing operations on network structures in the form of sets. The result is that data manipulation and computation algorithms can be made aware of system structures.
- **Axioms** that reflect the fundamental properties of combinatorially feasible process structures. This is a set of 5 axioms that allow explicit and unambiguous representation of fundamental rules of process system topologies.
- **Algorithms** for efficient enumeration, traversal and optimisation of topology structures.
- **N-Best Solutions Pattern**. This is an integral part of the P-graph toolset, which has arisen from the recognition that often multiple system topologies are possible that feature typically small variations of the objective function (e.g. cost or profit). A prominent example of a process design for hydrogen production can be found in [120], where four HEN designs were identified featuring comparable costs.

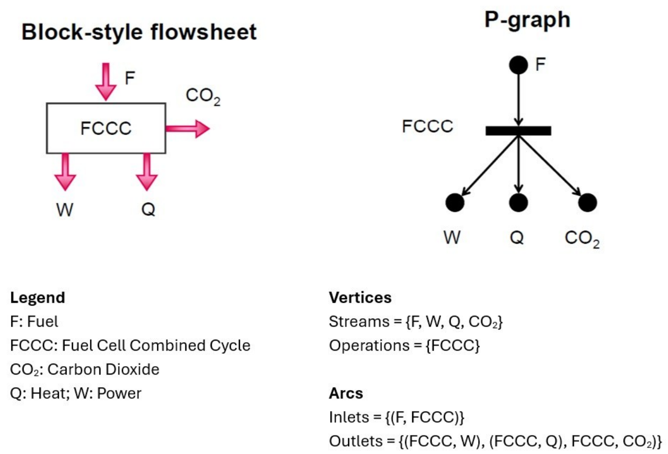

Figure 16. Representation of a Fuel Cell Combined Cycle as a block-style flowsheet (left) and as a P-graph fragment (right), after [121]

DISCUSSION

The development of effective strategies for achieving resource circularity necessitates a comprehensive, systems-based methodology that considers the interactions among diverse stakeholder groups and accommodates the dynamic nature of resource flows.

Features to develop

A circular resource system consists of a network of interconnected participants, including sources (e.g., extraction sites or waste generation points), sinks (e.g., landfills or emission sites), suppliers and consumers (demand nodes), storage facilities (intermediate buffers), transportation infrastructure, and hubs (locations for material aggregation or transformation). Efficient circulation of resources hinges on the capability to map, model, and manage these entities within an integrated framework that optimises material and energy flow while minimising losses and redundancies.

Considering that supply and demand patterns exhibit inherent variability over time and across different contexts, approaches to circularity must incorporate temporal dynamics and stochastic variability. The implementation of real-time monitoring systems, alongside predictive analytics and adaptable logistical frameworks, is vital to managing fluctuations in resource availability and consumption. These dynamic adaptations enhance system resilience and enable more agile resource management strategies, such as just-in-time recovery, redistribution, and remanufacturing of materials.

A critical aspect of fostering accountability and trust among stakeholders within circular systems lies in the fair and transparent allocation of environmental footprints. This involves establishing standardised methodologies for attributing environmental burdens and benefits, such as carbon emissions, energy consumption, and waste diversion across complex supply chains. Advanced tracking technologies (e.g., digital ledgers and product passports) can facilitate traceability and verification, while allocation algorithms must ensure an equitable distribution of impacts among both upstream and downstream actors.

Circularity strategies should encompass the economic valuation of environmental externalities and benefits. This integration involves utilising tools such as Life Cycle Costing, Environmental Profit and Loss, and shadow pricing of natural capital within resource planning and decision-making processes. By internalising environmental costs and acknowledging the avoided impacts linked to resource recirculation, these models enhance the accuracy of cost-benefit analyses and guide investments in circular technologies and infrastructures.

The optimisation of circular resource systems must strive to balance multiple objectives, including economic viability, ecological benefits, and sustainability performance. Multi-criteria decision analysis and mathematical optimisation models can aid in simultaneously pursuing these objectives, directing stakeholders toward solutions that are both financially feasible and environmentally sustainable. These models should be supported by incentive structures and regulatory frameworks that align individual interests with broader public sustainability goals.

Any strategy aimed at achieving resource circularity must holistically engage the three dimensions of sustainability: environmental, economic, and social. While considerable focus has been placed on ecological and financial outcomes, it is equally essential to assess social impacts, including equity, labour conditions, and community well-being. Integrated sustainability assessment tools and participatory governance mechanisms are necessary to ensure that circular solutions yield positive contributions across all dimensions, fostering inclusive and equitable transitions to circular economies.

Strategic Challenges

The coordination of the actions and interests of all key stakeholders in a Circular Economy can benefit significantly from the application of digital technologies, leading to the concept of Smart Symbiosis Networks [122]. This is a potential solution to one of the multiplicity challenges outlined in the review (section "**The multiplicity challenges**").

The implementation of Smart Symbiosis Networks within circular economy frameworks encounters several strategic challenges that demand a multidisciplinary and integrated approach. These challenges encompass the management of diverse operational contexts and the alignment of activities across multiple interconnected market scales at municipal, regional, and international levels. Effective coordination among a broad spectrum of stakeholders necessitates the processing and communication of extensive volumes of heterogeneous data in real-time. Addressing this complexity requires the synergistic application of advanced digital technologies, human decision-making capabilities, and efficient user interfaces. The integration of these components enables dynamic, data-driven resource optimisation and fosters the systemic collaboration crucial for advancing sustainable industrial symbiosis. It can be illustrated by the representation of Smart Symbiosis Networks as shown in **Figure 17**.

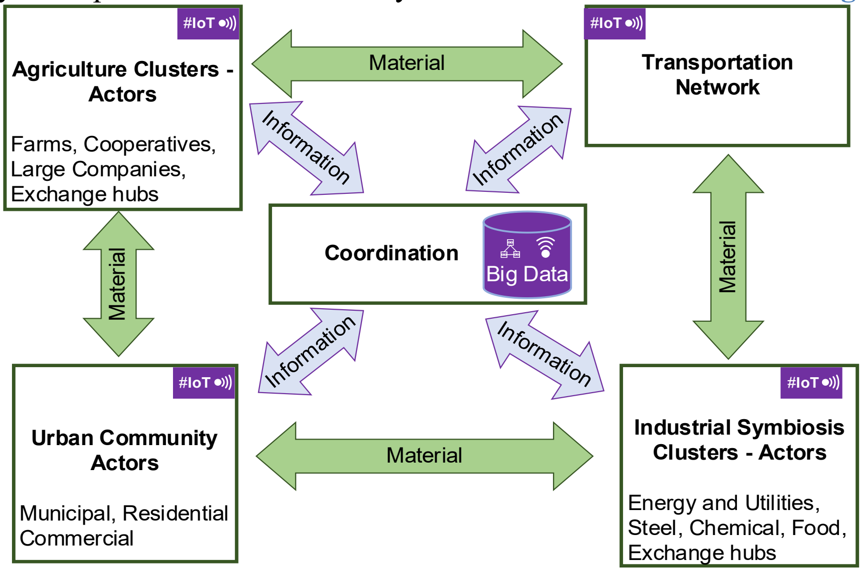

Figure 17. Smart Symbiosis Network, adopted after [122]

The study [123] demonstrates illustrative examples of the implementation of a Pinch-based smart contract system for resource management, utilising the Total Site Heat Integration concept to effectively allocate resources. The fundamental principle of Pinch Analysis is to maximise resource recycling while minimising dependence on external resources. Within this framework, a cryptocurrency can facilitate resource transaction agreements between facilities, utilising a central utility system as a neutral platform, as discussed with EnergyCoins. By ensuring data transparency for all prosumers and facilities, individual profits or cost savings can be enhanced while also promoting maximum energy efficiency across the site. The current case studies illustrate that cost savings of up to 15–16 % can be achieved at a consistent energy demand level by leveraging the transparency that is characteristic of Blockchain technology.

Summary on the circularity challenge and solutions

Achieving higher circularity rates and maximising the associated environmental and economic benefits represent significant challenges in the transition towards sustainable resource management. To effectively address these obstacles, it is essential to expand the degrees of freedom within circular systems. This can be accomplished by increasing the diversity of participating stakeholders, adopting a broader spectrum of technologies, and facilitating flexible storage and handling options. Furthermore, achieving circularity requires scaling efforts both geographically and systemically, which entails extending initiatives across larger regions and coordinating activities across multiple sectors and diverse supply chains.

A pivotal component of this transformation is the implementation of Smart Symbiosis Networks. These networks function as intelligent control systems designed to manage the flow of materials and energy within distributed industrial ecosystems. By leveraging advanced coordination mechanisms and real-time information exchange, Smart Symbiosis Networks optimise resource utilisation, enabling more efficient and sustainable practices.

To underpin such decision-making processes and foster stakeholder trust, circular systems must incorporate transparent accounting frameworks. These frameworks should facilitate accurate measurement and communication of environmental footprints, economic costs, and the shared benefits generated along the value chain. By ensuring transparency, stakeholders can better understand the implications of their actions and collaborate more effectively.

This innovative approach requires the integration of various technological, organisational, and informational advancements. Innovations may include the use of blockchain for traceability, advanced analytics for predictive decision-making, and automated systems for resource tracking and management. Through the combination of these strategies, it becomes feasible to accelerate the transition towards high-performance circular economies. This holistic approach not only enhances resource efficiency but also contributes to broader societal goals, such as increased resilience against environmental stresses, improved economic viability, and enhanced social equity across communities. By fostering interconnectedness and collaboration among diverse stakeholders, it is possible to create a robust framework that fully realises the potential of circular economies.

Key promising technologies

Recent advancements in materials science and process engineering have fostered the development of innovative technologies that enable more efficient, decentralised, and sustainable systems for resource conversion and energy utilisation. Notably, synthetic porous materials such as Metal-Organic Frameworks (MOFs), Covalent Organic Frameworks (COFs), and Hydrogen-bonded Organic Frameworks (HOFs) are particularly distinguished for their remarkable porosity, structural tunability, and high surface-area-to-volume ratios. MOFs, composed of metal ions or clusters linked by organic linkers, exhibit selective adsorption and catalytic properties that can be leveraged for gas storage, separation, and chemical transformation **[124]**. In a similar vein, COFs and HOFs, constructed from organic building blocks through covalent or hydrogen-bonding interactions, provide comparable functionalities with engineered chemical environments tailored for specific applications **[125]**. These materials are especially promising for tasks such as CO_2 capture, hydrogen storage, and catalytic conversion processes, in which molecular-level performance is crucial for enhancing system-wide efficiency **[126]**.

Water harvesting from air, or atmospheric water generation, is an emerging solution to address water scarcity by extracting moisture directly from the atmosphere. The table in the image compares various technologies based on MOFs and conventional refrigeration systems in terms of water yield and energy efficiency. Active MOF-based systems, such as those developed by Almassaad et al. **[127]** and Feng et al. **[128]**, demonstrate promising capabilities. Almassaad et al. report a water yield of 3.5 L/kg/day with energy demands ranging from 1.67 to 5.25 kWh/L, depending on the relative humidity (17–32 %). Feng et al. present a more advanced active system that achieves 9.9 L/kg/day at 2.96 kWh/L under 45 % relative humidity. These systems employ sorption-desorption cycles assisted by external energy input (typically solar or electrical heating), optimising water release even under low-humidity conditions. In contrast, passive MOF-based systems, such as the one reported by Sukel **[129]** based on research by the Omar Yaghi group, operate without external energy input. Although the energy requirement is effectively zero, the water yield is limited to 0.285 L/kg/day, making them more suitable for decentralised or off-grid applications where energy is scarce or costly. A conventional refrigeration-based AWG system, as described by Faraz Ahmad et al. [130], achieves a high-water output of 19.16 L/kg/day, but at a significant energy cost of 2.1 kWh/L under 44.9 % relative humidity. These systems rely on cooling air below its dew point, leading to condensation and water collection. While effective in humid environments, they are energy-intensive and less suitable for arid or energy-constrained regions.

Microfluidic processing systems have emerged as sophisticated tools for precise control over fluid flow and chemical reactions at the microscale. By directing small volumes of liquids through intricate networks of microchannels, these systems enable meticulous regulation of reaction conditions, including temperature, pressure, mixing, and residence time [131]. This level of precision not only facilitates high-throughput screening but also improves mass and heat transfer while minimising reagent consumption. The applications of microfluidics are expanding rapidly, encompassing fine chemicals [132], medicine [133], food [134] and materials processing [135], paving the way for modular, on-demand manufacturing systems that can be rapidly deployed and scaled as needed.

Another vital area of innovation is found in electrochemical conversion technologies, particularly regarding CO_2 utilisation and the production of green chemicals [136]. The electrochemical reduction of CO_2 allows for the transformation of this greenhouse gas into valuable products, including formic acid, methanol, ethylene, and syngas, utilizing electricity derived predominantly from renewable sources. Additionally, water electrolysis and various electrochemical pathways facilitate the environmentally friendly production of ammonia, hydrogen peroxide, or organic feedstocks [137]. These electrochemical systems provide an advantage by obviating the necessity for high-temperature or high-pressure reactors, thereby facilitating direct integration with intermittent renewable energy sources and enabling flexible operation in accordance with grid availability.

To further enhance the compatibility with variable energy sources, there is an increasing emphasis on designing processes that function similarly to energy storage systems [138]. This operational philosophy highlights the importance of flexibility, allowing processes to be activated or deactivated without sacrificing efficiency or safety. Such adaptability is particularly pertinent for modular electrochemical and catalytic systems, which can be integrated into distributed networks that align operations with the availability of renewable energy.

A common design principle uniting these technologies is the objective to maximise the energy or useful product density within the smallest possible physical volume. By concentrating energy or valuable outputs into minimal spatial areas, these systems reduce infrastructure requirements, minimise spatial and environmental footprints, and lower both capital and operational costs. High-density microreactors [139], nanostructured catalysts [140], and integrated reactor-separator systems [141] exemplify this approach. Collectively, these advancements establish a robust technological foundation for next-generation circular economy systems characterised by enhanced efficiency, adaptability, and diminished environmental impact.

CONCLUSIONS

This review paper has analysed the energy implications of circular economy solutions and the integration of renewable energy sources, elucidating key challenges, technologies, and strategies that can facilitate a transition towards more sustainable and resilient systems. A principal outcome of this study is the identification of the interdependencies between circular economy and renewable energy sources, demonstrating how their convergence can enhance resource utilisation, diminish environmental footprints, and contribute to the attainment of global sustainability objectives. The analysis underscored the necessity of accounting for thermodynamic constraints, spatial organisation, and logistical considerations in the design of efficient systems that capitalise on material circularity and decentralised energy flows.

The study highlighted recent innovative tools, such as Energy Quality Pinch Analysis, the P-graph Framework, to evaluate and optimise energy flows within symbiotic and recycling frameworks. It also emphasised the importance of intelligent coordination frameworks, as exemplified by Smart Symbiosis Networks, which facilitate the real-time, data-driven management of complex, multi-actor networks. The implementation of transparent accounting mechanisms for environmental footprints, costs, and benefits was emphasised as crucial for fostering trust and accountability along supply chains. Additionally, the review discussed key enabling technologies, including synthetic porous materials (e.g., MOFs, COFs, HOFs), microfluidic systems, and electrochemical CO_2 conversion, which provide scalable, high-efficiency solutions with low environmental footprints, aligning seamlessly with circularity and sustainability objectives.

For future research and development, the discussed tools have to be further developed and integrated with each other, to provide methods and the basis for software tools to deliver to final users – stakeholders in industrial and business processes, corporate decision makers, regulators, and legislators. It is essential to prioritise the integration of AI-driven resource and energy management, blockchain-based traceability systems, and flexible, modular infrastructure.

Further efforts should aim at enhancing the scalability and economic viability of emerging technologies, optimising reverse logistics networks for valuable waste streams, and ensuring equitable social outcomes through participatory governance frameworks. Moreover, expanding the application of life-cycle sustainability assessments across diverse technological domains and geographical contexts will be vital for informing policy and investment decisions. In conclusion, the successful integration of circular economy and renewable energy sources necessitates a systemic, multi-dimensional approach that bridges technological innovation with policy support and stakeholder collaboration, thereby facilitating a fair and sustainable transition.

ACKNOWLEDGMENTS

The research was supported by the European Commission and is a part of the HORIZON 2020 project RESHeat. This project received funding from the Horizon 2020 framework program in the field of research and innovation on the basis of grant agreement No. 956255. Petar Varbanov acknowledges the support of Széchenyi István University.

NOMENCLATURE

Abbreviations

CCS	Carbon capture and storage
CE	Circular economy
COF	Covalent Organic Framework
COP	Coefficient of performance
CSP	Concentrated solar power
DR	Demand Response
ESG	Environmental, social, and governance
GHG	Greenhouse gas
HOF	Hydrogen-bonded Organic Framework
LCT	Ladder carbon trading
LNG	Liquid natural gas
MOF	Metal-Organic Framework
MSW	Municipal Solid Waste

PV	Solar photovoltaic
PVT	Photovoltaic-thermal
RES	Renewable energy sources
SNG	Synthetic natural gas
SWOT	Strengths, Weaknesses, Opportunities, and Threats
WtE	Waste-to-Energy

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Paper submitted: 29.07.2025
Paper revised: 15.10.2025
Paper accepted: 21.10.2025