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Perspective

Net-Zero Action Recommendations for Scope 3 Emission Mitigation Using Life Cycle Assessment

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Abstract: Greenhouse gas emissions anywhere across the value chain cause the global temperature to rise. A responsible net-zero strategy is reducing and removing direct and indirect greenhouse gas emissions. The current net-zero actions aim to offset rather than reduce or remove *life cycle greenhouse gas emissions* (GHG). Unless the demands/consumptions are reduced, net-zero actions will merely be a burden-shifting practice. Scope 3 emissions are considered in the life cycle assessment (LCA) of goods and services and account for direct and indirect emissions with imported goods and services. Scope 3 emission tariff seems an effective way to shift consumption patterns to carbon-neutral options. This article explores tools and systems for 'just transition' using three buckets of scientific questions: (1) Technical: which GHG to remove, when, where, and by what mechanism; (2) Social-Policy: how to share GHG obligations between stakeholders to deliver the UN SDGs; (3) Data: how to create robust, trusted, and transparent data for reporting, accounting, and actions. Building on the analyses, this study recommends thirteen scientific evidence-based net-zero actions.

Keywords: just transition and net-zero city; lithium-ion battery and battery recycling; hydrogen CCUS BECCS biomass and biorefinery; nature-inspired solutions; biorefinery bioeconomy renewable energy; whole system optimisation and circular economy

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1. Introduction

At the 21st Conference of the Parties (COP21), the United Nations Framework Convention on Climate Change (UNFCCC), 135 countries pledged carbon neutrality. Sixty-six of them have put a target year on their policies, laws or propositions, according to data by Net Zero Tracker. Net-zero is when the amount of carbon dioxide equivalent (CO_2e) emitted into the atmosphere due to human activities equals the amount of CO_2e removed from the atmosphere over a specified period. Although this net-zero definition has been adapted from the IPCC, the IPCC's net-zero condition focuses only on CO_2 [1]. The Emissions Gap Report 2021 shows that to keep global warming below 1.5 °C this century, the aspirational goal of the Paris Agreement, the world needs to halve annual greenhouse gas emissions in the next eight years [2].

Net-zero is a scientific concept. The global warming potential is calculated by the integrated radiative forcing of an emitted greenhouse gas relative to carbon dioxide. The unit representing the global warming potential of greenhouse gas is the quantity of carbon dioxide equivalent (CO_2e). A decarbonisation target for individual entities or systems can be set so that the aggregated individual targets offer the global net-zero or net negative greenhouse gas emissions when anthropogenic removals exceed anthropogenic emissions [3].

Greenhouse gases cause global warming potential (GWP) and global temperature rise. Fossil resource uses are responsible for greenhouse gas emissions. Therefore, a massive defossilisation of the global economy is needed. Greenhouse gases need to be neutralised for net-zero across the scale. Net-zero must embed life cycle thinking in evaluating, removing, and reducing GWP, considering cradle-to-grave or cradle-to-cradle life cycles of all consumptions. By tracking the *life cycle greenhouse gas emissions* (GHG), following the life cycle assessment (LCA) methodology [4–8] of systems, we cannot only accomplish the global net-zero, but also the United Nations Sustainable Development Goals (UN SDGs) to develop an equal and just society.

GHG of a system can be presented as CO_2e per functional unit, a term defined in life cycle assessment (LCA) as a measure of the service(s) provided by any product, process, or activity under analysis [9]. Greenhouse gases are carbon dioxide, methane, nitrous oxide, substances controlled by the Montreal Protocol, hydrofluorocarbons, perfluorinated compounds, fluorinated ethers, perfluoropolyether, hydrocarbons, and other compounds [10]. Any stage of a product or service life cycle, comprising material acquisition, manufacturing, distribution logistics, use and resource circulation [11], as shown in Figure 1, can emit GHG. The stages can occur worldwide and interact with other supply chains globally [12–14]. A comprehensive LCA accounts for the impacts of all interacting global supply chains allocated to the concerned products, activities or services [11,15]. Net-zero of an entity accounts for the direct GHG from its sources (Scope 1). Scientifically, life cycle thinking is inherent in a net-zero system [3]. Net-zero pledges should not only account for the specific entity's owned GHG but also for caused GHG. Thus, indirect GHG from imported utilities (Scope 2) and direct and indirect GHG from imported goods and services (Scope 3) need to be considered within the system boundary of the entity. An entity could be a nation that needs to develop an effective LCA-driven net-zero strategy to end carbon-intensive consumption. LCA accounts for Scope 1–3 emissions and, thus, the whole system GHG. Comprehensive LCA-driven net-zero actions are thus imperative to end carbon-intensive consumption and for levelling up the 657-676 million people living in extreme poverty at the time of writing this paper, who are the least responsible for the GWP and most affected by the GWP.

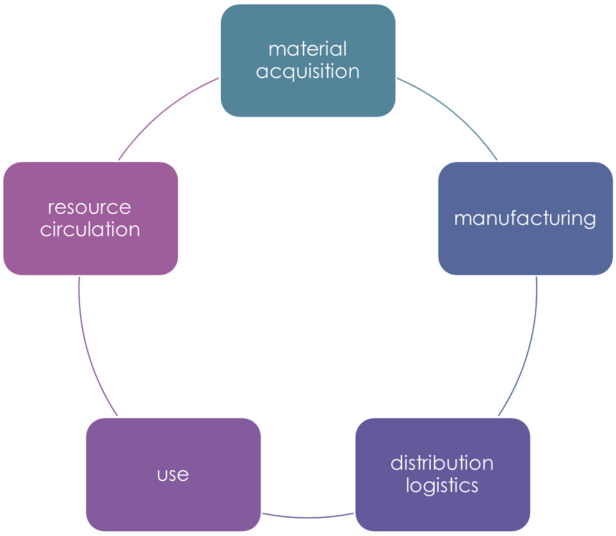


Figure 1. Life cycle stages in a circular economy paradigm.

As greenhouse gas emissions cause global warming irrespective of their source locations, the net-zero pledges must account for the Scope 1–3 GHG. Calculations of Scope 2–3 GHG raise the question of entity-specific burden allocation for shared inter-entity activities to avoid double counting GHG credits or impacts. Various ways allocations of GHG can be evaluated due to an entity's activity, by mass, energy, or economic contributions. Spearheading these allocation methods is the economy-based allocation, in which GHG are allocated according to the entity's specific contribution to the net economic margin. The allocation by energy or mass is possible for energy or material-based functions. For the latter, the material composition or quality must remain the same for the straightforward application of the mass-based allocation method.

There are concerns over net-zero pledges and actions. 'Greenwashing' is the term used to indicate when the net-zero actions become merely a burden-shifting exercise to offset GHG. The reality of the rapidly increasing global consumption is that production moves elsewhere with lower obligations to meet demand [16]. Reduction of GHG-intensive consumption needs re-operationalisation of net-zero, embedding LCA. This study makes scientific evidence-based net-zero action recommendations drawn from LCA-based appraisals of identified net-zero relevant systems.

The paper is structured as follows. The following section discusses the literature on net-zero and LCA. Section 3 highlights the LCA and LCA embedded value analysis methodology as an effective way to calculate Scope 3 emissions, i.e., direct and indirect GHG from imported goods and services and distribute carbon tariffs for a zero-sum game between participating entities for just transition. The two case studies on renewable energy and bioeconomy paradigms are presented before arising the recommendations and conclusions.

2. Literature Review for the Net-Zero and LCA

In the climate context, biomass burning for bioenergy and biofuel uses was argued to achieve net-zero emissions between 1991 and 2001 [17]. Biomass is a fossil-independent non-food organic waste. Biomass through biorefining produces a wide range of products, including chemicals, biofuel, and bioenergy [9]. Its use phase is carbon neutral because carbon dioxide is sequestrated during biomass growth [9]. Thus, a biorefinery, especially an integrated approach utilising local biodegradable resources into added-value products to meet societal demands without environmental impacts, is much desirable for a sustainable circular bioeconomy. A biorefinery is an activity with negligible Scope 2–3 GHG because biorefinery (1) can meet all its energy needs by heat integration and on-site combined heat generation to deliver products (eliminating Scope 2 GHG); and (2) has negligible material infrastructure impact (reducing Scope 3 GHG) [9]. Biorefineries have been developed over the last two decades for self-sustainability without reliance on external utility for added-value production [9]. Biorefinery in circular bio-economies can replace fossil carbon-based linear economic sectors [9]. Thus, biorefinery is an effective way forward to shift from carbon-intensive to carbon-neutral consumption.

A zero-emission neighbourhood concept has been applied considering buildings, mobility, infrastructure, networks, and on-site energy [18]. They considered embodied emissions from the production of materials to be compensated by emission credits from on-site local energy production substituting dirty energy production. A plethora of research articles exist on net-zero energy building, considering the balance between weighted supply and demand with on-site renewables, delivered energy from the grid and exported energy to the grid [19], production of materials [20], and embodied GHG in materials [21]. Energy [22,23], including electricity [3] and transport [24] systems, is the second-highest focus area in net-zero and LCA research.

A consensus to achieve a net-zero system is that the majority of energy demands are met by renewable energy, hydro (large and small), wind (onshore and offshore), solar (photovoltaic, concentrated solar power and thermal), geothermal (heat pump, flashing, binary, and enhanced) and marine (wave, tidal, and thermal) [25]. Most economic sectors are electrified because renewable supplies can generate enough electricity to serve global communities [3]. Energy storage, with hourly to weekly (batteries) and seasonal (compressed air energy storage, pumped hydro storage and hydrogen) storage duration, is required to use non-dispatchable surplus and fluctuating renewable energy supplies to meet unmet demand [26,27]. Further, net-zero strategies include *bioenergy, biorefinery or bioeconomy with carbon capture and storage* (BECCS) [9], nuclear and gas with *carbon capture, utilisation and storage* (CCUS) to meet any remaining demands.

Studies have determined that renewable systems' (hydro, wind, solar, geothermal, marine, energy storage, and infrastructure) operational greenhouse gas emissions are significantly lower than the embedded emissions of the materials making up these systems [3].

The strategy to offset materials' embedded greenhouse gas emissions is displacing fossil-based dirty energy with local clean, renewable resources. However, ending GHG-intensive production elsewhere (Scope 3 emissions) is imperative to avoid carbon tariffs and price inflation with the ever-increasing global consumption trajectory. Thus, the circular renewable bioeconomy must urgently replace the fossil-based linear economy to meet all goods' and services' demands. Here, we analyse the LCA-embedded sustainability of the two most relevant net-zero economies, renewable and bioeconomy. The methodology precedes these two paradigm analyses.

3. Materials and Methods

LCA is a standard methodology for whole-system environmental impact assessment [4–8]. LCA embeds life cycle thinking, as illustrated in Figure 1, cradle-to-cradle in a circular economy paradigm. LCA is an inherently multi-criteria method. It is used to evaluate GWP and other atmospheric emission impacts such as ozone depletion, acidification, urban smog, and particulate emission; aquatic emission impacts such as eutrophication and aquatic ecotoxicity; land emission impacts such as terrestrial ecotoxicity; and primary resource depletion such as water, land, fossil, and abiotic element resource use potentials [9]. While as few as one life cycle impact category can be chosen for a system evaluation, such as the climate change impact or GWP, fewer deemed important categories can be evaluated for the system [28]. Weighting can be applied to different life cycle impact categories for scoring a system to rank against others (valuation) [1,9,29]. Normalisation can be applied to evaluate a system's environmental performance concerning a geographic region [1,9,29]. The LCA methodology in practice has been comprehended [9].

Furthermore, life cycle sustainability assessment (LCSA) allows triple bottom line sustainability analyses encompassing environmental (LCA), social (SLCA), and economic (life cycle costing, LCC) dimensions [11,30,31]. LCSA criteria embed life cycle thinking considering spatial and temporal scales. Intrinsically connected supply chains (attributional LCA) or non-connected supply chains that are still impacted by rebound effects (consequential LCA) are included in the system boundary. The temporal scale spans several decades or a hundred-year time scale. While net-zero should be fundamental systemic LCA-driven, its implementation has taken a political turn. Although emerged from physicochemical climatic science [11], the net-zero concept has been operationalised in social, political, and economic contexts and is inadequate in governance, accountability, and reporting [32]. It is intended that individual organisational, institutional, and companies' net-zero strategies will collectively offer a country's net-zero and all countries' net-zero activities will present the global net-zero. However, a central unresolved question remains in climate pledges: how can embedded or indirect or Scope 3 emissions be considered in net-zero actions without double-counting?

Even without considering the indirect greenhouse emissions, the OECD countries' per capita greenhouse gas emissions are more than twice that of the rest of the world. There is a consensus that high-income countries reduce the GHG faster than the rest of the world and hit the net-zero target to help low-income countries come to equal terms. Concerns over net-zero strategies are raised around as an offsetting and merely a burden-shifting exercise [33]. 'Greenwashing' concerns lead to three buckets of scientific questions for effective climate pledges need to address the governing question of how embedded or indirect or Scope 3 GHG can be considered in net-zero actions. Figure 2 illustrates the net-zero paradigm challenges.

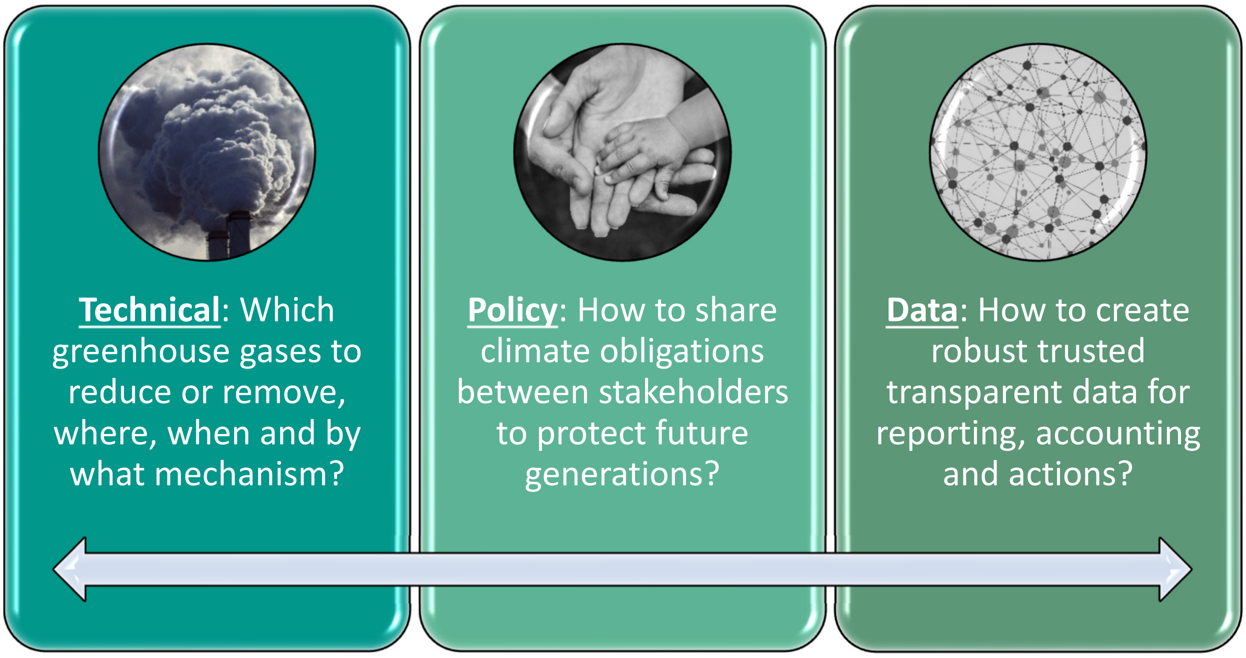


Figure 2. Three interactive buckets of LCA-embedded net-zero paradigm questions.

Technical: *Which greenhouse gases to remove, where and by when and what mechanism*:

There is no mechanism for directly capturing greenhouse gases from the atmosphere. Scientists agree on front-loading of GHG removal and recovery technologies [32]. However, the time scale, locations, and value chains are unidentified. CO_2 capture directly from the air is imperative to remove and reduce atmospheric carbon stock [9,34–37]. Technologies for direct CO_2 capture from the air are emerging. Similarly, other greenhouse gas stocks in the atmosphere must be reduced. Although active in the atmosphere for decades, methane is a relatively short-lived greenhouse gas. According to the IPCC Sixth Assessment Report [38], within 20 years, fossil-originated and non-fossil-originated methane is an 82.5 and 80.8 times more potent greenhouse gas than CO_2. These values are 29.8 and 27.2 within 100 years. Field fertiliser applications in agricultural and livestock farming sectors are the main cause of another highly potent common greenhouse gas, nitrous oxide with a global warming potency of 273 CO_2e in a 100 or 20-year time scale. Other greenhouse gases have several magnitudes higher global warming potencies than CO_2 [9]. Recently, a few studies have looked into direct methane capture alongside CO_2 from the atmosphere [39,40]. While some end-of-pipe cleaning may be needed, the preference in the hierarchy of options is to eliminate greenhouse gases at the source. This can be achieved by profoundly following twelve principles of green chemistry, LCA, and LCSA [31].

Nature-based solutions through forestation, ocean carbon cycle, rewilding, and biodiversity are sustainable ways forward for CO_2 capture from the atmosphere. However, the global land, water bodies, and biosphere must have cautiously fared for a diverse ecosystem and just society. There is no unified framework to address this challenge. One possibility is the use of satellite (and other) Earth Observation (EO) and night-light imagery technologies to observe and interpret land use and land-use change toward offering the UN SDGs (e.g., SDG13: Climate Action and SDG15: Life on Land) [41]. Underwater observatories to better understand and utilise the carbon cycle are another significant way for atmospheric CO_2 capture and for delivering the UN SDGs (e.g., SDG13: Climate Action and SDG14: Life below Water). More joined-up approaches combining process modelling, LCA, LCSA [3,11,25,31], and observatories [41] can develop sustainable nature-based net-zero systems. For robust data accounting and reporting, connected data systems between entities are needed, addressed in the third bucket of net-zero system questions.

Obligations for who, producer or consumer? *How entities can reduce and remove GHG (life cycle greenhouse gas emissions) of their consumed products and services; how double-counting of GHG reduction and removal can be avoided in producer and consumer responsibility obligations; how producer and consumer responsibilities support each other to mitigate inter-entity GHG:*

Net-zero pledges have a socio-political-economic dimension [32]. Producer responsibility obligations apply to packaging and e-wastes, legislating the polluter-paying-principle. This is an excellent way to reduce and eliminate disposal or landfilling and encourage ecodesign for remanufacturing or reprocessing. With this approach, products and commodities can have extended everlasting life. This will be a newer economic sector with a severe need to upskill the workforce. As such, there is no objection to the polluter-paying-principle. Scope 3 or indirect emission-intensive good/service consumers must shift to the least GHG options to avoid paying the carbon tariffs that drive the inter-entity net-zero activities. This will enforce just transition actions needed for an equal, fair, and just society (UN SDGs). Since the material acquisition and manufacturing life cycle stages are the highest global warming contributors, ecodesign, remanufacturing, and recycling must be supported [42]. Some post-decommissioning refining of tech-metals may be unavoidable, discussed later. However, all economic sectors must drive ecodesign, servicing for extended life and remanufacturing, including part replacements for extending life beyond the nominal service life for material security and reducing primary resource depletion. Resource security is a global crisis in addition to climate impact and biodiversity loss.

Systemic value analysis tools optimise the shares of costs and benefits in a win-win business model or a zero-sum game. Applied initially to graph theory-based process network synthesis, design, operation, retrofit, improvement, and optimisation problems, the value analysis tools [9,43–49] can be extended to production–consumption value analysis for the zero-sum game between producers and consumers. The system boundaries for value analysis can include life cycle stages (Figure 1) and consider attributional and consequential analyses and multi-criteria (LCA or LCSA).

Versatile function-focused allocation methods can be adapted to distribute responsibilities/obligations for equity. The present allocation methods, as discussed earlier, mass, energy, or finance-based, are inherent in the value analysis methods by accounting for individual flows' cost of production and value on processing and, thus, their marginal contributions. It must be noted that the 'cost' and 'value' in 'cost of production' and 'value on processing' have already been interpreted as 'impact cost' and 'impact saving or credit' in GHG terms [47–49]. Figure 3 illustrates a network of anthropogenic interactive activities. The GWP saving by an output from displacing fossil-based GHG of an equivalent function can be certified as the 'credit' of the output [9]. Such output credits can be netted down to calculate allocated credits to individual intermediate flows—this is the value on processing [9]. The GWP cost of a flow is an aggregation of allocated GWP costs of all flows contributing to the flow—this is the cost of production [9]. The difference between the GWP value and the GWP cost of a flow is its GWP margin [9]. The GWP margin can be allocated to participating entities for just transition. For example, if a carbon-intensive production is demand-driven, the consumer bears the liability of GWP caused by the consumption. The first and foremost choice for the consumer is to end carbon-intensive consumption. All imported goods and services must be fossil carbon-neutral or incur fossil carbon savings (mitigating Scope 3 emissions). At present, the carbon tax is not hefty to end the carbon-intensive consumption of imported goods and services.

Value on processing (VOP), cost of production (COP), and margin (VOP minus COP) are unique to each interconnection. VOP of interaction is the credits (from the removal of fossil-based GHG of equivalent outputs) of outputs to nature that will be ultimately produced from it, subtracted by the costs (GHG) of all activities that will contribute to its further processing into these outputs. COP of the interaction is the aggregation of all the costs (GHG) contributed to making up the interaction up to that point. Thus, VOP and COP calculations proceed in the backward (from output to input) and forward (from input to output) directions of the network. Allocation can be on individual mass, energy, function, or economic contribution bases. Ultimately, VOP, COP, and margin of individual interactions relate to input–output interactions with nature because of the LCA consideration. Different coloured nodes represent different entity ownerships (Figure 3). A simple illustration of the graphical value analysis visualisation on the left-hand bottom corner shows that VOP > COP of interaction creates a positive environmental outcome (Figure 3). The interactions' margins must be distributed between entities to attain equity and justice (a zero-sum game).

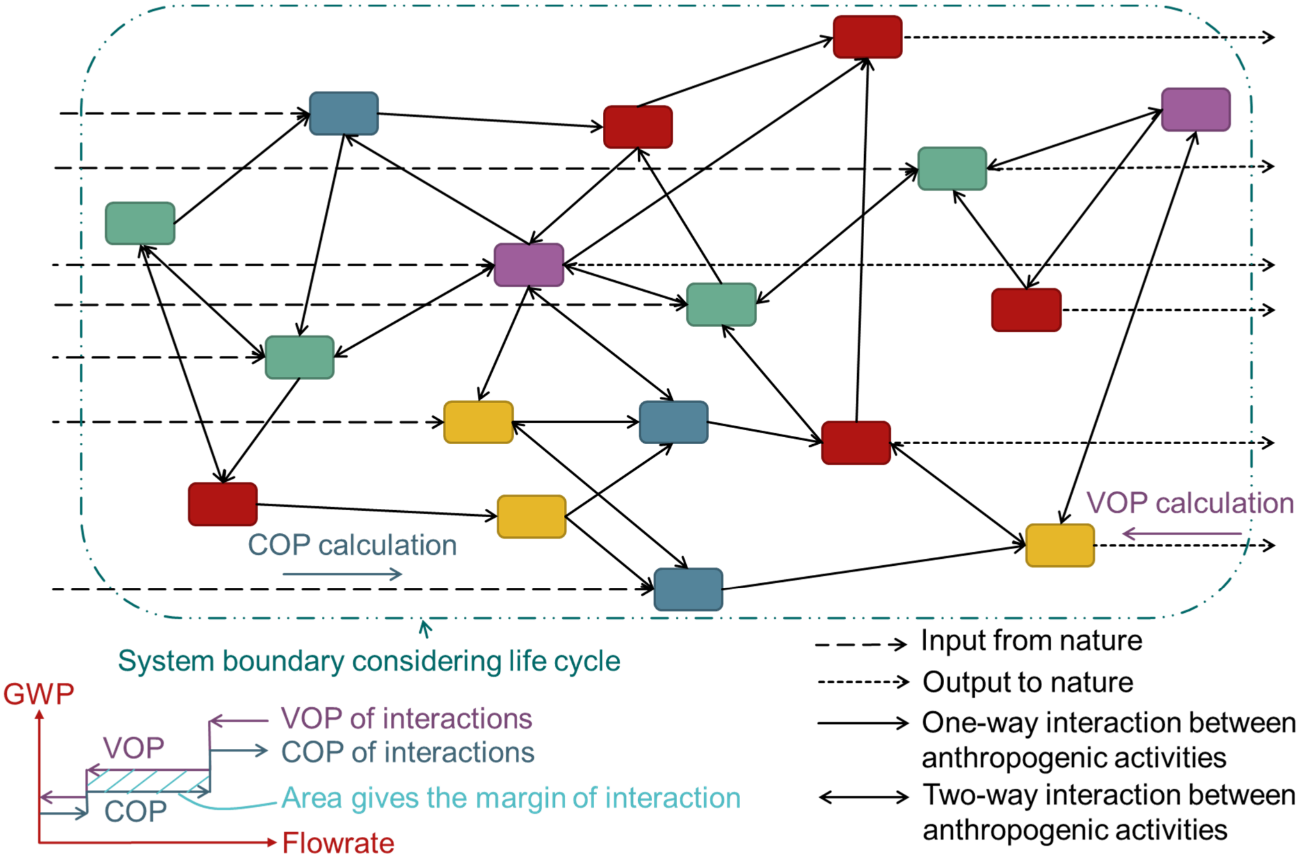


Figure 3. Anthropogenic interactions are represented as nodes (anthropogenic activities) and interconnections (interactions) in a spatially distributed network graph. Each colour of the nodes represents a unique entity.

Data system: *how various systems and products across global supply chains can interact through robust data systems; how such data systems can be developed and organised to support informed holistic whole-system decisions; how ethics and best practices can be adapted and the data transparency can be maintained*:

For profound net-zero commitments, robust trusted (independent specialised validation) and transparent data systems are needed that will show the collective removal and reduction of GHG. This is about digitalisation and intelligent systems interacting for more coordinated, planned, and globally optimal net-zero actions. There are digital tools to support specific systems' decision-making by allowing interactions between components, such as net-zero electricity planning, industrial park design, and agro-industrial value chain analyses using mathematical programming to name a few [25,50,51]. A data and machine learning-based era of Industry 4.0 emerged almost a decade ago because computers and smart systems allow communications between devices, equipment, and systems to optimise a whole economic sector. Powered by the Internet of Things (IoT), Big Data, Autonomous Robots, Additive Manufacturing, Cloud Computing, Simulation, Cybersecurity, Augmented Reality, and Systems Integration [52], Industry 4.0 is for optimum manufacturing with minimal resource use and waste or emission generation for triple bottom line sustainable development [53]. It is intended that each Industry 4.0 activity will communicate to others through transparent distributed data systems and centrally attain a global net-zero or negative GHG. It is desirable to have every activity transparently communicate its GWP to support informed holistic whole-system decisions.

The following sections analyse the GHG of renewable energy and bioeconomy systems by applying the three buckets of LCA-embedded net-zero system questions. It may be noted that not all questions are relevant to a system.

4. Renewable Energy Paradigm for Net-Zero

A net-zero economy must prioritise renewable electricity and electrification of the sectors. A renewable circular economy can end a fossil-based linear economy. Front-loaded renewable energy technologies are necessary for a just transition. The global mean GHG and life cycle environmental costs of renewable energy and bioenergy systems are (g CO_2eq/kWh, pence (USD)/kWh) [3]:

hydro-run-of-river (5, 0.26)
hydro-reservoir (28, 0.33)
wind: 1–3 MW (27, 1.4)
solar-20 MW (50, 1.5)
solar-50 MW (55, 1.7)
wind: >3 MW (34, 3.5)
geothermal (72, 3.5)
bioenergy (44, 13)

It can be noted that the entire GHG of renewable energy systems are Scope 3 emissions. The GHG-based ranking differs slightly from the life cycle environmental costing-based ranking (valuation). The life cycle environmental costs consider all environmental impact contributions through weighting the various impact categories in the ReCiPe or PEF (Product Environmental Footprint) life cycle impact methods. The weightings have EU relevance [3]. The ReCiPe method is a globally acceptable life cycle impact assessment method [3], while the EU suggests PEF. The ranking resulting from consequential LCA at the global scale [3] can be mapped against the renewable resource availability within the system. Thus, using the linear programming philosophy, maximum capacities of renewable technologies (available renewable resource utilisation considering efficiency loss in the technosphere) will be exhausted in the following order, hydro-run-of-river, hydro-reservoir, wind: 1–3 MW, solar-20 MW, solar-50 MW, wind: >3 MW, geothermal and bioenergy, to meet a system's energy demand with minimum life cycle environmental cost.

Whole-system analysis: In addition to the renewable resource transformation technologies, a 'whole system' has many other components, as conceptually shown in Figure 4. A whole-system considers resource availability, conversion, storage, logistic, use, and resource circulation systems. A model-based approach to individual components and their interactions is imperative for a sustainable system configuration [25]. Figure 4 illustrates a whole-system optimisation concept for sustainability. Renewable resources are intermittent. E.g., For 50% of the time, the sun is not available to shine. The only way we can shift renewable energy to periods of high demand is by energy storage, e.g., batteries for a few hours of storage. Pumped hydro storage, compressed air energy storage, and hydrogen and chemical energy storage offer seasonal energy storage. These systems can store energy during periods of excess availability and discharge energy when the demand is not met by available dispatchable energy. The bioeconomy system, such as BECCS, utilising carbon-neutral sources, is the only alternative to replace the fossil carbon-based linear economy by producing health, food, personal and home care products, and energy and water services [9,31]. The consideration of fundamental system components calls for mathematical modelling and programming. The mathematically modelled design configurations can be optimised for the various sustainability objectives such as economic, environmental, social, and UN SDGs, often involving tradeoffs that can be addressed through multi-objective optimisation approaches [9,25].

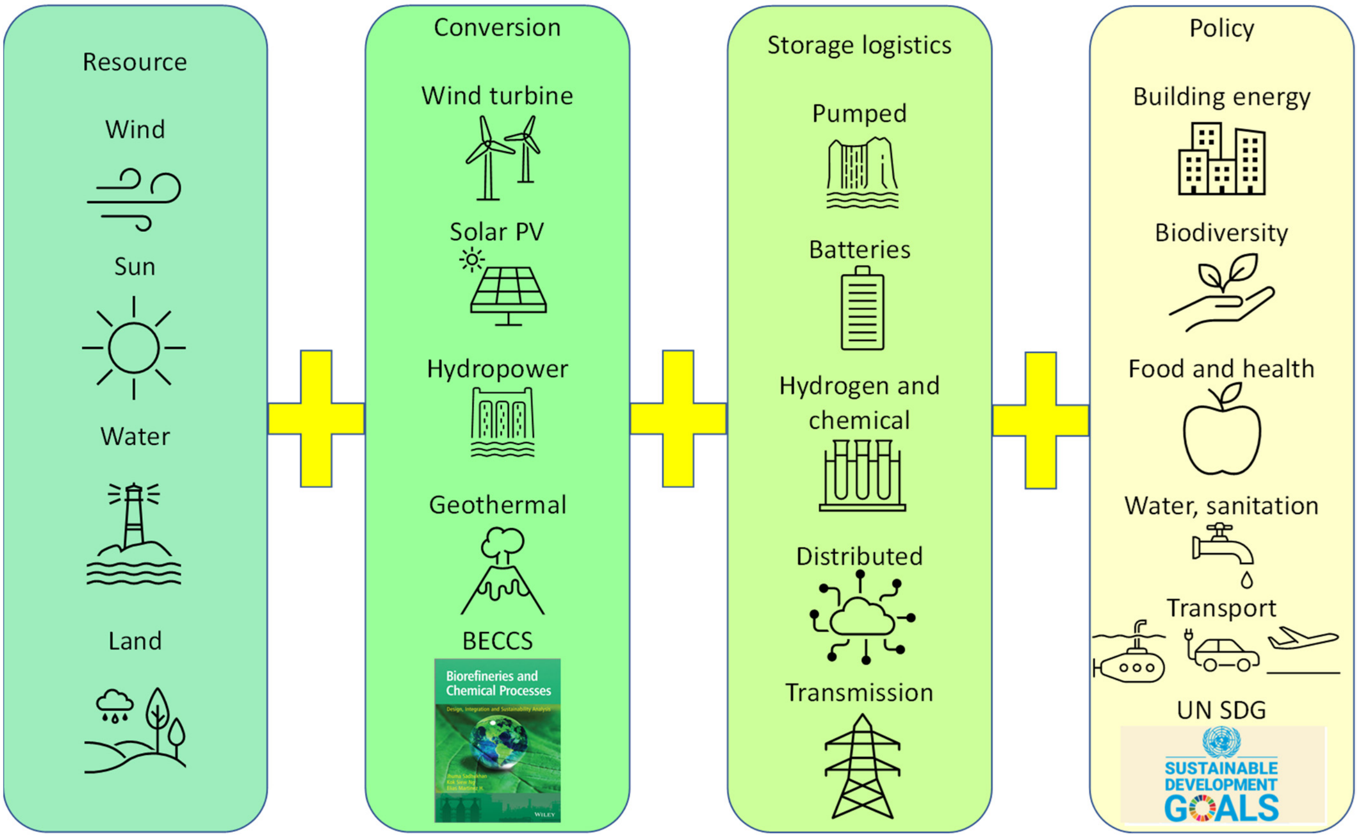


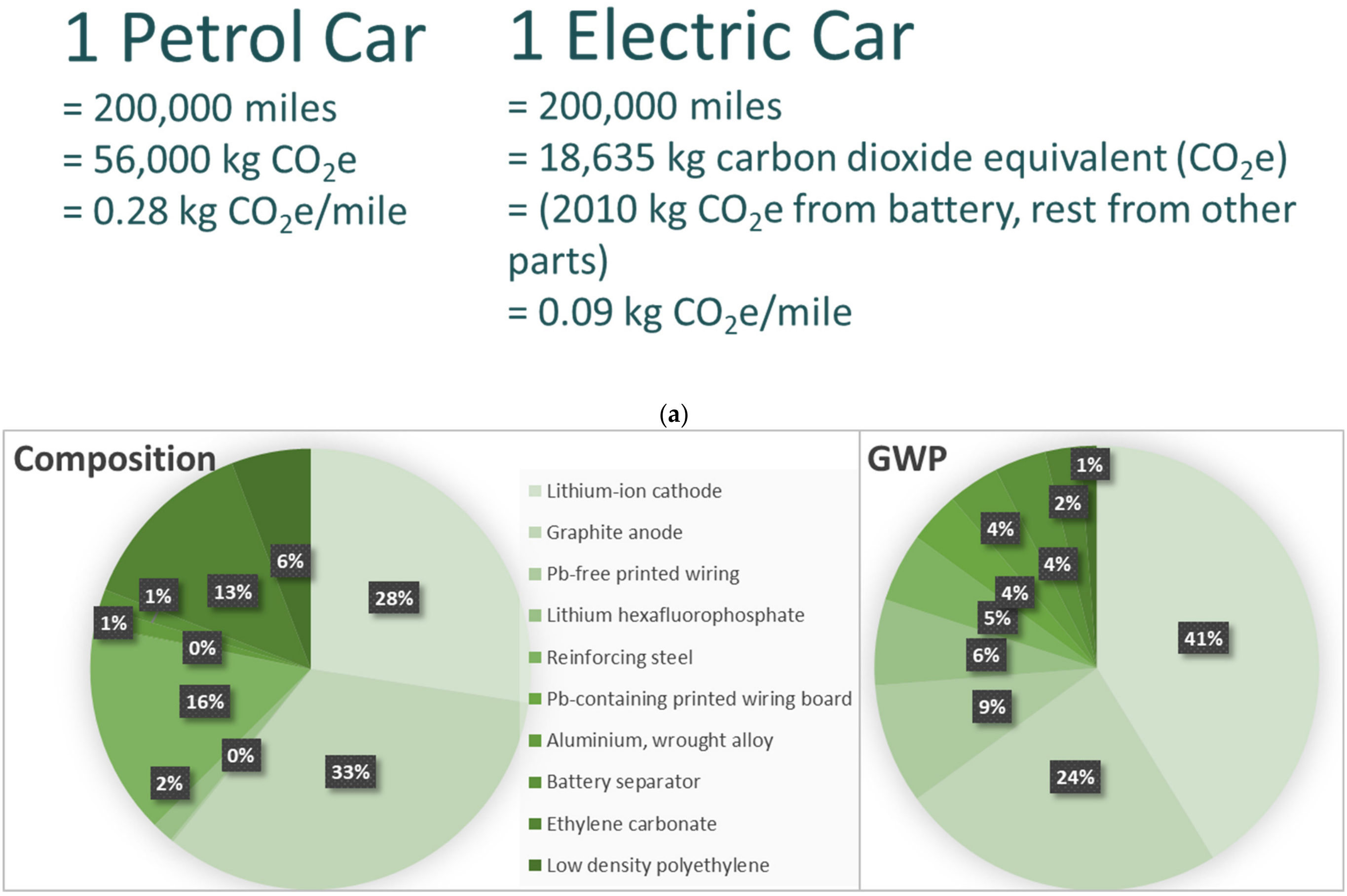
Figure 4. Global grand challenge: whole-system optimisation for sustainability.

Battery recycling: Renewable energy systems rely on tech metals with GHG hotspots. Lithium-ion batteries (LIB) are an example of tech-metal applications. The growing usage of LIB in stationary storage, electric vehicle, mobile phone, laptop, pedelec, and power systems results in increased spending on LIB. Lithium is a high-tech metal primarily mined in a few geographic locations, with Chile and Australia as the top two countries; its mining rate [54] served only 1.7% of the world's population if its usage in the electric vehicle was considered.

Currently, LIB recycling facilities are populated in Asia [55]. Several small-scale LIB recycling activities have been realised in Europe [55]. These activities include thermal treatment, mechanical separation, pyrometallurgy, and hydrometallurgy and can achieve high recoveries of >95% and low losses of <5% of cobalt, copper, and nickel [55]. The upstream thermal and mechanical treatments capture iron and aluminium and some copper. The remaining black mass comprising the LIB active materials is then subject to metal refining using pyrometallurgy and hydrometallurgy, recovering cobalt, copper, and nickel. However, there is an unprecedented challenge of lithium recovery from spent LIB, mainly fumed away in the refining processes or lost with slag (pyrometallurgical output) or effluent (hydrometallurgical output). Only a small quantity of lithium as an intermediate may be obtained. The lithium intermediate's value and recovery cost do not show commercial prospects. In addition, there are carbon or graphite and organic materials that are not recovered at a cost attractive as commodities. Therefore, biorefining is needed to recover Li and other tech-metals from effluents using microbial electrosynthesis or electrochemical technologies to close the LIB loop. This step must also recover acids, carbon or graphite, and organic materials and return water for recycling.

Battery recycling legislation: The EU Batteries Directive 2006/66/EG has already been revised several times and currently requires half the recovery of the battery material system. Producer obligations apply to battery recycling. Half the recovery of the battery material system can be easily attained by the technology that Asian and some European waste recyclers have deployed. Recycling the entire battery material system can secure the secondary material resourcing and reduce or avoid fresh material resourcing (mining), which could be an incentive for the battery or electric car importing entity. Recycled product grades and recoveries, process robustness, social justice, economic returns, health, safety, environment, and legislation [55] can be the importing entity's drive for recycling.

Tech metal-related LCA and costs: An average electric car curbs an average petrol car's emissions by a third provided the former is run by renewable electricity. Contrary to tailpipe emissions of fossil-derived transport systems, renewable transport systems have embedded Scope 3 GHG. Figure 5a compares an average electric car's and an average petrol car's GHG based on the assumption that the available electricity is largely renewable. A total of 11% of the average electric car's emissions come from its battery, usually LIB. Figure 5b shows the composition and GHG of LIB. An average 300 kg LIB (with 2.9 kg lithium) has 2010 kg CO_2e GHG [25,26]. An electric car's and its battery's primary emissions occur in the countries manufacturing them, for example, Germany and China. To avoid the risk of high GHG tariffs, the importing countries must look to secondary material acquisition and remanufacturing options. Battery recycling will offer critical tech metal security for the countries with no or little reserves of tech metals that is essential to confront monopolies.



1 Petrol Car
= 200,000 miles
= 56,000 kg CO_2e
= 0.28 kg CO_2e/mile

1 Electric Car
= 200,000 miles
= 18,635 kg carbon dioxide equivalent (CO_2e)
= (2010 kg CO_2e from battery, rest from other parts)
= 0.09 kg CO_2e/mile

(**a**)

(**b**)

Figure 5. (**a**) GHG performances of average petrol and electric cars with electricity largely sourced from renewable resources. (**b**) Battery material (300 kg) composition and GHG (1618 kg CO_2e). The total embedded greenhouse gas emissions of the battery materials are 1618 kg CO_2e, 80% of LIB (2010 kg CO_2e). The balance comes from waste treatment.

The net-zero energy will heavily depend on tech metals; as said, we live in a material world. What we mine today is far too short to meet the demands. A total of 97.5 kt of lithium and 123 kt of cobalt are mined today [56], serving only 1.7% of the current world population or twice the UK population. There will be a significant cost increase by 2000–6000 times the current mining cost to meet the world's demand for lithium alone [56]. With the world adopting the current consumption per capita of the OECD countries, even renewable electrification of the transport sector with one-third of the GHG of fossil-based transport systems will be unsustainable. The world cannot afford to deplete the tech metals. Resource depletion means a high level of dissipation of the resource in the environment that is beyond recovery. In addition, low-income countries are not served by the current mining rate/cost. Tougher recycling regulations are expected to confront resource security-related challenges. Net-zero systems rely upon industrial, tech, rare earth, and precious elements from a complex global supply chain system, which could threaten their supply security. A key environmental challenge is the need to account for these elements stocked in the environment and technosphere.

Net-zero relevant tech-material security: Tracking and keeping account of these net-zero energy-relevant materials within and between systems is urgently needed. An intelligent and transparent data system can track production and consumption and offer SDG12: Responsible Production and Consumption. Such metal resources include (but are not limited to) (1) tech and precious metals, such as tin, molybdenum, rare earth metals, cobalt, lithium, tungsten, vanadium, niobium, cadmium, tantalum, silver, gold, indium, platinum group metals, gallium, rhenium, and (2) industrial metals, such as copper, manganese, lead, nickel, chromium, zinc, titanium, zirconium, strontium, etc. [54]. These elements are also used in consumer electronics. More than a third of the known elements in the periodic table participate in this technosphere. Moving away from fossil resources to net-zero renewable resources requires an economy dependent on these abiotic resources. Their economies must be made circular through inter-intra-entity data systems.

LCA and value analysis: There are various levels of challenges to tackle across the tech-metal life cycle supply chains, material and product trade flows and stocks, transformative flows within a system boundary, losses to the lithosphere and the environment, landfilled flows and their biogeochemical cycles, and recycling flows, including chemical and energy, used to recycle them. Holistic, systemic LCSA approaches within and between the technosphere and the environment are much desirable. For a transformative reference frame for decision-makers, the global LCSA can be investigated and translated into regional, national, and sub-national boundaries so that a coherent approach can be adopted [9,11,30,31]. The digital frameworks can inform design decisions on systems configurations, flows, and LCSA performance tradeoffs [57,58].

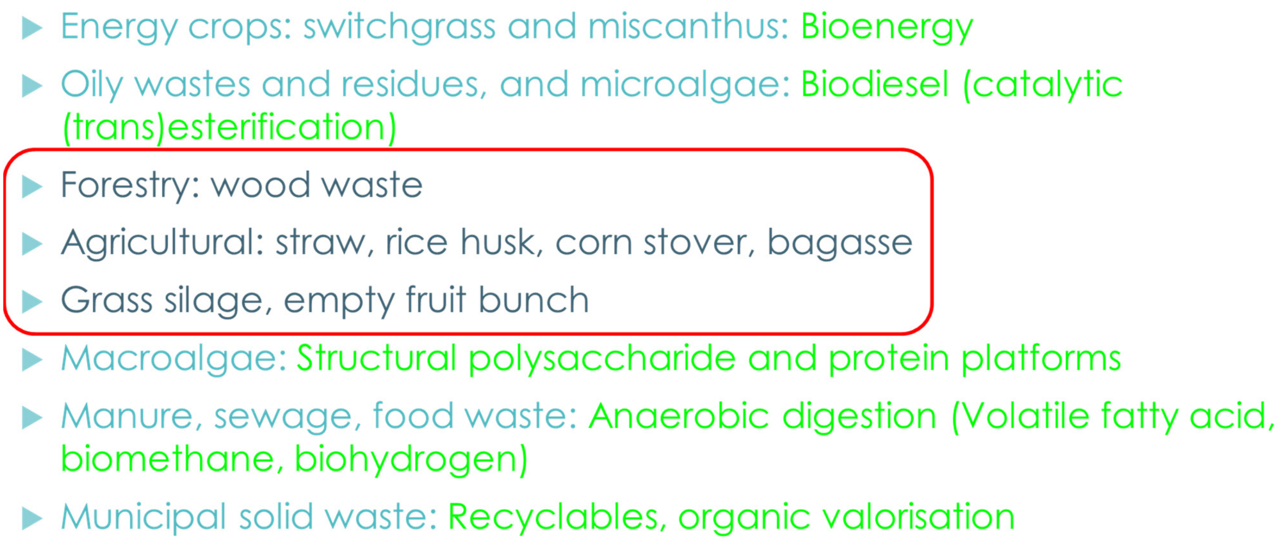
The whole system integration in Figure 4 needs enabling through digital technologies [59]. Each component can be mathematically modelled, including resource mapping, conversion, storage and logistic systems, and optimisation objectives to inform policy-making [25]. These components can communicate with each other to control the flows in real-time for maximising overall sustainability objectives. Compressed air, pumped hydro, hydrogen, and chemical energy storage options are prohibitively expensive. These are seasonal energy storage options. Alternative dispatchable renewable energy systems could be bioenergy.

Electrolytic hydrogen: Hydrogen is an effective means of seasonal energy storage because of its lowest GHG among all seasonal energy storage options provided hydrogen production and storage are fossil-independent. Solar energy activates semi-conductors, leading to a flow of electrons in photo-electrolytic systems. Electrons reduce protons into hydrogen at the point of use. Thus, hydrogen is a seasonal storage means. Unmet electricity demand can be met by fueling the stored hydrogen in fuel cells. A total of 1 kg of hydrogen is a source of 32 kWh of energy, equivalent to 4 days of electricity consumption of the average UK household or 56 days of electricity consumption of the average Indian household.

Biomass-derived hydrogen with CCUS: Larger-scale hydrogen production is possible from fossil-independent unavoidable non-food organic waste called biomass. A biomass-integrated gasification combined cycle producing syngas comprising carbon monoxide and hydrogen is a practical, scalable technology for hydrogen production. It comprises gasification, gas cooling, cleaning, gas turbine, and heat recovery steam generator with pre or post-combustion CCUS [60]. The pre-combustion CCUS produces hydrogen-rich or hydrogen-only combustible gas, thus eliminating tailpipe emissions. There is a 20% efficiency loss and a 20% increase in cost due to CCUS [61]. Physicochemical, electrochemical, and thermodynamic steady-state and dynamic modelling of these systems is critical for whole-system data communication, optimisation, and robustness [62–64].

5. Bioeconomy Paradigm for Net-Zero

Biomass, process, and product options: Biomass is a fossil-independent unavoidable non-food organic waste [65–68]. Biorefineries in a circular bioeconomy offer self-sustaining chemical and biofuel production and recycling options that can avoid GHG-intensive activities. Biorefineries must be embraced to mitigate Scope 2 and Scope 3 emissions. Biomass is organised in Figure 6 in decreasing order of ease of valorisation into products. Energy crops are the easiest to valorise into products, especially energy vectors. Oily waste and residues include waste cooking oils and kernels after oil extraction from oily seeds [28]. Catalytic processing technologies valorise oily wastes [69] and microalgae into biodiesel [9]. Macroalgae or seaweeds are distinctive because of their higher protein content and lower level of lignin [31]. Wastewaters could be a heterogeneous mixture of many resources, e.g., metals and minerals from electroplating, steel making, recycling and mining industries, organics from sewage, and other inorganics from chemical industries [64]. Organic is a good source of volatile fatty acids, biohydrogen, and biomethane in anaerobic digestion-based processes [70,71]. Municipal solid wastes at the bottom of the list are a heterogeneous mixture of many constituents, metals, minerals, and organics, requiring an advanced separation and reaction system for valorisation [72,73]. Forestry, agricultural, and garden wastes are abundant and offer functional versatility [30]. Biorefineries offer feedstock processing flexibility, product versatility, process robustness, and, most importantly, circular bioeconomies to end fossil-based linear economies. They must be prioritised based on their scale and ability to produce niche high-value products and self-sustain by meeting in-process utility demands [9].



- Energy crops: switchgrass and miscanthus: Bioenergy
- Oily wastes and residues, and microalgae: Biodiesel (catalytic (trans)esterification)
- Forestry: wood waste
- Agricultural: straw, rice husk, corn stover, bagasse
- Grass silage, empty fruit bunch
- Macroalgae: Structural polysaccharide and protein platforms
- Manure, sewage, food waste: Anaerobic digestion (Volatile fatty acid, biomethane, biohydrogen)
- Municipal solid waste: Recyclables, organic valorisation

Figure 6. Biomass resources and biorefinery process and product options.

Chemical-producing biorefineries: The biomass-derived chemicals have vast potential in the emerging bio-based economy, producing food, health, personal and home care product, as shown in Figure 7. Advanced biorefinery systems have been analysed for LCSA [31]. From chemistry-to-sustainability analyses have been conducted. Food and health care products extracted from structural polysaccharides and protein of biomass constitute the highest value products. Polysaccharides can also be pretreated to extract sugars into chemicals. A biorefinery can produce highly functional food, health and personal care products, through chemical, salt, mineral, nutrient to energy commodities, from niche to low-hanging fruit options [31]. LCSA assists in prioritising product and process choices in geographic contexts [31].

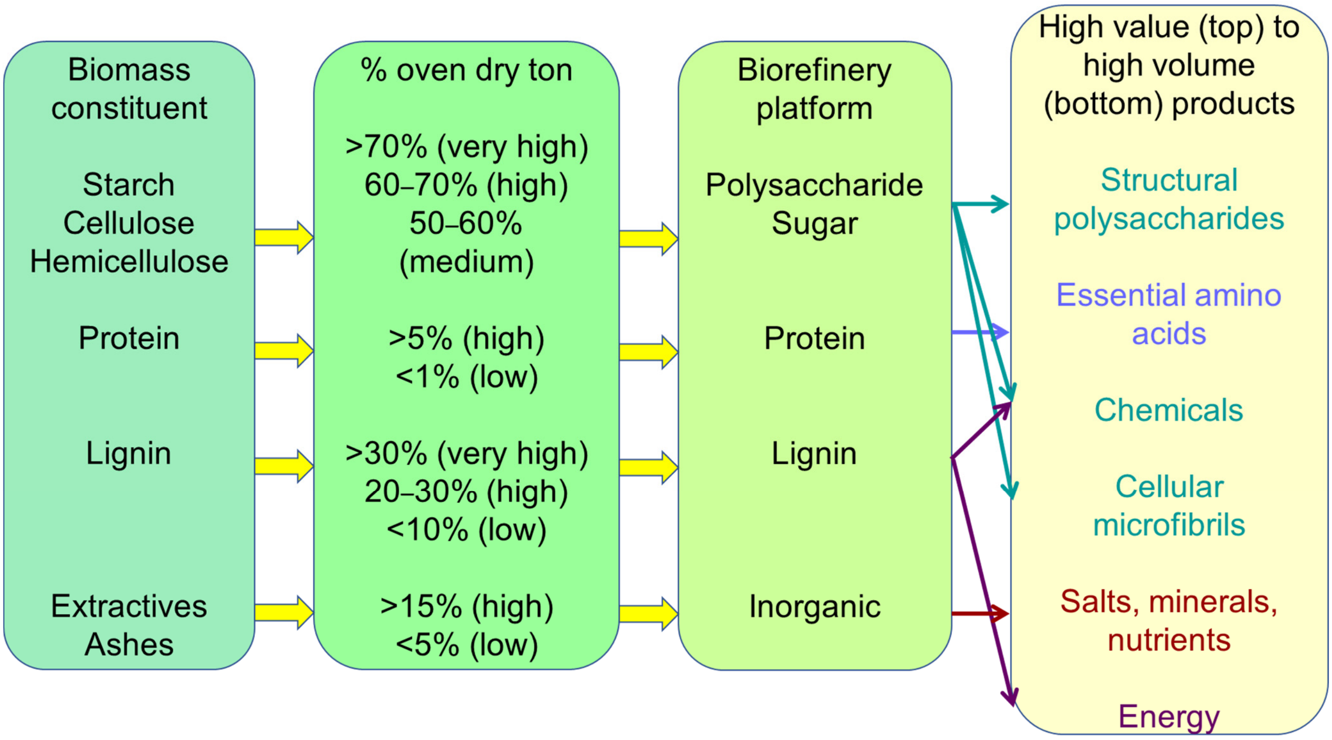


Figure 7. Integrated biorefinery/bioeconomy concept.

Bioethanol: Interim transport solutions can come from biofuel co-production in integrated biorefineries from biomass. Consumers pay the prices of biofuel and bioenergy. Bioethanol can be produced from lignocellulosic fermentation and make a neat fuel. Many biomass feedstocks have been studied for life cycle environmental and economic impacts of bioethanol co-production in biorefineries [67,74]. Certain feedstocks show environmental impact costs rather than savings. Self-sustainable biofuel-producing biorefinery implies meeting on-site energy demand through in-process energy recovery. Lignin is the primary fuel for combined heat and power generation. A certain proportion of lignin in the biomass is desirable to meet unmet utility demands after biorefinery in-process heat recovery. Sugars extracted from celluloses and hemicelluloses give bioethanol. The bioethanol and electricity proportions from integrated bioethanol and electricity-producing biorefineries can be adjusted, thereby charging feedstocks to the system to maximise environmental savings at minimum cost. Energy recovery through pinch and thermodynamic analyses is imperative for self-sustainable biorefinery designs at scale. Process industries have the skill to develop such systems. Environmental and economic ranking between biomass options shows tradeoffs and conflicts [67].

The value analysis tools [43–49] have been applied to calculate the value on processing and cost of production and, hence, the economic margin (value on processing minus cost of production) of each stream in the integrated biorefinery or bioeconomy schematics. The value analysis provides inter-entity marginal contributions. While bioethanol and biodiesel co-produced with bioenergy or chemical have been examined [75], emerging technologies need design conceptualisation. Bio jet fuel is one such emerging technology [76].

Bio jet fuel: Renewable jet fuel can be produced from biomass pretreatment, pyrolysis, and hydrotreatment. In situ hydrogen can be produced using alkane steam reforming, pressure swing adsorption, and high-temperature water electrolysis such as a mixed ionic-electronic conducting membrane process. A combined heat and power system, consisting of a boiler and a back pressure steam turbine, provides superheated steam for hydrogen production and electricity and heat for the site. The study provides the engineering design, mass and energy balance, techno-economic, LCA and SLCA of an integrated bio jet fuel producing system with in situ green hydrogen resourcing [76]. Further, by diverting the char to the combined heat and power system, it is possible to co-produce bioLPG, jet fuel or green diesel. BioLPG can be a clean cooking fuel for communities without access to electricity. Since decarbonisation is to be done within budget constraints (citizens pay), multi-entities could manage different components of the integrated biorefinery network and apply value analysis to develop win-win business models (equity in margin sharing) for all stakeholders involved (Figure 3).

MRFs: Material recovery facilities, known as MRFs, sort recyclables, metals, and refuse-derived fuel from municipal solid waste (MSW), are an excellent example of an intelligent system [72,73]. MRFs employ advanced sensing systems for automated sorting of various streams from MSW for further processing. MRFs have mechanical unit operations: screening, magnetic separator, Eddy current separator, manual, induction and automated sorting, near infrared sensor, X-ray sensor, etc. MSW needs to be source-segregated. The source-segregated streams are directed into various lines for recycling: paper and cardboard packaging; glass; dense plastic and plastic films (container, plastic packaging); wood, garden, and food waste; textiles; WEEE (waste electrical and electronic equipment) [72,73]. Other than these, metals and unidentified wastes are present in these streams. In addition, the source segregation is not perfect; hence, MRFs are essential for recycling these materials back to value chains. Organics or lignocellulosic fractions separated upon shredding and pulping process can be chemically valorised to extract platform chemicals. The remaining organics can be utilised in anaerobic digestion to biomethane and compost.

Biorefinery target products: From high-volume to high-value biomass products are energy or combined heat and power, biofuel, including hydrogen for road, rail, air, and marine transport, chemical and material, and food and pharmaceutical ingredients (Figure 8). Food and pharmaceutical ingredients constitute 5 wt% of biomass, chemical and biomaterial 10%, biofuel 50%, and heat and electricity the rest of the biomass—thus, an integrated biorefinery can displace the fossil-carbon-based economic sectors. Most significantly, complete circulation of MSW in integrated biorefineries is possible through an intelligent decision-making system [72,73]. According to economic margin, energy gives the least, biofuel medium, chemical and material high, and food pharmaceutical very high market values. Producing a niche product rather than low-hanging product options is critical for sustainable biorefinery systems. Because a niche target product constitutes less than 10% of biomass feedstock, the balance of the biomass is available for other product generations, including biofuel and bioenergy, in an integrated biorefinery fashion. In addition, biorefinery must be energy and mass-integrated to eliminate external utility requirements and become self-sustainable. Thus, combining heat and power generation alongside high-value productions defines sustainable biorefinery systems that can displace the fossil-carbon-based economic sectors.

Biorefinery has come of age in terms of sophistication, multi-feedstocks, processes and products, data system, modelling, design, optimisation, and conceptualisation. With the correct lobbying, it will become a reality, offering the circular bioeconomy, by replacing the fossil-based linear economy. The total mass and energy-integrated biorefinery designs can be developed and evaluated for sustainability using computer-aided process systems engineering and computational mathematical approaches [9,11]. While the data systems are prominent in the biorefineries in circular bioeconomy fields, process industries with the ability to up-scale the systems so that their mass and energy flows can displace the corresponding fossil-based flows and achieve a renewable bio-circular economy, have not engaged in biorefinery development. The reason is that carbon tax is not high and there is no limit to the economic profitability of fossil industries. More biorefining investments and firm commitments are needed from decision-makers to turn biorefineries and bioeconomy into practice. Data systems can help develop local symbiotic biorefinery systems. The Scope 2 GHG are zero and the Scope 3 GHG are negligible making biorefineries imperative for a sustainable circular economy.

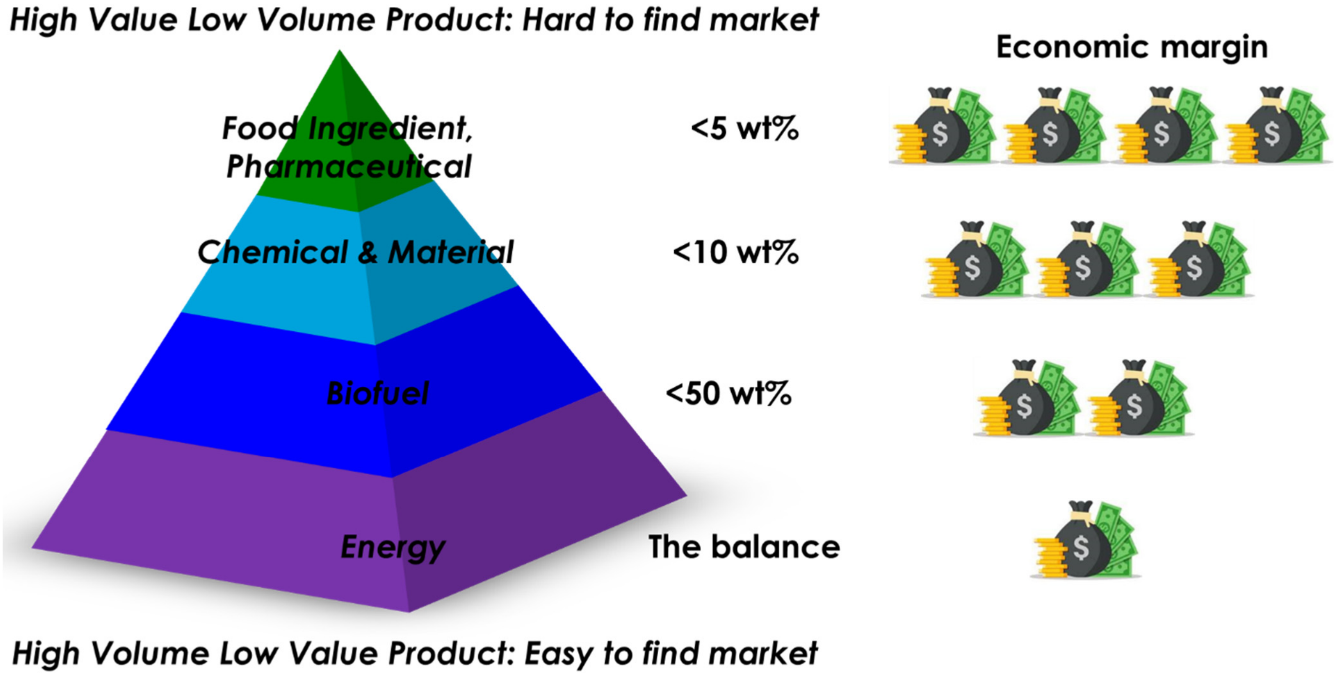


Figure 8. Bioeconomy products pyramid.

6. Recommendations

This study recommends thirteen net-zero actions from the methodology and case studies discussed. These recommendations can govern the 'just transition' of systems, e.g., cities.

1. Focus on GHG removal, reduction, and sinks: While the IPCC suggests only anthropogenic CO_2 sinks, removal of all greenhouse gases is necessary to keep the global average temperature rise below 1.5 °C by the end of this century to avoid climate catastrophe. Removal and reduction of CO_2 and other greenhouse gas stocks from the atmosphere are much needed.

2. Embed LCA in net-zero obligations: Net-zero must embed LCA in evaluating GWP, considering cradle-to-grave or cradle-to-cradle life cycles of all traded commodities and services. By tracking GHG, following the LCA methodology, traded commodity/service tariffs can be decided and distributed for just transition and delivering the UN SDGs.

3. Standardise LCA for net-zero strategies/actions: Greenhouse gases can be emitted from any product or service life cycle stage, comprising material acquisition, manufacturing, distribution logistics, use, and resource circulation. The stages can occur worldwide and interact with other global supply chains. A comprehensive LCA accounts for the impacts of all interacting global supply chains allocated to the concerned products, activities or services. LCA accounts for Scope 1–3 and, thus, the whole-system GHG. ISO14040-44 standardised LCA-driven net-zero actions are thus imperative.

4. Allocate GHG margin for levelling up: Calculations of Scope 2–3 GHG need entity-specific burden allocation for shared inter-entity activities to avoid double counting GHG margins (credits minus costs). Various ways allocations of GHG can be evaluated due to an entity's activity, by economic or functional contributions. GHG margins can be allocated

between participating entities for equity and justice. High-income economies must bear the cost of GWP caused to the world and allow low-income economies to level up.

5. Allocate Scope 3 credits or costs for equity: Versatile function-focused allocation methods can be adapted to distribute producer–consumer responsibilities for equity. The present allocation methods, mass, energy, or finance-based, are inherent in the value analysis methods by accounting for individual flows' cost of production and value on processing and, thus, their marginal contributions. The difference between the GWP value and the GWP cost of a flow is its GWP margin. The GWP margin can be allocated between participating entities to achieve an equitable and just society (a zero-sum game).

6. Consider life cycle sustainability assessment: Life cycle sustainability assessment (LCSA) allows triple bottom line sustainability analyses encompassing environmental, social, and economic dimensions. Across all the LCSA criteria, the life cycle thinking can be applied to consider the impacts of all activities across the spatial and temporal scales. Spatially, supply chains of traded goods and services may be intrinsically connected (attributional) or connected through rebound effects (consequential). Both must be considered in net-zero actions. LCSA, like LCA, can cover several decades or a hundred-year time scale. Financial flows can achieve LCSA targets by levelling up low-income economies.

7. Create transparent, robust data systems for traded flows for net-zero accountability: For profound net-zero commitments, robust and transparent data systems are needed to show the collective removal and reduction of GHG. Industry 4.0 for optimum manufacturing with minimal resource use and GHG can communicate to each other through transparent distributed data systems and attain a global net-zero or even negative GHG.

8. Consider the whole system by interdisciplinary modelling innovations: An effective net-zero system operation needs mathematical modelling of components and programming to optimise interactions. Whole-system holistic LCSA decisions demand fundamental physical models of individual components on the one hand and interactions' dynamic optimisation and data communications on the other. Such tools, although available, are not widespread. In addition, these mathematical/engineering approaches must draw from interdisciplinary quantitative/qualitative analyses and knowledge, Arts, Business, Law, Governance, Economics, and Social, Engineering, Physical and Health Sciences. To unite the world, upskilling the workforce with the gender/racial equity agenda is imperative.

9. Decarbonise with nature-based solutions: Nature-based decarbonisation through forestation, ocean carbon cycle, rewilding, and biodiversity can achieve sustainable net-zero systems. However, the global land, water bodies, and biosphere must have cautiously fared for a diverse ecosystem and just society. Integrated process modelling, LCA, and LCSA-embedded value analysis and observatory approaches can develop sustainable nature-based net-zero strategies. While synergies are recognised between their applications, standard practices need to be developed to apply them seamlessly in information communication.

10. Ecodesign, remanufacture for extended product life: While some post-decommissioning refining of tech-metals may be unavoidable, ecodesign, servicing for extended life and remanufacturing, including part replacements for extending life beyond the nominal service life of net-zero relevant systems, can provide material security and reduce global primary resource demand/depletion.

11. Configure biomass and biorefinery: Locally available non-food unavoidable waste resources are biomass. Biomass will become fossil-independent with the defossilisation of the economic sectors. Biomass can be processed in biorefineries. Biorefineries are, by definition, mass-energy-integrated self-sustainable multi-feed, multi-product, and multi-process systems.

12. Invest in biorefineries: An integrated biorefinery approach utilising biomass into added-value products to meet societal demands without environmental impacts is needed for a sustainable circular bioeconomy. A biorefinery is an activity with negligible Scope 2–3 GHG because a biorefinery (1) can meet all its energy needs by heat integration and on-site combined heat generation to deliver products (eliminating Scope 2 GHG); and

(2) has negligible material infrastructure impact (reducing Scope 3 GHG). Biomass source, processing, and other life cycle stages are co-located and considered within the system boundary for the best environmental outcomes, i.e., replacing fossil carbon-based linear economic sectors.

13. Target niche high-value commodities from biorefineries: According to economic margin, bioenergy gives the least, biofuel medium, chemical and material high, and food and pharmaceutical very high economic margins. Because high-value target product constitutes less than 10% of the biomass feedstock, most of the biomass is available for other product generations, including biofuel and bioenergy, in mass-energy-integrated self-sustainable biorefineries. Producing a niche product rather than low-hanging product options is critical for sustainable biorefinery systems.

7. Conclusions

Net-zero is a scientific term requiring neutralising anthropogenic atmospheric greenhouse gas emissions by removal into anthropogenic sinks. It is perceived that individual entities' net-zero actions will cumulatively offer global net-zero or negative greenhouse gas emissions. It needs cautious and committed monitoring, reporting, accounting and governing agenda from every entity. While the physicochemical fundamentals balancing greenhouse gas sources and sinks are well researched, individual entities' net-zero pledges could merely offer offsetting activities.

This study offers technical, social-policy, and data system appraisals to make net-zero recommendations. The overarching question is how Scope 3 *life cycle greenhouse gas emissions* (GHG) can be considered in net-zero actions. Technical questions aim to understand which greenhouse gases to remove, when, where, and the mechanism. The social-policy challenges raise concerns about delivering the UN SDGs through the net-zero agenda. The data system targets robust, transparent information communications so that GHG can be accounted for so that the individual entities' climate actions collectively offer the global net-zero.

There is an unmet need to embed life cycle assessment (LCA) in net-zero pledges and actions. Creating an internationally standard LCA embedded value analysis tool can help shift to a net-zero paradigm with GHG sinks. Furthermore, life cycle sustainability assessment (LCSA) keeps net-zero and sustainable development agendas aligned. The LCA-LCSA embedded value analysis methodology shows a universally profound way of allocating credits/impacts between entities for an equitable and just transition (a zero-sum game).

Thirteen recommendations are made through the methodological approach and net-zero relevant system analyses in the sustainable development framework. These include focused efforts on comprehensive LCA-embedded net-zero policy, LCA/LCSA-driven value analysis for climate incentivisation and equal and just society and whole-system interdisciplinary modelling research. A wide range of examples includes nature-based decarbonisation, renewable whole-energy systems, extended product lives, tech-metal security, biomass, biorefinery process, and product options for greening and circulating the economy epitomised to inform net-zero actions.

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