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Editorial

Balancing Energy and Environmental Sustainability: Innovations, Impacts, and Pathways, 1st Edition

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The transition toward sustainable energy systems is recognised as a complex, multi-dimensional challenge that extends far beyond the deployment of low-carbon technologies. The body of work considered here reinforces the need to move from fragmented assessments toward integrated perspectives that account for environmental, economic, and societal dimensions simultaneously. In doing so, it highlights both the progress achieved in recent years and the persistent gaps that must be addressed to ensure that energy transitions are truly sustainable.

A consistent theme across the contributions of this Special Issue is the central importance of life cycle thinking in evaluating emerging energy pathways. While many renewable and alternative technologies demonstrate clear advantages in terms of greenhouse gas mitigation, their broader environmental performance is often characterised by trade-offs across multiple impact categories. For example, the assessment of lignocellulosic renewable diesel pathways indicates substantial reductions in life cycle greenhouse gas emissions relative to conventional fuels, yet it reveals increases in particulate matter emissions and higher total cost of ownership in certain scenarios (Contribution 1). Such findings demonstrate that comprehensive, multi-impact evaluations remain essential.

In parallel, the growing relevance of circular economy approaches is evident in analyses of energy infrastructure and material flows. The evaluation of end-of-life management strategies for wind turbine components evidences that recycling and repurposing options can significantly reduce net environmental impacts compared to landfilling, particularly when credits due to avoided burdens are incorporated into the assessment framework (Contribution 2). These results highlight the importance of extending the system boundaries of energy analyses to include material recovery and substitution effects, as well as the need to improve the quality and efficiency of recycling processes to maximise environmental gains.

Beyond supply-side innovations, the relationship between energy consumption and societal outcomes emerges as a critical area of research. Evidence suggests that, beyond certain thresholds, increases in energy use yield diminishing returns in terms of well-being, indicating a partial decoupling between energy consumption and quality of life (Contribution 3). These findings challenge conventional assumptions that higher energy use is inherently associated with improved living standards and point to the potential of sufficiency-oriented strategies that prioritise reduced resource use while maintaining well-being. Addressing consumption patterns, lifestyle choices, and behavioural dynamics

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may therefore play a crucial role in reducing environmental pressures while maintaining or even enhancing human well-being.

At the same time, the contributions underscore the importance of context-specific analyses in understanding energy transitions. The deployment of distributed photovoltaic systems in regions with unstable energy supply demonstrates how renewable technologies can enhance energy security, reduce emissions, and generate economic benefits at the household level (Contribution 4). Conversely, the expansion of large-scale renewable energy infrastructure highlights potential unintended consequences, including land-use change, vegetation loss, and increased landscape fragmentation (Contribution 5). These contrasting outcomes illustrate that the sustainability of energy solutions cannot be generalised. On the contrary, they must be evaluated within their specific geographical, ecological, and socio-economic contexts, which calls for innovative approaches to assess the impacts throughout the life cycle of such solutions.

Further complexity arises from the development of bio-based and catalytic conversion pathways, which offer promising alternatives to fossil fuels but require careful optimisation of process conditions and product quality to ensure environmental and economic viability. Advances in the catalytic pyrolysis of biomass, for instance, demonstrate the potential to produce high-value hydrocarbons from renewable feedstocks, yet also reveal challenges related to product stability, oxygen content, and process efficiency (Contribution 6). These findings reinforce the need for continued research into process integration, catalyst design, and downstream upgrading technologies (e.g., hydrotreatment, catalytic cracking, and product separation).

Taken together, these insights point to a fundamental conclusion: achieving sustainable energy systems requires a shift from isolated technological solutions toward system-level approaches that integrate multiple dimensions of sustainability. This includes not only reducing emissions but also minimising resource use, avoiding environmental burden shifting, ensuring economic feasibility, and addressing social equity considerations. From this perspective, life cycle thinking tools should move towards an integrative approach that encompasses the different pillars of sustainability and goes beyond the carbon tunnel vision perspective.

Looking forward, several research priorities emerge. First, there is a clear need to advance integrated assessment methodologies that combine life cycle assessment with techno-economic analysis, social impact assessment, and systems modelling. Such approaches can provide a more comprehensive understanding of trade-offs and synergies across different sustainability dimensions.

Moreover, methodologies should consider context-specific aspects influencing the impacts of energy solutions. Future research should continue to emphasise regional and local perspectives, recognising that energy transitions are inherently shaped by contextual factors. Comparative analyses across different regions can help identify best practices while avoiding one-size-fits-all solutions.

Second, further work is required to strengthen the implementation of circular economy principles within energy systems, particularly in relation to the reduction in the use of critical raw materials and innovation in material-intensive technologies such as wind and solar infrastructure, as well as energy storage. Designing for recyclability, improving material recovery rates, and developing viable secondary markets for recovered materials will be critical.

Third, greater attention should be given to demand-side strategies, including energy efficiency, behavioural change, and consumption reduction. Approaches to reduce the overall demand, particularly in high-income countries, have the potential to complement

technological innovation and reduce the overall scale of energy demand, thereby alleviating pressure on natural resources and ecosystems.

Finally, bridging the gap between research and practice remains essential. Strengthening the interface between science, policy, and industry will be key to translating analytical insights into actionable strategies that support sustainable and equitable energy transitions. The findings presented here contribute to a growing recognition that sustainability in energy systems is not solely a matter of technological substitution, but also one of systemic transformation. Addressing the intertwined challenges of energy, environment, and society will require coordinated, interdisciplinary efforts and a continued commitment to innovation, critical evaluation, and adaptive governance.

Conflicts of Interest: The authors declare no conflicts of interest.

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