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Unlocking Established and Emerging Opportunities for the Bioeconomy Sector Globally Through Scaling Innovation at Demonstration Sites – Quo Vadis?

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The bioeconomy is emerging as an important sector for society to address the appropriate sustainable management of finite natural resources (Dietz et al., 2018; Richter et al., 2025). There is a commensurate pressing need to understand and communicate its purpose across other linked strategic policies, in order to effectively develop, scale and regulate new eco-innovation (Ubando e et al., 2020; Rowan, 2025; EU Bioeconomy Strategy 2025). Notwithstanding this, it is appreciated that there are multiple interpretations of the circular economy that can potentially cloud stakeholder understanding of its importance and value for society. For example, Tan and Lamers (2021) noted that "there are over 100 definitions of circular economy that principally means different things to different people". Therefore, it is of pressing importance to simplify and to demonstrate tangible viable bio-based products (and technologies) emerging from the circular economy to effectively inform broad stakeholders including policymakers using appropriate communication channels.

The aforementioned is in marked contrast to linear economic models as "circular economic models emphasize economic growth and activities that are dissociated from the consumption of finite resources and minimize system wastes, ultimately achieving positive society-wide benefits" (EU Bioeconomy Strategy, 2025). Thus, how companies interpret, develop and implement appropriate circular economy frameworks will be reliant upon how its decision makers or stakeholders including end-users also interpret the concept and its definitions (Rowan, 2025; EU Bioeconomy Strategy, 2025). Moreover, this will depend on what will enable new eco-innovation meet regulation and boost revenue. Accordingly, stakeholders have highlighted the importance of developing relevant pilot and commercial bioeconomy demonstration facilities that simplify, co-create and produce at scale tangible eco-products from waste biomass and cascades with stakeholders for viable business opportunities (O'Neill et al., 2024). Additionally, given its infancy, there is marked gap in the literature on selection of appropriate key performance indicators to guide, monitor and assess impact and added value of bioeconomy activities policies for the environment, economy and society (Rowan, 2026).

It is imperative to build an ecosystem of end-users that can test, develop and de-risk for viable new eco-innovation from ideation stage to commercial deployment for established or new markets. A critical potential bottleneck for co-creating and developing alternative innovation for the circular economy is scalability in real world applied settings that also provide important opportunities to attract investment and to ensure compliance with environmental balance (Rowan, 2025). Bioeconomy demonstration sites act as a critical nexus or bridge between laboratory research and commercial application by scaling up innovative bio-based solutions that are economically viable. The strategic economic and environmental added value of using appropriate bioeconomy demonstration sites are potentially considerable including (a) commercial acceleration and business model development, (b) resource efficiency (such as demonstrating how to effectively upcycle waste and by-products into high value revenue streams), (c) rural regeneration (such as enabling diversification, particularly in territories transitioning away from fossil fuels by creating alternative jobs and new income for primary producers), (d) innovation and knowledge transfer (such as serving as living labs that integrate stakeholders such as companies, universities and end-users to build technical capacity and upskill), and replication blueprints (where successful sites provide high-level blueprints for facilities that can be shared and potentially replicated in other regions or internationally) (Rowan, 2026). Demonstration sites enhance resilience by developing circular business models that convert waste, by-products, and residues into valuable, renewable and bio-based products. They foster collaboration across the entire bio-based value chain, bringing together companies, researchers, local authorities, and primary producers to transform local economies. Interestingly, use of "hub-and-spoke" and integrated "helix hub" models have been reported for many years to strategically advance opportunities with stakeholders in biotechnology, healthcare, agriculture and so forth. However, of over 40 integrated models published in

the literature, there remains a marked gap in knowledge that specifically addresses applied evidence-based stakeholder use of bioeconomy beyond perspective reviews for accelerating new viable biobased products for markets (Rowan 2025).

That said, the European Commission, and several Member states, advocated promotion of a robust circular bioeconomy to underpin implementation of Europe's Green Deal and to meet climate neutral ambitions by 2050. For example, Skondras et al. (2024) examined 20 cases studies arising from 61 circular bioeconomy governance models for enabling regional government good practices. The topology of regional bioeconomy governance models within the EU-27 distinguished between four bio-based transformation paths (TPs), each representing distinct trajectories towards a circular bioeconomy: fossil fuel substitution (TP1), boosting primary sector productivity (TP2), new and more efficient biomass uses (TP3), and low-bulk and high value-applications (TP4). While this provided valuable insights for policymakers to support co-development and replication of effective circular bioeconomy strategies across diverse European regions, the authors noted that managing conflicting goals remains a challenge. Findings highlighted that regions can attract investments in local demonstration or flagship projects for identifying the local availability of feedstocks from various sources (such as agriculture, agri-food industries, forestry, and residual material streams); thereby, "fostering local job creation, regional economic growth, and opportunities in the regional primary production sectors". While it was appreciated that incorporating of capital markets into regional circular bioeconomy governance models is in its infancy, the authors advocated that blending this function utilizing a penta-helix approach is essential to guarantee effective implementation and governance of regional circular models. However, this insightful review did not address the role of identifying and achieving consensus on relevant key performance indicators (KPIs) to assess data from bioeconomy hub activities that would inform tangible viable innovation, job creation along with regional resilience and regeneration. Emerging research also specifically emphasizes the role of biorefineries for meeting United Nations SDGs and transition to bioeconomy (Solarte-Toro et al., 2021).

Significant investment has been made by the Irish government to grow demonstration sites at scale to support various sectors of the bioeconomy (Rowan, 2025), particularly in collaboration with the Just Transition fund for developing "bioeconomy territories" combined with "living labs" to transform rural economies (DAFM/EU Just Transition, 2025). Recent co-funding bioeconomy demonstration investments with industry are advancing biochar for agriculture, upcycling brewing waste, microalgae (including precision fermentation), and aquaculture (through integrated multitrophic aquaculture (IMTA) system using a peatlands model that transitions away from extracting peat as a fossil fuel or for horticulture use) attest to validating new technologies and eco-products that will demonstrate high value revenue streams from natural resources. There appears to be an emerging opportunity to cluster bioeconomy demonstration sites as this provides a strategic platform for collaboration and value co-creation by connecting diverse stakeholders to accelerate the transition to a circular economy. There are increasing initiatives to address this need such as the European Circular Economy Stakeholder Platform that brings together leaders across members to advance an integrated circular bioeconomy. Such clustering should also consider adjacent developments with other hub initiatives such as for digital transformation and climate action to add value where a mapping exercise addressing unique propositions offered by each bioeconomy demonstration site and at scale would be beneficial. It remains challenging for early adopters including companies to understand technological readiness level for developing new innovation in the circular economy. Table 1 has been slightly modified as opportunity for stakeholders to use and modify the nexus between technical, social and policy readiness levels.Considerable emphasis, particularly for researchers, is centred on early phase readiness levels (below 3); however, there needs to be greater emphasis and consensus on innovation readiness levels beyond level 7 for scale up and commercial deployment that embraces cross sectoral and multi-disciplinary use. The origin of these informative readiness levels is attributed to the Irish Department of Agriculture, Food and Marine in Ireland who is leading and championing growth of the bioeconomy. It was subsequently modified in part by Rowan and Casey (2021) for supporting stakeholder integration for new products using "Empower Eco" triple helix hub model that acted as a blueprint for new IMTA circular demonstration model in Irish peatlands for meeting many of United Nations Sustainable Development Goals. This model is also likely to be evolved by using appropriate digital tools including sensors, drones, automation and so forth (Rowan, 2023; Rowan 2024).

Table 1: Interpreting end to end needs for bioeconomy innovation development based on technology and linked, societal and policy readiness levels

Technology Readiness Levels* (TRL)*		Society Readiness Levels** (SRL)		Policy Readiness Levels*** (PFL)	
TRL 1 – Basic Research - Principles postulated and observed - (Discovery)	Knowledge development Academia	**SRL 1 – Basic Research** - identifying problem and identifying societal readiness (Discovery)	Knowledge development Academia	**PRL 1 –Basic Research** - identifying issue/problem and identifying policy readiness (Discovery)	Knowledge development Academia
TRL 2 – Technology Concept Formulated – concept and application defined (Concept Definition) for bioeconomy innovation		**SRL 2 – Formulation** of problem, proposed solution(s) and potential impact, expected societal readiness; identifying intended stakeholders for project (Concept Definition)		**PRL 2 – Formulation** of issue/problem, proposed solutions and potential impact; expected policy readiness; concept identification relevant to stakeholders (Concept Definition)	
TRL 3 –Experimental Applied Research Concept – first lab and environmental tests completed (Proof of Concept)		**SRL 3 – Applied Research** - initial testing of proposed solution(s) with intended stakeholders (Proof of Concept)		**PRL 3- First testing** of proposed solution(s) with stakeholders; modelling, consultations, feedback, development complete (Proof of Concept).	
TRL 4- Technology Validated in Lab - Small scale prototype – built and tested in livinglab (validation) including safety, ecotrophic and biodiversity compliance		**SRL 4 – Pilot-Test Scale** - concept validated through pilot testing in relevant environment to substantiate proposed impact and societal readiness (Concept Validation)		**PRL 4 – Problem validated "in lab"** through pilot testing in intended environment to substantiate proposed impact, policy readiness, feedback development (lab validation)	
TRL 5 Large-Scale Prototype tested in intended environ (test facility validation)	Technology Collaboration	**SRL 5 – Large Scale Test/system** - proposed solution(s) validated; with intended stakeholders	Societal Collaboration	**PRL 5 – Proposed solution(s) validated**; now by intended stakeholders in the area for application	Policy Collaboration
TRL 6 – Technology demonstrated in intended environment – close to expected performance for intended circular economy		**SRL 6 – Demonstrated system** - solution(s) demonstrated in relevant environ and with intended stakeholders for feedback on policy		**PRL 6 – Demonstration system** in intended environ & with intended stakeholders at pre-role out scale for feedback on impact (system demo)	
TRL 7 – System prototype demonstration in operational environment at scale – at pre-commercial scale (system demo) for de-risking and to attract finance		**SRL 7- System Refinement** - refinement of product/solution(s), retesting in intended environment with stakeholders (refinement)		**PRL 7 – System refinement** of solution(s), possibly, retesting in intended environment with intended stakeholders to gain feedback (refinement)	
TRL 8 – First system complete, qualified, verified – First commercial system – (verification)	Business development Industry	**SRL 8 – First System** – issues solved, proposed solution(s), as well as plan for societal adaption complete, and qualified (verification)	Stakeholder Development Governing	**PTL 8 – First System** - proposed solution(s), as well as plan for policy **adaptation complete, and qualified** (verification)	Scheme development Government
TRL 9 – Actual Full commercial system proven in operational environment – technology available for beneficiaries (deployment)		**SRL 9 – Full Social System** - actual project solution(s) in intended or relevant environment (deployment)		**PRL 9 – Policy Implementation** - actual project solution(s) proven in relevant circular environment. Issues solved, continued monitoring, evaluation, and review of scheme/solution (deployment)	

*TRL – are indicators of status or maturity level of particular technology been researched and commonly used for European Commission in context of Horizon Europe.

**SRL – Used to assess the level of societal adaptation to project, technology, product, process or management practice , or innovation to be integrated into society

***PRL – Used to assess the level of societal adaptation to project, technology, product, process or management practice , or innovation to be integrated into policy (adapted from Rowan and Casey, (2021)

Consensus on the appropriate key performance indicators for emerging projects and eco-solutions for the EU Just Transition territories would be particularly beneficial given strong need to define and manage viable alternative eco-innovation such as for circular economy. This will be informed by appropriate life cycle assessment studies (Ruiz- Salmon et al., 2021; Cooney et al., 2025). There is increasing interest in defining appropriate KPIs for the bioeconomy as this addresses the effective spend of circular economy projects commensurate with tangible outputs and perceived impacts for return on investment that includes achieving balanced environment status. Historically, there was emphasis placed on linear KPIs such as journal publications; however, KPIs for the bioeconomy are enterprise orientated that also specifically reflects the need to create added value for broad stakeholders ranging from bottom up sustainable reuse of natural resources by farmers to top-down tailored regional and international strategic polices (Rowan, 2025). Indicative socio-economic KPIs that measure bioeconomy's contribution to growth, wealth and employment include (a) socio-economic (turnover, value added, direct employment, labour productivity, innovation R&D, competitiveness), (b) economic and sustainability (example climate change for green-house gas emissions and carbon footprint across value chain, resource efficiency addressing biomass use, land use change, and degree of material valorisation, renewable energy share, waste management addressing recycling rates and biowaste production and material recovery and ecosystem health addressing impact on biodiversity, soil quality and water usage efficiency); and Social and Governance (for example stakeholder welfare, community impact, food security, traceability and certification, and public awareness). Initial emphasis for bioeconomy demonstration potentially focuses on the nature, type and frequency of company engagement that was evident for the IMTA demonstration site in Irish peatlands (Rowan, 2026).

For example, Ares-Sainz et al. (2025) stressed that the European bioeconomy sector can be framed within offers a sustainable development model. However, these co-authors corroborate that its successful implementation requires robust and plausible monitoring and measurement. Moreover, meeting ambitious sustainability in bio-based value chains requires clearly defined operational characteristics and indicators that comprehensively address key sustainability and circularity aspects that must align with the EU sustainability framework, policies and directives. These authors reported a total of 142 sustainability indicators proposed across environmental (7 areas), social (5), and economic/circularity (4) pillars, along with 60 operational indicators in governance (4 principles), assurance (5), traceability (4), and standard setting (3). Based on observations from stakeholder engagement for potential change in land use using the IMTA demonstration site (Rowan 2025, Rowan, 2026), KPIs can potentially be also monitored for value at interrelated micro (end-users such as company, farmers), meso (interface between end-user and policymaker), and macro (boarder socio-economic, sustainability and social and for governance benefits) levels (Table 2). However, these indicative KPIs and added value gains are likely to evolve and change by way of priority over time based on observations, engagements and greater evidence-based feedback from end-users over a longitudinal period. Early financial investment by governments is important to pump-prime circular economy including incentives for early adopters and to champion these by way of hightlighting case studies in strategic policies, particularly for regional regeneration

Table 2: Candidate indicator name and unit for key performance indicators aiming at monitoring bioeconomy enterprise activities at demonstration site enabled by adopting penta helix framework at *micro*, *meso* and *macro* engagement levels

Micro (enterprise level)	*Meso* (Innovation hub level)	*Macro* (Policy level)
Number of Start-ups formed in with **circular** economy focus **including industrial and industrial-urban symbiosis; improving environmental sustainability; climate change mitigation and adaptation**	**Number of enterprise or companies supported** in innovation, equipment training (Start-ups to MNCs); such as access to • specialist equipment for testing tech • Subject Matter Experts • bespoke workshops • business canvass/plan • **Life cycle environmental performance** • **Attract Financial investment** • **Large scale valorisation of sustainable biomass**	Product and open data shared informing established or new regional or international policies on bioeconomy Examples: Ireland's Bioeconomy Action Plan 2023-2025 Ireland's Food Vision 2030 EU Bioeconomy Strategy 2025 Policy coherence (interplay with other policy initiatives) EU Just Transition EU Climate Policy European Green Deal United Nation's SDGs 2030

Number of IDFs or Patents	**Enterprises supported by grants** including derisking for investment	Frequency by which bioeconomy informs other adjacent strategic policies (health, biotechnology, agriculture)
Number of media and social media reports from enterprise on circular economy activities and breakthroughs	**Enterprises co-operating with Research Organizations** including repeat number supported at demonstration hub for co-creating eco-solutions	Reduction and upcycling of waste and resource management (number or biorefineries)
Enterprises blending different disciplines including biobased, tech with digital tools	Enterprises supported in introducing viable product or process	Growth in bioeconomy sector (GDP) including job creation and level of government strategic investment
Number of employees upskilled and retrained	Number of enterprises introducing marketing or organizational innovation including improving uptake of biobased products	Contributions **to climate change mitigation, adaptation** including **GHG reduction 60**, carbon sinks
Number of employees satisfied	Growth in scale and capacity in Hub and staff including: • Number of PhDs in bioeconomy domain • Number of internships or employee exchanges between industry and university (and vice-versa) • Students placements - e.g. PEP placements • CPD events organised/delivered	Increase in regional resilience, regeneration and development through number of innovative bio-based products and products
	Expansion of hub ecosystem for regional (NGOs, local Government), national and international partners	Environmental performance improvements such as receiving water, air quality (EPA)
	Appropriate eco-testing (biodiversity, ecology) • Unlocking sustainable and circular bio-based feedstock for industry • Ensure Environmental sustainability of feedstock • Improve environ sustainability of biobased production processes and value chains • Expand circularity in biobased value chains • Increase innovative bio based outputs and products	International mobility and training of enterprises in circular bioeconomy
	• Number of social enterprise projects addressing circularity	Number of planning permissions granted for sustainable waste management activities
	Number of sustainable new products and technologies	Increased resilience and capacity in biobased sector
Bold highlighting indicates KPIs agreed with Bioeconomy Demonstration Hubs under EU Just Transition Fund Programme for Ireland		

The aforementioned supports the new EU Bioeconomy Strategy that seeks to drive green growth, competitiveness and resilience across Europe by strengthening its strategic autonomy, replacing fossil-based materials and products, by creating new employment, and by leading the transition to clean industries (Power4Bio, 219). Notably, it is the vision of the EU to move towards a more circular and de-carbonized economy by using renewable biological resources from land and marine. By using renewable biological resources from land and marine, and by which will providing appropriate sustainable alternatives to using fossil-based and imported raw materials. This requires a combination of public and private investments, a streamlined regulatory environment, developing lead markets for bio-based materials and

technologies, and securing both a sustainable and viable use to diverse biomass for financially viable opportunities (Rowan, 2025). The perspective review of Rowan (2026) provided a greater bridge between stakeholder use of bioeconomy demonstration sites and informing policymakers for strategic policies. The future role of adopting appropriate methodology to increase awareness and to promote end-users behavioural change towards circular economy including using citizen science is also not to be underappreciated (Domegan, 2021). Championing effective simple to follow case studies will also support greater awareness and uptake for change of land use for bioeconomy sector (Gaffey et al., 2023), which will be enabled by digital livinglab (Rowan et al. 2026).

To conclude, the emerging bioeconomy sector is highly ambitious, and in its infancy, as attested by the need to define and to evolve appropriate KPIs. There is a commensurate need to elucidate and validate KPIs for the bioeconomy measure progress across the interlinked economic, social, and environmental pillars, such as focusing on metrics like new value chain development, circularity, investment in sustainable technologies, re-source efficiency, new job creation in green sectors, and biodiversity impact guided by new and update frameworks like the EU Bioeconomy Strategy.

Conflict of Interest

The author declares no conflict of interest

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