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Beyond the Fairy Tale: Lessons from the Danish Bioeconomy Model

- From Ugly Duckling to Circular Swan

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Part of *The Emerging Bio-Economy: California Opportunities and Challenges in a Global Trans* formation?

A UCOP project led by Tom Harmon, David Zilberman, John Zysman

Beyond the Fairy Tale: Lessons from the Danish Bioeconomy Model ©

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Prepared for the California LACA book project on the Development of Circular Economy in California

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1. Introduction[1]

Denmark has over the past century developed one of the world's most coherent, integrated, and strategically governed bioeconomy ecosystems. It is the fruit of the combined evolution of agriculture, industrial biotechnology, environmental regulation, green energy policy, and a deeply rooted collaborative culture linking public institutions, research organizations, private industry and users. The Danish experience offers lessons for how advanced economies can combine competitiveness, sustainability, and innovation in a biological, circular, and low-carbon economic system.

Denmark's bioeconomy represents a century-long structural transformation linking agriculture, industrial biotechnology, pharmaceutical manufacturing, renewable energy systems, and circular industrial ecology into a highly coordinated innovation system. The Danish bioeconomy evolved through layered institutional change: cooperative ownership structures, strong advisory systems, university-industry collaboration, and European and national regulatory frameworks incentivizing long-term technological upgrading.

For U.S. policymakers, particularly those states pursuing climate-aligned industrial strategies, the Danish examples demonstrate that long-term competitiveness depends not only on technological breakthroughs but also on institutional arrangements linking environmental regulation, infrastructure investment, and industrial development. Denmark's bioeconomy should therefore be understood as the product of long-term institutional coordination rather than short-term policy intervention. Cascading resource use, industrial ecology, and circular energy infrastructures are not isolated initiatives; they represent the cumulative outcome of decades of scientific investment, cooperative governance, and adaptive environmental regulation. As global economies seek pathways toward sustainable industrial transformation, Denmark provides a concrete example of how integrated bioeconomy systems can align economic growth with climate objectives.

2. Denmark's Bioeconomy

Bioeconomy refers to the production, conversion, and cascading use of renewable biological resources to generate food, materials, chemicals, energy, and services. In Denmark, this definition is not merely conceptual; it reflects a governance model in a systematic approach in which environmental policy, industrial strategy, and regional development are tightly

[1] In this chapter we refer to Denmark as only the southernmost part of the Kingdom of Denmark. The conditions in the arctic regions of the Kingdom, Greenland, as well as the Northern Atlantic Faroe Islands, differ vastly from the conditions in the southern part of the kingdom.

connected. The Danish case therefore provides a useful lens for policymakers seeking to align climate objectives with industrial competitiveness.

Three interlinked value chains structure the Danish system. The *agro-food chain* anchors employment and regional stability, particularly in rural areas, even as mechanization reduces labor demand over time. The *biosolutions and pharmaceutical chain* has become the primary engine of export growth, generating high value per employee through advanced fermentation technologies, intellectual property, and participation in global innovation networks. Between these domains, the *circular energy and resource recovery chain* connects agriculture, manufacturing, and energy systems through biogas infrastructure, district heating networks, and industrial symbiosis. Together, the chains illustrate a structural shift common for advanced bioeconomies, that biomass production remains essential, but that economic value is increasingly concentrated in research-intensive conversion stages. The special feature of the Danish case is the degree of institutional coordination that keeps upstream production connected to downstream innovation. Cooperative organizations, advisory systems, and cluster platforms help translate scientific advances into industrial applications, ensuring that agricultural production remains embedded within a broader innovation ecosystem, based on triple helix type approaches.

Even though Denmark is a world leader in circular economy, with an economy in many ways solidly rooted in advanced fermentation and green exports, it is clear, that the process towards a biobased economy is ongoing. Thus, Denmark's first Circularity Gap Report in 2023, showed that despite concerted and focused efforts over decades, Denmark is still just 4% circular.

Recent research in framework conditions for the development of bio solutions also point to needs for continued efforts related to areas such as commercialization of research, access to facilities, access to risk-capital, better regulation, and access to labor.

3. Historical Transformation and Value Chain Reconfiguration

Danish agriculture is characterized by intensive land use, with roughly two-thirds of the country under cultivation and a highly input-intensive production model based on fertilizers, irrigation, and crop protection. A large-scale livestock sector, particularly in pigs and dairy, underpins both domestic production and exports, but also contributes to significant environmental pressures, including nutrient runoff and greenhouse gas emissions - accounting for approximately one quarter of Denmark's total emissions. Environmental regulation has therefore been essential in addressing these externalities. At the same time, regulatory frameworks have been designed to act not only as constraints but as drivers of innovation and structural adaptation; reflecting a dual logic that has shaped the evolution of Denmark's circular bioeconomy.

BOX **Danish agriculture** occupies a dominant position, utilizing 61% of Denmark's total land area. Approximately 75% of Denmark's total agricultural and food production is exported, Main livestock is pigs for slaughter, dairy cows and chickens, and the Danish agricultural sector holds high world market shares:

commodity	World Market Share/Global Rank
Grass Seeds	30%, ranked 1st
Food ingredients including modified starch and enzymes	52%, ranked 1st
Blue-veined cheese	18%, ranked 3d
Live swine exports	25%, ranked 1st
Pork products	10-14%, ranked 3rd-4th

Table 1 Global market shares for selected Danish agri-food product categories latest available year - Danish Agricultural Council

Danish agriculture's market shares are particularly notable given Denmark's position as a high-cost producer where labor, land, and input costs substantially exceed competing nations.

The Cooperative Ownership Model: At the primary production level, self- and family ownership remain dominant, while investor-owned farms represent a growing segment for larger scale operations. Denmark's most distinctive structural feature is the prevalence of farmer-owned cooperatives throughout agri-food processing and input supply sectors. The cooperative movement originating in the 1880s, shaped Danish agriculture's competitive dynamics. enabling small-scale producers to collectively achieve economies of scale in processing and marketing while retaining ownership and control. A single farmer with one cow could not produce butter of acceptable quality independently, but uniting, farmers could build proper dairies with modern equipment producing premium products at higher prices. Co-operatives control approximately 90% of the Danish dairy market, 80% of pork processing, and 70% of feed and agricultural inputs. Contemporary Danish cooperatives include several world-leading agri-food enterprises:

- Arla Foods - dairy, ranked 2nd in Europe,
- Danish Crown - pork, ranked 2nd in Europe,
- DLG - feed industry, ranked 2nd in Europe,
- DLF Seeds - grass seed, ranked 1st globally, and
- KMC - potato starch, ranked 2nd in Europe.

The cooperative dominance facilitates strong vertical integration and coordination across value chain links from input supply through primary production to processing, marketing, and distribution. Vertical integration ensures faster dissemination of market signals while providing delivery and purchase security through contracts and delivery rights. Cooperative structures enable farmers to collectively control major upstream and downstream value chain portions, distributing profits back to farmer-members while maintaining scale, technological capability, and market access comparable to large corporations, and the cooperative development has been a key driver in the development of Danish agriculture's international competitiveness.

Denmark's contemporary bioeconomy is the outcome of a historical process through which structural constraints have gradually spurred institutional and technological innovation. The transition from a land-constrained agrarian economy to a knowledge-intensive bio industrial system emerged through repeated adaptation to external market pressures, evolving regulatory frameworks, and investment in scientific capability. Throughout this development, cooperative governance, institutional learning, and environmental regulation have interacted to reshape value chains, ultimately producing a hybrid economic system that combines biological resource production with advanced biomanufacturing and circular energy infrastructure.

Increasingly limited territory and dependence on export markets created strong incentives for productivity growth and institutional innovation from an early stage. Reclaiming land and agricultural innovation and intensification were historically important prerequisites for economic resilience. This structural condition fostered a political culture in which cooperation

between producers, researchers, and policymakers became central to competitiveness. Contemporary initiatives around rewetting and nature restoration illustrate how the objectives of the system have today evolved beyond production and export to include other important aims such as climate mitigation, biodiversity, and landscape governance, while still reflecting the historical institutional legacies.

BOX The limitations of land are best illustrated through Denmark's most recent loss of approximately one third of the territory in the second Schleswig war in 1864, which drove a massive effort of cultivating the heath and claiming fjords and wet areas for agriculture under the motto of "What is lost outwardly must be won inwardly". Many of those efforts are being reversed today as part of Denmark's efforts to combat climate change, but the societal and cultural impact remains, including the importance for Denmark's general collaborative approach to problem-solving and innovation and the widespread cooperative ownership structures in the Danish agroindustry, through the advent of the cooperative movement. In the short term, the loss of land caused economic disruption and trade reorientation, forcing Denmark to find new markets for its agricultural production. In the long term, the loss drove a fundamental shift in Danish agriculture toward a more efficient, export-oriented production of foods, which ultimately contributed to a period of rapid economic growth and specialization in the late 19th century. The cooperative movement (*Andelsbevægelsen*) originating in the 1880s, shaped Danish agriculture's competitive dynamics. The cooperative model enabled small-scale producers to collectively achieve economies of scale in processing and marketing while retaining ownership and control. A single farmer with one cow could not produce butter of acceptable quality independently, but by uniting, farmers could build proper dairies with modern equipment and skilled staff, producing premium products at higher prices and earnings.

With the mechanization of American agriculture in the years after the civil war and falling transportation costs, the US flooded European markets with cheap grains in the Great Grain Invasion from around 1870. Over twenty years the price of wheat fell about 40 per cent, and the price of rye 30 per cent. To protect their farmers most European countries, most notably France and Germany, departed from free trade policies and imposed protective import tariffs on US grains, but not Denmark. The changing market developments forced Danish farmers to pivot toward higher-value livestock and dairy exports; mainly butter and bacon for the UK markets. The developing cooperative movement provided the organizational framework enabling this transformation. Smallholders collectively financed modern dairies and slaughterhouses, standardized production, and built strong marketing institutions integrating Danish producers into global value chains while preserving distributed ownership. These cooperative institutions became platforms for collective learning, linking farmers, engineers, and emerging scientific communities in ways that laid the groundwork for later industrial clusters.

Throughout the twentieth century, Danish agriculture underwent continued modernization through mechanization, genetic improvement, feed optimization, and advisory systems. What distinguished the Danish trajectory was not just technological adoption but the institutionalization of continuous learning. Advisory organizations and cooperative networks translated scientific advances into everyday practice, creating feedback loops between research

institutions and production systems. This integration of science and practice enabled high productivity despite rising labor costs and environmental pressures, reinforcing export competitiveness while maintaining a relatively decentralized production structure.

From the 1970s onward, new requirements from environmental governance introduced a new layer of transformation that reshaped the bioeconomy. Regulations targeting water quality, nutrient runoff, and later greenhouse gas emissions required producers to operate within stricter ecological boundaries. Rather than replacing the productivity logic of agriculture, environmental policy reweighted it, making technological innovation, measurement systems, and coordinated compliance central to economic survival. Investments in manure management, precision nutrient application, and bioenergy infrastructure emerged partly as responses to this new regulatory pressure. Over time, environmental policy evolved from a corrective mechanism into a real driver of systemic integration, linking agricultural production with energy systems and waste management through circular solutions such as biogas and nutrient recycling.

The transition toward a knowledge-intensive bioeconomy accelerated in the late twentieth and early twenty-first centuries as automation and consolidation increasingly reshaped primary production. Farms became fewer and larger, supported by advanced mechanization and digital technologies, leading to a gradual decline in agricultural employment even as output volumes remained high. At the same time, Denmark leveraged its deep fermentation expertise, rooted in food processing and agricultural science, to build globally competitive bio solutions and pharmaceutical industries. Industrial enzymes, microbial cultures, and biomanufacturing processes transformed biological innovation into a major export driver, shifting value creation away from commodity production toward specialized scientific knowledge.

Environmental regulation continued to act as a selective pressure throughout this period, favoring operators capable of investing in advanced measurement systems and integrated production technologies. The Green Tripartite Agreement of 2024 (see below) represents an extension of Denmark's negotiated governance tradition, embedding climate targets within collaborative frameworks that align agricultural transformation with long-term policy objectives. By linking emissions pricing with land-use planning and innovation investment, the agreement reflects a shift from reactive environmental regulation toward proactive system design.

Institutionally, the rise of bio solutions and life science sectors was reinforced by translational infrastructures and patient capital that support early-stage innovation and industrial scale-up. The 2024 consolidation of Novozymes and Chr. Hansen into Novonesis illustrates the continued concentration of fermentation capabilities within globally competitive platforms, while long-term funding commitments from the Novo Nordisk Foundation demonstrate how philanthropic capital has become embedded within Denmark's innovation ecosystem. These developments highlight the extent to which the bioeconomy has shifted from a production-centered model toward one in which scientific expertise and institutional coordination drive economic performance.[2]

[2] Denmark's bioindustry emerged from a century-long heritage in fermentation and agricultural processing. The industrial anchors are most notably Novo Nordisk and Novonesis. Novonesis was created in 2024 through the merger of Novozymes (founded in 1925) and Chr. Hansen (1874) pioneered industrial enzyme production and microbial cultures respectively, achieving global dominance in specialized niches. Their merger created a USD 4.4

Within this evolving landscape, cascading biomass use has become the defining organizing principle. Biological resources are prioritized for food and high-value applications before residual streams are redirected toward energy recovery and nutrient recycling. This cascading hierarchy reflects both a material logic rooted in industrial ecology and a governance logic, maximizing value creation while reducing environmental externalities. Agro-food production, bio solutions manufacturing, and circular energy systems therefore operate interconnected value chains linked through by-products, shared infrastructure, and regulatory frameworks.

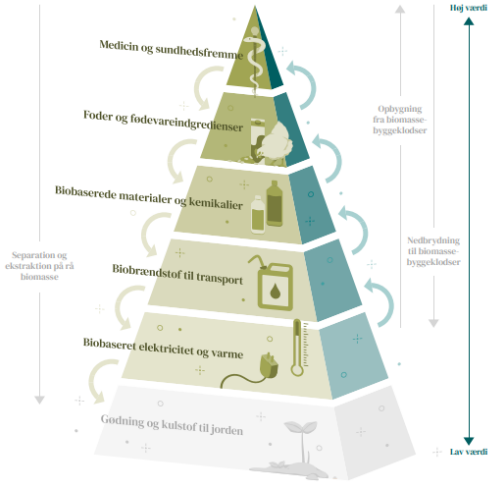


Table 1 Cascading principle – National Panel on Bioeconomy, 2024 – develop in English

The circular energy and resource recovery chain connects material flows across sectors, enabling industrial symbiosis through biogas production, district heating, and waste valorization.

An important structural feature is the divergence between employment distribution and value creation. Upstream and midstream segments retain large labor bases, particularly in rural regions, while downstream life science industries generate disproportionately high export value and productivity. Agriculture continues to provide the biological foundation of the system, supplying biomass, land-based resources, and platforms for circular flows, but economic growth increasingly depends on knowledge-intensive downstream activities integrated into global innovation networks. This inversion of the value chain illustrates a broader shift in advanced bio economies, where competitiveness is shaped less by production volume and more by the ability to embed and leverage scientific expertise within industrial processes.

Denmark's development demonstrates how long-term institutional coordination can transform structural constraints into sources of competitive advantage. The cooperative governance, environmental regulation, scientific investment, and cascading resource use, together underpin a hybrid bioeconomy in which agricultural production, advanced biomanufacturing, and circular infrastructure co-evolve within a shared institutional framework.

4. Structural Dynamics: Employment, Productivity, and Export Transformation

The historical developments explain how Denmark's bioeconomy emerged through cooperative coordination, environmental regulation, and scientific upgrading, the contemporary system is defined by a set of structural dynamics that reshape how value is created and distributed across the economy. A distinctive feature is the divergence between employment patterns and export

billion biosolutions company with 40,000 microbial strains, 38 research centers, and €350 million annual R&D investment [2]. Novo Nordisk's pharmaceutical facilities, particularly in Kalundborg where around 50% of the world's insulin as well as a range of biopharmaceutical products is produced, complement the industrial base. The pharmaceutical success generates substantial reinvestment capacity through foundations and the world leading philanthropic Novo Nordisk Foundation alone committed $US 872 million for 2026-2035 bioeconomy innovation infrastructure, enabling ecosystem-level investments far exceeding market-driven allocations

performance, reflecting a broader transformation from a production-centred agro-industrial model toward a knowledge-intensive bio industrial configuration.

The bio-solutions and pharmaceutical chain has become the principal driver of export growth and technological leadership. Firms specialising in industrial enzymes, microbial cultures, and biomanufacturing operate within global innovation networks where intellectual property, regulatory expertise, and advanced process engineering generate high value per employee. The rise of life science exports illustrates the structural transformation of Danish bioeconomy: while biomass production remains foundational, the highest economic rents increasingly accrue in research-intensive conversion stages rather than in primary production.

The circular energy and resource recovery chain occupies an intermediate position within this system. Biogas production, district heating systems, and industrial symbiosis networks link material flows across sectors, creating new employment niches while enhancing resource efficiency. Although export revenues from circular energy remain modest compared with pharmaceuticals or food products, circular energy plays a strategic role in stabilizing the broader system by reducing energy costs, improving environmental performance, and enabling cascading use of biological resources.

The divergence between employment and value creation reflects a general structural pattern across advanced bio-economies, but Denmark's case is distinctive because of the degree of coordination between relevant sectors. Rather than allowing downstream industries to detach from agricultural production, the Danish governance system secures strong institutional linkages between biomass supply, scientific research, and industrial application. Cooperative structures, advisory systems, and cluster organisations continue to function as connective tissue between rural production systems and globally competitive life science firms.

From a policy perspective, this raises questions about cohesion and industrial strategy. High value biomanufacturing clusters generate significant export revenues but are geographically concentrated and highly specialised. Upstream agro-food activities on the other hand remain spatially distributed and politically salient, sustaining employment in regions where alternative economic opportunities may be limited. Balancing these dynamics requires policy mixes that recognise the complementary roles of different value-chain segments rather than privileging one at the expense of the other.

Denmark's experience highlights the importance of aligning industrial upgrading with social and territorial considerations. The structural inversion of value chains does not imply the marginalization of agriculture but rather underscores the need for governance frameworks that connect primary production with downstream innovation systems. Denmark demonstrates that long-term competitiveness in the bioeconomy depends less on scaling biomass production alone than on embedding scientific expertise within industrial processes while maintaining institutional links to upstream resource bases.

Environmental regulation continues to function as a selective pressure shaping these structural dynamics. Policies requiring advanced measurement systems, nutrient management, and emissions reductions favour firms capable of integrating digital technologies and process innovation into production systems. The Green Tripartite Agreement of 2024 (see below)

exemplifies this development by linking emissions pricing with negotiated governance frameworks that encourage long-term investment in sustainable agricultural transformation. Rather than constraining economic development, regulation has become an instrument through which Denmark aligns industrial competitiveness with climate objectives.

At the same time, Denmark's fermentation heritage remains a key enabling factor in the rise of bio-solutions and life science sectors. The consolidation of Novozymes and Chr. Hansen into Novonesis reflects the ongoing scaling of fermentation-based capabilities into globally competitive platforms. Long-term funding commitments from the Novo Nordisk Foundation and related translational infrastructures further illustrate how patient capital has become embedded within the governance architecture of the bioeconomy, reducing risk for early-stage innovation while supporting industrial scale-up. These institutional arrangements reinforce the shift toward knowledge-intensive value creation while maintaining strong linkages between scientific research and industrial production.

They also underline the importance of the applied cascading principles and the Danish highly collaborative approach.

5. Cascading Value Chains, Industrial Ecology, and the Governance of Circular Bioeconomy Infrastructure

Building on the structural dynamics outlined above, Denmark's bioeconomy is increasingly organized around the principle of cascading biomass use, which integrates material efficiency with economic value creation. Rather than treating biological resources as single-use commodities, cascading systems prioritize high-value applications, such as food production and advanced biomanufacturing, before directing residual streams toward energy recovery and nutrient recycling. This hierarchy reflects both a material logic rooted in industrial ecology and a governance logic designed to maximise resource productivity while reducing environmental externalities.

In practice, cascading use blurs the boundaries between sectors that are often analysed separately. Agro-food production generates by-products that feed into industrial biotechnology processes, while waste streams from manufacturing and agriculture supply inputs for biogas plants and district heating networks. These interconnected flows create a form of industrial metabolism in which biological resources circulate through multiple stages of value creation. The result is not merely increased efficiency but a structural reconfiguration of value chains in which energy systems, agricultural production, and advanced manufacturing become mutually dependent.

Denmark's approach to industrial ecology reflects decades of institutional coordination. Shared infrastructures such as district heating grids, gas networks, and water management systems enable companies to exchange energy and material flows at scale. Again, these infrastructures

are not simply technical platforms; they are embedded within governance frameworks that align municipal planning, environmental regulation, and industrial investment. Consequently, cascading resource use has evolved from isolated pilot projects into a systemic organizing principle shaping the bioeconomy.

As mentioned above, the Danish system can be understood as comprising three dominant highly interdependent value chains. The agro-food chain continues to anchor employment and territorial cohesion, providing the biological inputs that sustain downstream industries. The bio solutions and life science chain captures high margins through specialised knowledge and intellectual property, transforming biological processes into globally competitive products. The circular energy and resource recovery chain connects these domains by enabling industrial symbiosis through biogas production, waste valorisation, and integrated energy systems. The value chains intersect through shared infrastructure, regulatory compliance systems, and collaborative governance arrangements.

Export statistics indicate that agro-food activities continue to play a macroeconomic role, with exports reaching approximately USD 29 billion in 2023 and supporting substantial employment across the value chain. These figures also reveal the structural divergence at the heart of Denmark's bioeconomy: upstream and midstream segments maintain large labour bases, while downstream life science industries generate disproportionate export value and productivity gains.

This divergence is not just an economic phenomenon but a governance challenge. Policymakers must balance the need for continued investment in knowledge-intensive industries with the social and territorial importance of land-based production systems. Denmark's experience suggests that cascading value chains can serve as a bridging mechanism between these domains by ensuring that agricultural production remains integrated within broader innovation ecosystems rather than being displaced by technological upgrading.

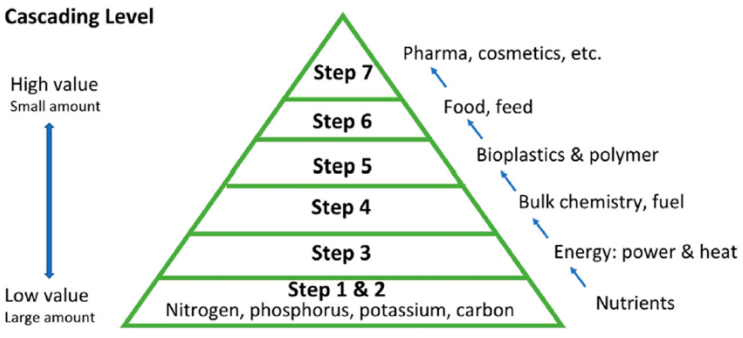


Table 2 Circular Bio-Economy (CBE) principles adopting Cascading of biomass residues, Lybæk R and Kjær T (2021)

From a comparative perspective, cascading resource use provides important lessons for international bioeconomy strategies. In regions such as California, where climate policy drives industrial transformation, the Danish model illustrates how circular infrastructure can be designed to support both environmental objectives and industrial competitiveness. Industrial ecology depends not only on technological innovation but also on stable regulatory frameworks, transparent data sharing, and long-term investment horizons that enable firms to coordinate resource exchanges.

Denmark's cascading value chains demonstrate how environmental constraints can be reframed as opportunities for systemic integration. By linking biological production with energy systems and advanced manufacturing, the Danish bioeconomy has developed a governance architecture that aligns sustainability transitions with industrial upgrading. Rather than representing a departure from historical development paths, industrial ecology and circular infrastructure emerge as the culmination of a century-long process of institutional coordination, scientific investment, and adaptive governance

BOX Energy Integration and Biogas Production as an example of applied cascading principles: One of the most obvious manifestations of agriculture-bioeconomy integration is the extensive development of biogas production systems. Since the 1970's oil crises, Denmark has transformed from 90% energy import dependency to becoming a leader in green energy, decoupling economic growth (GDP) from energy consumption and emissions, diversifying its energy mix, embracing renewables, and enhancing efficiency.

Over the past 5 years, Denmark has been among the fastest growing biogas producers in the OECD area with an increase of almost 200%.

The primary input for biogas production is animal manure, particularly from pig and cattle operations, along with crop residues, food processing by-products, separated household food waste, and industrial organic waste. Of the total biogas production in 2022, almost 80% was upgraded to biomethane and fed into the gas distribution system, while the remaining approximately 20% was used for combined heat and power generation. Increasingly CO2 is captured for either carbon capture and storage projects or for the rapidly developing markets. The proportion of biogas in the Danish gas system approached 40% in 2023, and projections indicate that Danish gas consumption could approach 100% biomethane by 2030. The digestate produced as a by-product provides nutrient-rich organic fertilizer is returned to agricultural soils, creating circular flows of nutrients and organic matter.

Several factors have contributed to successful biogas industry development; intensive agricultural production supply with high livestock density and modest distances between farms and biogas plants ensures reliable input; the existing nationwide gas pipeline infrastructure provides direct market access; financial support schemes favored biogas production; regulatory requirements for collection and separation of food waste strengthened feedstock availability; environmental policy changed attitudes toward livestock manure from problematic waste to valuable resource; clear climate policy goals regarding fossil fuel reduction made biogas increasingly attractive; R&D at universities and research organizations contributes to process optimization and technology development; and industry participants have identified genuine business opportunities with significant profitability potential.

Fundamentally, cluster collaboration in a quadruple helix among the biogas industry, agriculture as key supplier of feedstock, academia, and government, has created alignment around common goals and enabled coordination through formal and informal networks. This cluster collaboration reflects the importance of reliable feedstock supply and farmer engagement for biogas development. The approach has also enabled coordinated problem-solving, rapid knowledge diffusion, shared learning from operational experience, and adaptive policy development responsive to technical and economic realities.

6. Innovation Governance and Institutional Evolution

Denmark's governance architecture has evolved from triple-helix collaboration into a broader ecosystem model involving clusters, translational institutions, and philanthropic capital. Organizations such as SEGES Innovation translate research into agricultural practice, while cluster platforms facilitate collaboration between SMEs, universities, and global firms. Patient capital from industrial foundations provides long-term financing for deep-tech ventures, complementing public innovation policy and EU funding frameworks. Compared with US governance structures, Denmark's model emphasizes coordination and stability over competition between agencies. While the US benefits from larger capital markets, Denmark demonstrates how institutional coherence can accelerate technology diffusion across sectors.

Denmark's national Innovation Cluster Program has played an important role in strengthening the innovation ecosystem, including for bioeconomy-related sectors. 14 cluster organizations have been designated across diverse areas such as food and bioresources, environmental technology, and energy technology, all of which contribute to innovation in bio-based industries and circular economy solutions. Bioeconomy is the primary focus for the specially designated *Food & Bio Cluster Denmark* and a cross-cutting theme for clusters such as *CLEAN (environmental technology/circular economy) and Energy Cluster Denmark* (*bioenergy/biorefining*),

Denmark's national cluster program supports collaboration between companies, universities, and public actors to boost SME innovation and competitiveness, with cluster funding administered by the Danish Business Authority. The program comprises 14 nationally designated clusters across sectors such as food & bioresources, life science, energy, and clean technologies, integrating research, business, and government stakeholders in a triple helix collaboration.

Food & Bio Cluster Denmark is the flagship bioeconomy cluster, linking biomass and agricultural innovation with bioenergy, biochemicals, and bioresource value chains, and facilitating bioeconomy project development and financing. Food & Bio Cluster Denmark also engages with European initiatives, supporting Danish participation in programs such as the Circular Bio-based Europe Joint Undertaking (CBE JU) under the EU Commission through funding and matchmaking.

Cluster Excellence Denmark (CED) provides strategic support, professionalization, and internationalization assistance to the 14 nationally recognized cluster organizations, helping strengthen cluster management capacity.

Cluster Excellence Denmark is co-financed by the Danish Agency for Education and Research and the Danish Business Authority, reflecting high-level policy alignment between cluster strategies and national innovation goals. The Ministry of Higher Education and Science integrates clusters into national innovation policy, linking them to research networks, innovation grants, and international cooperation frameworks.

Danish clusters connect to European Union cluster initiatives, including the European Cluster Collaboration Platform (ECCP)and quality labelling through the European Cluster Excellence Initiative (ECEI) Cross-border

cluster networks like Medicon Valley Alliance (life sciences) and regional innovation ecosystems such as Kalundborg Eco-industrial Park illustrate Denmark's broader networked innovation environment supporting circular and bio-based development.

Science parks and innovation hubs like DTU Science Park and others complement cluster activities by hosting startups and cross-disciplinary ventures across biotech, clean tech, and bioeconomy segments.

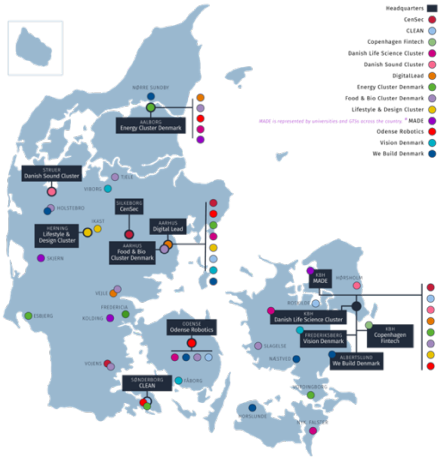
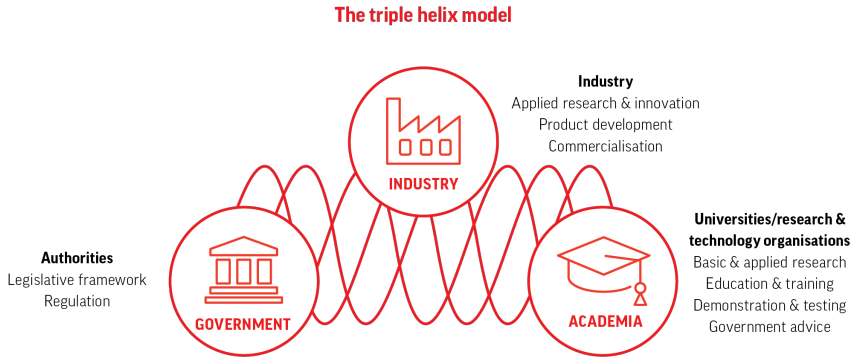


Table 3 Denmark's innovation Clusters - Aalborg University

As Denmark's bioeconomy agenda expanded from efficiency improvements toward deeper circularity, climate mitigation, and ecosystem stewardship, the limitations of narrowly defined research-industry-government collaboration became increasingly apparent. Bioeconomy transitions raised questions extending beyond technological performance, including land-use priorities, environmental trade-offs, social distributional effects, and public acceptance. In addressing these issues, it became important to engage with other actors outside traditional triple helix partnerships, including environmental organizations, labor representatives, local communities, financial institutions, and users of bio-based solutions.



In response, the collaborative frameworks have been gradually broadened, and civil society organizations and social partners are more systematically involved in shaping the bioeconomy,

while environmental considerations are embedded more explicitly in innovation and policy processes. This evolution is especially evident in institutional arrangements such as the Green Tripartite Agreement, which brings together government, industry, trade unions, and environmental organizations to jointly design and implement climate- and bioeconomy-related policies (see case description below). Similarly, The Alliance for Bio solutions ensures intentional ecosystem orchestration, coordination and dialogue with companies, research institutions, financial actors, and NGOs to accelerate the development and adoption of bio-based solutions in Denmark and internationally.

As the triple helix model collaboration matured into broader ecosystems, Denmark's bioeconomy is today characterized by dense networks of formal and informal collaboration spanning value chains, policy domains, and societal interests, enabling continuous knowledge exchange, iterative problem-solving, and adaptive governance, allowing bioeconomy strategies to evolve in response to technological advances, environmental constraints, and societal feedback

The transformation of dairy cooperatives into enzyme producers, agricultural waste into biogas, and farming expertise into precision fermentation capabilities illustrates how Denmark has converted agricultural constraints into bioeconomy opportunities, supported by focused development of innovation ecosystems ensuring coordination and innovation through collaborative translational research infrastructure, industry representation, in triple helix type collaborations.

In addition to the cluster organization, bioeconomy in Denmark is supported by highly enabling organizations such as the BioInnovation Institute (BII), established in 2018 by the Novo Foundation as an independent foundation, which is an important Danish response to the challenges of translating scientific excellence into commercial ventures. BII provides startups funding up to $US 3.5 million per project as well as dedicated infrastructure, network access, and business development support through Venture Lab, Bio Studio, and BII Quantum Lab programs. BII has supported over 130 companies that attracted more than 1.3 billion $US in external funding, while Danish biotech venture capital investment increased fourfold. BII welcomes international startups establishing Danish entities to position Denmark as a European commercialization hub, offering California companies potential EU market entry partnerships.

Industry coordination primarily takes place through *DI Biosolutions* within the *Confederation of Danish Industry*. DI Biosolutions provides political representation and regulatory advocacy and is a founding member of the European Biosolutions Coalition. This unified advocacy enables engagement on cross-cutting regulatory barriers and shared infrastructure needs.

Industrial symbiosis represents one of the most distinctive institutional and infrastructural features of Denmark's bioeconomy system. While many countries pursue circular economy

initiatives through technological innovation or regulatory mandates alone, Denmark's trajectory illustrates how symbiosis emerges through long-term coordination between firms, municipalities, utilities, and regulatory institutions.

Rather than a single project or policy instrument, industrial symbiosis in Denmark has evolved as a governance practice that links energy systems, material flows, water management, and biological production into interconnected industrial ecosystems.

7. Industrial Symbiosis and Circular Bioeconomy Infrastructure

From an analytical perspective, symbiosis should be understood as a structural layer within the Danish bioeconomy rather than an isolated sustainability initiative. It integrates upstream biomass production with downstream industrial processes by enabling the cascading use of resources across sectors. Waste heat becomes district heating, fermentation residues become feedstocks for energy recovery, and industrial by-products are redirected into adjacent production chains. This infrastructure reduces environmental externalities while simultaneously lowering production costs and stabilizing industrial clusters.

For American policymakers and researchers, especially in states such as California, where climate regulation increasingly intersects with industrial policy, Denmark's experience offers an alternative model of circular industrial development. Instead of relying solely on subsidies or market incentives, Danish symbiosis networks rely on shared infrastructure, predictable regulatory frameworks, and institutional trust. These elements create an environment in which firms are willing to invest in interdependent resource exchanges over long time horizons.

The Danish experience with industrial symbiosis can be understood through two complementary trajectories: the organic evolution of the Kalundborg Symbiosis and the deliberately planned infrastructure approach exemplified by GreenLab Skive. Together, these cases illustrate how symbiosis can emerge both through incremental industrial collaboration and through intentional design.

7.1 Case: The Kalundborg Symbiosis – the world's first industrial symbiosis organically developed

Located approximately 70 miles west of Copenhagen, the Kalundborg Symbiosis is widely regarded as the world's first fully developed example of industrial symbiosis and a foundational case for circular bioeconomy principles in practice. Unlike later, deliberately planned eco-industrial parks, the symbiosis emerged organically from the early 1960s through direct bilateral agreements between companies in the area, generally seeking cost reductions and operational efficiencies in their management of waste streams and by-products, rather than from centralized environmental planning.

Today, 17 public and private actors participate in a dense network of resource exchanges involving energy, water, and materials. Key participants include Novo Nordisk, Novonesis, the

Kalundborg refinery, Ørsted's biomass power plant, Gyproc's plasterboard manufacturing facility, Bigadan's biogas plant, Kalundborg Utilities and Kalundborg Municipality. Together, these actors have established more than 30 exchange streams through bilateral agreements in which residual outputs from one process become valuable inputs to another.

The Kalundborg Symbiosis exemplifies the cascading use of water, materials and biomass central to bioeconomy thinking. Surplus heat from power generation supplies district heating for thousands of households and public facilities; steam is delivered to industrial users for process heating and sterilization; water is reused or recycled up to 6 times in a fit-for-purpose approach, residual biomass (solid and dissolved) is shared locally in place based biogas solutions, where organic carbon is converted to biogas, upgraded to biomethane and distributed via the loval and national gas grid displacing fossil fuels in the local energy system, and where water and nutrients are recycled as agricultural fertilizers and biogenic carbon dioxide captured.

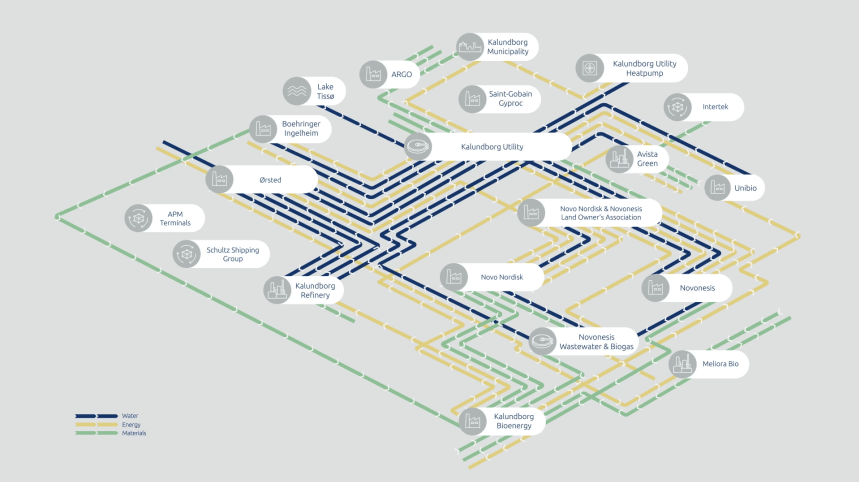


Table 4 Exchange of water, energy and materials at Kalundborg Symbiosis

The environmental and economic benefits of the symbiosis are substantial and well documented. The network has delivered significant reductions in water use, greenhouse gas emissions, and waste generation, while generating annual cost savings and new revenue streams for participating firms. These outcomes demonstrate that circular bioeconomy solutions can be built on sound business fundamentals, aligning economic incentives with environmental performance.

The Kalundborg Symbiosis also illustrates the importance of collaborative governance. Industrial actors initiate and operate commercial exchanges, the municipality provides enabling infrastructure and regulatory support, and research institutions contribute documentation, analysis, and innovation. Since the establishment of the Symbiosis Center in 2011, the collaboration has been actively curated to identify new synergies and share lessons internationally. Central to the model's durability is the very high level of trust among

participants, a precondition for information sharing, joint investment, and long-term commitment.

As a case for bioeconomy development, the Kalundborg Symbiosis demonstrates that circular industrial ecosystems can emerge where economic incentives, institutional support, and collaborative culture align. For California and other regions pursuing bioeconomy transitions, the key lesson is not the replication of specific exchanges, but the importance of creating conditions allowing for and promoting cascading resource use, trust-based collaboration, industrial leadership, local facilitation and continuous adaptation to take root.

7.2: GreenLab Skive – A Greenfield Model for circular Bioproduction Parks

Whereas the Kalundborg Symbiosis evolved organically over several decades, GreenLab Skive represents a deliberately planned greenfield approach in which circular economy principles and industrial symbiosis were embedded in infrastructure and governance from the outset. Established in 2019 as a public–private partnership between Skive Municipality, the Norlys energy utility, and private foundations, the 60-hectare industrial park was strategically located at the intersection of major electricity and gas infrastructure, with direct access to large-scale renewable energy generation. In 2021, the Danish government designated GreenLab as a regulatory test zone, enabling experimentation with new circular business models and direct renewable-energy connections beyond standard grid regulation.

At the core of GreenLab is SymbiosisNet™, an integrated energy and data infrastructure that enables participating firms to exchange electricity, heat, gases (including hydrogen and biogas), water, and data in real time. Tenant companies include biogas producers, pyrolysis and Power-to-X technology providers, and manufacturers of bio-based ingredients. Together, these activities demonstrate cascading biomass use by design: agricultural residues are converted into biofuels, biochar, and heat; surplus energy supplies district heating; biogas is upgraded for grid injection; and nutrients are recycled back to agricultural soils.

GreenLab operationalizes a triple-helix collaboration model within a broader innovation ecosystem. Universities including the Technical University of Denmark (DTU), Aalborg University, and Aarhus University use the site as a living laboratory for research on integrated energy systems and circular bioeconomy solutions. Governance follows an active “middle-out” approach, combining strategic public leadership with entrepreneurial flexibility. A dedicated operating organization manages shared infrastructure, identifies new synergies, and facilitates collaboration among tenants, while GreenLab Academy supports workforce development aligned with industrial transformation.

The significance of GreenLab Skive lies in demonstrating how greenfield industrial parks can deliberately integrate and operationalize basic bioeconomy principles from inception. Replicable design features include early investment in enabling infrastructure, regulatory flexibility, public–

private risk sharing, and active ecosystem orchestration rather than passive site development. By 2024, the park had attracted more than DKK 3 billion in investment and created over 100 jobs in a predominantly rural region. The project has been highlighted by UNIDO as a best-practice example of green industrial clustering.

For regions seeking to accelerate bioeconomy transitions, GreenLab Skive illustrates how intentional design, supportive governance, and ecosystem-based collaboration can significantly shorten the time required to move from concept to integrated, low-carbon industrial systems

7.3 Comparative lessons

Taken together, the Kalundborg and GreenLab Skive cases reveal two complementary trajectories through which industrial symbiosis can emerge: incremental evolution rooted in local industrial collaboration and intentional design based on integrated infrastructure planning. While the historical development of Kalundborg illustrates how symbiosis can grow organically from pragmatic exchanges between firms, GreenLab Skive demonstrates how newer projects attempt to embed circular resource flows directly into industrial park design. Despite these differences in origin, both pathways depend on governance frameworks that align environmental regulation with industrial development strategies, enabling firms to treat resource sharing not as an experimental add-on but as a core component of long-term competitiveness.

From a comparative perspective, particularly for American policymakers and researchers examining industrial decarbonization strategies, the Danish experience suggests that symbiosis should be understood primarily as an infrastructural and institutional challenge rather than a purely technological one. Advanced monitoring systems, digital platforms, and renewable energy technologies undoubtedly play important roles, yet the decisive factor lies in the governance arrangements that allow companies to coordinate investments, exchange operational data, and build trust over extended time horizons. The effectiveness of Danish symbiosis networks derives less from individual technological breakthroughs than from the stability of institutional frameworks that make interdependence economically viable.

The comparison between Denmark and California highlights a broader strategic question: how can industrial symbiosis be implemented within a federal system characterized by institutional diversity and market-driven innovation? Rather than attempting to replicate Danish structures directly, U.S. policymakers may consider adopting a modular approach that combines state-level experimentation with federal support for infrastructure development.

Several strategic implications emerge:

- Industrial symbiosis initiatives should be embedded within broader climate and industrial policy frameworks rather than treated as isolated pilot projects.

- State-level agencies, particularly in California, could function as conveners like Danish municipalities, facilitating collaboration between utilities, industrial firms, and research institutions.
- Federal funding programs may need to prioritize shared infrastructure and long-term investment horizons to enable circular industrial ecosystems.

Ultimately, the Danish experience demonstrates that industrial symbiosis is both a technical solution and a governance strategy. For California and other U.S. regions, the challenge lies in translating these governance principles into a context shaped by federalism, market competition, and rapid technological change.

This is where well designed and targeted regulation may have an important role to play.

8. Regulation

Denmark has a long tradition of strict environmental regulations, increasingly also in the framework of the Danish membership of the European Union[3]. Denmark's experience with circular bioeconomy development illustrates how environmental regulation can function as an enabler of innovation when integrated in a coherent policy design and adaptive governance.

European Union directives on water quality, renewable energy, and waste management created predictable policy signals that encouraged investment in bio industrial innovation. Denmark has leveraged these frameworks to integrate agriculture, energy, and life science sectors. The Danish experience suggests that regulatory clarity, combined with flexible implementation mechanisms, can accelerate industrial transformation without undermining competitiveness.

Since the 1970's, regulation has reshaped Denmark's material and energy systems. The Environmental Protection Act of 1973 established a broad legal foundation for environmental management, including waste, pollution control, and resource protection, which has guided subsequent regulatory development. In 1978, Denmark introduced comprehensive laws on recycling, mandating minimum recovery rates for key materials, which helped embed recycling into national policy goals. These measures were reinforced by the introduction of a landfill tax in 1987, designed to shift waste flows away from disposal toward recovery and recycling, and by a ban on landfilling waste suitable for incineration and recycling in 1997, which effectively redirected material flows into recycling and energy recovery pathways. This legislation helped create predictable market conditions that supported investment in circular bioeconomy and bio solutions-related technologies.

[3] Denmark became a member of the European Union (then the European Economic Community) on January 1, 1973. The Danish parliaments EU information estimates that just below 20% of all legislation adopted by the Danish parliament originates from the EU. Add to this of course the general effects of close ongoing collaboration and joint policy coordination and development. Today, the broad principles of waste management in Denmark are laid out in EU regulation, which also applies to the vision of a circular economy.

More recent initiatives include Denmark's Circular Economy Strategy and Action Plan (2020), which aligns national waste and resource policies with climate neutrality objectives by 2030, emphasizing recycling, biomass utilization, and decarbonization of the waste sector. In 2024, the Agreement on a Green Denmark (Green Tripartite Agreement) introduced the world's first CO_2-equivalent tax on livestock emissions as part of a broad political consensus process, together with land use changes and investment funds to reduce emissions and restore natural ecosystems (see case description below). These instruments illustrate Denmark's continued reliance on economic regulation alongside negotiated governance to drive sustainable transformation, including in developing pathways for biosolutions.

The Danish approach aligns with the conditional or "weak" Porter Hypothesis in as much as well-designed environmental regulation may stimulate innovation when it provides predictable signals and flexibility in compliance. Denmark's strong emphasis on market-based and performance-oriented instruments, such as environmental taxes and pricing mechanisms, has generally allowed private operators discretion in how environmental objectives are met, encouraging innovation without prescribing specific technological solutions.

That said, much work still needs to be done at the national, Danish, as well as European Union level, to adapt and develop smarter regulation appropriate for the dynamics and continued development of bio solutions and the circular bioeconomy. Bio solutions often differ fundamentally from conventional products and techniques but are still largely regulated by the existing regulatory framework (as pointed out by Iris Group and others).

It should be noted that Denmark combines ambitious environmental regulation with a high degree of overall economic freedom, ranking 7th globally in the 2024 Heritage Foundation Index of Economic Freedom, suggesting that stringent environmental policy can coexist with market-oriented economic institutions.

8.1 The Green Tripartite Agreement — Denmark's Multi-Stakeholder Approach to Agricultural Transformation

In June 2024, Denmark reached a landmark political agreement known as the *Green Tripartite Agreement (Aftale om et Grønt Danmark*), setting out a comprehensive framework for transforming Danish agriculture to reduce emissions, restore ecosystems, and improve water quality.

The agreement is an example of Denmark's ecosystem-oriented governance approach, bringing together the Danish government, agricultural organizations (including the Danish Agriculture & Food Council), environmental NGOs such as Danmarks Naturfredningsforening, and political parties and local authorities to negotiate climate, biodiversity, and water outcomes jointly.

A major element of the agreement is the introduction of a CO_2-equivalent tax on livestock emissions, making Denmark one of the first countries to apply climate pricing directly to

agricultural biological emissions. The tax is designed with a high deduction floor so that only emissions above defined performance benchmarks will be taxed, and revenues are intended to be reinvested into the transition through support funds.

The agreement also includes ambitious land-use measures aimed at restoring peatlands and forests to sequester carbon and improve biodiversity. A new public Green Area Fund (Grøn Områdefond) has been established to finance land conversion, nature restoration, and sustainable land-management incentives. In addition to climate mitigation, the agreement targets nitrogen pollution and water quality issues in a broad and integrated approach to agricultural environmental performance.

The Agreement is an example of advanced multi-helix collaboration combining also regulatory teeth and largescale government funding to address emissions.

8.2 European Collaboration and perspective for future bioeconomy

Denmark's bioeconomy policy and regulatory framework are deeply embedded in the broader context of its European Union membership, with national strategies aligned to the evolving EU priorities. Late in 2025, the European Commission presented a renewed strategic framework for a competitive and sustainable European bioeconomy, building on the EU Bioeconomy Strategies of 2012 and 2018. The framework positions the bioeconomy, valued at approximately €2.7 trillion and employing more than 17 million people, as a pillar of Europe's industrial competitiveness, aligned with the European Green Deal and the EU's broader industrial and competitiveness agenda.

The strategy defines the bioeconomy as the production and conversion of renewable biological resources from land and sea into food, feed, bio-based products, materials, energy, and services. Core priorities include cascading use of biomass with an emphasis on high-value applications, innovation in industrial biotechnology and biomanufacturing, and the development of regional bio economies to support rural development and climate action. Circularity, ecosystem protection, food security, and sustainable land and forest management are emphasized as guiding principles.

The updated EU approach links bioeconomy development and European strategic autonomy and industrial sovereignty, as bio-based value chains are framed to reduce dependence on fossil resources, critical raw material imports, and vulnerable global supply chains, while strengthening Europe's domestic capacity to produce food, materials, chemicals, and energy. In this sense, the bioeconomy is increasingly positioned as part of Europe's economic security and industrial resilience.

Implementation relies on a combination of regulatory coordination and financial instruments. Key mechanisms include the Circular Bio-based Europe Joint Undertaking (CBE JU), a €2 billion public–private partnership funding projects through 2031, alongside Horizon Europe, InvestEU,

and targeted support under the Common Agricultural Policy for agricultural and forest-based bioeconomy activities. New coordination platforms, including regulatory and investment forums, are intended to accelerate market creation and deployment of bio-based solutions across sectors such as chemicals, construction, textiles, and materials.

The Net-Zero Industry Act (NZIA) provides an important framework for developing competitive zero-emission industries, including within the bioeconomy. The regulation introduces obligations for Member States while also offering enabling tools such as regulatory sandboxes, designed to accelerate innovation, testing, and deployment of new bio-based and low-carbon technologies.

For Denmark, this evolving EU bioeconomy framework reinforces the existing national strengths in circular agriculture, industrial biotechnology, and its innovation-oriented governance and ecosystems. The framework also illustrates how European bioeconomy policy has evolved from a sustainability-focused strategy into a core element of industrial transformation, competitiveness, and the management of long-term resource and climate challenges

9. Conclusion: Governing Scarcity – Lessons from the Danish Bioeconomy

Denmark's bioeconomy demonstrates that long-term competitiveness in a low-carbon economy is not primarily a function of resource abundance, but of institutional capacity to coordinate, prioritize, and innovate across sectors. As the system matures, a central insight becomes increasingly clear: the potential for cascading use of biomass remains far from fully realized, while at the same time sustainable biomass is inherently limited. This creates a structural imperative for strategic allocation.

Recent Danish developments reflect this shift toward deliberate optimization. Agricultural systems are gradually being reoriented toward green biomass for biorefining, where proteins are extracted for feed and food, while residual streams are successively valorized into materials such as textiles and packaging, and ultimately into energy. Parallel pathways are emerging in the use of biobased construction materials to substitute carbon-intensive inputs such as cement, enabling carbon storage, as well as in the integration of CO_2 capture from biogas upgrading with renewable hydrogen to produce new green fuels (PtX). These developments illustrate a transition from efficiency improvements toward system-level prioritization of biomass across interconnected value chains.

Seen in this perspective, Denmark's bioeconomy is best understood not as a sector, but as a governed system in which agriculture, energy, industry, and research are linked through cascading resource flows, shared infrastructure, and adaptive regulatory frameworks. The strength of the Danish model lies in its ability to transform environmental constraints into drivers of innovation and industrial upgrading through long-term institutional coordination.

Some Danish Key Takeaways for California Decision-Makers are:

- **Move from pilots to system design**
  Fragmented initiatives will not deliver scale. Bioeconomy development requires integrated policy frameworks linking agriculture, energy, water, industry, and innovation systems.
- **Recognize biomass as a constrained strategic resource**
  California should develop explicit prioritization frameworks to allocate biomass toward highest value uses across food, materials, fuels, and carbon management.
- **Use regulation as a strategic market-shaping tool**
  Predictable, performance-based regulation can simultaneously address environmental externalities and accelerate innovation, investment, and industrial transformation.
- **Build enabling infrastructure for circular value chains**
  Scaling the bioeconomy depends on investments in shared systems: biogas, CO_2 infrastructure, hydrogen, water reuse, and digital coordination platforms.
- **Strengthen institutional coordination and ecosystem governance**
  Long-term competitiveness requires alignment across state agencies, universities, industry, finance, and local actors - moving beyond fragmented governance toward orchestrated ecosystems.
- **Link climate policy with industrial strategy**
  The Danish experience shows that decarbonization and industrial competitiveness can be mutually reinforcing when policy, infrastructure, and innovation systems are aligned.