



SYMSITES

ECOSITES implementation for industrial-urban symbiosis through social and technological solutions

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Abstract

This Replication Analysis Report evaluates the potential for replicating the SYMSITES integrated technological and social models in new regional contexts. Drawing from extensive pilot data and stakeholder engagement across four diverse sites, Austria, Denmark, Greece, and Spain, the report identifies replicable components, enabling conditions, and contextual barriers. Key technologies such as anaerobic membrane bioreactors, biogas systems, and flotation units are examined for scalability. Social innovation, exemplified by the Bornholm spin-off, is highlighted as critical to community engagement and sustainability. The analysis serves as a foundation for the SYMSITES replication package, offering a strategic and evidence-based roadmap to support broader implementation of sustainable waste and wastewater valorisation systems across Europe.

List of Abbreviations and acronyms

Abbreviation	Meaning
AnMBRs	Anaerobic Membrane Bioreactors
BEOF	Bornholms Energi & Forsyning
BOFA	Bornholms Affaldsbehandling
BOKU	Universität für Bodenkultur Wien
CSTRs	Continuous Stirred Tank Reactors
FACSA	Sociedad De Fomento Agrícola Castellonense, S.A.
FOG	Fats, Oil and Grease
HRT	Hydraulic Retention Times
HRT	Hydraulic Retention Times
I-US	Industrial-Urban Symbiosis
LCA	Life Cycle Assessment
LMH	Litres per square meter per hour (Liter/m ² /h)
MLSS	Mixed Liquor Suspended Solids
MSW	Municipal Solid Waste
NF	Nanofiltration
NTUA	National Technical University of Athens
OFMSW	Organic Fraction of Municipal Solid Waste
P&IDs	Process and Instrumentation Diagrams



RO	Reverse Osmosis
TMP	Transmembrane Pressure
TSS	Total Suspended Solids
UF	Ultrafiltration

Table of Contents

Abstract	2
List of Abbreviations and acronyms	2
1. Executive Summary	4
2. Introduction to SYMSITES	4
3. Purpose of the Replication Analysis Report	5
3.1 Replication in the context of the SYMSITES Project	6
3.2 Benefits of replicating SYMSITES EcoSites	8
4. Method of Analysis	9
5. Analysis	10
5.1 Social Spin-off	10
5.2 Replicability of SYMSITES EcoSites	13
5.2.1 Is SYMSITES Suitable for replication in your Region?	13
5.2.2 Sourcing residues and waste from relevant stakeholder	13
5.2.3 Operation of the pilot	15
5.2.4 Establishing symbiotic exchanges	22
6. Conclusions	25
7. Bibliography and sitography	26



1. Executive Summary

The SYMSITES Project at its core integrates technological innovation with community-driven strategies to valorise underutilized resources, including municipal waste, industrial by-products, and wastewater. The initiative deploys advanced treatment technologies, such as anaerobic membrane bioreactors (AnMBRs), pyrolysis, and smart digital platforms, across four pilot EcoSites in Austria, Denmark, Greece, and Spain. These pilots serve as real-world laboratories to test and optimize circular economy solutions.

This Replication Analysis Report provides a comprehensive evaluation of the replication potential of SYMSITES technologies and practices. It outlines which components are ready for broader implementation and highlights the social, technical, economic, and regulatory factors critical for successful transfer. Key findings include:

- High replication potential for biogas systems and flotation units, with proven efficiency and stability.
- Social innovation models, such as Bornholm's Go-SYM, demonstrate effective community engagement strategies adaptable to small towns and rural areas.
- Technical replication readiness is uneven; while biogas production is mature, membrane technologies require further optimization due to energy consumption, fouling risks, and cost uncertainties.
- Operational success factors include robust pre-treatment, automation, quality monitoring, and stakeholder collaboration.
- Barriers to replication involve legal limitations, logistical challenges, and demand-supply mismatches for reclaimed resources.

The report also outlines the importance of enabling conditions for replication, such as proximity of industrial actors, quality and consistency of waste inputs, regulatory support, and strong local governance. The findings emphasize that successful replication requires not just transferring technology, but adapting it to the social, economic, and environmental context of each region.

Ultimately, the report lays the groundwork for the SYMSITES replication package: a practical guide to scaling I-US systems. By aligning technological innovation with social inclusion and policy frameworks, SYMSITES offers a strategic pathway for European regions to transition toward circular, resilient, and low-carbon economies.

2. Introduction to SYMSITES

The SYMSITES Project (2022–2026) is a four-year project funded by the European Union under the Horizon Europe Programme, dedicated to transforming how European regions manage and reuse their waste and wastewater. Rooted in the principles of Industrial and Urban Symbiosis (I-US), SYMSITES aims to foster local and regional collaborations between citizens, municipalities, and enterprises, enabling a more sustainable and circular use of resources.

At the heart of the project lies the valorisation of underutilized materials and energy, including industrial by-products, end-of-life urban waste, and wastewater, by converting them into valuable inputs for other industrial processes. In doing so, SYMSITES seeks to replace the traditional linear



model of “extract–use–dispose” with circular flows inspired by the closed loops found in natural ecosystems. To achieve these goals, SYMSITES develops and demonstrates an integrated suite of high-tech treatment and reuse technologies, including an AnMBR with advanced anti-fouling membranes for the co-treatment of wastewater and biowaste; a tertiary adsorption treatment using activated carbon with antiviral and antibacterial properties; a pyrolysis system to convert non-recyclable waste into platform chemicals and activated carbon; and an IT-based Regional Management Platform (ITRMP) integrating Internet of Things (IoT), Artificial Intelligence (AI), and a Social Decision Support System (SDSS) for efficient resource exchange and stakeholder coordination.

To validate these solutions, the project is implementing real-life demonstrations in four pilot sites, called Ecosites, across Europe, each selected for its distinct socio-economic and environmental characteristics. These EcoSites represent diverse regional contexts and are strategically located in: 1) Austria, focusing on industrial wastewater and flotation-sludge integration; 2) Denmark, optimizing co-treatment systems under highly automated conditions; 3) Greece, integrating decentralized organic waste and wastewater streams in semi-urban settings; 4) Spain, managing complex residual streams such as the organic fraction of municipal solid waste and urban and industrial wastewater in advanced membrane-based treatment. These EcoSites serve as living laboratories for developing, testing, and optimizing symbiotic exchanges between urban and industrial systems. Each site facilitates the circular reuse of water, energy, and materials while building regional partnerships and stakeholder engagement strategies. Together, they provide a scalable blueprint for replicating sustainable industrial-urban symbiosis in other parts of Europe and beyond.

3. Purpose of the Replication Analysis Report

This Replication Analysis Report serves as a key document within the SYMSITES project replication activities, focused on evaluating and documenting the status of the SYMSITES EcoSites. Its primary objective is to collate, assess, and interpret the data gathered to date, in order to establish a clear and realistic understanding of which aspects of the SYMSITES EcoSites are ready for replication, and which components still require refinement, adaptation, or further research. Industrial-Urban Symbiosis (I-US) is a complex and context-sensitive process that integrates waste and wastewater management into sustainable regional ecosystems. As such, replication of the SYMSITES EcoSites in new regions demands a rigorous and honest appraisal of what has been achieved and what can be transferred effectively. The Replication Analysis Report aims to function as a comprehensive baseline for the upcoming development of the SYMSITES replication package.

This report identifies and analyses the outputs and practices that can be realistically adapted and implemented in other geographic or industrial contexts. These include technical solutions, governance models, collaborative practices, and digital tools developed through the project. By highlighting these transferable elements, this report could enable replicators (i.e., stakeholders or regions interested in adopting the SYMSITES model) to make informed decisions about which components to integrate and how to do so effectively.

Additionally, the report plays a critical role in identifying existing gaps in knowledge, technology, or process integration that might hinder successful replication. These insights not only guide local stakeholders but also shape the content and direction of the forthcoming replication package. This future package will offer more detailed guidance, tools, and step-by-step materials to support the



replication process, ensuring it is tailored, efficient, and aligned with the specific needs of each replication site.

In summary, the Replication Analysis Report is not just a record of progress; it is a strategic document that bridges current knowledge with future implementation. It ensures that replication efforts are grounded in evidence, contextually appropriate, and primed for success, ultimately enabling broader adoption of sustainable industrial-urban symbiosis practices.

3.1 Replication in the context of the SYMSITES Project

In the SYMSITES project, *replication* refers to the implementation of any individual component or the complete integration of an EcoSite's technologies, strategies, or I-US approach by a different region, business, or waste/wastewater utility company. This concept lies at the core of SYMSITES' ambition to scale sustainable solutions beyond the four demonstration sites, making circular resource flows and integrated waste and wastewater management a reality across varied territorial and industrial contexts in Europe.

Replication is intentionally flexible. It may involve the direct transfer of specific technologies, such as AnMBR, nutrient recovery systems, or water reclamation technologies, or the broader adoption of governance structures, stakeholder collaboration models, and digital tools used within SYMSITES EcoSites. Importantly, replication is not limited to technological transfer alone; it also encompasses social innovations, such as the community-based initiatives seen in Bornholm (Denmark), and data-driven models that allow theoretical exploration of replicability in new contexts.

Each of the four SYMSITES EcoSites exemplifies a distinct model of I-US, reflecting different configurations of technology, resources, and industrial partnerships:

- **Spain (Alcoy & Muro de Alcoy):** Focuses on co-treatment of urban and industrial wastewater alongside organic solid waste to produce green hydrogen, high-quality reclaimed water, and high-value biofertilizers using AnMBR technology and tertiary treatments.
- **Austria (Fleischwaren Berger GmbH):** Converts meat-processing wastewater and organic residues into biomethane, process water, and fertilizer, showcasing a closed-loop industrial solution.
- **Denmark (Svaneke):** Treats brewery and urban wastewater with municipal biowaste to produce methane and reclaimed water, integrating anaerobic and activated carbon processes.
- **Greece (West Achaia):** Processes fermentable household waste and wastewater via a brown-bin collection system to enable decentralized treatment and resource recovery.

Below are infographics showing the flows and treatment of each EcoSite. For further information, please refer to the document "SYMSITES EcoSites: A Guide to Industrial-Urban Symbiosis", available here: <https://symsites.eu/explore-the-symsites-ecosites-a-guide-to-industrial-urban-symbiosis/>



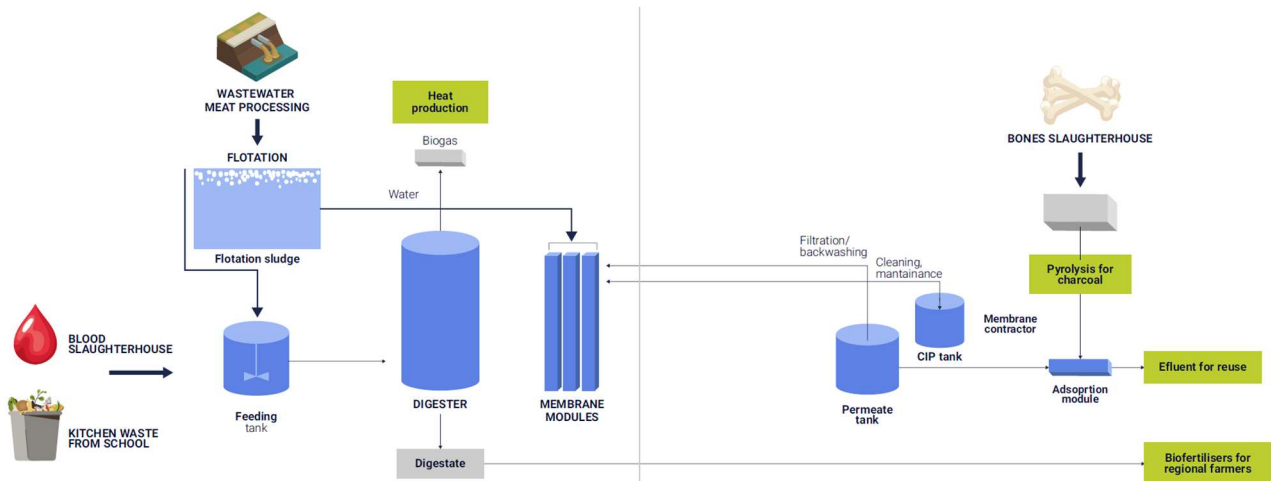


Funded by
the European Union

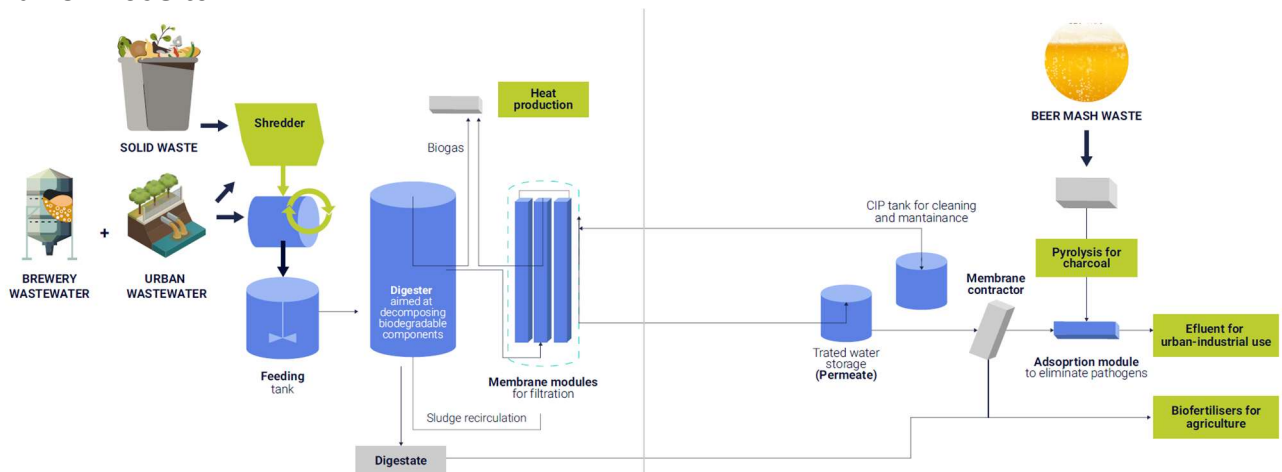


SYMSITES

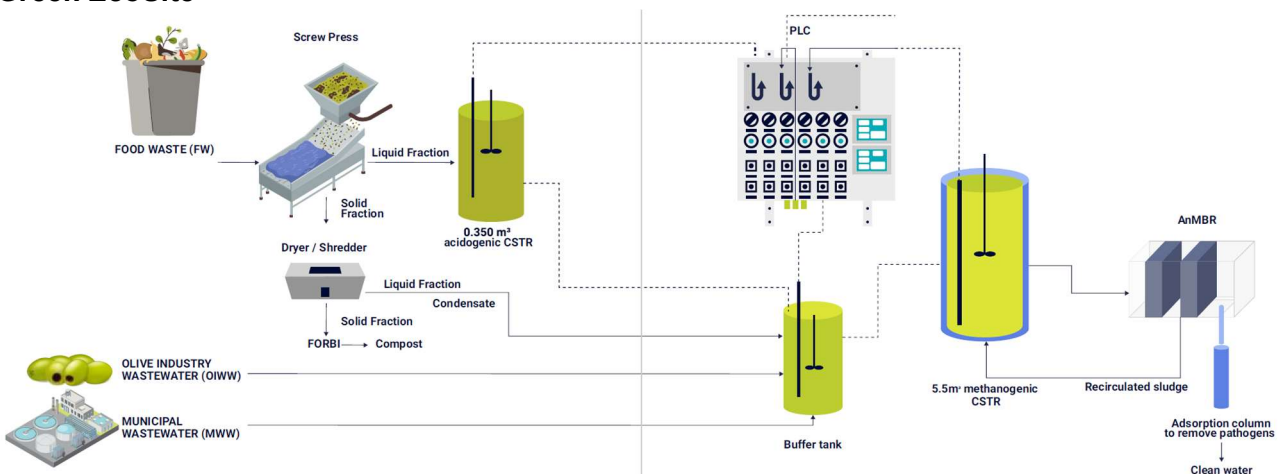
Austrian EcoSite



Danish EcoSite

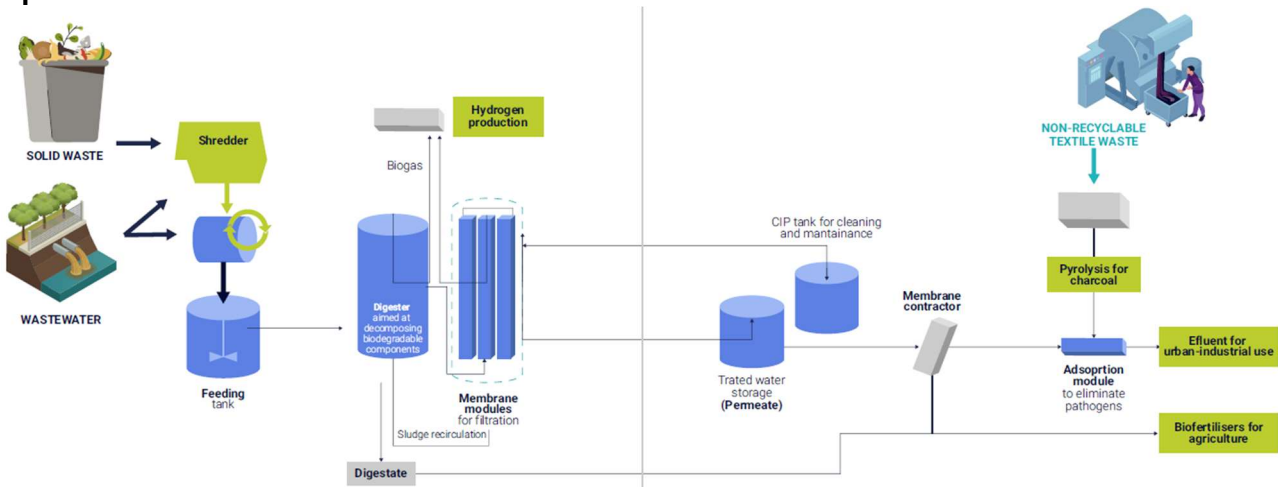


Greek EcoSite



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Spanish EcoSite



Each of these sites serves as a real-world model of what can be achieved through I-US. Through replication, these models, or selected elements thereof, can be transferred to other regions facing similar challenges or aiming for similar sustainability goals. Replication within SYMSITES is both a practical and strategic pathway to scaling I-US solutions. It bridges the gap between successful demonstrations and broader systemic change, offering other regions a blueprint for adapting and implementing proven solutions to fit their unique needs.

3.2 Benefits of replicating SYMSITES EcoSites

Replicating the SYMSITES project offers significant benefits at economic, environmental, and social levels by enabling regions to implement effective I-US strategies. These strategies facilitate a circular approach to managing organic waste and wastewater, converting these streams into valuable resources while fostering stronger regional economies and sustainable urban development.

Replication of SYMSITES models allows regions to harness **economic benefits** by transforming waste into resources. Companies and municipalities that adopt I-US strategies can reduce expenses related to raw materials sourcing, energy consumption, and waste disposal. These savings are further amplified by the creation of circular business models where by-products such as reclaimed water, green hydrogen, biogas, and nutrient-rich fertilizers can be marketed, generating new revenue streams. The replication of these processes supports regional economic development, maintaining key industries active while attracting investment and creating jobs in sectors focused on innovation, waste valorisation, and sustainable technologies.

One of the core goals of I-US is to reduce **environmental impact** through smarter resource use. By integrating wastewater and organic waste treatment processes, replicators of the SYMSITES technologies and I-US strategies can valorise waste, improve energy efficiency at an industrial scale, and minimize the extraction of virgin resources. The result is a reduction in greenhouse gas emissions, lower water and energy consumption, and indirect enhanced climate resilience. Replication helps cities and regions move closer to climate neutrality and circular economy goals by extending the lifecycle of resources, reducing waste generation and resource extraction, and preventing biodiversity loss.



The **social benefits** of fostering symbiotic exchanges have been extensively proven, and replicating SYMSITES technologies can potentially have a direct and positive impact on communities. Creating cleaner environments, improving public health through reduced pollution, and ensuring more efficient local resource management strengthen the quality of life in cities and regions. I-US initiatives promote local economic resilience by reducing dependence on global supply chains, strengthening resilience to price and supply shocks and enhancing local resource security. This makes regions better equipped to withstand economic shocks related to material or energy supply. Moreover, the collaborative nature of I-US fosters knowledge-exchange, stakeholder engagement, and a shared commitment to sustainability, ultimately strengthening the social fabric of participating communities.

The SYMSITES approach provides a unique set of technical and strategic benefits. It enables the co-treatment of organic waste and wastewater, maximizing resource recovery through innovative technologies like AnMBR, advanced nutrient recovery systems, and energy optimization frameworks. Life Cycle Assessment (LCA) tools developed within the project also help identify the most efficient balance between energy use and output value, supporting informed, data-driven decisions for sustainable planning. Cities that replicate the SYMSITES model gain a tangible lever for achieving climate and circular economy objectives, while reinforcing regional self-sufficiency and decarbonisation goals. By providing the knowledge to co-treat and manage organic waste and wastewater, producing a variety of valuable by-products which can be sold as part of a circular business model approach, SYMSITES can contribute significantly to the environmental, economic and social sustainability of replicators.

Despite its many advantages, scaling I-US across Europe comes with challenges, including limited opportunities for cross-sector collaboration, a lack of standardized assessment tools, and the need for site-specific resource evaluations. The SYMSITES project directly addresses these barriers through the development of tailored replication guides, stakeholder engagement tools, and decision-support systems. These resources, which will be included in the upcoming replication guidance package of the SYMSITES Project, enable replicating regions to assess feasibility, map resource flows, and design integrated waste and energy systems with greater confidence and clarity.

4. Method of Analysis

The Replication Analysis Report was developed through a structured and multi-source methodology, primarily grounded in qualitative and quantitative data collected from within the SYMSITES project. The core of the analysis was based on a targeted survey distributed to representatives from each of the four SYMSITES EcoSites and designed to capture detailed insights across the full chain of I-US processes piloted in the project.

The survey covered a wide range of both technical and social dimensions. Technically, it addressed each step of the symbiosis cycle, from the initial sourcing of residues and waste (including inputs from schools, industries, and households) to pre-treatment processes, pilot-scale operations, and the establishment of symbiotic exchanges among local actors. Social aspects included stakeholder engagement, public awareness, and institutional involvement. Additionally, the survey sought to



identify common challenges, required investments, enabling conditions, and key success factors that affect the potential for replication of the SYMSITES approach in other regions.

To ensure a robust and realistic assessment, the survey responses were contextualized with information extracted from various project deliverables that detail the technological processes and implementation experiences across the EcoSites. These internal resources provided background on technical innovations, system integration, and operational performance, enriching the interpretation of survey findings.

A specific section of the analysis focused on the Social Spin-off model developed in Bornholm. This component of the report was informed by a project deliverable detailing the spin-off establishment and its actions plan by BOFA, the island's waste management facility, which led this aspect of the work. From this document, conclusions about the replicability of community-driven resource management models were extracted, offering valuable lessons for integrating social innovation into I-US replication strategies. Further details and tools developed within the Bornholm Social Spin-off will be included in the upcoming SYMSITES Replication Guidance Package.

Together, these data sources and methods offer a comprehensive, evidence-based foundation for assessing the replicability of SYMSITES solutions, serving as a baseline for the development of the subsequent replication package.

5. Analysis

5.1 Social Spin-off

The small Danish town of Svaneke on the island of Bornholm has become an unexpected frontrunner in circular innovation, not through high-tech infrastructure or top-down regulation, but by anchoring sustainable change in the everyday practices and social fabric of its community. As part of the SYMSITES project, the social spin-off Go-SYM was established to foster I-US in a deeply participatory and context-sensitive way. The experience in Bornholm offers a compelling model for replication, particularly in small towns and rural communities across Europe seeking to translate environmental ambition into practical, community-embedded action.

What happened in the social spin-off in Bornholm?

Go-SYM emerged as a local innovation platform in Svaneke, aiming to bridge the gap between technical circular economy concepts and lives of citizens. Driven initially by BOFA (Bornholm's waste management authority), the spin-off began by mapping existing community assets and testing small-scale symbiotic practices. Rather than beginning with formal governance structures, Go-SYM started informally, mostly with outreach, experimentation, and relationship-building. Citizens, associations, schools, and local businesses co-created initiatives around resource sharing and waste reduction. These included reusing wine bottles for juice production, collecting bio-waste from cafés for biogas, and developing educational tools to teach circular thinking to students. A key highlight was the creation of a board game that simulates local resource symbioses, making abstract concepts like I-US tangible for youth.



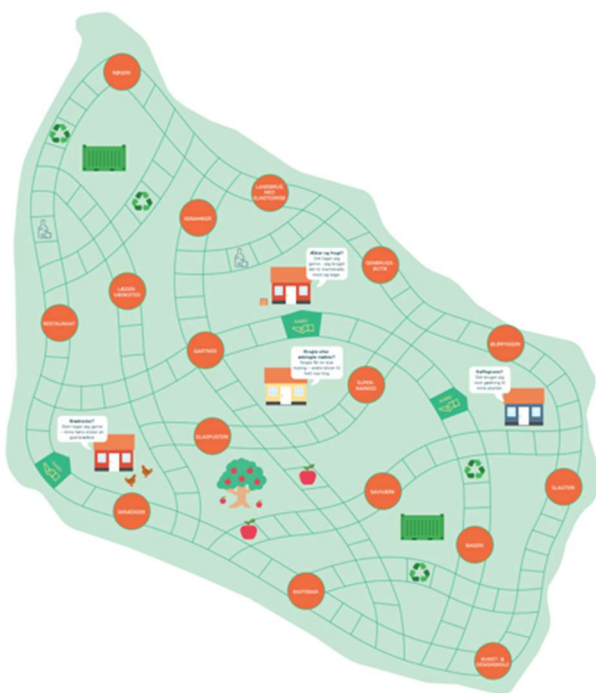


Image: Board game for the youth developed as part of the social spin-off

The process relied heavily on Svaneke's existing social capital: a strong volunteer culture, active civic associations, and dense local networks. Engagement didn't come through formal town hall meetings but through trust, local champions, and practical, visible actions. A single BOFA coordinator initially carried much of the initiative forward, catalysing community involvement and sowing the seeds for long-term organizational development. Despite limited participation in formal stakeholder events, those who engaged became powerful drivers of change. Their contributions ranged from providing physical resources to co-developing educational content and resource loops. Over time, Go-SYM's approach evolved into a more structured framework, with plans for a formal advisory group and broader community-based governance.

Why is this worth replicating?

The Go-SYM experience illustrates that social innovation, when grounded in place-based realities, can act as a powerful enabler of systemic environmental goals. Several features make it especially promising for replication:

- **Low-Barrier, High-Impact Interventions:** Go-SYM's activities, such as voluntary sorting, reuse initiatives, and school engagement, require minimal infrastructure but deliver tangible outcomes. This makes the model accessible to communities with limited resources.
- **Replicable Methodology:** The use of BOFA's four-step design manual and a 7-step replication guide ensures that the approach is not only effective but also methodically transferable. These guides support communities in mapping resources, engaging stakeholders, prototyping solutions, and building organizational capacity.
- **Scalable Educational Tools:** The symbiosis board game and modular school curricula are designed to be adapted to other towns. Their hands-on, engaging formats make circular economy learning accessible to youth, a vital demographic to ensure long-term transformation.



- **Flexibility and Context Sensitivity:** The model's emphasis on informal beginnings, iterative learning, and tailored communication strategies allows it to adapt to a wide range of socio-cultural contexts. This is especially important for replication in diverse European regions.
- **Integrated Value Creation:** Go-SYM demonstrates that environmental, social, and economic value can be generated simultaneously. Resource sharing reduces waste and emissions, strengthens local identity, and creates business opportunities, which is generally a compelling proposition for local economic actors.

What aspects are valuable, and for whom?

The Go-SYM initiative in Bornholm demonstrates how socially driven circular economy practices can create diverse forms of value across different segments of society. By engaging a broad range of stakeholders, the project delivers benefits that go beyond environmental impact, strengthening local networks, enhancing education, and opening new economic pathways. Below is a breakdown of what specific aspects are valuable, and for whom:

- **Citizens and Families:** Gain agency in the sustainability transition, acquire practical knowledge, and strengthen community ties.
- **Educators and Students:** Access context-specific learning tools that foster critical thinking, creativity, and responsibility.
- **Businesses:** Discover new value chains, reduce waste costs, and enhance their local reputation.
- **Municipalities and Civil Society Organizations:** Acquire models for inclusive community development and climate action.
- **Policymakers and Researchers:** Gain real-world evidence of how social innovation can anchor complex sustainability frameworks like I-US.

Each of these groups benefits not only from environmental improvements but from new forms of collaboration, shared ownership, and civic empowerment.

What characteristics would a replicable region need?

While the Go-SYM model is adaptable, successful replication requires certain enabling conditions:

- **Strong local identity and social cohesion:** Like Svaneke, ideal replicable regions should have a degree of community trust, volunteer culture, and civic pride.
- **Willing local institutions:** Engagement from schools, municipalities, or waste authorities enhances legitimacy and provides practical support.
- **Modest scale and clear boundaries:** Smaller towns or neighbourhoods are ideal starting points due to the ease of coordination and visibility of outcomes.
- **Visible resource flows and opportunities for symbiosis:** A mix of businesses, public institutions, and households producing usable by-products is essential for forming symbiotic relationships.
- **Openness to experimentation:** Communities that value innovation, or are already engaged in local sustainability efforts, are more likely to embrace the model.
- **Champions and facilitators:** Success often hinges on dedicated individuals who can activate local networks and guide early efforts.

The Go-SYM spin-off in Bornholm offers a living example of how socially anchored innovation can drive circular transitions from the bottom up. It reframes waste as opportunity, education as



empowerment, and communities as co-creators of sustainable futures. With its adaptable tools, participatory methods, and demonstrated results, the model holds strong potential for replication across Europe. By emphasizing the social dimension of symbiosis and providing a roadmap for practical, scalable action, Go-SYM shifts the narrative of the green transition from institutional obligation to communal opportunity and in doing so, it lays the groundwork for a more inclusive, resilient, and regenerative Europe.

5.2 Replicability of SYMSITES EcoSites

5.2.1 *Is SYMSITES Suitable for replication in your Region?*

The SYMSITES model for I-US is highly suitable for replication in regions that exhibit a combination of key enabling conditions. At its core, successful replication requires the presence of a diverse mix of industries located in close geographic proximity. This facilitates the exchange of resources such as waste, water, and energy, which is foundational to the I-US approach. Areas with clusters of industrial activity, especially those generating significant volumes of wastewater and organic waste, are particularly well-suited for implementing SYMSITES-inspired solutions.

From a technical perspective, the quantity and quality of wastewater are critical considerations. As highlighted by the Austrian EcoSite, the characteristics of industrial wastewater must be well understood to ensure compatibility with treatment technologies like the AnMBR. Availability of data on wastewater quality, and the capacity to analyse it, is a vital precondition for replication.

Equally important is a supportive policy and regulatory environment. Regions where there are clear guidelines and positive incentives for the use of reclaimed water, biogas, or nutrient-rich by-products are far more likely to benefit from the adoption of SYMSITES technologies. This is especially relevant in areas facing water scarcity or with a high demand for irrigation, where the reuse of treated water can support agricultural or landscape needs (such as in the Mediterranean regions, thus pertinent to the areas of the Spanish and Greek EcoSites).

In addition to physical and policy conditions, stakeholder readiness plays a crucial role in replication success. Key stakeholders include local industries, municipalities, waste utility companies, research institutions, and civil society actors. All the Ecosites emphasized the importance of having engaged industrial partners, academic or research support, and an active local community that understands and supports the goals of circular resource management.

In summary, SYMSITES is well-suited for replication in regions that combine industrial clustering, wastewater data availability, policy alignment, a well-separated organic fraction of residues, water reuse potential, and strong stakeholder ecosystems. Tailoring the approach to local conditions, especially with regards to water demand, waste streams, and institutional capacity, will be essential to ensure the long-term success and sustainability of replication efforts.

5.2.2 *Sourcing residues and waste from relevant stakeholder*



The viability of each EcoSite hinges on its ability to consistently access specific types of organic waste, ranging from household food waste and industrial by-products to wastewater, under appropriate conditions for treatment and valorisation. Across the four SYMSITES pilot regions, different approaches and stakeholder relationships have been developed to secure these resources, highlighting a number of common success factors and challenges that must be taken into account when planning replication in new contexts.

One of the most important factors enabling successful sourcing of waste is the establishment of reliable, long-term agreements. For instance, in the Danish EcoSite on the island of Bornholm, food waste provision is supported by a 10-year municipal contract managed by BOFA, the local waste management authority. Such long-term arrangements offer operational stability and ensure a continuous input stream to support technological processes like anaerobic digestion. Similarly, industrial waste streams on Bornholm are bolstered by the interest of the island's central biogas facility, which creates an additional channel for processing and value creation. However, even where institutional support is strong, logistical challenges persist. In the Danish case, for example, transporting waste over long distances introduces significant costs and operational complexity. This underlines a common challenge across sites: the geographic distribution of waste sources relative to treatment facilities must be carefully considered to ensure economic feasibility and environmental sustainability with regards to transport-related emissions.

Stakeholder engagement also plays a vital role in sourcing. The Spanish EcoSite demonstrated the importance of building strong, trust-based relationships with local authorities and institutions. Success in this context was not driven solely by formal agreements, but by proactive outreach, clear communication, and efforts to involve local administrations in project planning and awareness activities. Informative meetings, collaborative actions, and transparent communication channels helped integrate the project into the local governance structure, encouraging municipal partners to become active contributors. Nonetheless, technical barriers can complicate this process. A major concern in the Spanish context (but also applicable to the other EcoSites) was the quality of the waste stream, especially the Organic Fraction of Municipal Solid Waste (OFMSW), which needs to be free of impurities to ensure effective treatment and safe output. Similarly, monitoring the quality of industrial effluents is essential, as unsuitable inputs can hinder or damage downstream processes. This highlights a recurring challenge for replication: beyond establishing supply, it is equally critical to ensure that the waste meets the necessary standards for processing technologies.

In the Austrian EcoSite, the focus has been on sourcing food residues from local institutions, such as schools, as well as industrial by-products like blood from the meat-processing project partner, Berger Schinken. The willingness of such stakeholders to participate is influenced by a range of factors, including their existing contracts with waste disposal services and legal obligations related to hygiene and environmental regulation. Even when waste is available and technically suitable, replicators must navigate regulatory requirements and assess whether potential partners are both legally able and practically willing to divert their waste streams.

A similar blend of logistical and institutional considerations appears in the Greek EcoSite. Here, the sourcing of fermentable household waste depends heavily on the availability of local collection personnel and transport infrastructure. Participation from households is voluntary, which introduces variability in the volume and reliability of supply. Community engagement is key in such contexts, and the presence of active local institutions, such as universities or research centres, can help support outreach and education efforts to sustain long-term involvement.



Across all pilot sites, several themes emerge as critical for replication. First, regions with a dense concentration of compatible waste producers (such as schools, food processors, or households) located near potential treatment facilities are better positioned to support effective symbiotic systems. Second, legal and contractual frameworks must be carefully assessed, both to identify opportunities for new partnerships and to avoid conflicts with existing obligations. Third, quality assurance processes must be embedded from the outset to ensure that the collected waste meets technical and environmental standards.

5.2.3 Operation of the pilot

The operation of the SYMSITES pilot facilities across different European contexts reveals both shared and site-specific insights into managing organic and wastewater streams for valorisation through I-US. While each pilot adapts its setup to local waste characteristics and treatment goals, common operational considerations emerge across the sites in the selection of technologies, pre-treatment processes, reactor performance, and components deemed ready for replication.

Selection of Anaerobic Membrane Bioreactors (AnMBRs) or Flotation Units

One of the central technological decisions across several SYMSITES pilots concerns the deployment of Anaerobic Membrane Bioreactors (AnMBRs). An AnMBR is an advanced wastewater treatment technology that integrates anaerobic biological processes with membrane filtration¹. This system enables complete separation of solids from treated water while enhancing organic matter degradation under anaerobic conditions. Unlike aerobic MBRs, AnMBRs generate significantly less excess sludge, allow for high concentrations of biomass, and produce biogas (primarily methane) which can be used as an energy source². These benefits make AnMBRs attractive for treating both low- and high-strength wastewaters from municipal, industrial, and agricultural sources.

As noted by the SYMSITES EcoSites managers, the AnMBR systems offer significant advantages when treating complex waste streams, particularly where a high organic loading rate, reduced sludge production, and compact system design are desirable. AnMBRs are most suitable in scenarios where operation at low Hydraulic Retention Times (HRT) is needed or when organic loading is high but concentrated in relatively low-volume streams. Moreover, AnMBRs are well-suited for decentralized applications in remote or smaller communities, especially where the simultaneous generation of biogas and high-quality reclaimed water is a priority. For example, tropical regions could benefit from AnMBRs due to their ambient temperatures, which reduce the energy required to maintain optimal reactor conditions (typically around 35°C). In such climates, operational costs and energy input may be significantly lower than in colder regions, improving system efficiency.

Nevertheless, caution is warranted when comparing AnMBRs to more conventional reactor configurations, such as Continuous Stirred Tank Reactors (CSTRs), especially in systems with more solid substrates or highly particulate organic waste. As highlighted by the Austrian Pilot, AnMBRs and flotation units serve different but complementary roles in wastewater treatment, and the choice between them depends largely on the characteristics of the wastewater and the treatment goals.

¹ Osman, R. M., & Hodaifa, G. (2023). An overview of anaerobic membrane bioreactors: Current developments, fouling problems, and future prospects. *Journal of Environmental Chemical Engineering*, 11(6), 111482.

² *Ibidem*



AnMBRs are best suited for treating high volumes of wastewater with relatively low organic concentrations. They offer complete solid-liquid separation, efficient biogas production, and high-quality effluent that can be reused in industrial processes such as cooling. However, due to high energy demands and the risk of membrane fouling, AnMBRs are more effective with dilute waste streams and require careful management of membrane maintenance and operating pressures. Flotation units, on the other hand, are recommended when dealing with wastewater containing high levels of organic matter, particularly fats, oils, and grease (FOG), which can clog membranes. A flotation unit is a multiphase separation device used across various industries, including wastewater treatment, mineral beneficiation, and chemical processing, to isolate contaminants like fine particles or oil droplets from liquids³. In wastewater treatment a flotation unit separates contaminants such as particles or oil droplets from water using gas bubbles, which attach to the impurities and carry them to the surface for removal⁴. These units act as a crucial pre-treatment step to remove bulk organics, improving the efficiency and lifespan of downstream membrane systems. Flotation units are especially useful in stabilizing influent quality for membrane filtration, though their effectiveness can be compromised by fluctuations in wastewater composition. Operating costs for flotation, including chemicals and energy, can be significant, and manual operation or lack of automation can further limit scalability. Therefore, flotation is ideal when the goal is to protect membranes and enhance biogas yield through more concentrated sludge, whereas AnMBRs are preferable when water reuse and resource recovery are the primary objectives.

Pre-Treatment Requirements and Challenges

The importance of pre-treatment in ensuring smooth and efficient pilot operation cannot be overstated. Across all SYMSITES pilots, the first step in managing solid and liquid organic inputs is to remove coarse contaminants and reduce particle sizes, safeguarding the membranes and reactors from clogging and fouling.

At the Danish EcoSite, for example, food waste is subjected to grinding and coarse filtration through a drum filter to remove particles above 500 microns. Brewery wastewater is similarly filtered. However, challenges with the drum filter were noted, particularly the high volume of reject material and difficulty processing certain types of food waste (i.e., waste containing bones or kernels). These observations indicate that while mechanical filtration is necessary, its optimization requires further research to balance efficiency with operational cost and waste minimization.

In the Greek and Austrian pilots, pre-treatment includes on-site sedimentation or screening processes. Industrial effluents are often pre-settled at the source, for instance within the food industry facility, while secondary screening at the pilot site removes solids larger than 4-5 mm.

The Spanish EcoSite applied a multi-stage approach: wastewater undergoes coarse and fine grating, followed by de-sanding and degreasing, and is then passed through a 0.1 mm roto-filter. Solid organic waste is crushed and passed through the same filter before mixing in a homogenization tank. This approach emphasizes the need for automated pre-treatment where both municipal and industrial wastes are co-treated.

³ Prakash, R., Majumder, S. K., & Singh, A. (2018). Flotation technique: Its mechanisms and design parameters. *Chemical Engineering and Processing-Process Intensification*, 127, 249-270.

⁴ Han, J., Chen, P., Liu, T., & Li, Y. (2023). Research and application of fluidized flotation units: A review. *Journal of Industrial and Engineering Chemistry*, 126, 50-68.



However, the issue of variability and impurities in the organic fraction, particularly in the municipal solid waste (MSW) stream, remains a persistent challenge. Careful control of input quality, both through physical filtration and source-level awareness, is essential to avoid disruptions such as pump clogging or membrane damage.

When properly pre-treated, the behaviour of input materials in the anaerobic reactors is generally stable. Pilot teams reported that reactor inputs, once processed to remove large particles, performed smoothly in the system. Liquid fractions resulting from food waste and wastewater proved compatible with the reactor requirements and posed minimal risks of membrane fouling or blockages.

However, all teams emphasized the need for close daily supervision of anaerobic systems. These reactors are sensitive to changes in parameters such as organic loading rate, pH, and temperature. Deviations outside of the optimal operational ranges can only be tolerated for short periods (typically two to three days) before reactor performance degrades, often resulting in souring or failure of the digestion process. Dosing and organic loading management are particularly crucial. The Austrian EcoSite cited optimal loading rates for food waste and blood mixtures at around 3–4 kg OTM/m³/day. Following this trend, the Spanish EcoSite operated at average organic loading rates of 2.7 kg COD/m³·day. Surpassing these thresholds can compromise microbial and membrane performance increasing the risk of reactor upset.

Components Most and Least Ready for Replication

The replication potential of the SYMSITES pilot technologies varies significantly across components, with some systems demonstrating high readiness for scale-up, while others still face technical uncertainties and operational challenges that require further research and refinement. Firstly, it should be noted that these conclusions are still preliminary as the replication potential cannot be fully determined until the project reaches completion, and comprehensive data on performance, lifecycle costs, and environmental impact, from the LCA studies, are available. Thus, a comprehensive evaluation at the end of the SYMSITES project will be necessary to fully validate which components are most scalable and under what conditions.

The biogas production units consistently emerge as the most mature and readily replicable element of the pilot systems. These systems have proven to be technically stable and efficient, offering a high degree of transferability to other regions that have similar feedstocks and industrial symbiosis frameworks. The biogas units have successfully demonstrated their ability to process organic waste streams into valuable energy carriers, providing a sustainable and economically attractive output that aligns with circularity goals.

The flotation unit, particularly as implemented in the Austrian EcoSite, has also been identified as a technology with high replication potential. It successfully isolates fats and particulates that could compromise membrane performance, allowing the digested sludge to be sent for biogas production and the clarified liquid to undergo further treatment. The unit's role in separating organics prior to membrane filtration has proven effective in protecting downstream treatment systems and improving overall operational stability. The flotation step enables a pre-concentration of high-organic content waste streams, channelling the organics towards anaerobic digestion while preventing clogging and fouling in membranes.

At the Danish, Greek and Spanish EcoSites, the integration of anaerobic digestion with AnMBR is considered as ready for replication. Despite the challenges associated with membrane systems



(detailed below), the entire pilot setup is replicable, largely due to its comprehensive system integration and stable operation under monitored conditions. This includes the digestion phase as well as the membrane-based water reclamation process.

In contrast, several components have been identified as less mature and requiring further research before large-scale replication can be recommended. One of the main areas of concern is pre-treatment, particularly for heterogeneous or highly variable waste streams such as MSW or food waste. In Denmark, as well as in Spain, the high costs and operational inefficiencies linked to food waste pre-treatment, especially when dealing with food waste containing hard material, such as bones or kernels, were noted. Similarly, the Greek EcoSite highlighted the difficulty in consistently managing and pre-processing waste inputs due to their changing composition and the voluntary nature of participation by waste suppliers. Successful replication will require local adaptation of pre-treatment processes depending on the waste types available and their contamination levels.

The membrane systems, particularly ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), were also broadly categorized as not yet ready for wide-scale replication. This concern was mainly raised by the Austrian EcoSite, where uncertainties regarding membrane durability, fouling rates, cleaning frequency, and associated energy consumption remain unresolved. While membrane-based technologies have shown promise in terms of water quality outputs, the long-term operational data necessary to validate their cost-effectiveness and maintenance profiles are still insufficient. Additionally, membrane performance can be severely impacted by the type and concentration of FOG in the wastewater stream, necessitating robust and consistent pre-treatment. In this sense, the Spanish EcoSite, which treated wastewater and an organic fraction with less content of fats, did not experience severe operational problems. The Danish EcoSite echoed this concern, noting that post-treatment systems tied to membranes and final effluent polishing still need further evaluation, as it is unknown the potential duration of the membranes. These stages are crucial for ensuring the reclaimed water meets quality standards for reuse. Membrane fouling, operational costs, and uncertainty about lifespan still require further investigation before recommending widespread replication, particularly in resource-constrained contexts.

A common thread among both the most and least replicable aspects is the importance of process integration and operational consistency. Even in the case of mature technologies like biogas production, effective replication depends on the availability of compatible feedstock, skilled operators, and supportive regulatory frameworks. For technologies facing replication challenges, such as membranes and pre-treatment systems, progress will depend heavily on further research, pilot-scale optimization, and cost-benefit validation in diverse regional contexts. While SYMSITES offers several promising and technically viable solutions for I-US, its replication strategy must prioritize adaptable, low-maintenance technologies with demonstrated stability, like biogas production and flotation units, while continuing to invest in refining complex or resource-intensive components such as membrane treatment and waste pre-processing systems.

Degree of Automation, Monitoring Parameters & Labour Needs per EcoSite

The operation of the SYMSITES pilot plants at scale requires careful monitoring of a range of parameters to ensure stable performance, process efficiency, and compliance with environmental standards. Additionally, labour needs vary depending on the complexity and automation level of each system. This table below summarizes the automation levels across four key treatment stages (pre-treatment, biogas plant, MBR reactor and post-treatment), as well as the monitoring parameters and staffing demands at each of the four EcoSites involved in the project.



The SYMSITES pilots demonstrate a diverse range of monitoring requirements and labour needs, influenced by the technologies employed, the complexity of inputs, and the level of automation. While some systems, like the Danish EcoSite, operate with minimal human intervention, others like the Austrian and Greek pilots require more intensive daily supervision and specialized technical staff. Across all sites, key parameters such as pH, temperature, flow rates, and biogas production are commonly monitored, underscoring their importance in anaerobic digestion and membrane processes. The labour intensity tends to increase with the variability of waste input and the complexity of the treatment configuration, providing useful guidance for designing scalable and context-sensitive replication strategies.

	Austrian EcoSite	Danish EcoSite	Greek EcoSite	Spanish EcoSite
Degree of automation of the pilot (1: lowest value, 5: highest value)⁵				
Pre-treatment	2	3	2	3
Biogas plant	3	5	4	5
AnMBR reactor	3	4	4	5
Post-treatment	2	3	3	-
Parameters				
Biogas Production / Flow	✓	✓	✓	✓
Flows / Flow Rates	✓ (To membrane systems for UF)	✓	✓ (incl. internal flows, per hour)	✓
Temperature	✗	✓	✓	✓
pH	✗	✓	✓	✓
Turbidity	✗	✓	✗	✗
Suspended Solids	✗	✓ (Total Suspended Solids TSS)	✓ (Mixed Liquor Suspended Solids MLSS)	✗
Redox Potential	✗	✗	✗	✓
Reactor Level	✗	✗	✗	✓
System Pressure	✗	✗	✗	✓ (Monitors membrane system)
Transmembrane Pressure (TMP)	✗	✗	✗	✓ (Membrane fouling indicator)

⁵ These values were submitted by the EcoSite managers themselves through the questionnaire on the basis of the perceived subjective degree of automation, but they have been slightly adjusted by taking into consideration the estimates for the labour needs indicated below.



COD (Chemical Oxygen Demand)	X	X	✓	X
Flotation Unit Inputs / Outputs	✓ (Water & sludge management)	N.A.	N.A.	N.A.
Labour needs				
Hours per week	~20–30 hrs	~8–16 hrs	~50+ hrs	~20–30 hrs
Details	Medium: 0.5–1x full-time operator for 4-6 hrs/day	Low: Highly automated	High: 1x Operator 3 hrs/day, 5 days 3x Analyst for 8 hrs/week 2x Collection workers for 8 hrs/week	Medium: 1–2 operators for 2-3 hrs/day
Notes	Manual checks for industrial flows	Remote monitoring reduces staffing	Complex system with variable feed	Labour needs depend on inputs complexity and system load

The successful operation of the SYMSITES pilot systems depends on a combination of technical design, process control, skilled labour, and adaptability to local waste characteristics. While all pilots share a similar framework, combining anaerobic digestion and membrane technologies to produce biogas, biofuels or reclaimed water for irrigation, the specific challenges and requirements encountered during setup and operation have shaped important lessons for replication and scale-up. Across the pilots, consistent themes emerge in terms of cost investment, operational success factors, and performance-limiting challenges.

Primary Cost Investment

One of the dominant operational investments across all pilot sites is staffing. While the technical infrastructure, such as membranes, pumps, digesters, and automation, requires significant upfront capital, the recurring cost of human labour remains a central expenditure, particularly in facilities with limited automation. Operators are not only required to manage input materials and monitor performance indicators but also to troubleshoot membrane fouling, pump failures, or unexpected shifts in process stability.

In addition to labour, maintenance materials and chemical inputs represent notable ongoing costs. For example, operating chemicals such as polyacrylamide and iron chloride, used in coagulation, flocculation, or other conditioning steps, are essential for process reliability, especially in flotation or sludge handling. Another area of financial concern is the membrane systems, in the AnMBRs, as the unknown lifespan of the membranes presents a significant economic risk. Should membranes degrade or foul beyond recovery, replacement would incur high costs, both in materials and system downtime.



Moreover, energy consumption, particularly for pumps and membrane systems, is a leading operational cost driver. Pressure demands, transmembrane resistance, and circulation flows all require consistent electrical input, which can be a burden, especially in regions with high energy tariffs or where renewable offsets are unavailable. Despite efforts to optimize efficiency, high electricity costs remain a limiting factor, particularly at scale.

While these operating costs are relatively well understood at the pilot scale, comprehensive cost analysis for upscaling remains largely incomplete. Most EcoSites have not yet conducted detailed extrapolations to estimate the costs of full-scale implementation. Several partners emphasized the need for more performance data and extended operational experience before such calculations can be accurately made. For instance, scaling from a pilot treating just 3 m³/day to a full-scale system of 500 m³/day involves numerous technical, logistical, and economic considerations that go beyond the current scope of pilot-level data. These include material durability, process optimization at larger volumes, infrastructure requirements, and regional cost differences.

Nevertheless, some progress has been made, and cost estimates for scaling up biogas plants and flotation units are already available, providing initial benchmarks for investment planning. Additionally, investment cost projections for membrane systems have been developed. However, there are still notable gaps in understanding the running costs of the membrane unit at scale, particularly with respect to energy consumption, cleaning cycles, and long-term maintenance. Until other findings in the project are consolidated, a full financial picture of scale-up feasibility remains incomplete. As such, any replication or investment planning should proceed cautiously, incorporating flexible assumptions and allowing for adjustments based on future operational data and economic modelling.

Success Factors in Operation

From a design and implementation perspective, several factors are repeatedly emphasized by pilot operators as essential to successful operation. First among these is the importance of a robust and well-designed pre-treatment system, particularly for food waste and mixed organic inputs. Unrefined input streams containing bones, seeds, fibrous material, or plastic contaminants can rapidly lead to downstream problems such as membrane clogging, pipe blockages, and overall system inefficiency. Ensuring a consistent and high-quality feedstock is therefore critical not only to protect sensitive components like membranes but also to stabilize microbial digestion processes.

A second critical success factor is the quality of engineering design, specifically the development of detailed process instrumentation diagrams (P&IDs) and flow control strategies. Sites that lacked clear design specifications reported frequent disruptions due to oversights in flow balancing, mixing efficiencies, or mechanical control. In systems using immersed membranes, such as AnMBRs, close monitoring of flux rates (litres per square meter per hour, LMH) and extraction pressures is essential to avoid irreversible fouling and mechanical stress.

Additionally, the ability to automate core operational tasks, such as feed dosing, sludge withdrawal, and flow redirection, directly influences process stability and labour efficiency. Where automation was limited, pilots required near-constant onsite presence, leading to increased operational strain and reduced flexibility for troubleshooting or optimization.



Finally, maintaining stable environmental conditions (temperature, pH, redox potential) and ensuring adequate process monitoring, through checking of parameters such as biogas flow, COD, Suspended Solids, etc., were repeatedly cited as keys to long-term success. These parameters not only affect the biological performance of the digestion process but also dictate how well membranes perform over time.

Operational Challenges

Despite successes, several challenges continue to limit the scalability and energy efficiency of these systems. One of the main issues is the inconsistent quality of input waste, particularly in decentralized or municipal settings. Variability in organic loading rates, dry matter content, and contaminant levels can cause fluctuations in process efficiency, upset microbial populations, and increase the frequency of manual intervention.

Energy efficiency also remains a major concern. Anaerobic digestion systems require steady thermal input, particularly in temperate climates, to maintain optimal microbial activity. Although biogas production offers a partial energy offset, it is often insufficient to fully cover the electricity needs for pumping, membrane filtration, and ancillary systems. In membrane-based systems, transmembrane pressure (TMP) and flow rates are key drivers of energy consumption, and without advanced recovery systems or energy-efficient pumps, these units risk becoming economically unviable at large scale.

In terms of replicability, while biogas production is broadly viewed as ready for scale-up, AnMBR systems still face significant hurdles. The high energy demand, potential for rapid membrane fouling, and maintenance burden mean that conventional systems using flotation units followed by membrane treatment of clarified water may currently be more feasible. However, the flotation unit itself must be highly efficient at removing organics - especially fats and oils - to prevent downstream blockages in the membranes. Membrane technologies (including UF, NF, and RO) also require further study to determine their operational longevity, cleaning frequency, and associated pressure losses. Without this data, it is difficult to fully assess their economic viability over multi-year operating periods.

5.2.4 Establishing symbiotic exchanges

Establishing symbiotic exchanges lies at the heart of the circular economy model promoted by the SYMSITES EcoSites. These exchanges aim to enable the reuse of wastewater, energy, and nutrients by linking waste producers with nearby users across industrial, agricultural, or municipal sectors. However, implementing such exchanges requires more than just a functional pilot setup; it demands infrastructure, regulatory alignment, strategic partnerships, and operational foresight. This chapter summarizes the key findings from the pilot Ecosites in Spain, Austria, Denmark, and Greece regarding what is additionally needed, what challenges have arisen, and what factors are crucial for success.

Additional Practical Needs

While the pilots demonstrated the technical feasibility of resource recovery from wastewater and organic residues, their long-term operability and scalability rely on several additional elements not initially part of the pilot configuration. Several Ecosites highlighted the need for dedicated reuse and recovery infrastructure to handle reclaimed resources. For instance, storage space for reclaimed



water was cited as a practical necessity, particularly in regions where irrigation is seasonal. Without such storage, the water produced cannot be effectively reused during periods of low agricultural demand. Likewise, a biogas upgrading, storage, and transport system was identified as an essential investment. Without biogas cleaning (i.e., removal of CO₂) and compression or conversion to biomethane, the energy recovered remains underutilized or wasted.

All sites underscored the importance of monitoring the final quality of treated outputs, especially regarding water. Real-time quality assurance is not only a regulatory requirement but also essential for building trust among potential users in agriculture or industry. To this end, online monitoring of parameters such as nitrogen content, pathogens, and micropollutants was mentioned as a critical need. In Austria, meeting stringent quality thresholds for process water in the food industry means deploying a combination of membranes systems through UF, NF and RO. Ensuring enough capacity and operational reliability of these membrane stages remains a practical necessity before full-scale reuse.

Beyond technical infrastructure, knowing the potential market, identifying viable end-users and aligning reclaimed outputs with their specific needs is an integral step. This requires building partnerships, conducting water demand mapping, and adjusting treatment outputs accordingly. For instance, tailoring nutrient-rich digestate to the needs of nearby farms or matching water quality to the standards of local industries is fundamental to successful symbiosis creation.

Challenges in Establishing Reuse Practices

Despite the clear benefits, each pilot encountered tangible challenges in establishing the reuse of treated resources, ranging from regulatory limitations to technical and contextual obstacles. A recurring issue across sites was the misalignment between innovation and regulation. In Denmark, for instance, the reuse regulation is not yet fully implemented in the region, creating legal ambiguity for reclaimed water applications. Even when regulations exist, as in Greece, they often impose rigorous documentation, quality checks, and permits that delay or limit practical reuse. In Spain, while the regulatory framework has advanced, challenges remain in aligning stakeholder responsibilities and funding mechanisms. In Spain the reuse of treated wastewater, particularly in agriculture, urban and industry is encouraged. However, the cost burden of implementing and maintaining advanced treatment technologies often sparks debates over financial responsibility between public authorities, private companies, and end-users. Additionally, regional disparities in water governance add complexity, with some areas more advanced in adopting reuse practices than others. In Austria, the national stance on wastewater reuse has leaned toward caution. The country exercised an “opt-out” from agricultural reuse under the EU Wastewater Reuse Regulation, creating a significant barrier for farmers interested in utilizing reclaimed water. Similarly, in the food and beverage sector, concerns about water purity and safety have hindered acceptance, even when technical treatment standards were met.

Another challenge reported was mismatch between production and demand. For instance, in Denmark, when there is no irrigation need, surplus treated water containing residual nitrogen poses an environmental risk if discharged. This situation calls for advanced post-treatment, such as activated carbon adsorption or nitrogen stripping, but such solutions may not be cost-effective at large scale. In addition, some sites experienced logistical and operational issues, such as lack of automation, inefficient water distribution systems, or limited storage capacity for digestate and sludge. These bottlenecks underscore that technical viability alone does not guarantee successful symbiosis; the supporting system must be equally robust.



Finally, ecosystem-wide collaboration proved challenging in some cases, and there were reports of institutional and social hurdles across the EcoSites. Building trust and cooperation among municipalities, utilities, and private firms can be difficult, especially when benefits are not evenly distributed. A few EcoSites noted the importance of social acceptance and the need for more transparent communication around the safety and benefits of resource reuse.

Success Factors for Enabling Symbiotic Resource Exchanges

In light of the above challenges, several success factors were identified by the EcoSites that can help support replicability and long-term viability of resource symbiosis:

- **Presence of Industrial or Agricultural Demand:** Replicating the pilot setups elsewhere requires assessing whether a genuine need for reclaimed resources exists. Sites with high irrigation demands or strong industrial water usage, especially in water-scarce regions, offer the best potential for integration. For example, in Spain and Greece, irrigation and biogas use were clearly aligned with regional demands.
- **Strategic Location and Partnerships:** Proximity to potential end-users, including farms, factories, and municipalities, is a key determinant of feasibility. Furthermore, successful pilots emphasized the importance of having engaged local stakeholders, including industrial partners, research institutions, and local authorities. These actors help bridge technical outputs with societal or commercial needs.
- **Well-Studied Engineering and Operational Design:** Several EcoSites advised that replication efforts must be grounded in a comprehensive engineering design, including a P&IDs, redundancy measures, and clear monitoring protocols. Without these, daily operation becomes error-prone, especially in systems such as AnMBRs that are sensitive to loading variations and operational stress.
- **Legislative Alignment and Policy Support:** Finally, alignment with national or EU-level legislation is pivotal. The EU Wastewater Reuse Regulation offers a harmonized framework, but its implementation varies greatly across member states. EcoSites operating in more progressive regulatory environments found it easier to advance symbiotic exchanges. Legislative clarity reduces investment risk and encourages broader market uptake.



6. Conclusions

The SYMSITES pilot EcoSites collectively demonstrate the real-world feasibility of sustainable I-US, leveraging anaerobic digestion and advanced membrane processes to recover valuable resources from wastewater and organic waste. While the pilots vary widely in technological setup, scale, and input complexity, they share common challenges and opportunities that offer actionable insights for future replication.

A central takeaway across all sites is the critical role of monitoring and labour. Key parameters, such as pH, temperature, flow rates, and biogas production, are universally monitored due to their importance in process control and system stability. The labour intensity is closely tied to the degree of automation, with highly automated sites like the Danish and the Spanish EcoSites requiring only limited manual intervention, while others like the Greek and Austrian sites demand more frequent supervision and specialized staffing due to operational complexity or lower automation levels.

Establishing symbiotic exchanges is promising but not without hurdles. Key practical needs such as storage for reclaimed water, infrastructure for biogas upgrading and transport, and robust monitoring systems must be addressed. Additionally, regulatory constraints, particularly around wastewater reuse and digestate application, remain major barriers in some regions. Ensuring demand-side readiness, identifying local end users and building the required infrastructure, is equally essential to unlocking circular value chains.

Crucially, successful replication requires more than technical transfer; it demands a holistic approach that accounts for human, infrastructural, and regulatory dimensions. Replication efforts should be anchored in flexible system design, cross-sectoral collaboration, and context-sensitive strategies that align with local market conditions and policy environments. The pilots have underscored the importance of stakeholder engagement, quality feedstock sourcing, and adaptive operation based on performance data.

As of now, full-scale cost analysis remains a gap in the overall assessment. While some estimates exist (particularly for biogas, flotation, and membrane units) many operational costs, especially those tied to membrane lifespan and long-term maintenance, are still being evaluated. This highlights the importance of continued data collection and analysis to refine economic projections for larger-scale implementation.

This Replication Analysis Report aimed to be more than a technical summary but to serve as a strategic foundation for expanding circular economy solutions. By connecting lessons learned with future planning, it ensures that replication efforts across Europe and beyond are evidence-based, contextually appropriate, and primed for success. Scaling up SYMSITES-style systems will ultimately depend on our ability to integrate environmental innovation with economic pragmatism and social readiness, paving the way toward a more resilient and resource-efficient future.



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