Digital Twins in the Energy Industry and Emerging Three Innovation Ecosystems: Battery Factory, Data Center, and Greenhouse Farming Business Ecosystems: A Knowledge-based Scoping Review for Strategic Industrial Foresight Processes in Finland

Author(s): Kaivo-Oja, Jari; Sievers, Henrik; Hermans, Raine

Title: Digital Twins in the Energy Industry and Emerging Three Innovation Ecosystems: Battery Factory, Data Center, and Greenhouse Farming Business Ecosystems: A Knowledge-based Scoping Review for Strategic Industrial Foresight Processes in Finland

Year: 2026

Version: Accepted manuscript

Please cite the original version:

Kaivo-Oja, J., Sievers, H., & Hermans, R. (2027). Digital Twins in the Energy Industry and Emerging Three Innovation Ecosystems: Battery Factory, Data Center, and Greenhouse Farming Business Ecosystems: A Knowledge-based Scoping Review for Strategic Industrial Foresight Processes in Finland. In L. Uden & I. Varlamis (Eds.), Knowledge Management in Organisations: 20th International Conference, KMO 2026, Manila, Philippines, August 24–27, 2026, Proceedings (pp. 139–154). Springer. https://doi.org/10.1007/978-3-032-34189-1_12

Digital Twins in the Energy Industry and Emerging Three Innovation Ecosystems: Battery Factory, Data Center and Greenhouse Farming Business Ecosystems: A Knowledge-based Scoping Review for Strategic Industrial Foresight Processes in Finland

Jari Kaivo-oja[1] (✉), Henrik Sievers[2], Raine Hermans[2]
[1] Finland Futures Research Center (FFRC), Turku School of Economics, University of Turku, Turku, Finland
[2] School of Technology and Innovations, University of Vaasa, Vaasa, Finland
Corresponding author: jari.kaivo-oja@utu.fi

Abstract. This study investigates three emerging innovation ecosystems and their Digital Twins: (1) the Data Center business innovation ecosystem, (2) the Battery Factory innovation ecosystem, and (3) the Greenhouse farming innovation ecosystem, together with Digital Twin (DT) energy industry solutions, aiming to identify technological potential, pathways for ecosystem/cluster growth and development, and policy implications. A systematic review of DT applications was conducted across conventional and renewable energy production, storage, and multi-energy systems. Both conventional and less conventional energy DTs were identified and reported. The three innovation business ecosystems were conceptualized and defined as summary tables integrating technological, organizational, and market dimensions. The study analyses how DT solutions can be mobilized to foster competitive new innovative industrial cluster business ecosystems and evaluates the associated strategic policy measures.

Keywords: Digital Twins, Energy industry, Knowledge management, Scoping review, Data center business innovation ecosystem, Battery factory innovation ecosystem, Greenhouse farming innovation ecosystem

1. 1 Introduction

The accelerating digitalization of the global energy sector has created fertile ground for new forms of industrial innovation, organizational transformation, and technological integration. Among the most significant developments is the rise of Digital Twin solutions of the energy industry, which enables the real-time virtual representation of physical assets, processes, and systems together, which can help to develop efficient and sustainable solutions in various innovation ecosystems. As energy industries confront mounting pressures to enhance efficiency, strengthen resilience, and meet ambitious sustainability targets, novel Digital Twin technologies offer a promising pathway for bridging operational realities with data-driven intelligence, which can decrease transaction costs of production processes and business model implications.

1.1 1.1 The role of Digital Twin in industrial transformation

Digital Twin (DT) Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin [1] (see also [2-4]). The critical role of Digital Twins in the energy industry is recognized in various studies [5-8]

Digital Twins (DTs) virtually represent physical assets and systems so comprehensively that information obtainable from the real object can, in principle, be retrieved from its virtual counterpart, enabling analysis and control without intrusive inspection [1]. In the contexts of data centers, battery factories, and greenhouses, DTs are applied at asset, process, and system/multi-energy levels to mirror operations, couple energy flows, and coordinate interactions across devices and markets ([9] Key benefits include operational optimization—such as predictive control, demand response, storage orchestration, and waste-heat reuse—leading to improved efficiency, resilience, and sustainability ([9-10]. DTs also enhance risk management and lifecycle decision-making by enabling what-if simulations, condition monitoring, and cybersecurity-aware oversight before physical changes are implemented [1. 10]. At the ecosystem level, interoperable DT deployments support data governance and scalable integration, helping accelerate the formation of competitive industrial clusters [9] (see also [11-12]).

2. What are Innovation Ecosystems?

In parallel with innovation ecosystem typologizing and role clarification, the broader landscape of innovation is undergoing a profound technological shift. Emerging innovation ecosystems, characterized by dense networks of firms, research organizations, digital platforms, and regulatory institutions, increasingly determine the pace and direction of technological change. Within this context, Digital Twin solutions of the energy industry do not evolve in isolation. Rather, they are embedded in—and shaped by—interconnected ecosystems that foster learning, collaboration, and competitive advantage.

McKinsey [13] states that innovation ecosystems provide access to data and opportunities for data commercialization. In addition, ecosystems increase the market value of companies and help maintain competitiveness. Innovation – i.e. a new or renewing product, service, market, business model, organizational method – creates economic growth, improves the competitiveness of companies and renews the structures of society (e.g. 15-18]. The aim is also to have a systemic view of the development of society and business (e.g. [18-19].

We use the following definition of ecosystem [18]. "An ecosystem is defined by the relationships between multilateral partners that need to interact in order to create a common ecosystem value proposition."

To specify the Innovation ecosystem, we follow the definition of Autio et. al. [19] that innovation ecosystem comprises of business ecosystems, platform ecosystems and modular ecosystems.

A scoping review is a type of research review used to map out what is known about a broad topic or research area. Key features of a scoping review are (1) broad focus and it looks at a wide topic rather than a narrow question. It maps (2) some evidence – identifies types of studies, key concepts, and gaps. A scoping review has systematic approach and follows clear, transparent steps to search for and select studies. It (3) does not have a detailed quality appraisal unlike systematic reviews, and (4) it usually does not assess how “good” each study is. A scoping review includes (5) many sources and may include quantitative studies, qualitative studies, reviews, reports, and grey literature [23-25].

This scoping review study examines three innovation ecosystems that underpin the development and diffusion of Digital Twin solutions in the energy industry. These innovation ecosystems are: (1) Data Center business innovation ecosystem, (2) Battery Factory business innovation ecosystem, and (3) Greenhouse farming business innovation ecosystem. Novel Digital Twin solutions explore the technological potential revealed by current industrial applications, analyses how these ecosystems reinforce one another, and consider how Digital Twin innovations could be mobilized to strengthen or establish new competitive industrial clusters.

3. Emerging Three Innovation Business Ecosystems

We have defined three critical innovation and business ecosystems for Finland and the Finnish energy cluster. Desk work was led by Dr Henrik Sievers (Memo of Dr Sievers 2025). Firstly, an emerging innovation ecosystem relevant for Finland nowadays is the Data Center business ecosystem. Data Centers are nowadays needed for the need of big data analytics and Internet of Things [26-31, 33]. Electricity demand for data centers more than doubles by 2030 [31]. We have defined 6 systemic innovation ecosystem domains of this growing innovation ecosystem in Table 1.

Table 1. Data Center Industry business ecosystem: Key innovation ecosystem domains, core functions, and activities.

Innovation ecosystem domains	**Core functions and activities**
1. Infrastructure Management	• Design, construction, and maintenance of data centre facilities. • Management of servers, switches, storage systems, and other critical hardware. • Power management and backup systems (e.g., UPS, generators). • Advanced cooling solutions such as liquid cooling and free cooling technologies.
2. Network and Connectivity	• Provision of high-capacity network connections, including Internet transit, peering agreements, and routing services. • Deployment of edge computing infrastructures to distribute computational resources closer to end-users.
3. Services and Solutions	• Colocation services enabling clients to install and operate their own equipment within the data centre. • Cloud services, including Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS). • Managed services such as server administration, security management, and data backup solutions.
4. Security and Compliance	• Physical security measures (access control, surveillance systems). • Cybersecurity solutions (firewalls, DDoS protection, encryption). • Compliance with international standards and certifications (ISO 27001, SOC 2, GDPR).
5. Operational Management	• System monitoring, automation, and real-time alerting mechanisms. • Capacity management to ensure scalability and optimal resource utilisation.
6. Sustainability and Energy Efficiency	• Adoption of renewable energy sources to support carbon-neutral operations. • Waste-heat recovery and utilisation in district heating networks.

Secondly, an emerging new industrial innovation ecosystem relevant for Finland nowadays is the Battery Manufacturing Industry business ecosystem. Battery Manufacturing Industry and associated energy storage systems are an interesting business ecosystem for Finland [34-35]. We have defined systemic innovation domains of this strategic innovation ecosystem in Table 2.

Table 2. The Battery Manufacturing Industry business ecosystem: Key innovation ecosystem domains, core functions, and activities.

Innovation ecosystem domains	**Core functions and activities**
1. Raw Material Acquisition and Processing	• Extraction and chemical refining of lithium, nickel, cobalt, and graphite. • Pre-processing activities, including purification and standardisation of materials to meet battery-grade requirements

2. Cathode and Anode Manufacturing	• Production of cathode materials such as lithium-nickel-manganese-cobalt (NMC) and lithium-iron-phosphate (LFP). Manufacturing of anode materials, including graphite and silicon-based composites. • Coating, calendaring, and related electrode-fabrication processes.
3. Electrolyte and Separator Production	• Formulation of liquid electrolytes comprising lithium salts dissolved in organic solvents. • Manufacture of polymer-based separator films that prevent short circuits while permitting ionic transport.
4. Cell Manufacturing	• Assembly of battery cells in cylindrical, pouch, or prismatic formats. • Electrode lamination, stacking, and encapsulation processes.
5. Module and Pack Assembly	• Integration of individual cells into modules and complete battery packs. • Development and implementation of Battery Management Systems (BMS) for controlling charging, discharging, and thermal conditions.
6. Testing and Quality Assurance	• Electrical performance testing, including capacity, voltage, and current measurements. • Safety validation, such as thermal management assessment and short-circuit testing.
7. Logistics and Distribution	• Transportation and delivery of batteries from manufacturing facilities to clients in sectors such as automotive production and stationary energy storage.
8. Recycling and End-of-Life Processing	• Recovery of critical materials such as lithium, nickel, and cobalt. • Hydrometallurgical and pyrometallurgical processes for the treatment of end-of-life batteries.
9. Supporting Functions	• Research and development activities, including exploration of new chemistries (e.g., solid-state batteries). • Automation and digitalisation through IoT integration and data analytics for production optimisation. • Certification and regulatory compliance, including adherence to ISO standards and EU battery regulations.

Thirdly, an emerging new industrial innovation ecosystem relevant for Finland nowadays is the Greenhouse farming business ecosystem. It is important for food production in Finland. Also, this business ecosystem is interesting for Finland [36-39]. We have defined systemic innovation domains of this strategic innovation ecosystem in Table 3.

Table 3. Greenhouse farming industry business ecosystem: Key innovation ecosystem domains, core functions, and activities.

Innovation ecosystem domains	**Core functions and activities**
1. Design and Construction	• Development of greenhouse structures using steel or aluminium frames with glass or polymer coverings.

	• Heating and cooling solutions, including energy-efficient systems, heat pumps, and district heating. • Advanced lighting systems such as LED and HPS technologies, alongside daylight-optimisation strategies.
2. Cultivation Systems	• Hydroponic and aeroponic cultivation methods enabling soil-free plant growth in nutrient solutions. • Use of substrates including peat, coconut fibre, and mineral wool. • Automated irrigation and nutrient-delivery systems.
3. Climate and Environmental Control	• Temperature and humidity regulation through sensors and automation technologies. • CO_2 enrichment for optimised plant growth. • Natural and mechanical ventilation systems.
4. Technology and Automation	• Internet-of-Things (IoT) applications and sensor networks for continuous monitoring of growth conditions. • Intelligent control systems and cloud-based management platforms. • Robotics for planting, harvesting, and material handling.
5. Production and Harvesting	• Cultivation of crops such as tomatoes, cucumbers, lettuces, herbs, and berries. • Manual or automated harvesting, sorting, and handling of produce.
6. Logistics and Distribution	• Packaging solutions designed to maintain freshness and quality. • Cold-chain management for efficient transportation to markets and processors.
7. Energy and Sustainability	• Integration of renewable energy sources, including solar power and bioenergy. • Waste-heat recovery and utilisation for thermal efficiency.
8. Research and Development	• Breeding, testing, and optimisation of plant varieties suited to controlled environments. • Circular-economy solutions such as water recycling and nutrient recovery systems.

Now we have defined our three emerging innovation ecosystems (Data Centers, Battery Manufacturing and Greenhouse Farming BE) in Finland. We focus next on the challenges of the energy industry in these three innovation business ecosystems. Building on the ecosystem tables, Section 4 synthesises our scoping-review findings into a structured catalogue of Digital Twin applications and their expected benefits for data centers, battery manufacturing, and greenhouse farming.

4. Digital Twin Solutions in the Energy Industry: Identifying Technological Potential of Digital Twins

This section is based broad scoping review work based on key sources and key reviews of DTs in the energy sector [39-62]. In Table 4, we report special Digital Twins in the energy industry based on broad knowledge management assessments [39-62], and especially more focused assessments [63-67, 69-72].

Table 4. Special Digital Twin Solutions in the energy industry. Cross-technology production, Conventional power (thermal) generation, wind energy, solar energy,

hydropower production, geothermal, nuclear, hybrid and multi-energy production, industrial co-generation, and waste-to-energy production.

Special Field of Energy Technology	**Digital Twins**
Cross-Technology Production of the Energy Industry	Plant-Level Operational Digital Twin Process Control Digital Twin Predictive Maintenance Twin Energy Efficiency & Optimisation Twin Asset Health Management Twin Safety & Risk Simulation Twin Emissions Monitoring and Compliance Twin Fuel Supply and Feedstock Flow Twin Digital Worker/Training Twin (AR/VR-enabled) Integrated Power-Heat-Steam Production Twin (CHP/Cogeneration)
Conventional (Thermal) Power Generation:	Boiler/Combustion Digital Twin Steam Cycle Digital Twin Turbine Digital Twin (gas or steam) Heat Recovery Steam Generator (HRSG) Twin Flue Gas Cleaning & Emission Control Twin Cooling Tower & Heat-Exchanger Twin Fuel Handling and Feed System Twin Biomass Combustion and Gasification Twin
Wind Energy Production	Wind Turbine Structural Twin Gearbox and Drivetrain Twin Blade Aerodynamics and Fatigue Twin Generator and Inverter Twin Wind Farm Wake-Flow Digital Twin Turbine Performance & Power Curve Twin Offshore Platform Structural Twin Environmental Load and Wave-Impact Twin (offshore)
Solar Energy Production	PV Module Degradation Twin Inverter and Power Electronics Twin Tracker System Digital Twin (single/dual axis) Solar Thermal Plant Twin (CSP, tower, trough) Thermal Storage Twin (molten salt, phase-change materials) Plant-Level PV Yield Forecasting Twin
Hydropower Production:	Turbine Dynamics Twin (Francis, Kaplan, Pelton) Hydraulic Flow and Cavitation Twin Dam and Structural Integrity Twin Reservoir Management and Water-Flow Twin Pumped Storage Cycle Twin Sedimentation and Erosion Twin
Geothermal Energy Production	Subsurface Reservoir Twin Wellbore and Drilling Twin Geothermal Heat-Exchange Twin Binary Cycle (ORC) Twin Reinjection Strategy Twin
Nuclear Energy Production	Reactor Core Simulation Twin Fuel Rod and Cladding Twin Cooling Circuit and Thermal-Hydraulics Twin Containment Safety and Stress Twin Radiation Shielding and Monitoring Twin Spent Fuel Handling Twin

Hybrid and Multi-Energy Production	Hybrid Plant Dispatch Optimisation Twin Integrated Wind–Solar–Storage Twin Microgrid Production Twin Power-to-X Production Twin (hydrogen, ammonia, e-fuels) Thermal + Electric Co-Production Twin (industry parks)
Industrial Co-Generation and Waste-to-Energy	CHP (Combined Heat and Power) Production Twin Waste-to-Energy Combustion Twin Industrial Steam Production Twin Biogas Digestion and Upgrading Twin

To sum up our investigations, we were able to identify (1) DTs of Cross-Technology Production, (2) DTs of Conventional (Thermal) Power Generation, (3) DTs of Wind Energy Production, (4) DTs of Solar Energy Production Digital Twins, (5) DTs of Hydropower Production, (6) DTs of Geothermal Energy Production, (7) DTs of Nuclear Energy Production, (8) DTs of Industrial Co-Generation and Waste-to-Energy, (9) DTs of Hybrid and Multi-Energy Production and DTs in Industrial Co-Generation and Waste-to-Energy.

5. Digital Twin Solutions of the Energy Industry for Three Business Ecosystems

Now we can link potential strategic Digital Twins of the energy industry to three business ecosystems, Data Center, Battery, and Greenhouse farming business. In Table 5, we report our preliminary results of our KM investigations and arguments concerning relevance based on Tables 6-8.

Table 5. Digital Twins relevant for three business ecosystems: Data Center BE, Battery BE, and Greenhouse BE.

Business ecosystem	**The most relevant Digital Twins**	**Arguments**
Data Centre BE	- Plant-Level Operational Twin - Energy Efficiency Twin - Cooling System Twin(s) - Microgrid Twin -Energy Efficiency & Optimisation Twin -Predictive Maintenance Twin -Microgrid Production Twin -Cooling Tower & Heat-Exchanger Twin -Wind–Solar–Storage Integration Twin	See Table 1. Energy reliability and cooling optimisation- Energy efficiency Resiliency of energy system Optimal dispatch Minimal cooling cost Renewable share %

Table 6. Digital Twins relevant for three business ecosystems: Battery BE.

Business ecosystem	**The most relevant Digital Twins**	**Arguments**
Battery BE	- Process Control Twin - Predictive Maintenance Twin - Asset Health Twin - Emissions Twin - Safety Twin	*See Table 2.* Manufacturing efficiency and safe operations-

	-Energy Efficiency & Optimisation Twin -Predictive Maintenance Twin -Emissions Monitoring & Compliance Twin -Digital Worker / Training Twin -Microgrid Production Twin -Hybrid Plant Dispatch Twin -Boiler/Combustion Twin -Cooling Tower & Heat-Exchanger Twin	Energy efficiency Resiliency of energy system Emission control Workforce training Optimal dispatch Cost optimisation Minimal heat cost Minimal cooling cost

Table 7. Digital Twins relevant for three business ecosystems: Greenhouse Farming BE.

Business ecosystem	**The most relevant Digital Twins**	**Arguments**
Greenhouse Farming BE	- Process Control Twin - Energy Efficiency Twin - Operational Twin -Energy Efficiency & Optimisation Twin -Predictive Maintenance Twin -Asset Health Management Twin -Safety & Risk Simulation Twin -Microgrid Production Twin -Hybrid Plant Dispatch Twin -Boiler/Combustion Twin -Cooling Tower & Heat-Exchanger Twin -Wind–Solar–Storage Integration Twin	*See Table 3.* Climate control with minimum energy input Energy efficiency Resiliency of energy system Optimal dispatch Cost optimisation Minimal heat cost Minimal cooling cost Renewable share %

The most specific Digital Twins for three business ecosystems are reported in Table 8.

Table 8. The most specific Digital Twins for three business ecosystems

Business ecosystems	**Most specific Digital Twins**
Data Centers	Cooling Tower & HX Twin, Microgrid Twin
Battery	Emissions & Safety Twins
Greenhouse farming	AR/VR Training Twin for operators

These three specific Digital Twins are, of course, strategically critical Digital Twins of the energy industry.

6. Future research avenues

Future research should focus on using AI to make digital twins smarter by blending physics-based models with data-driven insights, so they can predict, control, and spot problems in energy systems more reliably. Digital twins can also give full lifecycle visibility by connecting design, daily operations, and end-of-life, while tracking materials and energy use to support practical circular decisions. They enable a shift to service-based business models—such as predictive maintenance and guaranteed energy performance—through continuous monitoring, remote optimization, and control aligned with service level agreements. At the same time, we need to address the risk that optimising a single subsystem can undermine the performance of the whole. To avoid those "local wins, global losses," future work should build ecosystem-aware Digital Twins that coordinate flows across multiple energy sources and interfaces and consider market interactions, so decisions made in one part of the system do not create unintended downsides elsewhere.

7.Conclusions

Digital Twins are mainly context-dependent but also include strong cross-industry commonalities. To guarantee knowledge-based management, we defined three innovation and business ecosystems, Data Centers BE, Battery production BS, and Greenhouse farming BE. Digital Twin solutions are and will be critical in energy storage and battery production, data centers, and greenhouse farming production because they combine real-time data, system modeling, and predictive analytics. In all three critical systemic domains, even small improvements in optimization can lead to significant savings in energy, cost, and resources and improve resiliency. The key contribution of this study is to combine business ecosystem analyses into the comprehensive knowledge-based mapping of Digital Twins of the energy industry. For Battery and Data Center BEs, relevant categories are Conventional power generation DTs, Renewable energy power generation DTs, Transmission systems DTs, Distribution systems DTs, Energy storage DTs, Industrial energy systems DTs, Buildings & district energy DTs, and Cross-sector applications DTs. For Greenhouse Farming BEs, the most relevant categories are in most cases all the energy DT categories, but context-dependent variations on local conditions and energy pricing structures. Key results of special relevant DTs of the energy industry were reported in Tables 6-8.

References

[1] Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), Transdisciplinary perspectives on complex systems: New findings and approaches (pp. 85–113). Springer. https://doi.org/10.1007/978-3-319-38756-7_4 [link.springer.com]

[2] Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA (p. 1818)

[3] Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the digital twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

[4] Rasheed A, San O, Kvamsdal T: Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access. 2020; 8:21980–22012. https://doi.org/10.48550/arXiv.1910.017

[5] Yu, W., Patros, P., Young, B., Klinac, E., Walmsley, T.G. (2022). Energy digital twin technology for industrial energy management: Classification, challenges, and future. Renewable and Sustainable Energy Reviews. Vol. 161, article 112407- https://doi.org/10.1016/j.rser.2022.112407

[6] Ismail, F.B., Al-Faiz, H., Hasini, H., Al-Bazi, A., & Kazem, H.A. (2024). A comprehensive review of the dynamic applications of digital twin technology across

diverse energy sectors. Energy Strategy Reviews, 52, article 101334. https://doi.org/10.1016/j.esr.2024.101334
[7] Ghenai, C., Husein, L. A., Al Nahlawi, M., Hamid, A.K., Bettayeb, M. (2022). Recent trends of digital twin technologies in the energy sector: A comprehensive review. Sustainable Energy Technologies and Assessments. Vol. 54, article 102837. https://doi.org/10.1016/j.seta.2022.102837
[8] Ba, L., Tangour, F., El Abbassi, I., & Absi, R. (2025). Analysis of Digital Twin applications in energy efficiency: A systematic review. Sustainability, 17(8), 3560. https://doi.org/10.3390/su17083560
[9] Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415. https://doi.org/10.1109/TII.2018.2873186
[10] Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. IEEE Access, 8, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358 [ieeexplore.ieee.org]
[11] Pivoto, Diego G.S., de Almeida, Luiz. F.F. da Rosa Righi, R., Rodrigues, J. J.P.C., Lugli, A.B. & Alberti, A.M. (2023). Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. Journal of Manufacturing Systems. Vol. 58, 176-192. https://doi.org/10.1016/j.jmsy.2020.11.017
[12] Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic construction digital twin: directions for future research. Automation Construct. 114:103179. doi: 10.1016/j.autcon.2020.103179
[13] McKinsey & Company. (2019). How the best companies create value from their ecosystems. https://www.mckinsey.com/~/media/McKinsey/Industries/Financial%20Services/Our%20Insights/How%20the%20best%20companies%20create%20value%20from%20their%20ecosystems/How-the-best-companies-create-value-from-their-ecosystems-final.ashx
[14] Thomas, L. D. W., & Autio, E. (2020). Thomas, L. D. W., & Autio, E. (2020). Innovation ecosystems in management: An organizing typology. Oxford Research Encyclopedia of Business and Management. https://doi.org/10.1093/acrefore/9780190224851.013.203
[15] Schumpeter, J. A. (1943/2003). Capitalism, socialism and democracy (reprinted.). London: Routledge.
[16] Moore, J. F. (1993). Predators and prey: A new ecology of competition. Harvard Business Review, 71(3), 75–86.
[17] Moore, J. F. (2016). The death of competition: Leadership and strategy in the age of business ecosystems. New York, NY: HarperCollins
[18] Malerba, F., & Orsenigo, L. (1995). Schumpeterian patterns of innovation. Cambridge Journal of Economics, 19(1), 47–65.
[19] Georghiou, L., Smith, K., Toivanen, O., & Ylä-Anttila, P. (2003). Evaluation of the Finnish innovation support system (Publications of the Ministry of Trade and Industry, 5/2003). Helsinki: Ministry of Trade and Industry.
[20] Nenonen, S., & Storbacka, K. (2020). Don't adapt shape! Use the crisis to shape your minimum viable system – And the wider market. Industrial Marketing Management, 88, 265–271
[21] Adner, R. (2017). Ecosystem as structure: An actionable construct for strategy. Journal of Management, 43(1), 39–58.
[22] Thomas, L. D. W., & Autio, E. (2020). Innovation ecosystems in management: An organizing typology. Oxford Research Encyclopedia of Business and Management.
[23] Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. International Journal of Social Research Methodology, 8(1), 19–32. https://doi.org/10.1080/1364557032000119616
[24] Levac D, Colquhoun H. & O'Brien KK. (2010). Scoping studies: advancing the methodology. Implement Science. Vol. 5, Issue 69. https://doi.org/10.1186/1748-5908-5-69.

[25] Peters MDJ, Marnie C, Tricco AC, Pollock D, Munn Z, Alexander L, McInerney P, Godfrey, C.M., Khalil H. (2020). Updated methodological guidance for the conduct of scoping reviews. JBI Evid Synth. 18(10):2, 119–2126. https://doi.org/10.11124/JBIES-20-00167
[26] Leon, E. C., & Harmon, R. R. (2016). Cloud as a Service: Understanding the Service Innovation Ecosystem. CERN Document Server (European Organization for Nuclear Research).
[27] Athavale et al., (2024). Digital Twins for Data Centers. Computer, Vol. 57, No. 10, 151-158, Oct. 2024, doi: 10.1109/MC.2024.3436945.
[28] 360iResearch. (2024). Global Data Center Services Market 2024. 360iResearch. https://www.360iresearch.com/library/intelligence/data-center-services.
[29] Cushman & Wakefield. (2023). 2023 Global Data Center Market Comparison.
[30] DCP (Datacentrepricing). (2022). Data Center Nordics—2022 to 2026. Tariff Consultancy Ltd. http://www.datacentrepricing.com/product
[31] International Energy Agency (2025). Energy and AI. World Energy Outlook Special Report. Executive summary and report. https://iea.blob.core.windows.net/assets/601eaec9-ba91-4623-819b-4ded331ec9e8/EnergyandAI.pdf
[32] Tan, X., Jiao, J., Jiang, M., Chen, M., Wang, W., & Sun, Y. (2024). Digital policy, green innovation, and digital-intelligent transformation of companies. Sustainability, 16(16), 6760–6760. https://doi.org/10.3390/su16166760[27] Leon, E. C., & Harmon, R. R. (2016). Cloud as a Service: Understanding the Service Innovation Ecosystem. CERN Document Server (European Organization for Nuclear Research).
[33] Tan, X., Jiao, J., Jiang, M., Chen, M., Wang, W., & Sun, Y. (2024). Digital policy, green innovation, and digital-intelligent transformation of companies. Sustainability, 16(16), 6760–6760. https://doi.org/10.3390/su16166760
[34] Thielmann, A., Christoph, N., Hettesheimer, T., Thomas, S., Annegret, S., Weymann, L., Wicke, T., Stephan, M., Krauß, K., & Unav. (2023). Sustainability pathways in a future European battery ecosystem. https://doi.org/10.24406/publica-2294
[35] Dehaine, Q., Michaux, S. P., Pokki, J., Kivinen, M., & Butcher, A. R. (2020). Battery minerals from Finland: Improving the supply chain for the EU battery industry using a geometallurgical approach. Zenodo (CERN European Organization for Nuclear Research). https://doi.org/10.5281/zenodo.3938855
[36] Tong, X., Zhang, X., Fensholt, R., Jensen, P. R. D., Li, S., Larsen, M. N., Reiner, F., Tian, F., & Brandt, M. (2024). Global area boom for greenhouse cultivation revealed by satellite mapping. Nature Food, 5(6), 513–523. https://doi.org/10.1038/s43016-024-00985-0
[37] van Tuyll van Serooskerken, A., Boedijn, A. T., Brunsting, M., Barbagli, T., Blok, C., & Stanghellini, C. (2022). Quantification of material flows: A first step towards integrating tomato greenhouse horticulture into a circular economy. Journal of Clean-er Production, 379, 134665. https://doi.org/10.1016/j.jclepro.2022.134665
[38] Xue, L., Cao, Z., Scherhaufer, S., Östergren, K., Cheng, S., & Liu, G. (2021). Mapping the EU tomato supply chain from farm to fork for greenhouse gas emission miti-gation strategies. Journal of Industrial Ecology, 25(2), 377–389. https://doi.org/10.1111/jiec.13080
[39] Amaral, J. V. S. do, Santos, C. H. dos, Montevechi, J. A. B., & de Queiroz, A. R. (2023). Energy Digital Twin applications: A review. Renewable and Sustainable Energy Reviews, 188, 113891–113891. https://doi.org/10.1016/j.rser.2023.113891
[40] Hwang, J., Kim, J., & Yoon, S.-M. (2025). DT-BEMS: Digital twin-enabled building energy management system for information fusion and energy efficiency. Energy, 326, 136162–136162. https://doi.org/10.1016/j.energy.2025.136162
[41] Heluany, J.B. & Gkioulos, V. (2024). A review on digital twins for power genera-tion and distribution. International Journal of Infrastructure. Security, 23, 1171–1195. https://doi.org/10.1007/s10207-023-00784-x

[42] Alao, K.T., Gilani, S.I., Sopian, K. et al. (2024). A review on digital twin application in photovoltaic energy systems: challenges and opportunities. JMST Adv. 6, 257–282 (2024). https://doi.org/10.1007/s42791-024-00083-z
[43] Huang, Q., Zeng, W., Liu, J., Zhang, Z., Deng, J., Qiu, Z., Xu, L., Wei, Z., Lu, Q., Gong, L, Shi, C., Zhong, X. (2025). Shaping the future of nuclear reactors with digi-tal twins: Current developments and perspectives. Applied Energy. Vol. 402, article 126922. https://doi.org/10.1016/j.apenergy.2025.126922
[44] Bhatti, G., Mohan, H. & Raja Singh, R. (2021). Towards the future of smart electric vehicles: Digital twin technology. Renewable and Sustainable Energy Reviews. Vol. 141 Article 110801. https://doi.org/10.1016/j.rser.2021.110801
[45] Kandemir, E., Hasan, A., Kvamsdal, T. et al. (2024). Predictive digital twin for wind energy systems: a literature review. Energy Informatics, Vol. 7, 68, 1-36. https://doi.org/10.1186/s42162-024-00373-9
[46] Mantilla-Guerra, A., Mejia-Escobar, C., Azorin-Lopez, J., Jose Garcia-Rodriguez, J-G. (2025). Methodological Framework for the Creation of Digital Twins for Photovoltaic Power Plants Advances in Computational Intelligence: 18th International Work-Conference on Artificial Neural Networks, IWANN 2025, A Coruña, Spain, June 16–18, 2025, Proceedings, Part I, pp. 575 – 585. https://doi.org/10.1007/978-3-032-02725-2_45
[47] Mbasso, W.F., Harrison, A., Dagal, I., Jangir, P., Khishe, M., Kotb, H., Shaikh, M.S., Smerat, A., Fendzi Donfack, E. &Kumar, R. (2025) Digital twins in renewable energy systems: A comprehensive review of concepts, applications, and future directions. Energy Strategy Reviews. Vol. 61, article 101814. https://doi.org/10.1016/j.esr.2025.101814
[48] Cvetkovic, M., Palensky, P., Joseph, A. & Digvijay Gusain, D. (2022). Digital twins and their use in future power systems. (2022). Digital Twin, 1, 4. https://doi.org/10.12688/digitaltwin.17435.2, https://digitaltwin1.org/articles/1-4/v2
[49] Batty M: Digital twins. Environment and Planning B: Urban Analytics and City Science. 2018; 45(5): 817–820.
[50] Zhi, H., Mao, R., Hao, L., Chang, X., Guo, X., & Ji, L. (2024). Digital Twin for modern distribution networks by improved state estimation with consideration of bad date identification. Electronics 13, no. 18. article 3613. https://doi.org/10.3390/electronics13183613
[51] Shen, C.; Cao, Q.; Jia, M.; Chen, Y.; Huang, S. (2022). Concepts, characteristics and prospects of application of Digital Twin in power system. Proceedings of the Chinese Society for Electrical Engineering, CSEE North_East, Volume 42 (2), 487– 498. https://doi.org/10.13334/j.0258-8013.pcsee.211594 north_east
[52] Semeraro, C., Olabi, A.G., Aljaghoub, H., Alami, A.H., Al Radi, M., Dassisti, M. & Abdelkareem, M.A. (2023). Digital twin application in energy storage: Trends and challenges. Journal of Energy Storage Vol. 58 Article 106347. https://doi.org/10.1016/j.est.2022.106347
[53] Semeraro, Concetta, A., Haya, A., Mohammad Ali, A., Abdul, H. & Olabi, A.G. (2023). Digital twin in battery energy storage systems: Trends and gaps detection through association rule mining. Energy. Vol. 273. Article 127086. https://doi.org/10.1016/j.energy.2023.127086
[54] Belo, R.C., Pimenta, M.S., Salvador, T.T., Petry, R. H. &Abel, M. (2025). Fundamental requirements of Digital Twins for production system in Oil and Gas Industry: A systematic literature review. Information and Software Technology Vol. 184. Article 107742. https://doi.org/10.1016/j.infsof.2025.107742
[55] Yu, W., Patros, P., Young, B.. Klinac, E. & Walmsley, T.G. (2022). Energy digital twin technology for industrial energy management: Classification, challenges and future. Renewable and Sustainable Energy Reviews. Vol- 161. Article 112407. https://doi.org/10.1016/j.rser.2022.112407
[56] de las Morenas, J., Belmonte, L.M., Morales, R. (2025). Designing an AI-driven digital twin architecture for building energy prediction. Journal of Building Engineering. Vol. 113. Article 113966, https://doi.org/10.1016/j.jobe.2025.113966

[57] Cespedes-Cubides, A.S. & Jradi, M. (2024). A review of building digital twins to improve energy efficiency in the building operational stage. Energy Inform 7, 11 (2024). https://doi.org/10.1186/s42162-024-00313-7
[58] Arsecularatne, B., Rodrigo, N., & Chang, R. (2024). Digital Twins for Reducing Energy Consumption in Buildings: A Review. Sustainability, 16(21), 9275. https://doi.org/10.3390/su16219275
[59] Bibri, Simon Elias & Huang, J. (2025). AI and AI-powered digital twins for smart, green, and zero-energy buildings: A systematic review of leading-edge solutions for advancing environmental sustainability goals. Environmental Science and Ecotech-nology. Vol. 28. Article 10062. https://doi.org/10.1016/j.ese.2025.100628
[60] Wang C, Lee B, Shirowzhan S, Zhao Y, Wang N, Liu Z, Mu E (2022) Construc-tion theory for a building intelligent operation and maintenance system based on digital twins and machine learning. Buildings 12(2):87. https://doi.org/10.3390/BUILDINGS12020087
[61] Volk R, Stengel J, Schultmann F (2013) Building Information Modeling (BIM) for existing buildings-Literature review and future needs. Automation in Construction. Volume 38, March 2014, 109-127. https://doi.org/10.1016/j.autcon.2013.10.023
[62] Palley, B., Poças Martins, J., Bernardo, H., & Rossetti, R. (2025). Integrating Ma-chine Learning and Digital Twins for Enhanced Smart Building Operation and Energy Management: A Systematic Review. Urban Science, 9(6), 202. https://doi.org/10.3390/urbansci9060202
[63] Huang, Q., Zeng, W., Liu, J., Zhang, Z., Deng, J., Qiu, Z., Xu, L., Wei, Z., Lu, Q., Gong, L, Shi, C., Zhong, X. (2025). Shaping the future of nuclear reactors with digi-tal twins: Current developments and perspectives. Applied Energys. Vol. 402, article 126922. https://doi.org/10.1016/j.apenergy.2025.126922
[64] Bhatti, G., Mohan, H. & Raja Singh, R. (2021). Towards the future of smart electric vehicles: Digital twin technology. Renewable and Sustainable Energy Reviews. Vol. 141 Article 110801. https://doi.org/10.1016/j.rser.2021.110801
[65] Mazzetto, S. (2024). A Review of Urban Digital Twins Integration, Challenges, and Future Directions in Smart City Development. Sustainability, 16(19), 8337. https://doi.org/10.3390/su16198337
[66] Nedaei, A., Aghaei, M., Eskandari, A., Maurer, F., Cali, U. (2025) Digital twins for hydropower applications. Chapter 10. In Moazami, Amin, Lobaccaro, Gabriele & Cali, Umit (eds). Digital Twin Technology for the Energy Sector. Elsevier, pp. 213-234. https://doi.org/10.1016/B978-0-443-14070-9.00010-X
[67] Hashemi, L., Palochis, D., Poort, J., Octaviano, R. & Pejman Shoeibi Omrani 2025). Advancing geothermal operations with Digital Twin technology: Proactive monitoring and optimization. Paper presented at the SPE Europe Energy Confer-ence and Exhibition, Vienna, Austria, June 2025. https://doi.org/10.2118/225592-MS
[68] Bibri, S. E., & Huang, J. (2025). AI and AI-powered digital twins for smart, green, and zero-energy buildings: A systematic review. Environmental Science and Eco-technology, 28, 100628. https://doi.org/10.1016/j.ese.2025.100628
[69] Cvetkovic, M., Palensky, P., Joseph, A., & Gusain, D. (2022). Digital twins and their use in future power systems. Digital Twin, 1(4). https://doi.org/10.12688/digitaltwin.17435.2
[70] Kandemir, E., Hasan, A., Kvamsdal, T., et al. (2024). Predictive digital twin for wind energy systems: A literature review. Energy Informatics, 7, 68. https://doi.org/10.1186/s42162-024-00373-9
[71] Palley, B., Poças Martins, J., Bernardo, H., & Rossetti, R. (2025). Integrating machine learning and digital twins for enhanced smart building operation and energy management: A systematic review. Urban Science, 9(6), 202. https://doi.org/10.3390/urbansci9060202
[72] van Tuyll van Serooskerken, A., Boedijn, A. T., Brunsting, M., Barbagli, T., Blok, C., & Stanghellini, C. (2022). Quantification of material flows: A first step towards integrating tomato greenhouse horticulture into a circular economy. Journal of Cleaner Production, 379, 134665. https://doi.org/10.1016/j.jclepro.2022.13466