TWINRD
ECODIGITAL FUTURES

MACROECONOMIC
MODELLING
OF R&D
FOR THE TWIN
TRANSITION

D5.1 | Twin transition: concept and challenges

Author(s)	**Carlo Sessa (ISINNOVA), Daniel Cassolà (ISINNOVA), Valentina Malcotti (ISINNOVA)**
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Coordinator	**Leonidas Paroussos (E3-Modelling)**
E-mail	**paroussos@e3modelling.com**

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Executive Summary

This deliverable establishes the foundational understanding required for modelling Europe's twin transition by comprehensively reviewing EU twin transition strategy documents, assessing critical gaps in current macroeconomic models, and developing conceptual frameworks for capturing the interdependencies between green and digital R&I activities.

Key Findings

- *Policy Integration*: EU policy analysis reveals that green and digital transitions must be deeply intertwined rather than parallel processes. Current frameworks exhibit fragmentation, skill development gaps, and limited integration of demand-side measures. Macroeconomic models must capture green-digital interdependencies.
- *Technology Flows*: Patent-based technology flow matrices (2020-2021) distinguish 'new digital' (AI, big data, autonomous systems) from 'old digital' technologies, revealing significant green-digital overlap and concentrated knowledge flows within and between technology types across NACE sectors.
- *Modelling Gaps*: Current models inadequately represent innovation system dynamics, knowledge spillovers, physical/material constraints, financing frictions, labour market heterogeneity, and regional differentiation. R&I policy impacts—particularly innovation directionality and time lags—are poorly captured.
- *Sectoral Trajectories*: Foresight analysis maps innovation timelines to 2050 across agriculture, construction, energy, and transport, integrating digital enablers and green technologies to inform scenario development and stakeholder engagement.
- *Regenerative Framework*: Beyond sustainability and circular economy, the regenerative paradigm aims for net-positive environmental and social impacts through 'handprint' creation. This framework enables scenarios from incremental efficiency to transformative deep decarbonization toward Net-Zero and Net-Positive outcomes.
- *Measurement Approach*: Methodologies for environmental handprint assessment, systemic economic health indicators (efficiency-resilience balance), and the Doughnut Economics framework provide comprehensive tools for evaluating twin transition scenarios within safe planetary boundaries and social foundations.

Impact

This analysis directly informs enhancement of GEM-E3 and NEMESIS models and development of the TWINRD model by: establishing requirements for capturing green-digital interdependencies through technology flow matrices; identifying critical enhancements for realistic R&I policy representation; providing empirical technology flow data and sectoral innovation trajectories as model inputs; defining scenario frameworks from incremental improvements to transformative regenerative transitions; and articulating measurement frameworks evaluating environmental, economic, social, and systemic health dimensions. These foundations support subsequent TWINRD work on model enhancement, stakeholder co-designed scenarios, and policy-relevant analysis of Europe's twin transition pathways.

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List of Acronyms and Abbreviations

AI	Artificial Intelligence
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium
D	Deliverable (project reports or outputs)
EC	European Commission
EPO	European Patent Office
ERDF	European Regional Development Fund
ESF+	European Social Fund Plus
ETS	Emissions Trading System
EU	European Union
FP10	10th Framework Programme
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GPT	General Purpose Technology
IAM	Impact Assessment Model
ICT	Information and Communication Technology
JRC	Joint Research Centre
JTF	Just Transition Fund
MFF	Multiannual Financial Framework
NACE	Statistical Classification of Economic Activities in the European Community
NGO	Non-Governmental Organization
NZIA	Net-Zero Industry Act
OI	Other Intangibles
PDF	Portable Document Format
PV	Photovoltaics
RRF	Recovery and Resilience Facility
R&D	Research and Development
R&I	Research and Innovation
WIPO	World Intellectual Property Organization
WP	Work Package
5G	Fifth Generation of cellular network technology

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Introduction

TWINRD is set to transform Europe’s macroeconomic modelling to support the Twin Transition, focusing on harmonizing sustainable economic development with digital progress. Current models employed at the EU level, although supportive of strategic planning in sustainable research and innovation (R&I), often fail to capture the extensive scope of R&I activities, especially in emerging green and digital technologies.

To address these gaps, TWINRD (**macroeconomic modelling of R&D for the Twin Transition**) aims to enhance existing models like GEM-E3 and NEMESIS by integrating innovative and interdisciplinary approaches that more accurately represent R&I policies. This will include the introduction of new data and technology classifications, specifically improving the modelling of green and digital technologies and refining tools to evaluate the impacts of R&I policies on socio-economic and environmental outcomes.

In commitment to openness and collaboration, TWINRD will make all models and resources developed freely available on its online platform, encouraging transparency and community engagement. The TWINRD’s Open Stakeholder Forum will facilitate active stakeholder interaction and inclusive dialogue, co-designing research and scenarios to ensure findings are comprehensive and actionable both for the scientific community and policymakers.

Over three years, TWINRD brings together four leading research institutes and SMEs with extensive expertise in economic modelling and the R&I sector. This collaboration spans applied and research-oriented environments, including systems analysis and data management, ensuring a multidisciplinary approach to achieving the project’s goals.

This deliverable includes:

- a review the key EU twin transition strategy documents in Section 1;
- a taking stock overview of existing macro-economic modelling of R&D and innovation approaches, with a special focus on those used in TWINRD (GEM-E3 and NEMESIS), in Section 2;
- existing evidence about the potential future impact of key green and digital technologies, taking stock of the most comprehensive green and digital transitions foresight exercise identified after scanning the relevant literature - namely the JRC Report - (for the relevant literature see further references in the annex), in section 3;
- an overview of the concept of regenerative transitions beyond sustainability, introduced in section 4 tacking stock of the literature on circular (restorative) and regenerative business innovation models. This is useful to suggest later a framework of alternative twin transition scenarios to be discussed with the stakeholders involved in the WP6 strategic foresight workshops.

1. Review of Twin Transition relevant EU Strategy Documents

This chapter provides a comprehensive review of key EU strategy documents that shape Europe's twin transition toward sustainability and digitalization. Each major policy framework is examined not only in terms of its explicit objectives and instruments, but also through the lens of critical cross-cutting dimensions that determine the success and equity of the transition: skills and employment transformation, technology and industrial development, regional and spatial impacts, and consumer behaviour dynamics.

Understanding these policy contexts and their multidimensional implications is essential for developing enhanced macroeconomic models that can accurately assess the socioeconomic and environmental impacts of research and innovation policies supporting the twin transition.

1.1. European Green Deal policy framework

The European Green Deal[1], launched by the European Commission in December 2019 under President von der Leyen, constitutes the European Union's flagship growth strategy and comprehensive policy framework to transform Europe into the first climate-neutral continent by 2050. This ambitious initiative responds directly to the Paris Agreement commitments, establishing binding targets to limit global warming to a maximum of 1.5°C above pre-industrial levels.

The framework sets intermediate targets of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, with the ultimate 2050 climate neutrality goal enshrined in the European Climate Law (Regulation EU 2021/1119). The Green Deal encompasses policies across energy, industry, transport, agriculture, buildings, and taxation and positions itself as a comprehensive strategy to create a fair and prosperous society with a modern and competitive economy, emphasizing that all policy areas must contribute to climate change mitigation.

Funding and budget allocation

The European Green Deal is supported by substantial financial resources mobilized through various EU funding mechanisms for the period 2021-2027, which corresponds to the EU's Multiannual Financial Framework (MFF) — the seven-year budget cycle that sets the financial planning and spending limits for the European Union. The Recovery and Resilience Facility (RRF) constitutes the largest funding instrument with a budget of €672.5 billion (in grants and loans), of which at least 37% must be dedicated to the green transition, representing approximately €249 billion. Cohesion Policy, with a total EU allocation of €392 billion, dedicates approximately €120 billion to climate action and green investments, encompassing support from the European Regional Development Fund (ERDF), Cohesion Fund, Just Transition Fund (JTF), and European Social Fund Plus (ESF+). The ESF+ provides €99.3 billion for 2021-2027, with €5.8 billion specifically earmarked for green skills and jobs, supporting vocational training, upskilling, and reskilling initiatives. The JTF has a budget of €19.2 billion to support regions most affected by the transition to a low-carbon economy, financing economic diversification, worker reskilling, clean energy investments, and job creation in emerging green sectors. For the digital transformation specifically, the total budget for 2021-2027 is estimated at €207-208 billion.

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[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

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Skills and Employment Implications

The green transition profoundly affects labour markets through sectoral restructuring and changing skill requirements. Employment effects at the aggregate level are expected to be modest by 2030, as most EU jobs are in low-emission sectors. However, sectoral impacts are significant and varied. Electricity supply will see employment growth driven by renewable energy expansion. Construction faces transformation through building renovation and energy efficiency requirements. Manufacturing sectors, particularly energy-intensive industries such as steel, cement, and chemicals, require breakthrough technologies and associated skilled workforces for near-zero emissions production.

The transition creates substantial employment displacement in primary industries, particularly coal mining and fossil fuel extraction, concentrated in specific regions. These workers require comprehensive reskilling programs to transition toward green industries. Simultaneously, new green jobs emerge across renewable energy installation and maintenance, energy efficiency services, circular economy activities, and sustainable transport infrastructure.

Green skills encompass technical competencies for renewable energy technologies, energy efficiency, sustainable construction, waste management, and circular economy practices. Beyond technical knowledge, green skills include understanding of environmental regulations, climate risk assessment, sustainability reporting, and transversal competencies such as systems thinking and adaptability for implementing sustainable practices across sectors.

Industrial and Technological Transformation

The Green Deal drives industrial transformation across multiple dimensions. Energy-intensive industries must deploy breakthrough technologies including hydrogen-based steel production, carbon capture and utilization, and electrification of process heat. These technologies are at various stages of development and deployment, requiring sustained research and innovation support alongside market creation mechanisms.

Circular economy transition fundamentally reshapes industrial practices through design for durability and recyclability, industrial symbiosis where waste streams become input materials, and development of markets for secondary raw materials. This transition requires both technological innovation and business model transformation, supported by regulatory frameworks including extended producer responsibility and eco-design requirements.

The renewable energy sector drives demand for manufacturing capacity in solar panels, wind turbines, batteries, electrolyzers, and heat pumps. Building European manufacturing capacity in these strategic technologies balances reducing import dependencies with ensuring cost competitiveness, particularly given established production capacity in other global regions.

Regional and Spatial Dimensions

The Green Deal's territorial impacts are inherently uneven due to differential regional exposure to decarbonization requirements. Regions with high concentrations of carbon-intensive industries, particularly coal mining areas in Poland, Germany, Romania, and Bulgaria, face acute transition challenges including employment losses, reduced economic activity, and potential social disruption.

The Just Transition Mechanism provides targeted support to these vulnerable regions through the Just Transition Fund, enabling economic diversification, worker transitions, and community development. Rather than managing decline, the mechanism emphasizes creating opportunities in clean industries, attracting investment, and building on existing industrial capabilities. However, the scale of support relative to transition challenges remains subject to debate, with questions about adequacy of resources and coordination with other regional development instruments.

Regional variations in renewable energy potential create new patterns of advantage and disadvantage. Regions with strong wind or solar resources can become clean energy exporters, while regions lacking such resources face higher energy costs unless grid infrastructure enables efficient power transmission. Investment in transmission infrastructure and storage capacity therefore becomes critical for regional equity in the energy transition.

Consumer Behaviour and Demand-Side Dynamics

Achieving Green Deal objectives requires substantial shifts in consumer behaviour alongside supply-side transformation. Energy consumption patterns must evolve through adoption of energy-efficient appliances, renewable energy sources, and sustainable heating and cooling solutions. Policies combine regulatory measures including energy labelling and minimum efficiency standards with financial incentives and awareness campaigns.

Sustainable mobility transition depends on consumer adoption of electric vehicles, increased use of public transport, and behavioural shifts toward active mobility. Support mechanisms include purchase subsidies for electric vehicles, deployment of charging infrastructure, improvement of public transport services, and urban planning favouring sustainable mobility. However, upfront cost barriers, range anxiety, and charging convenience concerns persist as obstacles to consumer adoption, particularly for lower-income households and rural residents with limited public transport alternatives.

Circular consumption requires moving from linear 'take-make-dispose' patterns to circular models emphasizing product longevity, reuse, and recycling. Right to repair legislation aims to extend product lifetimes by ensuring availability of spare parts and repair information. Support for second-hand markets, sharing economy platforms, and product-as-a-service models promotes more resource-efficient consumption patterns. However, cultural attachments to ownership, concerns about quality of repaired or second-hand products, and convenience of disposal create behavioural barriers requiring sustained engagement and norm change.

Measurable Targets and Key Performance Indicators

The European Green Deal establishes binding targets of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, with the ultimate goal of climate neutrality by 2050 enshrined in the European Climate Law. The renewable energy share must reach at least 42.5% of the EU's energy mix by 2030, up from the previous 32% target, with an aspiration to reach 45%. The Net-Zero Industry Act (NZIA) sets a goal for at least 40% of the EU's annual deployment needs for strategic net-zero technologies to be manufactured domestically by 2030. For transport, all new cars and vans registered in Europe must be zero-emission by 2035, with intermediate targets of 55% emission reduction for new cars and 50%

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for new vans by 2030. Implementation of all Green Deal laws is projected to lead to doubling of renewable energy capacity, a two-fold increase in heat pump installations, and tripling of the building renovation rate per year compared to 2021, with at least 29 million electric vehicles expected on European roads by 2030.

Critical Challenges and Policy Gaps

Despite comprehensive policy frameworks, several challenges persist. Policy coordination across multiple domains creates complexity, with potential conflicts between environmental objectives and other policy goals. The proliferation of separate emissions trading systems covering different sectors creates coordination challenges inadequately represented in existing models. Technology deployment assumptions often fail to account for material constraints in critical raw materials, manufacturing capacity bottlenecks, and rebound effects where efficiency improvements generate increased consumption.

Governance architecture faces coordination challenges across horizontal policy domains, vertical governance levels from EU to regional, and temporal policy windows with different optimization horizons. Implementation cascades through EU, national, and regional levels with differential administrative capacities and political economies, complicating effective policy delivery.

1.2. Digital Strategy for Europe

The Digital Strategy for Europe, officially titled "Shaping Europe's Digital Future"[2], represents the European Union's comprehensive framework for digital transformation alongside the green transition. Launched in February 2020 as one of the European Commission's key priorities for 2019-2024, this strategy aims to make Europe fit for the digital age while ensuring that digital technologies benefit citizens, businesses, and society as a whole. The strategy is built on three pillars: technology that works for people, a fair and competitive digital economy, and an open, democratic, and sustainable digital society.

Funding and Budget Allocation

The Digital Strategy for Europe is supported by multiple funding mechanisms under the EU's MFF for 2021-2027. The Digital Europe Programme, with a budget of approximately €8.1 billion for 2021-2027, constitutes the dedicated funding instrument for building the EU's strategic digital capacities in areas such as supercomputing, artificial intelligence, cybersecurity, semiconductors, and advanced digital skills. This is complemented by digital investments across other EU programmes, including Horizon Europe (for research and innovation), the Connecting Europe Facility (for digital infrastructure), and Cohesion Policy funds, which allocate substantial resources to support digitalization, ICT connectivity, and smart economic transformation across EU regions. The RRF also significantly supports digital transformation alongside the green transition, as Member States are required to allocate substantial portions of their national recovery plans to digital investments.

Skills and Digital Competence Development

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[2] https://digital-strategy.ec.europa.eu/en

Digital skills represent both an enabler of individual opportunity and a critical factor in European competitiveness. The Digital Competence Framework for Citizens identifies five key competence areas: information and data literacy, communication and collaboration, digital content creation, safety, and problem solving. The target that 80% of the population should have at least basic digital skills by 2030 requires comprehensive efforts reaching diverse populations including older adults, people with disabilities, and socioeconomically disadvantaged groups.

Digital transformation profoundly affects job markets across most sectors, reducing demand for routine cognitive and manual tasks while increasing demand for non-routine analytical and interpersonal skills. Specialized digital skills for the digital economy are developed through vocational education and training, higher education programs, and lifelong learning opportunities. The shortage of ICT specialists, projected at millions across Europe, requires scaling up education in computing, software development, data science, cybersecurity, and emerging fields.

Digital literacy beyond technical skills includes critical evaluation of online information, understanding of algorithmic systems and their biases, awareness of digital business models and their implications for privacy, and ethical reflection on technology's societal impacts. Media literacy addressing disinformation, computational thinking, and digital civics understanding rights and responsibilities all contribute to informed digital citizenship.

Industrial Digitalization and Sectoral Transformation

Manufacturing transforms through Industry 4.0, with integration of Internet of Things, artificial intelligence, robotics, and digital twins requiring new technical and analytical skills. Digital technologies enable optimization, flexibility, and new business models. Digital twins for industrial processes, AI for energy optimization, platforms for industrial symbiosis, and blockchain for supply chain transparency all contribute to more efficient industrial operations.

Financial services transform through fintech innovations and digital banking, requiring combined financial and technical competencies. Retail evolves through digital platforms reshaping consumer markets and requiring digital marketing, logistics optimization, and customer analytics capabilities. Healthcare digitalization through telemedicine, electronic health records, and AI diagnostics creates new roles while transforming existing medical professions.

The ICT sector itself experiences rapid growth in software development, data analytics, cybersecurity, cloud services, and artificial intelligence development. These sectors concentrate in metropolitan regions with strong higher education institutions and innovation ecosystems, creating geographic patterns of digital economy development.

Digital Divide and Regional Disparities

Digital divides persist both between and within member states, across demographic groups, and between urban and rural areas. While connectivity and device access gaps narrow, usage gaps and skills gaps prove more persistent. Innovation-driven regions, particularly those specializing in knowledge-intensive services or high-tech manufacturing, are well-positioned

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to benefit from digital transformation. Regions with weaker industrial bases, lower innovation potential, and inadequate infrastructure risk falling further behind.

Urban and metropolitan areas generally show higher digital readiness compared to rural regions. Digital infrastructure gaps in broadband connectivity and 5G coverage create barriers to participation in the digital economy. The Digital Europe Programme addresses these gaps through investments in high-performance computing capabilities, artificial intelligence development and deployment, cybersecurity infrastructure, and digital skills development.

Ensuring that digital transformation benefits all Europeans rather than creating winners and losers requires sustained attention to inclusion, accessible design, and proactive measures supporting disadvantaged groups. Digital inclusion initiatives provide access to devices and connectivity, training opportunities, and ongoing support addressing various barriers to digital participation.

Digital Consumption and Platform Economy

Digital transformation fundamentally reshapes consumer behaviour and market structures. E-commerce and digital platforms transform shopping behaviour with implications for traditional retail employment and urban planning, logistics and delivery infrastructure, product selection and price transparency, and data privacy and consumer protection. Growing consumption of digital services affects media consumption patterns, social interaction, work-life balance with remote work capabilities, and digital literacy requirements.

Platform economy including online marketplaces, social networks, search engines, app stores, and sharing economy services concentrates significant economic power while creating new opportunities. European regulatory responses through the Digital Services Act and Digital Markets Act aim to ensure platform markets remain contestable and fair while preserving innovation and consumer benefits.

Consumer data becomes a valuable resource, raising issues of personal data protection and consent management, algorithmic transparency and fairness, digital identity and authentication, and cybersecurity. The General Data Protection Regulation establishes strong data protection rights, though implementation and enforcement challenges persist, particularly for cross-border digital services.

Measurable Targets and Key Performance Indicators

The Digital Strategy for Europe establishes that by 2030, at least 80% of all adults aged 16-74 should have at least basic digital skills, and there should be 20 million employed ICT specialists in the EU, with increased women's participation. As of 2023, only 56% of EU citizens had at least basic digital skills and only 10.3 million ICT specialists were employed. For business transformation, 75% of EU companies should use cloud computing, big data, or artificial intelligence by 2030, and more than 90% of SMEs should reach at least a basic level of digital intensity. Infrastructure targets include universal gigabit connectivity for all European households and 5G coverage in all populated areas by 2030. For public services, 100% online provision of key public services, 100% of EU citizens having access to their electronic health records, and 80% using digital ID solutions are targeted by 2030.

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Implementation Challenges

Balancing innovation and regulation remains a perpetual tension, with risks of either constraining beneficial innovation through excessive precaution or failing to address harms through regulatory gaps. Geopolitical competition in technology intensifies with implications for European autonomy and influence. Strategic dependencies on non-European providers for semiconductors, cloud infrastructure, and advanced digital technologies create vulnerabilities requiring building European capabilities while maintaining openness to global talent and markets.

1.3. REPowerEU Strategy

The REPowerEU[3] strategy represents the European Union's comprehensive response to the urgent need for energy security, independence, and accelerated clean energy transition. Launched in May 2022 in response to the global energy crisis triggered by geopolitical tensions and Russia's invasion of Ukraine, REPowerEU builds upon and accelerates the objectives of the European Green Deal while addressing immediate energy security concerns. This strategy fundamentally reshapes Europe's energy landscape by simultaneously reducing dependence on fossil fuel imports, particularly from Russia, and accelerating the transition to renewable energy sources.

Funding and Budget Allocation

REPowerEU mobilizes approximately €300 billion in investments to be deployed by 2030, with €210 billion targeted for implementation by 2027. The strategy is financed through multiple EU mechanisms, with the RRF at its core, providing €225 billion in loans that Member States can redirect toward REPowerEU objectives. An additional €20 billion in new grants has been allocated through revenues from the EU Emissions Trading System (ETS), sourced from the Innovation Fund and frontloaded ETS allowances. Member States can also access €5.4 billion through transfers from the Brexit Adjustment Reserve. The European Investment Bank significantly bolstered this effort by committing €45 billion in additional financing over five years (2022-2027), which is expected to mobilize over €150 billion in green investments.

Skills Requirements for Energy Transition Acceleration

Accelerated deployment of renewable energy and energy efficiency measures intensifies skills requirements across multiple occupations. Solar panel installation, wind turbine maintenance, heat pump installation and servicing, building energy retrofitting, and smart grid operation all face skills shortages constraining deployment rates. Training programs must rapidly scale to meet demand while maintaining quality standards ensuring safety and system performance.

The acceleration creates particular challenges for vocational education and training systems that typically require years to develop new programs and scale capacity. Fast-track training

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[3] https://www.consilium.europa.eu/en/policies/repowereu/

programs, recognition of prior learning, and industry-led certification schemes help address immediate needs while building longer-term educational capacity.

Industrial Capacity and Supply Chain Considerations

REPowerEU's accelerated timelines require rapid scaling of manufacturing capacity for renewable energy equipment, energy storage systems, and efficiency technologies. European manufacturing capacity for solar panels, wind turbines, batteries, and heat pumps must expand significantly to meet deployment targets while reducing import dependencies that create vulnerabilities.

Supply chain resilience becomes critical as accelerated deployment strains availability of components, materials, and skilled installation capacity. Critical raw materials for batteries, electrolyzers, and renewable energy technologies face supply constraints requiring diversification of sources, development of domestic extraction and processing where viable, and acceleration of recycling and circular economy approaches.

Regional Energy Security and Just Transition

REPowerEU's focus on energy security intersects with regional variations in energy system characteristics and transition challenges. Regions heavily dependent on fossil fuel imports face acute energy cost pressures, while regions with fossil fuel production face employment and economic impacts from accelerated phase-out. Ensuring that accelerated transition maintains social cohesion requires strengthened just transition support.

Regional variations in renewable energy potential become more significant under accelerated deployment scenarios. Grid infrastructure investments enabling power transmission from regions with high renewable potential to demand centres become critical for system integration and regional equity. Energy storage deployment requirements vary across regions depending on renewable energy profiles and demand patterns.

Measurable Targets and Key Performance Indicators

The EU Solar Strategy aims to double solar photovoltaic capacity to 320 GW by 2025 and install 600 GW by 2030. The renewable hydrogen target is set at 10 million tonnes of domestic production and an additional 10 million tonnes of imports by 2030. Heat pump deployment aims to double the current rate, reaching 10 million cumulative units over 2023-2027, with some estimates suggesting nearly 60 million total heat pumps installed in the EU by 2030. Biomethane production should reach 35 billion cubic metres per year by 2030. The EU needs to roll out close to 6 million new heat pumps each year from 2025 onwards to meet the 2030 climate target, more than doubling the annual deployment rate.

Consumer Engagement and Behavioural Adaptation

REPowerEU's success partially depends on consumer energy conservation and efficiency improvements. Awareness campaigns, price signals, and behavioural nudges encourage energy saving in immediate term. Longer-term building renovation, heat pump adoption, and electric vehicle uptake require sustained consumer engagement alongside financial support addressing upfront cost barriers.

Smart meters and demand response systems enable consumers to adjust consumption patterns in response to price signals and grid conditions, supporting system integration of variable renewable energy. However, consumer acceptance of dynamic pricing and automated control requires trust in technologies and clear understanding of cost and environmental benefits.

1.4. Green Industrial Plan

The Green Deal Industrial Plan for the Net-Zero Age[4] represents the European Union's strategic response to maintain and strengthen Europe's industrial competitiveness while accelerating the transition to climate neutrality. Announced in February 2023, this comprehensive industrial strategy addresses the imperative to ensure that European industry leads the global race toward net-zero emissions while securing quality jobs, economic prosperity, and technological sovereignty. The Plan addresses regulatory simplification, financing mobilization, skills development, and supply chain resilience; and emerges at a critical juncture when major economies worldwide are deploying substantial industrial policies and subsidies to attract clean technology investments, creating both competitive pressures and opportunities for European industry.

Funding and Budget Allocation

The Green Deal Industrial Plan does not constitute a standalone funded programme with a dedicated new budget. Instead, it mobilizes approximately €250 billion from existing EU funding mechanisms, primarily through redeployment and facilitated access to resources already allocated under the RRF, REPowerEU, InvestEU, the Innovation Fund (which has approximately €40 billion available over ten years for clean technology projects), and the European Investment Bank. Beyond EU-level financing, the Plan enables Member States to provide national support through relaxed state aid rules under the Temporary Crisis and Transition Framework, allowing governments to grant aid for green transition projects with simplified procedures.

Net-Zero Industry Skills and Workforce Development

Net-Zero Industry Academies provide training programs aligned with industry needs in manufacturing, installing, operating, and maintaining net-zero technologies. These academies bring together educational institutions, industry partners, and social partners to design curricula, deliver training, and certify competencies in areas such as heat pump installation, battery manufacturing, hydrogen technologies, and advanced renewable energy systems.

Upskilling and reskilling programs support workers transitioning from declining sectors to growing clean industries. Recognition of qualifications across borders facilitates labour mobility within the single market, allowing skills to flow where most needed. Attracting international talent in strategic areas complements domestic skills development.

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[4] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_en

Partnerships between industry and education strengthen the pipeline of skilled workers entering clean industries. Apprenticeship programs, dual education systems, and industry involvement in curriculum design ensure that training programs produce graduates with immediately relevant skills. Career awareness campaigns highlight opportunities in growing clean tech sectors.

Strategic Technology Value Chains

The plan identifies specific technology value chains as strategic priorities where Europe must build or maintain competitive advantages. Solar energy technology, wind energy particularly offshore, battery technologies for electric vehicles and energy storage, hydrogen technologies including electrolyzers and fuel cells, heat pump manufacturing, and carbon capture technologies all receive targeted support for capacity building within Europe.

Each technology value chain faces distinct challenges. Solar manufacturing must compete with established capacity elsewhere while leveraging advanced technologies and automation. Battery value chain development requires securing critical raw materials, scaling cell manufacturing, and developing recycling capabilities. Hydrogen technologies must demonstrate commercial viability while building manufacturing capacity in emerging market.

Industrial Clusters and Regional Specialization

Industrial clusters where multiple industries co-locate to share infrastructure, energy, and material flows enable economies of scale in clean energy supply, shared carbon capture infrastructure, and circular economy approaches. Dedicated support for cluster development includes coordination support, shared infrastructure investment, and regulatory facilitation.

Regional smart specialization strategies align with the Industrial Plan, enabling regions to identify and develop competitive advantages in clean technologies suited to their specific assets and capabilities. Some regions may specialize in particular technologies, others in components or services, creating a distributed but coordinated European industrial ecosystem. However, this approach risks reinforcing rather than addressing existing regional disparities if regions with weaker capabilities cannot identify viable specialization opportunities.

Social and Regional Equity Dimensions

Industrial regions heavily dependent on carbon-intensive industries receive targeted support through the Just Transition Mechanism, enabling economic diversification, worker transitions, and community development. Rather than simply managing decline, the approach emphasizes creating new opportunities in clean industries, attracting investment, and building on existing industrial capabilities.

Social dialogue and collective bargaining are promoted as mechanisms for managing industrial transitions respecting workers' rights and interests. Early anticipation of changes, comprehensive training opportunities, and income support during transitions help workers adapt successfully. Quality job creation in new clean industries emphasizes maintaining good working conditions, fair wages, and worker representation.

Measurable Targets and Key Performance Indicators

The NZIA sets a goal that the Union's overall strategic net-zero technologies manufacturing capacity approaches or reaches at least 40% of the EU's annual deployment needs by 2030. The Act includes streamlined permitting with time limits of maximum 18 months for construction or enlargement of net-zero technology projects over 1 GW, and 12 months for smaller projects, with even shorter timelines (9-12 months) for strategic projects. Carbon capture and storage targets include an annual injection capacity of at least 50 million tonnes of CO2 in storage sites located in the EU by 2030, expected to grow to 300 million tonnes by 2040. The NZIA also sets a non-binding benchmark for the EU to reach 15% of the global market value for net-zero technologies by 2040. Strategic net-zero technologies covered include solar panels, wind turbines, batteries, heat pumps, electrolyzers, fuel cells, carbon capture technologies, and sustainable alternative fuels.

1.5. Europe Fit for the Digital Age

A Europe Fit for the Digital Age[5] represents one of the six headline ambitions of the European Commission for 2019-2024, establishing digital transformation as a defining priority alongside and interconnected with the green transition. This comprehensive agenda encompasses the vision, policies, and initiatives through which the European Union seeks to shape its digital future in ways that reflect European values, empower citizens and businesses, and position Europe as a global leader in trustworthy, human-centric technology. Unlike purely technocratic approaches to digitalization, the European vision emphasizes that technology must serve people and society, respecting fundamental rights, promoting fairness, and contributing to sustainability and democratic values.

Funding and budget allocation

A Europe Fit for the Digital Age does not constitute a standalone funded programme but rather serves as an overarching framework that coordinates and guides digital transformation across multiple EU funding instruments. The priority is implemented through various programmes, including the Digital Europe Programme with €8.1 billion dedicated to strategic digital capacities (2021-2027), and the requirement that Member States allocate at least 20% of their RRF funds to digital priorities. Cohesion Policy contributed over €14 billion from the ERDF for digital investments during 2014-2020, with continued significant support in the 2021-2027 period. The European Chips Act, launched under this priority, has triggered over €115 billion in public and private investment plans to strengthen EU semiconductor manufacturing capacity. Additionally, the EU set a goal of investing more than €1 billion annually in artificial intelligence research and innovation throughout the decade.

Twin Skills Integration

The integration of digital and green skills creates twin jobs essential for the twin transition. Smart grid technicians manage digitalized renewable energy systems combining electrical engineering knowledge with data analytics and control systems expertise. Circular economy

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[5] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age_en

platform developers create digital marketplaces requiring software development skills alongside understanding of material flows and sustainability principles. Building energy management specialists use IoT and AI for optimization requiring expertise in both building systems and digital technologies.

Despite recognition of twin jobs' importance, policy frameworks provide limited guidance on integrated skill development. Education and training programs typically address green skills and digital skills separately, missing synergies and complementarities. Curriculum development integrating both dimensions remains fragmented, with few established educational pathways explicitly designed for twin transition occupations.

Digital Enablement of Green Transition

Digital technologies significantly enable green transition objectives. Smart energy management through IoT sensors, AI optimization algorithms, and automated control systems improves efficiency in buildings, industry, and transport. Precision agriculture applying digital technologies reduces environmental impacts through optimized input use, targeted interventions, and improved resource management. Smart grids integrate variable renewable energy through real-time balancing, demand response, and distributed energy resource coordination.

Circular economy platforms facilitate sharing, reuse, and recycling through digital marketplaces connecting supply and demand for secondary materials, sharing economy services, and product-as-a-service models. Digital product passports providing lifecycle information enable circular business models and informed consumer choices. Supply chain transparency through blockchain and other technologies supports verification of environmental claims and ethical sourcing.

However, the digital sector itself must become sustainable. Data centres, network infrastructure, and electronic devices consume significant energy and materials. Addressing the environmental footprint of digitalization requires energy-efficient hardware and data centres, circular economy approaches for electronics including design for longevity and recyclability, and renewable energy powering digital infrastructure.

Regional Digital and Green Capabilities

Regional variations in digital readiness and green transition vulnerability create complex patterns of advantage and disadvantage in the twin transition. Regions with strong digital capabilities and innovation ecosystems can leverage these assets for green technology development and deployment. Regions with renewable energy resources can attract data centres and other digital infrastructure seeking clean energy. However, regions lacking both digital capabilities and green transition opportunities face compounding disadvantages.

Territorial approaches through Just Transition Fund, Smart Specialisation, and Digital Europe Programme largely operate independently with insufficient coordination to support integrated regional twin transition strategies. Just Transition territories are selected based on fossil fuel dependence without emphasis on digital transformation needs. Digital infrastructure

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investments don't systematically prioritize regions facing green transition challenges. This fragmentation risks reinforcing regional disparities rather than promoting convergence.

Digital Tools for Sustainable Consumption

Digital tools enable and support sustainable consumption through multiple channels. Smart home technologies provide real-time feedback on energy consumption, automated control of heating and lighting, and integration with renewable energy systems and electric vehicle charging. Mobility apps enable multimodal journey planning, car-sharing, and ride-hailing reducing private vehicle ownership. E-commerce platforms can provide product sustainability information, though risk of greenwashing requires regulatory oversight.

However, digital platforms also enable consumption patterns that may undermine sustainability goals. Convenience of e-commerce and fast delivery can increase consumption frequency and transportation impacts. Algorithmic recommendations may prioritize engagement over sustainability. Planned obsolescence and rapid technology upgrade cycles generate electronic waste. Ensuring digital transformation supports rather than undermines sustainability requires regulatory frameworks, business model innovation, and consumer awareness.

Measurable Targets and Key Performance Indicators

The Path to the Digital Decade Policy Programme establishes targets of 80% of adults having at least basic digital skills and reaching 20 million employed ICT specialists by 2030, while promoting access of women to the ICT field and increasing the number of ICT graduates. The 2024 State of the Digital Decade report shows significant work remains, with only 55.6% of the EU's population having at least basic digital skills, and at the current pace, the number of ICT specialists will reach just 12 million by 2030. Member States collectively committed to over 1,900 ICT-focused measures through National Digital Decade Strategic Roadmaps, pooling a total investment of €288.6 billion, with most funding coming from public budgets (€205.1 billion, or 1.14% of the EU's GDP). The gender gap remains significant, with women accounting for only 19.5% of ICT specialists in 2024.

1.6. The Future of Europe Competitiveness (Draghi Report)

In September 2024, European Commission President Ursula von der Leyen received a landmark report from Mario Draghi, former President of the European Central Bank and former Italian Prime Minister, titled "The Future of European Competitiveness." Commissioned in September 2023 during the State of the Union address, this comprehensive document provides both a stark diagnosis of Europe's competitive challenges and a detailed roadmap for reversing its relative economic decline vis-à-vis the United States and China. The report represents a pivotal moment in EU economic policy discourse, with its findings and recommendations explicitly incorporated into the Commission's Political Guidelines for 2024-2029 and reflected in the Competitiveness Compass presented in January 2025.

Funding and Investment Requirements

The Draghi Report does not represent a funded programme with an allocated budget but rather a comprehensive set of recommendations that identifies substantial investment gaps. The report concludes that Europe requires additional annual investments of €750-800 billion (approximately 4-5% of EU GDP) to maintain competitiveness, a scale comparable to the Marshall Plan's investment intensity and equivalent to the entire RRF budget but needed annually rather than spread over six years. This total comprises approximately €450 billion per year for decarbonization and the energy transition, €150 billion annually for digitalization and technology leadership, and €100-150 billion per year for innovation and productivity enhancement. Specifically for research and innovation, Draghi calls for Member States to finally achieve the long-standing 3% of GDP target for R&D expenditure, proposes increasing the next Framework Programme (FP10) budget to €200 billion (compared to Horizon Europe's €95.5 billion), and recommends doubling support for fundamental research through the European Research Council. To finance these massive investments, the report proposes completing the Capital Markets Union to mobilize Europe's substantial private savings, issuing common EU debt similar to the NextGenerationEU model, and combining public and private funding sources.

Research, Innovation, and Skills for Competitiveness
The report identifies massive R&I investment requirements of €750-800 billion annually, approximately 5% of GDP, emphasizing the scale of transformation required. The 10th Framework Programme should receive doubled funding with increased focus on breakthrough innovations. Skills development features prominently, recognizing that human capital represents both a critical bottleneck and key competitive advantage.

The report's emphasis on skills development, regional cohesion, and avoiding social divisions during twin transition reflects concerns for just transition. However, implementation challenges include coordinating across twenty-seven member states with diverse industrial structures and priorities, mobilizing unprecedented levels of public and private investment, managing supply chain vulnerabilities for critical materials, and maintaining political consensus over decades required for full transformation.

Sector-Specific Twin Transition Challenges
The report's sector-by-sector approach recognizes distinct challenges across industries. Energy-intensive sectors require technology breakthroughs alongside skills development and investment mobilization. Digital technology sectors face dependencies on Asian semiconductor manufacturing requiring European capacity building. Clean technology manufacturing must compete globally while building domestic supply chains.

The report acknowledges tensions regarding Europe's dependence on Chinese clean technology manufacturing, with China's solar PV capacity expected to double global demand by 2030. This creates dilemmas between cost-effective deployment supporting climate goals and building European industrial capacity supporting competitiveness and strategic autonomy. Similar tensions exist for batteries, critical raw materials, and digital technologies.

Regional Implications and Convergence Challenges

The report's proposals have significant regional implications. Regions with strong innovation ecosystems, skilled workforces, and industrial capabilities can capitalize on opportunities in clean and digital technologies. Regions lacking these assets risk further marginalization unless policies explicitly promote convergence through targeted support, capacity building, and ensuring that all regions can participate in twin transition value chains.

The investment requirements and technological transformation may exacerbate regional disparities unless accompanied by strong cohesion policies and just transition support. The report acknowledges these risks but provides limited detail on mechanisms ensuring equitable distribution of transition benefits and costs across regions and social groups.

Measurable Targets and Strategic Recommendations

As of September 2025, one year after publication, only 43 out of 383 recommendations (11.2%) had been fully implemented, with transport (26.8%) and critical raw materials (33.3%) showing the most progress, while areas such as clean technologies, digitalization, and energy saw little advancement. For skills development, the report calls for a five-fold increase in the Erasmus+ budget to reach all young people in the EU in the coming funding period (2028-2034), addressing the currently low participation rate of 15%.

Implementation Status and Outstanding Gaps

One year after publication, progress has been uneven across sectors, with transport and critical raw materials most advanced while clean technologies, digitalization, and energy have seen limited implementation. This slow implementation reflects both the complexity of proposed reforms and political economy challenges of mobilizing necessary resources and achieving consensus across diverse member states and stakeholders.

1.7. Cross-Cutting Challenges and Modelling Implications

This review of EU policy frameworks reveals both the ambition and the challenges of Europe's twin transition. While major policy initiatives establish comprehensive frameworks for transformation, persistent fragmentation between green and digital policy domains creates gaps requiring enhanced analytical tools.

Policy Fragmentation and Integration Deficits

Green transition policies focus on decarbonization, renewable energy, and circular economy without systematically integrating digital enablers. Digital policies emphasize innovation, connectivity, and competitiveness without consistently addressing environmental sustainability implications. This creates suboptimal outcomes where digital transformation may undermine green objectives or green policies may fail to leverage digital opportunities.

Industrial policies recognize that sectors face twin transition challenges, but detailed strategies often address green and digital dimensions sequentially rather than holistically. Territorial approaches target regions based on either green transition vulnerability or digital readiness, rarely considering both dimensions simultaneously, risking reinforcement of disparities rather than promoting convergence.

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Skills Development Coordination Needs

Despite recognition of twin jobs requiring both green and digital competencies, policy frameworks provide limited guidance on integrated skill development. Education and training programs tend to address green skills and digital skills separately, missing synergies and complementarities. This gap constrains development of workforce capabilities essential for twin transition implementation.

Regional variations in capacity to develop and deploy twin transition skills create patterns of advantage and disadvantage. Innovation-driven regions with strong education systems and robust innovation ecosystems can develop twin skills more easily than regions with weaker capabilities, potentially exacerbating existing disparities.

Regional Convergence versus Divergence Dynamics

The twin transition creates significant spatial inequalities due to uneven distribution of capabilities, specializations, and infrastructure across territories. Regions dependent on carbon-intensive industries face employment losses and economic disruption. Regions lacking digital infrastructure and capabilities face barriers to participating in digital economy. Regions facing both challenges experience compounding disadvantages.

Policy frameworks include mechanisms for supporting vulnerable regions through Just Transition Fund, Smart Specialisation, and Digital Europe Programme. However, these instruments largely operate independently with insufficient coordination. The scale of support relative to transition challenges remains subject to debate, with questions about adequacy and effectiveness in promoting convergence rather than reinforcing existing disparities.

Consumer Behaviour and Demand-Side Gaps

Consumer-facing policies address green consumption through eco-design and energy labelling and digital rights through data protection and platform regulation, largely independently. This misses opportunities to harness digital tools for sustainable consumption and ensure digital transformation supports environmental goals. The consumer dimension requires coordination across multiple policy domains including energy, transport, digital, environment, and consumer protection, which currently operate largely in silos.

Implications for Macroeconomic Modelling

These policy gaps and challenges have direct implications for macroeconomic models. Models must capture interdependencies between green and digital technologies, not just parallel deployment trajectories. This requires representing digital enablers of green technologies, environmental impacts of digital technologies, and complementarities in research and innovation including skills spillovers and knowledge recombination.

1.8. Upcoming Policies and Future Twin Transition Investments (2028-2034)

The European Union is preparing a transformative investment package for the period 2028-2034 that will dramatically scale up support for the twin digital and green transitions. In July

2025, the European Commission proposed a fundamentally redesigned EU budget — the Multiannual Financial Framework (MFF) — amounting to almost €2 trillion (1.26% of the EU's gross national income on average between 2028 and 2034). This represents the EU's most ambitious attempt to position Europe for long-term competitiveness while addressing geopolitical challenges, climate resilience, and technological sovereignty.

European Competitiveness Fund

At the heart of the new budget lies the European Competitiveness Fund with €409 billion, which consolidates existing competitiveness funding into a unified framework designed to support the entire investment journey from research to manufacturing and deployment. The Fund consists of two components: €234 billion in new dedicated funding and the €175 billion Horizon Europe programme, operating together under one rulebook with a single gateway for funding applicants. The Fund focuses on four strategic policy windows that directly address the twin transition:

1. Clean transition and industrial decarbonisation.
2. Health, biotechnology, agriculture and the bioeconomy.
3. Digital leadership.
4. Resilience, defence industry, and space.

Within these priority areas, the Commission proposes multiplying digital investment by 5x compared to the current period to build a secure and innovative digital ecosystem, and increasing clean tech, bioeconomy and decarbonisation funding by 6x from the EU budget. The defence and space window alone receives €131 billion, representing a 5-fold increase over current levels.

Horizon Europe 2028-2034

The 10th Framework Programme for Research and Innovation, continuing under the Horizon Europe brand, will nearly double in budget from the current €95.5 billion to €175 billion for 2028-2034. This represents an 83% increase that will support Europe's research and innovation capacity with a new four-pillar structure:

- **Pillar I (Excellent Science)** receives €44 billion — nearly doubling funding for the European Research Council and Marie Skłodowska-Curie Actions to support fundamental research and talent mobility through the new "Choose Europe" initiative aimed at attracting and retaining top global researchers.
- **Pillar II (Competitiveness and Society)** is allocated €75.9 billion and will be tightly integrated with the European Competitiveness Fund through mirrored policy windows, ensuring coherent support throughout the investment journey from basic research to commercialization.
- **Pillar III (Innovation)** dramatically increases funding for the European Innovation Council to €38.8 billion — approximately tripling current support — to back startups, SMEs, and breakthrough technologies using expanded ARPA-style approaches for high-risk, high-reward projects.
- **Pillar IV (European Research Area)** strengthens widening participation and research infrastructure with €16.2 billion, up from €3.4 billion in the current programme. The new framework will introduce "moonshot" projects—large-scale, scientific-driven initiatives in

strategic fields such as quantum computing, next-generation AI, automated mobility, data sovereignty, regenerative therapies, clean aviation, and the space economy — with pooled funding from Horizon Europe, the Competitiveness Fund, and national, public and private sources

Complementary Programmes Supporting the Twin Transition
Beyond the Competitiveness Fund and Horizon Europe, the 2028-2034 MFF includes strategic increases in complementary programmes. The Erasmus+ programme will see its budget increase by 50% to €40.8 billion (from the current €26 billion), incorporating the previously independent European Solidarity Corps and expanding support for digital skills development and talent mobility — critical for building the workforce needed for the twin transition. The Connecting Europe Facility receives a major boost to over €81 billion to support trans-European transport networks (including military mobility), energy networks, and digital infrastructure, addressing the physical and digital connectivity essential for both transitions. The Digital Europe Programme will be substantially expanded within the Competitiveness Fund structure, with investments multiplied by 5x to strengthen Europe's digital capacities in artificial intelligence, cybersecurity, high-performance computing, semiconductors, and advanced digital skills.

2. Taking stock of existing macro-economic modelling of R&D and innovation approaches

Ufuk Akcigit et al. (2022) provides an overview of the state-of-the-art of macroeconomic models featuring innovation channels. There is widespread consensus among academic economists and policymakers, that research and development (R&D) activities play a decisive role in fostering growth in productivity and, hence, in the standards of living, as innovation intensive industries create highly skilled jobs, exhibit higher wages, are more productive, are often export-led and enhance competitiveness during the thick and thin of business cycles.

In the innovation policy debate, the following topics usually take centre stage: (i) best policy practices to spur innovation by the private sector with as large society-wide impacts as possible, (ii) technology diffusion (both across countries and firms), (iii) the apprehension of disruptive innovations, and ways to promote them, iv) the role of non-R&D innovation, v) the role of public versus private R&D.

Innovation and technological progress are the key determinants of long run economic growth and welfare. Given the tight link between innovation, economic growth, and welfare, designing the right public policies to achieve inclusive and sustainable growth requires a good understanding of what lies behind the innovation process. The mapping between innovation and economic growth can be described broadly as:

Firms → Inventors → Ideas → Aggregate Growth where firms hire inventors to produce new ideas/technologies which lead to economic growth. In line with this mapping, existing studies can be divided into three broad categories: (*i*) firm (R&D[6]) studies, (*ii*) inventor (Education[7]) studies, and (*iii*) idea (patent) studies.

The TWINRD purpose is improving especially the link between producing new ideas and delivering economic growth and prosperity. New ideas are the seeds for economic growth. The rise in living standards depends not only on the production of new ideas, but also on the effectiveness of transforming new ideas into consumer products or production processes. Incarnating an idea into a product or a production process is by no means immediate. What happens to ideas and patents once they are produced? While a lot of the policy discussions centre around increasing the number of ideas/patents/technologies produced, very little attempt is made at understanding how these new ideas are utilized after their invention. Ideas are not necessarily born to their best users and firms often develop patents that are not close to their primary business activity. This initial “mismatch" could potentially be mitigated in a secondary market where firms can buy and sell patents through patent agents (intermediaries).

2.1. Estimating knowledge spillovers

To understand more fully the impact of technology a broader understanding of the impact of knowledge spillovers is needed. Quite crucially, three different dimensions of technology need to be distinguished: as *knowledge*, as *practical skill* and as *artefact*. Each is accumulated by different mechanisms and in different institutional contexts. Moreover, while it is economic to codify much knowledge, substantial portions of technological knowledge remain tacit and accessible only through the development of individual skill. This tacit knowledge is communicated by personal contact and demonstration; it is accumulated by experience gained in specific contexts. We should note carefully that the tacit knowledge depends to a considerable degree on the economics of writing codes, with both coding and decoding costs being important determinants of tacit knowledge. Two important points follow from these distinctions. First, even publicly available information is not automatically absorbed in a costless fashion – e.g. scientific knowledge is a public, but not a free good.[8] Secondly, technology transfer is a nontrivial problem. When codes are written by different organizations, it is hardly surprising that communication can be a particularly intractable and costly business.

While it is the artefact dimension of technology which is always at the cutting edge of technological competition, it is the knowledge and skill dimension of technology which raises some of the most complex issues for technology management. There is, for example, the appropriability problem, which can effectively undermine the incentive to invest in skills and knowledge. That others can reap where the innovator sows may be competitively efficient, but it is not competitively creative: competition works dynamically only if there is sufficient sand in the wheels of commerce, creating opportunities for first mover advantage. Thus, innovative competition depends on the existence of information asymmetries which make competition

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[6] Besides private R&D, some studies may include public-funded R&D.

[7] Increased education makes it more likely for someone to become an inventor. Public policy needs to ensure access to education for potential future inventors who could generate economic growth through their creative ideas.

[8] Indeed, much corporate basic R&D can be understood as an attempt to listen-in and participate in the open scientific debate.

imperfect, but which certainly cannot be termed market failures. In short, a dynamic, innovation-based economy will fail all the tests of static market efficiency. Because markets for knowledge and skills are necessarily imperfect, one would expect a variety of different co-ordination mechanisms to emerge, and they have. Vertical control of innovation within organizations, networks for the formal and informal exchange of knowledge, and collaborative innovative activities across independent organizations are all examples of necessarily non-market co-ordination.

Summing up, “knowledge” including “new artifacts” spillovers are an important source of economic growth. One of the channels through which such spillovers work are indeed traded goods (new artifacts diffused on the market), which is especially stressed in the open economy endogenous growth models as pioneered by Grossman and Helpman (1991). The idea of traded goods as carriers of spillovers was already prominent in the seminal exposition by Griliches (1979), although he introduced the issue in terms of traded intermediaries between firms rather than between nations. There are, however, as stressed by Griliches, many other mechanisms through which technological spillovers may take place. In the terminology of Griliches, spillovers transmitted through traded goods are so-called *rent spillovers*. *Pure knowledge spillovers*, on the other hand, are transmitted by channels such as conferences, scientific literature, labour mobility (generally without 'transfer sums' paid by the employee's new firm), patent information, or pure imitation.

One way of estimating more wide knowledge spillovers, aiming to endogenize technological innovation into macro-economic models, is using the so-called *technology flow matrices*. These, as developed e.g. by Scherer (1982) and Putnam and Evenson (1994), describe how technological knowledge developed in one sector of the economy spills over to other sectors. Extending this into an international context, the method used in Verspagen (1997) attempts to measure how technology from one sector in a particular country spills over to other sectors in a set of countries, including the one in which the knowledge was originally developed. As was argued. Different technology flow matrices may result, depending on which transmission mechanism for spillovers one takes as the main focus of analysis. Thus, one might argue that the matrices developed by Scherer (1982) and Putnam and Evenson (1994) are mainly aimed at tracking rent spillovers, while the matrices proposed by Verspagen (1997) are aimed at measuring pure knowledge spillovers.

From a practical point of view, R&D spillovers are crucially related to the issue of 'why growth rates differ'. Technology being the main source of long-run economic growth, the economic performance of nations is related to the ability to generate new knowledge domestically and the ability to apply this knowledge, as well as knowledge generated abroad, in the economy. Technology policy, especially in the somewhat larger countries, as well as at the international level (e.g., the EU technology programmes) has traditionally focused on the domestic generation of knowledge, and the diffusion of knowledge from government research institutions to firms, in particular to small and medium-sized firms. The concept of spillovers puts this emphasis of knowledge generation and/or diffusion from the public to the private sector in a different perspective, because it suggests that an important part of the knowledge used domestically is generated abroad. This raises a practically oriented research question: what is the importance of foreign vs domestic sources of knowledge?

Overall, the results shown in Verspagen (1997) underline the importance of international and domestic R&D spillovers for productivity growth in the major OECD countries. The different ways in which this impact is being estimated, seems to suggest that there are indeed many ways in which these spillovers work. A simple interpretation, either in the form of R&D spillovers embodied in purchased inputs, or in the form of knowledge freely floating across international borders is not favoured, rather the evidence points to a mix of these different ways being at work simultaneously.

2.2. Evidence on R&I Impacts

Understanding the economic impacts of research and innovation (R&I) investments is essential for calibrating macroeconomic models of the twin transition. This section synthesizes empirical evidence on R&I impacts addressing three key questions:

- What range of impacts do studies find in terms of macroeconomic and sectoral performance?
- Do they include spillovers and specify their magnitudes?
- Do they distinguish between private and social returns to R&I?

Returns to R&I Investment

Meta-analytical evidence demonstrates substantial positive returns to R&I investment. Frontier Economics (2014) synthesized nearly 900 estimates, finding private returns to business R&D average approximately 20% annually. Output elasticities with respect to R&D range from 0.01 to 0.25 across firm-level studies, clustering around 0.08, though recent evidence shows this rising to 0.15-0.20 (Hall et al., 2010; Bessen and Wang, 2025).

The distinction between private and social returns provides the rationale for public support. Private returns typically range from 20-30%, while social returns incorporating spillover benefits range from 40-60%, implying a spillover premium of 20-40 percentage points (Frontier Economics, 2014; Ugur et al., 2020). For mission-oriented R&D targeting specific challenges, evidence shows that a 1% increase generates 0.45% additional total productivity and 0.56% GDP growth (Ziesemer, 2021), reflecting broader inter-sectoral spillovers from coordinated innovation across multiple sectors.

Macroeconomic Multipliers

Public R&I investment generates substantial macroeconomic multipliers. OECD panel data analysis reveals government R&I investment multipliers ranging from 1.5 to 2.5, compared to 0.5-1.0 for consumption spending (Ciaffi et al., 2024; Deleidi and Mazzucato, 2021). These high multipliers reflect three mechanisms: direct demand for skilled labor and equipment, productivity increases in adopting firms, and crowding-in effects on private R&D investment rather than crowding-out.

State-dependence is significant: multipliers reach 2.39 during recessions versus 1.0-1.5 during expansions (Auerbach and Gorodnichenko, 2012). Mission-oriented R&I expenditures directed at specific societal challenges generate larger multipliers than horizontal support due to their inter-sectoral character, engaging multiple sectors simultaneously and creating broader spillovers.

Sectoral and Technological Heterogeneity

Returns vary substantially across sectors and technologies. Green innovation in heavy pollution industries exhibits an inverted U-shape: initial costs from R&D investment and restructuring precede benefits from efficiency gains and market differentiation (Frontiers in Energy Research, 2021). Green investment affects energy efficiency both directly through technology deployment and indirectly through induced R&D intensity, with effectiveness depending critically on institutional quality thresholds (Dong et al., 2024).

Several empirical studies show that increased R&D intensity (often associated with digital innovation) tends to boost labor productivity while temporarily impairing asset efficiency (e.g., reducing asset turnover), reflecting classic trade-offs between innovation and short-term operational efficiency (Pangallo, 2025). Spillovers vary by technology maturity — frontier green technologies generate spillovers 2-3 times larger than mature technologies. R&D spillovers are stronger from digital-intensive sectors and among market leaders, while spillovers to young and small firms are systematically lower.

Temporal Dynamics

Returns to R&D materialize with significant lags. Productivity impacts typically peak 3-5 years after investment for industrial R&D (Hall et al., 2010; Rouvinen, 2002), reflecting sequential innovation stages: research (1-3 years), development (2-4 years), commercialization (1-3 years), production scaling (1-2 years), and market adoption (3-7 years).

Lag structures vary systematically by technology type. Radical innovations and capital-intensive green technologies require 5-10 years from research to market impact, while digital/software innovations achieve impact within 2-3 years (Gross et al., 2018). Knowledge production functions demonstrate path-dependency, with returns increasing with accumulated knowledge stocks depreciated at 10-15% annually (Hall et al., 2010).

Threshold Effects and Non-linearities

The relationship between R&D and productivity is markedly non-linear. Evidence from panel threshold regression models shows that the productivity effects of R&D depend critically on enabling conditions such as financial development, institutional quality, and human capital. Below certain thresholds, R&D investment yields limited productivity gains, whereas above these thresholds, returns increase substantially (Cappelen et al., 2021).

Resource allocation efficiency exhibits an inverted U-shape relationship with innovation outcomes: moderate misallocation of capital and labor may encourage experimentation and urban adaptability, but once misallocation passes critical thresholds (capital ≈ 1.334, labor ≈ 0.374), its effect becomes significantly negative, suppressing green technological innovation (Liang et al., 2025). Absorptive capacity — the ability to recognize and apply external knowledge — critically moderates spillovers. Empirical estimates suggest spillover elasticities are 2-3 times higher for high absorptive capacity recipients (Cohen and Levinthal, 1990), implying spillovers concentrate in regions and sectors with strong existing capabilities.

Twin Transition Interactions

Emerging evidence suggests digital innovation both complements and substitutes for green innovation depending on context. Digital technologies — AI, IoT sensors, big data analytics — amplify green investment effects on energy efficiency through optimization and real-time control (Dong et al., 2024). Spatial analysis confirms digital innovation promotes green economic growth with positive spillovers, though effects exhibit 2-3x regional heterogeneity favoring digitally advanced regions (Frontiers, 2025).

Potential trade-offs exist through resource competition when skilled labor and capital are scarce, and digital infrastructure energy consumption creates tension with decarbonization, though this may be offset by digital enablement of emissions reductions in other sectors.

2.3. The TWINRD technology flow matrix approach

2.3.1. Methodology

Our data on green and digital technology are based on patent counts for the period 2020-2021. The primary source of data is the PATSTAT database. Our primary unit for counting is the patent family. A patent family is a group of patent applications, usually in multiple geographical areas (countries), covering the same invention. For example, if a firm applies for a patent on the same invention in Europe and the US, there will be two applications (at the European Patent Office, EPO, and at the US Patent and Trademark Office) that will form one patent family.

We apply a “quality filter” to the data, where we assume that inventions that are only applied at one patent office can be disregarded because their technological importance is low. To be precise, we use patent families as the basic counting unit, but include only families that have at least two members, or for which the single member is an international office, such as the EPO or WIPO. There are slightly more than 6.7 million patent families for 2000 – 2021 that satisfy these criteria.

We also apply a breakdown into countries, production sectors (NACE) and green and digital technology subclasses. The basis for these breakdowns is fractional counting of inventors. For example, if a patent has two inventors, of which one is located in Greece and one in Italy, the patent will be assigned half to Greece and half to Italy. Furthermore, PATSTAT gives us weights for the NACE sectors to which the patent belongs. For example, the above-mentioned Italy-Greece patent could have weights 0.3, 0.5 and 0.2 for NACE codes 26.2, 26.3 and 26.6, respectively. In this case 0.3×0.5 would be assigned to NACE 26.2 in Italy and 0.5×0.5 to NACE 26.3 in Greece. The sum of all these weights (inventor country by NACE sector) will be 1 exactly.

Assigning patents to green or digital technology classes is done on the basis of tagging, for which we use 66 green subclasses and 23 different digital subclasses. These tags are added on the basis of technology classes such as the IPC or CPC codes, and/or on the basis of keywords found in the title and abstract. We use two different schemes for attaching digital tags. One of these is based on the J-tag classification, and the other on a new classification scheme proposed for so-called Digital General Purpose Technologies.

The WIPO and J-tag classification schemes differ in important ways. While J-tag is aimed at generic digital technologies, the WIPO scheme aims to identify new digital technologies associated with the idea of the 4th Industrial Revolution. In the ultimate version of the data that we use, 39% of all patents is digital in either J-tag and/or the WIPO sense. However, the overlap between the two digital schemes is relatively modest, as is shown in Figure 1. Only 12% of all patents with a digital tag has a WIPO tag, and of that 12%, only a quarter (i.e., 3%) has a both a WIPO- and a J-tag. This leads us to adopt a combined form of J-tag and WIPO: we will refer to those patents that have a J-tag but no WIPO tag as “old digital”, and those that have a WIPO tag (irrespective of whether they also have a J-tag) as “new digital”. Although we can subdivide WIPO tags into 10 subclasses, and J-tag into 13 subclasses, we will not use these subclassifications here.

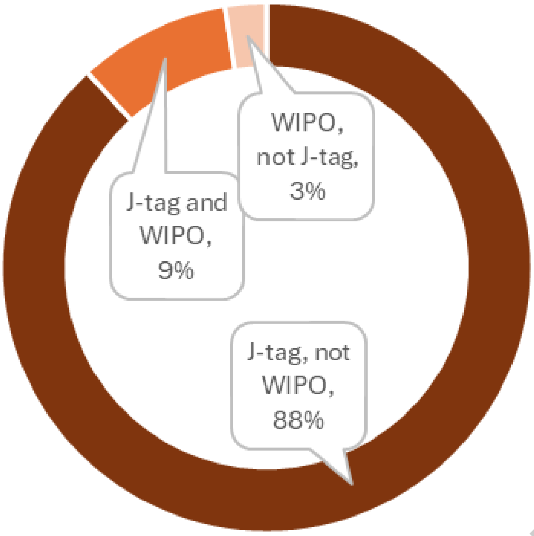

Figure 1. Composition of patents with at least 1 digital tag

2.3.2. Overall summaries and trends

Figure 2 shows trends for the number of green and digital patents. As explained above (Section 1) there are two primary ways identifying digital patents: J-tags and WIPO-tags. In the remainder of the exposition, we will combine J-tag and WIPO-tagging of patents to distinguish two different types of digital: “old digital” and “new digital” where the latter includes new technologies such as AI, big data, cloud computing and autonomous systems (generally associated with the so-called 4th Industrial revolution). Old digital includes all other digital technologies. Figure 2 includes trends for J-tagged patents (these can be old or new), WIPO patents (these are always new digital), and old digital (these are J-tagged patents that are not WIPO-tagged).

We can clearly see that the strongest rise of new digital technology starts from about 2015. This is also the fastest-growing one of the five categories of patents in the figure, at 43% growth per year on average. Green patents grow at 10.8% per year and are the next fastest growing category. Old digital patents grow at 4.1% per year, and non-green and non-digital patents grow at 3.1% per year. The J-tag category is a mix between new and old digital and grows at 5.9% per year.

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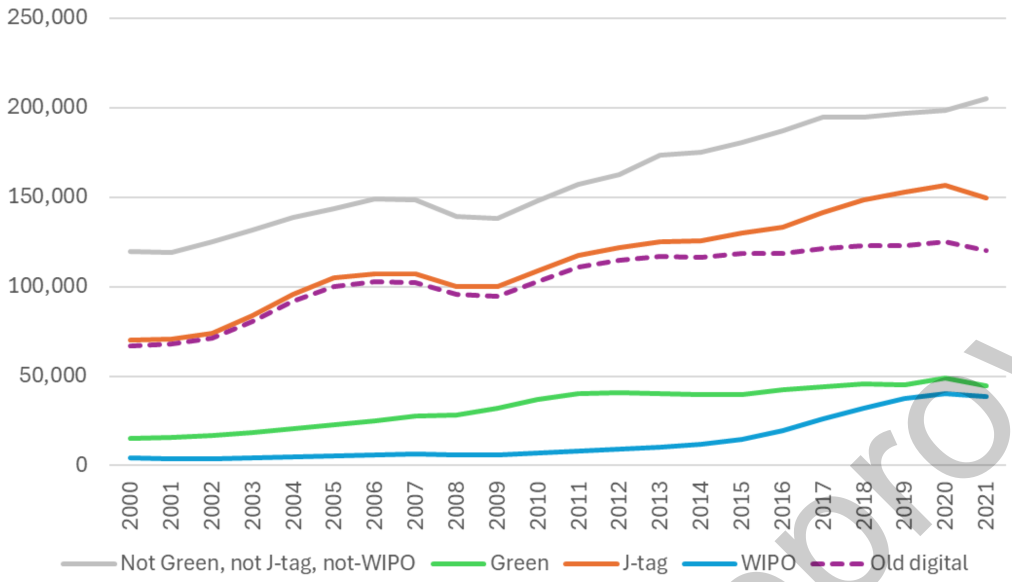

Figure 2. Patent family numbers by year, various kinds of patents (subclasses Green, J-tag and WIPO will overlap)

The various digital and green categories of Figure 2 clearly overlap. In Figure 3, this overlap is explicitly visualized. There are 6 categories, of which the not-green-and-not-digital one is the largest, followed by old-digital-and-not-green. Green patents including the overlap with digital (old and new) are 10.9% of all patents, and 2.3 percentage points of the 10.9 are digital. Figure 4 shows these data on a per-year basis. In this figure, the category of green and new-digital patents is the fastest-growth, at 60.5% per year, but this remains a very small category overall.

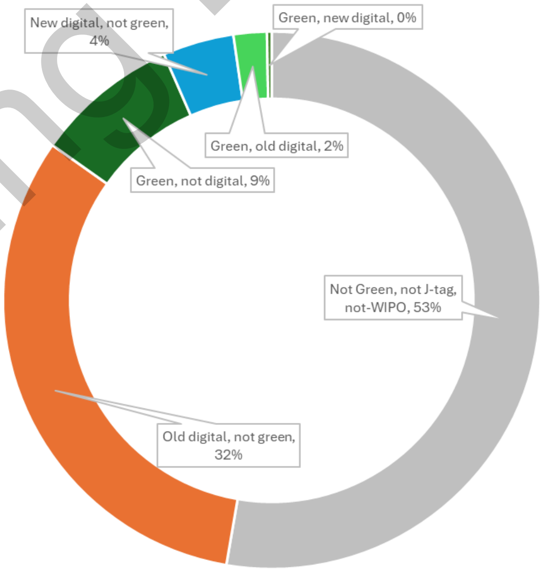

Figure 3. Composition of all patents, 2000 - 2021

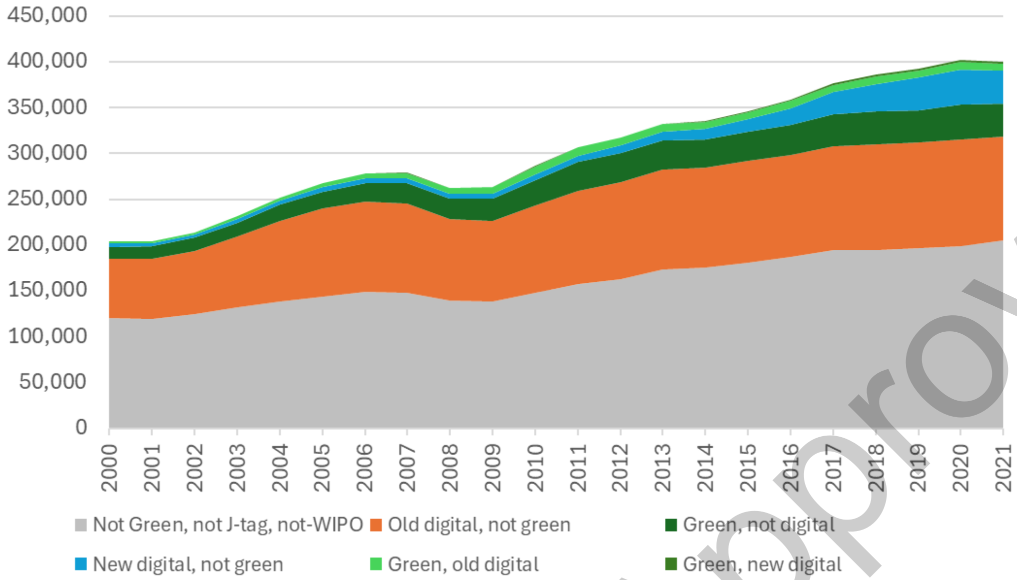

Figure 4. Composition of all patents, per year

2.3.3. Subcategories and sectors

In order to characterize green and digital technology further, we can split the data into NACE sectors, which give an idea of which production activities are related to technology, and/or into green technology fields, related to the type of green technology goals. This is a fine-grained split-up, as there are 84 different NACE codes and 66 green technology codes, yielding 5,544 different combinations. A majority of these possible combinations (4,387 pre-2016 and 3,982 post-2015) has more than zero patents. To provide a broad overview the NACE-Green field combinations that realize the largest part of patenting activity, we first split the total period into 2000 – 2015 and post-2015. For each of these periods, we construct three lists of NACE-technology field combinations, corresponding to the top-N combinations for pure (i.e., non-digital) green patents, old digital and green patent, and new digital and green patents. Because these groups of patents differ in terms of how many NACE-Green field combinations they cover, we vary the number of items on the various top-N lists.[9] Each NACE-Green field combination may appear on multiple of the three top-N lists.

The results for the pre-2016 period are in Table 1. The table lists shares of pure Green, old digital and new digital in total patents in the combination of NACE and green field, as well as the share of the combination in total patents. Items on the lists are ranked by the latter share. Shares of pure, new and old digital are color-coded within the column for high (red) to low (blue). In this period, Battery technology (appropriately) produced in the Batteries and

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[9] In precise terms, our procedure is to first calculate the share of each combination in the total, then calculate the sum of squares of these shares, and finally calculate the inverse of this sum of squares. The result if the 'Herfindahl equivalent number of combinations', which is also an indicator for the degree of concentration of patents over all possible combinations. Thus, the more (less) concentrated patents are over combinations, the less (more) items are on our top-N list.

Accumulators NACE is the combination with most patents, followed by technology aimed at reducing emissions produced in the NACE sector Motor Vehicles. Both of these combinations are mostly non-digital, i.e., pure green.

The share of digital technologies is high in a limited number of combinations, e.g., in emission mitigation in ICT (mostly about power saving in ICT equipment)/Communication equipment, and on PV energy generation/NACE electronic components. New digital technology is mostly found at the bottom of the list, i.e., in small combinations. Here we find NACE electricity distribution/ Smart grids, but also, for example, NACE electricity distribution/ Enabling technologies in buildings.

It is outside the scope to discuss here the entire list. Instead, we may take this list (or even the complete tables from which it is built) as an overview of where in the production system the most important green technologies are created, or, alternatively, which parts of the production structure generate which kind of green technologies. Table 2 gives the same results for the post-2015 period. This list is somewhat shorter, because patents are more concentrated in terms of the NACE/ Green field combinations. This table also includes a column that documents whether the combination already appeared in the pre-2016 table (1), or not (0).

Table 1. Most prominent NACE/ Green field combinations generation green and digital technologies

	shares			On Top List						
% total	Pure G	New D	Old D	Pure G	New D	Old D	NACE	Short NACE	EnvTech	Short EnvTech
5.803	0.968	0.001	0.031	1	0	1	27.2	Batteries and Accumulators	2.6.1.1	Batteries
5.441	0.938	0.006	0.056	1	1	1	29.1	Motor Vehicles	1.1.2	Emissions, mobile
3.339	0.000	0.048	0.952	0	1	1	26.3	Communication	8	Mitigation in ICT
3.317	0.009	0.010	0.981	0	1	1	26.1	Electronic Components	2.1.3	Solar PV energy
2.917	0.987	0.001	0.013	1	0	0	27.2	Batteries and Accumulators	2.6.3	Fuel cells
2.876	0.986	0.001	0.013	1	0	0	20.1	Basic Chemicals	1.2	Water pollution
2.438	0.955	0.004	0.040	1	1	0	29.1	Motor Vehicles	4.1.1	Conventional vehicles
2.033	0.992	0.001	0.008	1	0	0	21	Pharmaceuticals	0.5	CC adaptation, human protection
1.848	0.807	0.005	0.187	1	1	1	27.5	Domestic	5.2	Energy efficiency in buildings
1.831	0.000	0.094	0.906	0	1	1	26.2	Computers	8	Mitigation in ICT
1.691	0.985	0.000	0.015	1	0	0	20.1	Basic Chemicals	7.2	Chemical industry
1.607	0.958	0.013	0.029	1	1	0	28.1	General-Purpose Machinery	2.1.1	Wind energy
1.475	0.976	0.000	0.024	1	0	0	27.2	Batteries and Accumulators	7.6	Final products
1.343	0.225	0.005	0.770	1	0	1	26.1	Electronic Components	7.6	Final products
1.243	0.980	0.001	0.020	1	0	0	28.29	Other General-Purpose	1.1.3	Emissions, other
1.233	0.988	0.001	0.010	1	0	0	28.11	Engines and Turbine	1.1.3	Emissions, other
1.152	0.876	0.026	0.098	1	1	0	29.1	Motor Vehicles	4.1.3	Electric vehicles
1.100	0.861	0.002	0.137	1	0	1	27.9	Other electrical	5.2	Energy efficiency in buildings
0.940	0.987	0.002	0.011	1	0	0	28.1	General-Purpose Machinery	4.3	Aeronautics or air transport
0.906	0.986	0.001	0.013	1	0	0	28.29	Other General-Purpose	1.2	Water pollution
0.868	0.980	0.001	0.019	1	0	0	28.29	Other General-Purpose	1.1.1	Emissions, stationary
0.770	0.982	0.001	0.017	1	0	0	20.1	Basic Chemicals	1.3	Waste management
0.757	0.919	0.008	0.073	1	0	0	29.1	Motor Vehicles	4.1.2	Hybrid vehicles
0.693	0.991	0.002	0.008	1	0	0	24	Basic Metals	7.1	Metal processing
0.686	0.957	0.013	0.030	1	1	0	30	Other Transport	4.3	Aeronautics or air transport

0.682	0.987	0.000	0.013	1	0	0	20.1	Basic Chemicals	1.1.2	Emissions, mobile
0.665	0.987	0.002	0.011	1	0	0	28.11	Engines and Turbine	4.1.1	Conventional vehicles
0.619	0.993	0.000	0.006	1	0	0	21	Pharmaceuticals	7.2	Chemical industry
0.618	0.978	0.001	0.021	1	0	0	20.1	Basic Chemicals	2.6.2	Hydrogen technology
0.601	0.993	0.002	0.006	1	0	0	21	Pharmaceuticals	2.2	Energy non-fossil fuels
0.585	0.981	0.003	0.016	1	0	0	28.11	Engines and Turbine	1.1.2	Emissions, mobile
0.547	0.835	0.001	0.163	1	0	0	25.2	Tanks etc.	2.1.2	Solar thermal energy
0.537	0.976	0.001	0.023	1	0	0	28.9	Oth Special-Purpose Mach.	1.3	Waste management
0.537	0.344	0.136	0.520	0	1	1	26.51	Measuring Instruments	7.8	Enabling in production
0.530	0.957	0.006	0.036	1	0	0	25.3	Steam Generators	2.4.2	Nuclear fission
0.522	0.969	0.006	0.025	1	0	0	28.25	Cooling and Ventilation	5.2	Energy efficiency in buildings
0.511	0.975	0.003	0.022	1	0	0	29.1	Motor Vehicles	1.1.3	Emissions, other
0.498	0.972	0.002	0.026	1	0	0	27.2	Batteries and Accumulators	4.1.3	Electric vehicles
0.493	0.983	0.000	0.017	1	0	0	20.1	Basic Chemicals	1.1.1	Emissions, stationary
0.491	0.987	0.001	0.013	1	0	0	28.11	Engines and Turbine	4.3	Aeronautics or air transport
0.449	0.987	0.001	0.012	1	0	0	28.29	Other General-Purpose	5.2	Energy efficiency in buildings
0.435	0.863	0.009	0.128	1	0	0	29.3	Motor Vehicles parts	4.1.2	Hybrid vehicles
0.398	0.984	0.001	0.015	1	0	0	20.1	Basic Chemicals	2.6.3	Fuel cells
0.391	0.857	0.007	0.136	1	0	0	27.12	Electricity Distribution	2.6.1.1	Batteries
0.391	0.810	0.001	0.189	1	0	0	23.1	Glass and Products	7.4.3	Glass production
0.378	0.953	0.003	0.044	1	0	0	28.1	General-Purpose Machinery	1.1.2	Emissions, mobile
0.367	0.964	0.004	0.032	1	0	0	28.3	Agricultural Machinery	0.4	CC adaptation, agriculture
0.358	0.873	0.013	0.113	1	0	0	27.12	Electricity Distribution	4.1.3	Electric vehicles
0.354	0.053	0.006	0.941	0	0	1	20.1	Basic Chemicals	2.1.3	Solar PV energy
0.352	0.989	0.002	0.009	1	0	0	20.1	Basic Chemicals	6.1	Waste water treatment
0.345	0.992	0.003	0.005	1	0	0	28.1	General-Purpose Machinery	2.1.6	Marine energy
0.344	0.911	0.009	0.080	1	0	0	29.1	Motor Vehicles	4.1.4	Fuel-efficiency design
0.333	0.996	0.000	0.004	1	0	0	21	Pharmaceuticals	0.4	CC adaptation, agriculture
0.322	0.495	0.172	0.333	0	1	0	27.12	Electricity Distribution	9	Smart grids

0.318	0.990	0.002	0.008	1	0	0	43	Specialised Construction	1.2	Water pollution
0.314	0.973	0.000	0.027	1	0	0	20.1	Basic Chemicals	2.6.1.1	Batteries
0.311	0.864	0.010	0.126	1	0	0	26.5	Instruments	1.1.2	Emissions, mobile
0.302	0.991	0.003	0.006	1	0	0	28.1	General-Purpose Machinery	2.1.7	Hydro energy
0.297	0.990	0.001	0.009	1	0	0	28.29	Other General-Purpose	1.1.2	Emissions, mobile
0.289	0.816	0.035	0.150	0	1	0	29.1	Motor Vehicles	4.5.1	Electric vehicle charging
0.288	0.926	0.001	0.074	1	0	0	26.1	Electronic Components	2.6.1.2	Capacitors
0.286	0.959	0.011	0.031	1	0	0	27.1	Electric Motors etc.	4.1.3	Electric vehicles
0.278	0.997	0.000	0.003	1	0	0	23.5	Cement etc.	6.2	Solid waste management
0.256	0.995	0.001	0.005	1	0	0	20.1	Basic Chemicals	2.2	Energy non-fossil fuels
0.250	0.320	0.011	0.670	0	0	1	26.1	Electronic Components	5.2	Energy efficiency in buildings
0.230	0.001	0.170	0.829	0	1	1	26.2	Computers	7.8	Enabling in production
0.230	0.616	0.110	0.274	0	1	0	27.12	Electricity Distribution	5.2	Energy efficiency in buildings
0.220	0.005	0.240	0.755	0	1	1	26.3	Communication	9	Smart grids
0.203	0.000	0.100	0.900	0	1	1	62	Computer Programming etc.	7.8	Enabling in production
0.164	0.140	0.074	0.786	0	1	0	26.5	Instruments	0.6	CC adaptation, indirect
0.125	0.002	0.242	0.756	0	1	0	26.2	Computers	9	Smart grids
0.115	0.323	0.420	0.257	0	1	0	26.5	Instruments	9	Smart grids
0.093	0.408	0.382	0.209	0	1	0	28.4	Machine Tools	7.8	Enabling in production
0.089	0.000	0.198	0.802	0	1	0	62	Computer Programming etc.	9	Smart grids
0.082	0.000	0.241	0.759	0	1	0	26.2	Computers	0.6	CC adaptation, indirect
0.063	0.012	0.144	0.844	0	1	0	26.3	Communication	7.8	Enabling in production
0.061	0.374	0.194	0.433	0	1	0	32.5	Medical instruments	0.6	CC adaptation, indirect
0.056	0.178	0.393	0.428	0	1	0	26.51	Measuring Instruments	9	Smart grids
0.052	0.120	0.870	0.010	0	1	0	27.12	Electricity Distribution	5.4	Enabling technologies, buildings
0.045	0.010	0.988	0.002	0	1	0	26.5	Instruments	5.4	Enabling technologies, buildings
0.033	0.000	0.954	0.046	0	1	0	26.3	Communication	5.4	Enabling technologies, buildings
0.029	0.268	0.598	0.135	0	1	0	27.33	Wiring Devices	9	Smart grids
0.018	0.008	0.991	0.001	0	1	0	27.33	Wiring Devices	5.4	Enabling technologies, buildings

0.017	0.017	0.978	0.005	0	1	0	26.51	Measuring Instruments	5.4	Enabling technologies, buildings
0.014	0.000	0.884	0.116	0	1	0	26.2	Computers	5.4	Enabling technologies, buildings
0.009	0.000	0.993	0.007	0	1	0	62	Computer Programming etc.	5.4	Enabling technologies, buildings

Table 2. Most prominent NACE/ Green field combinations generation green and digital technologies, post-2015

	shares			On Top List							
% total	Pure G	New D	Old D	Pure G	New D	Old D	NACE	Short NACE	EnvTeh	Short EnvTech	pre-2016
9.742	0.982	0.004	0.015	1	1	0	27.2	Batteries and Accumulators	2.6.1.1	Batteries	1
4.992	0.000	0.076	0.924	0	1	1	26.3	Communication	8	Mitigation in ICT	1
2.623	0.981	0.006	0.013	1	0	0	20.1	Basic Chemicals	1.2	Water pollution	1
2.534	0.965	0.019	0.016	1	1	0	29.1	Motor Vehicles	1.1.2	Emissions, mobile	1
2.061	0.014	0.219	0.767	0	1	1	26.2	Computers	8	Mitigation in ICT	1
2.028	0.996	0.003	0.002	1	0	0	21	Pharmaceuticals	0.5	CC adaptation, human protection	1
2.012	0.016	0.015	0.969	0	1	1	26.1	Electronic Components	2.1.3	Solar PV energy	1
1.962	0.875	0.054	0.071	1	1	0	29.1	Motor Vehicles	4.1.3	Electric vehicles	1
1.752	0.989	0.004	0.007	1	0	0	27.2	Batteries and Accumulators	2.6.3	Fuel cells	1
1.688	0.988	0.001	0.011	1	0	0	27.2	Batteries and Accumulators	7.6	Final products	1
1.400	0.940	0.041	0.019	1	1	0	28.1	General-Purpose Machinery	2.1.1	Wind energy	1
1.382	0.983	0.010	0.007	1	0	0	29.1	Motor Vehicles	4.1.1	Conventional vehicles	1
1.371	0.833	0.022	0.146	1	1	1	27.5	Domestic	5.2	Energy efficiency in buildings	1
1.297	0.831	0.004	0.166	1	0	1	27.9	Other electrical	5.2	Energy efficiency in buildings	1
1.271	0.987	0.001	0.012	1	0	0	20.1	Basic Chemicals	7.2	Chemical industry	1
1.071	0.971	0.005	0.024	1	0	0	28.29	Other General-Purpose	1.1.3	Emissions, other	1
0.952	0.986	0.006	0.008	1	0	0	28.1	General-Purpose Machinery	4.3	Aeronautics or air transport	1
0.876	0.221	0.009	0.771	0	0	1	26.1	Electronic Components	7.6	Final products	1

0.869	0.985	0.003	0.011	1	0	0	20.1	Basic Chemicals	1.3	Waste management	1
0.839	0.953	0.019	0.027	1	0	0	28.25	Cooling and Ventilation	5.2	Energy efficiency in buildings	1
0.824	0.401	0.254	0.345	0	1	1	26.51	Measuring Instruments	7.8	Enabling in production	1
0.823	0.982	0.003	0.015	1	0	0	20.1	Basic Chemicals	2.6.2	Hydrogen technology	1
0.808	0.987	0.005	0.008	1	0	0	28.11	Engines and Turbine	1.1.3	Emissions, other	1
0.794	0.918	0.055	0.027	1	1	0	30	Other Transport	4.3	Aeronautics or air transport	1
0.791	0.991	0.002	0.007	1	0	0	24	Basic Metals	7.1	Metal processing	1
0.787	0.984	0.004	0.012	1	0	0	28.29	Other General-Purpose	1.2	Water pollution	1
0.752	0.793	0.073	0.134	1	1	0	29.1	Motor Vehicles	4.5.1	Electric vehicle charging	1
0.688	0.978	0.005	0.017	1	0	0	28.29	Other General-Purpose	1.1.1	Emissions, stationary	1
0.669	0.989	0.001	0.010	1	0	0	20.1	Basic Chemicals	2.6.1.1	Batteries	1
0.636	0.928	0.019	0.053	1	0	0	28.9	Oth. Special-Purpose Machinery	7.1	Metal processing	0
0.629	0.978	0.012	0.010	1	0	0	29.1	Motor Vehicles	4.1.2	Hybrid vehicles	1
0.610	0.953	0.012	0.035	1	0	0	25.5	Forging etc.	7.1	Metal processing	0
0.570	0.702	0.026	0.272	1	0	0	27.1	Electric Motors etc.	2.1.3	Solar PV energy	0
0.548	0.899	0.043	0.058	1	1	0	28.3	Agricultural Machinery	0.4	CC adaptation, agriculture	1
0.532	0.978	0.008	0.014	1	0	0	27.1	Electric Motors etc.	4.1.3	Electric vehicles	1
0.522	0.856	0.024	0.120	1	0	0	27.12	Electricity Distribution	2.6.1.1	Batteries	1
0.492	0.997	0.000	0.003	1	0	0	21	Pharmaceuticals	7.2	Chemical industry	1
0.487	0.963	0.012	0.025	1	0	0	27.2	Batteries and Accumulators	4.1.3	Electric vehicles	1
0.475	0.876	0.051	0.073	1	1	0	26.5	Instruments	2.6.1.1	Batteries	0
0.470	0.959	0.011	0.030	1	0	0	29.1	Motor Vehicles	4.1.4	Fuel-efficiency design	1
0.468	0.990	0.000	0.010	1	0	0	20.1	Basic Chemicals	1.1.2	Emissions, mobile	1
0.460	0.992	0.003	0.005	1	0	0	28.11	Engines and Turbine	4.3	Aeronautics or air transport	1
0.449	0.988	0.005	0.007	1	0	0	28.11	Engines and Turbine	4.1.1	Conventional vehicles	1
0.445	0.000	0.225	0.775	0	1	1	62	Computer Programming etc.	7.8	Enabling in production	1
0.441	0.951	0.017	0.032	1	0	0	28.9	Oth. Special-Purpose Machinery	1.3	Waste management	1

0.430	0.915	0.019	0.066	1	0	0	22	Rubber and Plastic Products	7.1	Metal processing	0
0.429	0.921	0.027	0.053	1	0	0	28.3	Agricultural Machinery	7.5	Agriculture	0
0.425	0.833	0.053	0.113	0	1	0	27.12	Electricity Distribution	4.1.3	Electric vehicles	1
0.407	0.983	0.005	0.012	1	0	0	28.29	Other General-Purpose	5.2	Energy efficiency in buildings	1
0.389	0.934	0.044	0.022	1	0	0	29.3	Motor Vehicles parts	4.1.2	Hybrid vehicles	1
0.386	0.989	0.002	0.009	1	0	0	20.1	Basic Chemicals	6.2	Solid waste management	0
0.372	0.084	0.391	0.525	0	1	0	26.2	Computers	7.8	Enabling in production	1
0.355	0.503	0.193	0.304	0	1	0	27.12	Electricity Distribution	9	Smart grids	1
0.296	0.294	0.022	0.684	0	0	1	20.1	Basic Chemicals	2.1.3	Solar PV energy	1
0.269	0.088	0.057	0.855	0	0	1	26.1	Electronic Components	8	Mitigation in ICT	0
0.259	0.195	0.125	0.680	0	1	0	26.5	Instruments	0.6	CC adaptation, indirect	1
0.241	0.818	0.130	0.052	0	1	0	29.3	Motor Vehicles parts	4.1.3	Electric vehicles	0
0.195	0.352	0.537	0.111	0	1	0	28.4	Machine Tools	7.8	Enabling in production	1
0.193	0.035	0.194	0.771	0	1	0	28.23	Office Machinery	8	Mitigation in ICT	0
0.170	0.820	0.124	0.056	0	1	0	30	Other Transport	4.1.3	Electric vehicles	0
0.153	0.004	0.301	0.696	0	1	0	26.3	Communication	9	Smart grids	1
0.151	0.000	0.304	0.696	0	1	0	62	Computer Programming etc.	9	Smart grids	1
0.133	0.010	0.265	0.725	0	1	0	26.3	Communication	7.8	Enabling in production	1
0.110	0.763	0.202	0.035	0	1	0	28.1	General-Purpose Machinery	4.1.3	Electric vehicles	0
0.108	0.513	0.239	0.248	0	1	0	26.5	Instruments	9	Smart grids	1
0.106	0.056	0.661	0.283	0	1	0	26.2	Computers	0.6	CC adaptation, indirect	1
0.103	0.032	0.478	0.490	0	1	0	26.2	Computers	9	Smart grids	1
0.073	0.395	0.443	0.161	0	1	0	32.5	Medical instruments	0.6	CC adaptation, indirect	1
0.062	0.051	0.360	0.589	0	1	0	28.23	Office Machinery	7.8	Enabling in production	0
0.050	0.171	0.424	0.405	0	1	0	26.51	Measuring Instruments	9	Smart grids	1
0.050	0.064	0.676	0.260	0	1	0	26.2	Computers	4.1.1	Conventional vehicles	0
0.042	0.072	0.926	0.002	0	1	0	27.12	Electricity Distribution	5.4	Enabling technologies, buildings	1

2.3.4. Technology flows

Finally, we turn to technology flows data. This focuses on the idea that new knowledge builds on existing knowledge, and therefore that existing knowledge is an input in the R&D process. In the context of green and digital knowledge, the question becomes what role existing green and/or digital knowledge plays in the generation of new green and/or digital knowledge.

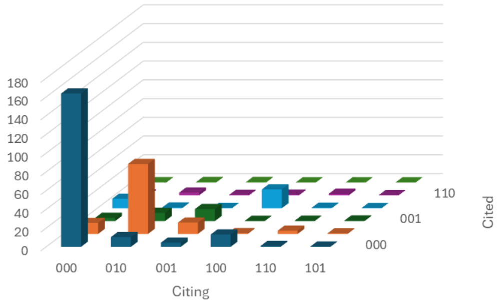
We use patent citations to quantify these knowledge flows, assuming that knowledge flows from the cited patent to a citing patent. This immediately introduces a large role for time, because a patent can only be cited after it has been published, or, in other words, knowledge can only start influence the generation of knowledge after it has been created itself. And, from the other point of view, the creation of new knowledge can only draw on knowledge that has been created before. In terms of citations, if we are looking at a patent that would be created in 2015, it can be cited only in (the remainder of) 2015 or after 2015. Or a patent that is created in 2017 can only cite other patents that were created before 2017, or in the part of 2017 that comes before its own creation.

These basic ideas can be used to construction a technology flow matrix or citation matrix, as in Table 3. Here we focus on the period 2012-2017, we do not subdivide green patents into subclasses. The strings on the axes denote green-old digital-new digital, e.g., 000 represents citations that are not green and not digital in any way. The numbers in these table represent 100,000 citations, i.e., in the top row, we have approximately 16,370,000 citations between the 000 type. The bar charts on the righthand side are simple graphical representations of the numeric tables on the left.

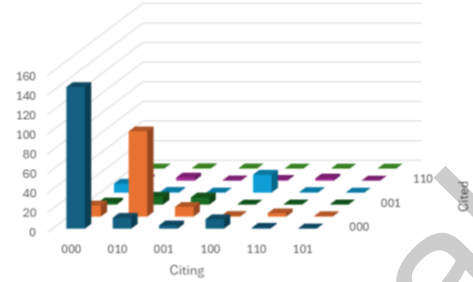
The table illustrates the two possible perspectives on citations and knowledge flows. On the top row, we count units of knowledge (represented by citations) created in the 2012-2017 period and flowing into the knowledge creation process of the future. On the other hand, in the bottom row, we take the perspective of units of knowledge (again represented by citations) created in the past and flowing into knowledge creation in the period 2012 – 2017.

Table 3. Technology flow matrices, 100,000 citations

		Citing, 2012 and onwards					
		000	**010**	**001**	**100**	**110**	**101**
Cited, 2012-2017	**000**	163.7	10.5	4.4	13.2	1.0	0.4
	010	11.8	74.8	12.1	0.9	3.5	0.7
	001	3.6	8.8	12.9	0.3	0.4	0.7
	100	10.1	0.8	0.3	20.1	0.5	0.3
	110	0.9	2.9	0.4	0.6	1.7	0.2
	101	0.3	0.5	0.5	0.2	0.2	0.2



		Citing, 2012-2017					
		000	**010**	**001**	**100**	**110**	**101**
Cited, up to (incl.) 2017	**000**	144.4	11.1	3.4	9.6	1.0	0.3
	010	11.5	86.9	9.9	0.8	3.5	0.5
	001	2.2	8.1	7.4	0.2	0.3	0.3
	100	9.2	0.8	0.2	18.4	0.6	0.2
	110	1.1	3.2	0.3	1.0	2.3	0.2
	101	0.2	0.5	0.3	0.1	0.2	0.1

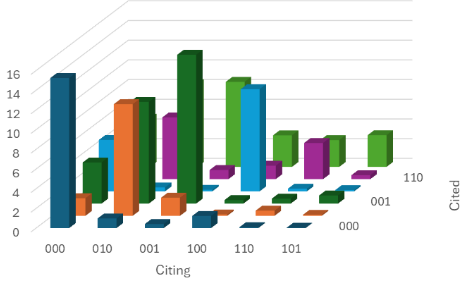


The data on knowledge flows are easier to interpret if we normalize them in some way. This is done in Table 4. In the top row, which still represents knowledge flowing into future knowledge creation, we normalized by the number of patents of the row in the period 2012 – 2017. We see, for example, that on average, a non-green-non-digital patent created in the 2012-2017 period generates 15.2 units of knowledge flows into non-green-non-digital patents created in the future, and 1.2 units of knowledge flows into green and non-digital patents created in the future.

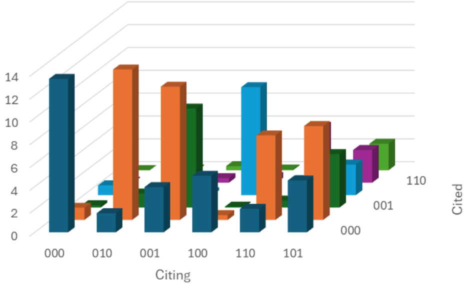
In the bottom row of the table, numbers are divided by the number of patents of the column-type created during 2012 – 2017. Using the same example cells, this means that non-green-non-digital patents created during 2012 – 2017, on average 'used' 13.4 units of non-green-non-digital knowledge flowing from the past, and green but not digital patents used 5.0 units of non-green and non-digital units of knowledge flowing from the past.

Table 4. Technology flow matrices, normalized (citations per-patent)

		Citing, 2012 and onwards					
		000	**010**	**001**	**100**	**110**	**101**
Cited, 2012-2017	**000**	15.2	1.0	0.4	1.2	0.1	0.0
	010	1.8	11.3	1.8	0.1	0.5	0.1
	001	4.2	10.3	15.1	0.4	0.5	0.8
	100	5.2	0.4	0.2	10.4	0.3	0.1
	110	2.0	6.3	0.9	1.4	3.7	0.4
	101	4.9	8.4	8.6	3.2	2.7	3.2



		Citing, 2012-2017					
		000	**010**	**001**	**100**	**110**	**101**
Cited, up to (incl.) 2017	**000**	13.4	1.7	4.0	5.0	2.1	4.5
	010	1.1	13.2	11.7	0.4	7.4	8.2
	001	0.2	1.2	8.7	0.1	0.6	4.7
	100	0.9	0.1	0.3	9.5	1.3	2.7
	110	0.1	0.5	0.4	0.5	4.9	2.9
	101	0.0	0.1	0.4	0.1	0.4	2.3



What is notable from Table 4 is that knowledge flows are fairly concentrated in specific combinations of the types of knowledge (in terms of green and old- and new-digital). For example, there is a tendency for the diagonal elements of the matrices to be large, which means that knowledge flows intensively within each type. But there are also off-diagonal cells that have relatively high values, such as green and new-digital to non-green and old-digital in the top row, or green and new-digital sourcing a relatively high amount of knowledge from old digital in the bottom table.

2.4. Modelling the macroeconomic effects of innovation policies

As a general *modelling strategy*, one needs to first identify the policy relevant question, second, investigate what the profession already knows (i.e., the relevant literature) as well as look for the available macro and microdata and, third, develop a model that is able to answer the policymakers' questions while fitting the data to the best degree possible. The overarching fundamental principle underlying this stepwise approach to modelling is that models are question and data dependent. In the process of identifying a good model, the dialogue between policy and economic analysts in policymaking institutions, on one hand, and academia, on the other, is crucial. This helps to identify and design the most appropriate models to answer the most relevant questions in the policy arena at a given point in time.

In TWINRD, the dialogue of the modelling team with the stakeholders is being organized in WP6 by engaging participants in two strategic foresight workshops, aiming to co-design twin transitions illustrative scenarios and select R&I policy priorities. The results of the workshops will feed later the quantitative analysis and twin transition scenarios simulations undertaken using a combination of two macroeconomic models – NEMESIS and GEM-E3 – which are being upgraded and linked to eventually constitute a comprehensive TWINRD modelling framework.

In this section of the deliverable, taking stock of the relevant literature (see the selected bibliography) and especially of Akcigit U. et al. 2022 and European Commission 2017 providing an overview respectively of NEMESIS and GEM-E3, we describe how R&D spillovers and macro-economic effects of innovation policies are modelled in state-of-the-art versions of these models which constitute the starting point for the TWIN-RD modelling upgrade activities.

2.4.1. NEMESIS model overview and innovation mechanisms

The NEMESIS model is a detailed sectoral macro-econometric model estimated for every country of the EU. It distinguishes between 30 sectors operating within five-level nested-CES functions. The model covers both the supply and demand sides of the economy and incorporates endogenous technical change. The conversion matrices of the model for final consumption, investment goods, intermediate consumption, energy/environment and technological transfers, capture the interdependence between production sectors (with one representative firm per sector) and between producers and other agents in the economy, namely households, the government and foreign countries. Every country model includes an *economic core* that can be simulated in interaction with a detailed energy/environment module. Simulation of policy effects can be carried out for an individual country or for all countries simultaneously.

Two types of equations are at play in NEMESIS: (i) the accounting equations, reflecting the system of national accounts, and (ii), the behavioural equations, which capture, based on both theoretical and empirical grounds, how economic agents operate. The latter include long-term structural equations featuring an error correction mechanism that captures convergence towards the variables' long-term values. The key elasticity parameters of behavioural equations are either estimated using panel data techniques or calibrated based on consensus values arising from the relevant literature.

On the supply side, each sector is modelled with a representative firm that makes decisions regarding output and the use of factors, given expectations on demand and input prices. Firms produce output according to five-level nested-CES production functions, employing the following inputs: low-skilled labour, high-skilled labour, capital, energy and intermediate consumption. In addition, firms include innovation in their investment decisions to improve their productivity and/or their products, implying that technical progress is endogenously determined in the model. Innovation is the result of investments in three types of assets: R&D, ICT and Other Intangibles (including software and training). The specification of the innovation process in the model allows to account for a large range of innovative activities, including ICT, which are considered a general purpose technology (GPT). Furthermore, while R&D investments are central in industrial sectors, the other types of innovation assets capture more appropriately the process of innovation in the service sectors. Finally, interdependencies between sectors and countries are captured by a collection of matrices describing the exchanges of intermediary goods and capital goods as well as the flows of knowledge spillovers (using estimated technology flow matrices).

On the demand side, the representative household determines its aggregate consumption as a function of its disposable income arising from wages, capital income and social transfers. Child and old-age dependency rates are also included to capture changes in consumption patterns caused by changes in the structure of the population. The unemployment rate is used, in the short term, as a proxy for the perceived degree of uncertainty in the economy. Total aggregate household consumption is split into 27 different consumption sub-functions capturing relative prices, substitution elasticities and the specific nature of the products (e.g., durable/non-durable).

As for the general functioning of the model, the starting point of the economic dynamics in NEMESIS arises from a shock to some of the exogenous variables: demographic, world demand, exchange and interest rates, world commodity prices (including fossil fuels prices) and internal policy rules. The dynamics are recursive and based on three main elements: (i) state variables (stocks), (ii) adaptive expectations and adjustment lags, and (iii) adjustment processes to each variable's optimal level. There are two types of stock variables, namely physical capital and knowledge. Regarding the former, there is a maturation lag of one year to transform investments into operational capital. On the other hand, knowledge is generated through investment flows in R&D, ICT and other intangibles (OI), with maturation lags of two years for public R&D and one year for private R&D, ICT and OI. The transformation of knowledge into innovation is also progressive and affected by sector-specific lags. All these delays are important for the assessment of innovation support policies, which take about 15 years for their full impact to take place.

Looking at the innovation mechanism in greater detail, in the current version of the NEMESIS model, the flow of innovations in the different sectors and countries, do not result anymore only from public and private R&D investments, but also from investments in ICT and in two categories of intangible other than R&D, namely training and software. As in previous vintages

(Brécard et al., 2006), the model distinguishes between product and process innovations. The theoretical approach builds on the semi-endogenous and fully endogenous growth theory (Ha & Howitt, 2007). This approach has been adapted to be bridged with the concept of ICT as general purpose technology, as proposed by Bresnahan and Trajtenberg (1995). In the current framework, there are therefore sources of externalities other than investments in R&D. In particular, externalities can also arise from the interactions between: (1) producers and users of ICT, (2) ICT users' co-inventions, and (3) ICT users' investments in complementary intangible assets.

Finally, the current version of NEMESIS includes an energy-environment module that captures results on energy supply and demand by fuel type and technology, and on CO2 emissions. This will be adapted in the new TWINRD version of the model to improve the representation of twin digital and green technologies, by linking the model with GEM-E3 on the energy supply side and considering direct and indirect ICT energy effects on the demand side.

For the former, see section 2.3.2 below, while for the latter a useful taxonomy of ICT energy effects is provided in (Horner et. al. 2016). According to this source, direct energy use - referring to energy used during the operation, manufacture (embodied energy) and disposal of ICT equipment - is likely the simplest and least important ICT energy effect. The indirect energy effects are likely to be of much greater magnitude, owing to the breadth of the various mechanisms by which ICT services alter energy use. Furthermore, the electrical efficiency of computing has consistently doubled every 1.5 years, meaning that each kWh of direct energy use has the potential for ever-larger associated indirect effects. The following Figure 5 shows the taxonomy graphically.

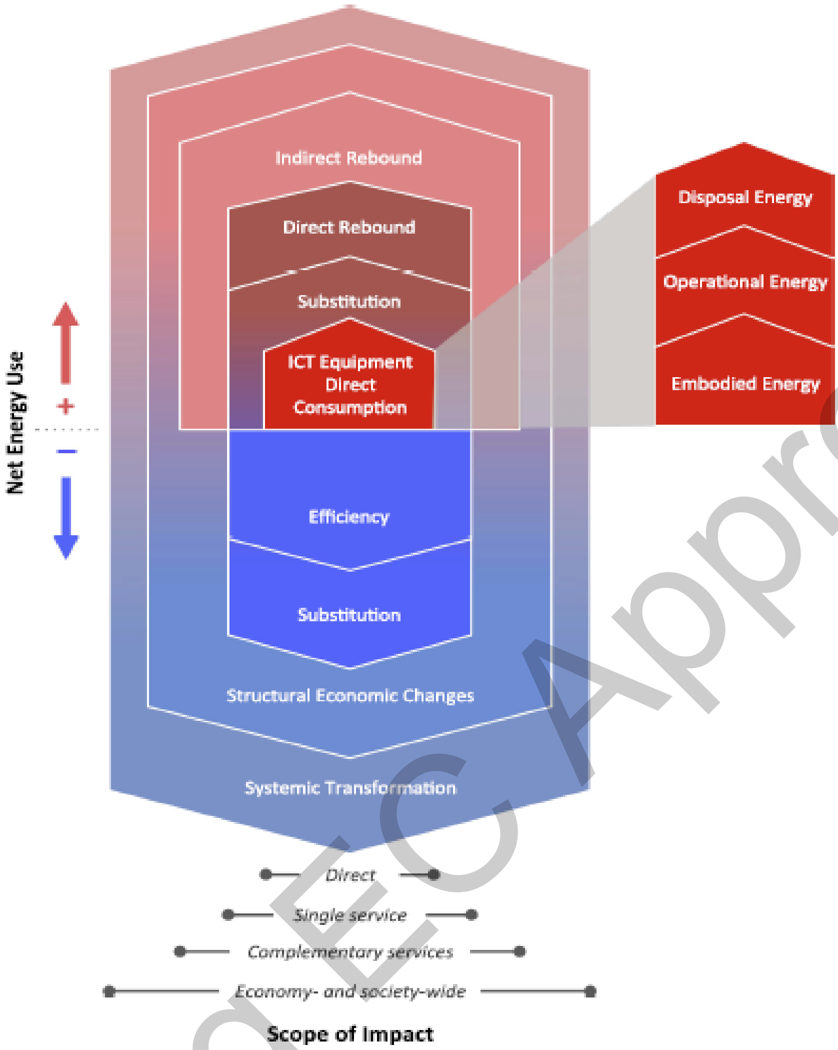


Figure 5. Taxonomy of ICT energy effects

First, ICT adoption leads to efficiency in and substitution for conventional products and services. Efficiency improvement occurs when, for example, smart building technology reduces air conditioning energy consumption by tailoring climate-control to the real-time needs of building occupants. An example of substitution is the replacement of air travel with teleconferencing. There is no guarantee, however, that the substituted ICT service will be less energy intensive than the conventional service it replaces, and even evaluation of simple cases is not always straightforward.[10]

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[10] An electronic billboard, for instance, may use more energy than a static, printed billboard, since it uses electricity to display the image. This energy consumption can be compared to the energy required to print the same image. However, the electronic version also avoids energy associated with changing the billboard—i.e., sending a worker out to make the switch. An additional complication is that the services are not strict functional equivalents: the electronic version allows animated displays, which may lead to higher success rates and profits—perhaps making energy consumption per successful ‘target’ lower even as per-billboard consumption is higher.

Second, any energy reduction achieved through efficiency or substitution can be plagued by rebound effects, in which expected gains are offset by induced additional consumption. Rebound is typically broken into direct rebound, indirect rebound, and economy-wide structural change effects. Direct rebound effects are energy service own-price-elasticity effects: as prices fall (due to improvements in efficiency or productivity), substitution and income effects increase consumption. For an ICT example, if an e-book is less costly than a conventional book, then consumers might purchase more books. Direct rebound is constrained by saturation: there is a limit to the number of books people will buy, no matter how cheap they become. Alternatively, these savings could be spent on other goods and services, which are indirect rebound effects. Indirect rebound effects result from cross-price elasticity of demand for other products and services due to increased real consumer income.

Third, economy-wide effects occur when the ICT introduction causes macroeconomic adjustments across economic sectors. That is, the ICT industry can promote or inhibit growth in other sectors of the economy, inducing structural changes that have energy use implications of their own. For example, e-commerce is having broad effects on the logistics industry, including growth in urban freight vehicle sales and changing patterns in distribution centre floor space, increased trucking and adoption of new pricing strategies by freight carriers, and use of more specialized packaging and a broader range of box sizes.

Fourth, and finally, systemic transformation effects refer to the altering of human preferences and economic and social institutions caused in part by the development of ICT. Historical examples include the advent of the telephone and automobile, which heavily altered where and how people lived and worked. We might conceive of a similar transformation (one of many possible ICT-enhanced futures) in which the fundamental constraints on where people live and work continue to loosen: e-commerce and home delivery make proximity to traditional retail outlets less important, seamless telework results in less commuting, and driverless vehicles allow for more productive use of the commuting time.

2.4.2. Representation of technological leadership and first mover advantages in the GEM-E3 modelling framework

Countries first adopting and developing a technology innovation are considered as a lead market, the market in which innovation takes place and the demand for the new technology is higher than in other countries of the world. This implies that firms can realize cost and quality advantages and technological leadership, as seen from such examples like the wind industry of Denmark. Technological innovation is associated with several interacting factors, including technological deployment, specialized human capital, public and private R&D expenditures, spillover effects between industries, sectors and countries and experience in specialised high-tech technology production. The potential of countries to become market leaders in a specific technology primarily depends on the following factors:

- **Price and quality competitiveness**: Competition is not only driven by price differentials but also by quality differentiation. This is especially the case for knowledge-intensive goods and services.
- **Export dynamics**: Innovations of a country should not only serve domestic demand but also be suitable for exports. Established export capacities of a country can enhance trade of new innovations.

- **Learning, innovation and absorption potential**: the ability of a country to perform technological learning and to absorb knowledge as well as its overall innovation dynamics.
- **Domestic demand**: A country which has an innovation-oriented demand and firmly supports new technologies can become a lead market.
- **Institutional framework**: Innovation-friendly regulation and subsidies for R&D investments.

Assessments of the potential first mover advantage of the EU have been conducted using variants of the GEM-E3 model in previous studies. As documented in European Commission 2017, the GEM-E3-FIT model was used to evaluate in quantitative terms the potential first-mover advantages that the EU economy can get from pursuing unilateral and ambitious climate policies and the role of spillover effects in assessing the economic and competitiveness impacts of climate and energy policies of the EU region. The GEM-E3-FIT model is equipped to perform this type of analysis as it comprehensively represents the sectoral structure of the economy and accounts for the complex interactions between the energy system and the overall economy.

As for the innovation dynamics, the GEM-E3-FIN modelling assumes that increased energy costs drive increases in R&D spending, which in turn enables productivity gains in the production of clean technologies and alternative low-carbon fuels. At the same time, high fossil fuel prices lead to substitutions towards clean energy forms and technologies but also higher spending in R&D to mitigate costs. Higher R&D spending enables productivity gains along the learning potential curves, which exhibit diminishing returns to scale. Gains take place primarily in the region or the country pursuing ambitious climate policies. A secondary effect simulated in GEM-E-FIT3 is that productivity gains are also spilled to a certain degree over other regions, because of technology diffusion, assumed to take place in addition to equipment trading. The use of R&D services increases productivity for specific production inputs or for products depending on the orientation of R&D. Improved productivity leads to lower factor prices and lower prices of products. Therefore, R&D expenditures induce lower prices and higher demand for the targeted products; this is the so-called learning-by-doing process, which in the model is calibrated to follow learning-by-doing potential curves with learning rates for each type of clean energy technology derived from extensive literature review.

As it concerns the way in which technological spillovers are incorporated in the GEM-E3 modelling for clean energy technologies, the type of spillovers that are taken into account into are the following:

- **Spillovers through trade**: Once a firm improves its product as a result of R&D expenditures this increases productivity in other firms to the extent that this is used as an intermediate product.
- **Spillovers through knowledge diffusion**: The knowledge generated in one firm as a result of R&D diffuses in other industries and countries according to a patent-citation matrix.

Knowledge spillover is introduced for both intra/inter-regional and intra/inter-sectoral flows. In line with the literature, time lags are imposed on both the development of useful knowledge

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from R&D expenditures to innovation and on the diffusion of this knowledge to other sectors or regions.

However, the current modelling approach of spillovers does not include: i) the impacts of patents with extreme value that can change radically production and consumption patterns (e.g. nuclear fusion) ii) the spillovers that are not covered by patents and typical R&D methods, e.g. knowledge spillover from biofuels to other crops iii) a quality assessment of patents (e.g. citation-weighted patent data analysis as in Jaffe and Trajtenberg, 2002).

BOX 1 – Macro-economic modelling limitations and priorities for TWINRD upgrades

In the following we provide a list of limitations currently observed in macroeconomic modelling approaches (e.g. **GEM-E3** — a multi-sector CGE with energy–environment blocks; **NEMESIS** — macro-econometric model of the EU; other large-scale CGE or macro-sectoral models). We then list priority model gaps to be addressed in TWINRD.

Common critical limitations

1. **Weak representation of enabling digital capital and complementarities.**
    - Many models treat digital goods as conventional final consumption or simple ICT investment categories rather than as *enabling capital* that raises the productivity of other capital (green technologies) or changes operating costs. Complementarity between digital and green capital is often missing or fixed exogenously.
2. **Innovation & R&D dynamics are too stylized.**
    - R&I is often modelled via aggregate productivity growth or exogenous TFP paths. Models frequently miss: directed R&D, knowledge spillovers (cross-sectoral, cross-border, cross-technologies), patenting mechanics, and time-lags between R&D, commercialization and diffusion.
3. **Limited firm heterogeneity and market structure.**
    - Aggregated sector representation masks differences between frontier firms that drive technology diffusion and laggards; models struggle to capture scale-dependent adoption, platform effects, or incumbent resistance to disruptive green/digital technologies.
4. **Insufficient treatment of adoption/diffusion and non-linearities.**
    - Diffusion dynamics (S-curves, network externalities, threshold effects) and path dependence are typically absent or represented simplistically; this understates transition inertia and the role of early policy interventions.
5. **Physical and material flows under-represented.**
    - Models focusing on monetary flows often ignore embodied energy/materials and critical-input constraints (e.g., semiconductors, rare earths), which are central to twin-transition feasibility and timing.
6. **Finance, liquidity and investment frictions.**
    - Financing constraints, risk premia on innovative green/digital projects, and public-private finance interactions are often absent or oversimplified.
7. **Labour market heterogeneity and skills transitions.**
    - Skills mismatch, retraining needs, and short- to medium-term unemployment due to structural change are not modelled with sufficient granularity for policy design.
8. **Spatial/regional differentiation is limited.**
    - National- or EU-level aggregates hide important regional differences in industrial structure, adoption capacity, and social impacts, which matters for cohesion policy.
9. **Policy sequencing and institutional constraints.**

  - Models usually simulate static or single-policy shocks rather than complex packages or sequenced policy mixes (e.g., R&D grants combined with procurement and market regulation).

R&I policy impacts that are often poorly captured include:

- **Directionality of innovation:** how policy steers the *type* of innovation (e.g., energy-efficient AI) rather than only the magnitude of R&D.
- **Time lags and incubation:** long gestation times between basic research, prototype, and market diffusion.
- **Cascading spillovers:** cross-sectoral spillovers from digital R&D to green productivity (and vice versa).
- **Public procurement and demonstration effects:** these demand-side levers are powerful but poorly modelled.
- **Network and platform effects** that amplify R&I returns in digital markets.

Priorities for future model developments - guidelines for TWINRD upgrades

1. **Model digital capital as enabling, complementary capital.**
   - Add explicit production functions where digital capital augments the productivity (or lowers operating costs) of green capital and services. Capture complementarities and substitution elasticities empirically.
2. **Endogenize innovation and diffusion.**
   - Introduce an R&D → patents/innovation → productivity/diffusion chain with time lags, directed R&D choices, and spillovers. Use patent/innovation indicators (PATSTAT, ANBERD) to parametrize spillovers.
3. **Add firm heterogeneity and adoption thresholds.**
   - At minimum, split sectors into adopters/innovators and laggards; ideally link with firm-level microdata (ORBIS/Amadeus) or use stylised agent classes.
4. **Integrate physical flows & critical inputs.**
   - Ideally link IO/FIGARO product detail to energy/material/clusters (semiconductors, critical minerals) so shortages and price feedbacks emerge endogenously.
5. **Represent financing and investment frictions.**
   - Ideally model asymmetric financing costs for high-uncertainty green/digital projects and test policy instruments (guarantees, concessional finance).
6. **Explicit modules for policy mixes and sequencing.**
   - Implement policy levers (R&D subsidies, standards, public procurement, taxation, regulation) within scenarios to study sequencing and interactions. Run counterfactuals for policy mixes: R&D grants combined with procurement, regulation of digital platforms and targeted industrial policy (e.g., chips & battery supply), and compare outcomes on emissions, GDP, employment and regional inequality.

3. The potential future impact of key green and digital technologies

The green transition aims to achieve sustainability, and combat climate change and environmental degradation. At the same time, the growing significance of digital technologies is transforming societies and economies. In the digital transition, the European Union aims to harness digital technologies for sustainability and prosperity, and to empower citizens and business.

To unlock their potential and to prevent negative effects, the green and digital transitions require a proactive and integrated management, as a “twin” transition.

The study “Towards a Green and Digital Future” (Muench, S. et al, 2022) examines how the European Union can ensure that the green and the digital transitions mutually reinforce each other, analysing how current and future digital technologies could become key enablers for the green transition by 2050, which is when the European Union aims to be climate neutral. It also examines tension points between the twin transitions, such as how digital technologies might bring additional environmental burdens with them. The study takes also a closer look at five economic sectors that are among the highest greenhouse gas emitters in the EU: 1) agriculture, 2) buildings and construction, 3) energy, 4) energy-intensive industries (steel, cement, chemicals, paper and pulp), and 5) transport and mobility.

The study is the result of an eight-month participatory foresight process. It takes the goals of the twin transitions as a starting point and examines technologies that could be developed and combined to get there. It also looks at the obstacles that might arise. This foresight process included a thorough literature review and continuous expert engagement in discussions and workshops. The results of this process have been validated through further workshops and conferences with a wide range of stakeholders from academia, civil society, public administration, and industry. In total, over 200 experts participated in the foresight process.

In TWINRD we will take stock of the results of the study, considering the highlights illustrated in the following sub-sections.

3.1. What are the goals of the twin transitions

The green and digital transitions are two main trends that will shape the future of the European Union. The term “twin transitions” refers not only to two concurrent transformational trends (the green and digital transitions); the term also refers to uniting the two transitions, which could accelerate necessary changes and bring societies closer to the level of transformation needed. To succeed with the green and digital transitions, a better understanding of the possibilities to link them is fundamental, especially when it comes to knowing what must be done most urgently.

While both transitions will transform our societies and economies, they are different in nature and in their dynamics. The green transition is driven by the need to reach the aims of climate neutrality and sustainability, and to reach them quickly. It will not happen on its own and requires a political and societal push. In contrast, the digital transition is an ongoing process of technology-driven change, with the private sector as one of the primary drivers. Therefore, steering and support are important to make sure that the digital transition becomes a powerful instrument for achieving a fair and just green transition.

In many areas, the green and digital transitions can reinforce each other, but they do not necessarily always align. Digital technologies can be key enablers for reaching the European Green Deal objectives. For example, cities are responsible for approximately 75% of global

CO2 emissions. Smart cities and communities are possible solutions to reduce these emissions and show how the twin transitions can take place in a holistic, systemic manner. Information and Communication Technology-based solutions could reduce commuting by 15-20% and cut greenhouse gas emissions by 10-15%, while local Digital Twins could significantly improve cities' ability to simulate or model the impact of policies. At the same time, there are areas where the two transitions can hamper each other. For example, the expansion of digital infrastructure will need to be kept in line with the aims of the green transition, particularly regarding the energy consumption and the environmental footprint of such digital infrastructure.

Taking an integrated approach to the challenges of reaching successful twin transitions is therefore essential to avoid the traps of pushing two agendas separately. The green and digital transitions run in parallel but linking them could allow us to benefit from synergies and manage the risks. Given the wide-reaching nature of these transitions, it is essential to examine their complexity and possible outcomes and consequences of their interactions.

3.2. Which contextual factors are relevant for achieving the twin transitions?

Taken together, the green and digital transitions are about profound changes in our way of life. Their implementation will depend on multifaceted and often interconnected economic, social and political contextual factors. As in past transitions, technology will play a role, but it is unlikely that the changes needed to succeed with the twin transitions will be solely technology driven. For example, massive changes in behaviour and social norms are needed for many innovations, such as moving from owning a car to car-sharing.

Given the purpose of enhancing the analysis of macro-economic impacts of investments in new green and digital technologies, in TWINRD we can consider the following core highlights on economic factors[11]:

- **The costs associated with the twin transitions can be a significant barrier to change**. In many areas, there are significant sunk costs associated with the transformation of sectors. For example, businesses may be reluctant to abandon the infrastructure, or the methods (e.g. established procedures) that they have invested in. These create path dependencies and lock-ins, which give existing technologies an advantage over new technologies.
- **Technological innovation can create new economic opportunities**. As the transitions progress, increasing returns from economies of scale and scope for green and digital technologies could create new markets. With green and digital technologies becoming more widespread, they can open up new development paths and lead to more innovation. Industry networks can expand activities around a green-digital solution through supply chains, infrastructure, and complementary technologies. This expansion can lead to new business opportunities. The expected shifts between sectors because of the twin transitions indicate how the economy could adapt.

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[11] The study describes social and political factors as well.

- **The impact of the twin transitions on employment and skills needs are also central issues**. Each economic sector will be impacted differently, and many of the new technologies and methods require skills and labour that is not readily available in today's economy. Examples of skill gaps are digital skills or building renovation skills. Some sectors may lose jobs (e.g. coal, oil and gas) and some regions of the European Union will be more affected than others. Reskilling is therefore an essential factor to bring workers into new or changing sectors.
- **Financing is an essential steppingstone for twin transitions**. Financing can be the determining factor for whether green-digital solutions see the light of day. Many of the technologies and solutions needed have reached 'technological readiness' but will need various complimentary funding sources and mechanisms to succeed. Investments are being directed towards the green and digital economy today, but much capital still flows into the old economy. This is in part due to investment incentives that follow market prices, which do not account for social and environmental long-term costs. Sustainable finance has the potential to drive the green transition.

3.3. How can digital technologies support twin transitions?

The digital economy is crucial for the competitiveness of the European Union and can help to drive the green economy. There is a strong political commitment to deliver on Europe's 'digital decade' by harnessing the full potential of the digital transition. A thriving digital economy is instrumental not only for the competitiveness of the European Union, but also for the green transition. Digital technologies can be an enabler for the transition towards a green economy, which is sustainable, fair, and inclusive.

The digital technology landscape has been rapidly evolving over the past three decades. The main drivers of the digital transformation are companies, particularly in the computing and internet sectors. These companies are mostly located outside of the European Union. Their growth and development are, to a large extent, driven by advancements in computing power, data storage capacity, and algorithms. The scope of the digital technologies considered in the study includes: Artificial intelligence and smart robotics; data-driven technologies; Internet of Things (IoT); computing infrastructure; communication technologies; software and service technologies; distributer ledger technologies (blockchain); bio-inspired and neuromorphic computing; extended reality and metaverses; other.

Emerging digital technologies have a lot of future potential for the green transition. Looking towards 2050, DNA-based digital data storage offers the possibility of storing data much more efficiently, with information densities ten million times higher than the storage options available today. For the green transition, this efficiency coupled with lower cooling requirements of DNA-based data storage results in a much lower energy consumption. Quantum computing and novel approaches to computing promise computing power far beyond the capabilities of current computers. This leap in computational power opens up new possibilities and could allow for the optimization of many current practices. It can, for example, compute and simulate molecular behaviour to find viable options to create next generation batteries or more efficient processes to produce nitrogen-based fertilisers, which are needed for the agriculture sector. Quantum computing can provide simulations of large complex molecules, which could, for example, lead to discoveries of new and more efficient catalysts for carbon capture.

Solutions and innovations may lie in the combination of digital technologies. Digital technologies are not independent of one another, there are several connections and interdependencies between them. In fact, the combination of different digital technologies and tools could in itself be an impactful innovation for greening. The Internet of Things is an example of the combination of several different digital technologies with breakthrough potential. Here, devices, sensors, and wearables have been adapted following the mass usage of smartphones and other devices that are now used as a gateway to connect to the internet. This change is fuelling the uptake of Internet of Things-connected devices, relying on smartphones, geolocation technology, and constant and secure internet connectivity. It is therefore important to look not only at emerging digital technologies, but also at new combinations and applications of the existing digital technologies available to us already today.

Digital technologies provide functions that can catalyse the green transition. *Monitoring and tracking* can provide real-time information and be a catalyst for the circular economy. *Simulation and forecasting* can improve efficiency, for example in the form of Digital Twins that can simulate the entire life cycle of a product or process. *Virtualization* of production and consumption changes sectors and reduces environmental impact by moving economic activities online, especially if the digital technologies are energy-efficient and circular. Using digital technologies, *systems management* can cope with an increasing complexity while optimizing operations, for example in smart cities. Lastly, digital *information and communication* technologies enable new levels of interaction. Data and data analysis will be the backbone of the green and digital transitions. Modern information and communication technologies, such as sensors, can help to collect and disseminate such data.

While there is a potentially large contribution by digital technologies to the green transition, their increased use can come at a cost for the environment. This impact results from different processes involved in building and running digital systems, such as the resources required to manufacture digital and electronic technologies (including the exploitation of rare elements and critical materials), the high quantity of energy required to run them, and the resulting nonrecyclable and partially toxic waste. However, the green transition is also affecting digital technologies because they too have to reduce their environmental impact. Digital technologies, and the electronic components and systems value chain, could be transformed towards environmental sustainability. Towards 2050, emerging digital technologies, such as quantum computing, bio-based electronics, or self-powered devices could support a digital transition that is also climate- and environmentally friendly. At the same time, digital technologies and infrastructure will need to build up resilience to the effects of climate change, such as temperature increases and extreme weather events.

3.4. How can the goal of green transition be met in key sectors?

The study focuses on the green transition in the five sectors emitting most greenhouse gases in the European Union, namely agriculture, buildings and construction, energy, energy-intensive industries, and transport and mobility. An overview of each sector is presented together with the main trends and challenges. The main sub-sectors and key green technologies are presented in order to illustrate future innovation timelines for them to become more environmentally friendly towards 2050, as well as how digital technologies can support the green transition in the sectors. Lastly, case studies outline the advantages, challenges, and possible implications of two specific examples of green-digital solutions per sector and provide a brief “snapshot of a possible future” to sketch out what the solution might bring by 2050. The specific examples for each sector are shown in Table 5:

Table 5. Green-Digital solutions per sector

Sectors	**Green-Digital solutions case studies**
Agriculture	Digital environmental monitoring systems Smart sustainable farming
Buildings and construction	Reduced demand for space Integrated building design and redesign
Energy	Meshed microgrids and self-organized grids Energy-As-A-Service
Energy-intensive industries (steel, cement, chemicals, paper and pulp)	Data-driven materials optimization Materials tracing for circularity
Transport and mobility	Mobility-As-A-Service Digital Twins in transport

In the context of TWINRD we can consider these sectoral results while focusing on twin transition scenarios and modelling economic and environmental impacts for the same key sectors, taking stock of the case studies’ outcomes and using the innovation timelines produced for each sector (reproduced in the following pages). These are useful inputs for delineating an updated future technological landscape which will be presented and discussed with the stakeholders invited at the first TWINRD workshop (in WP6).

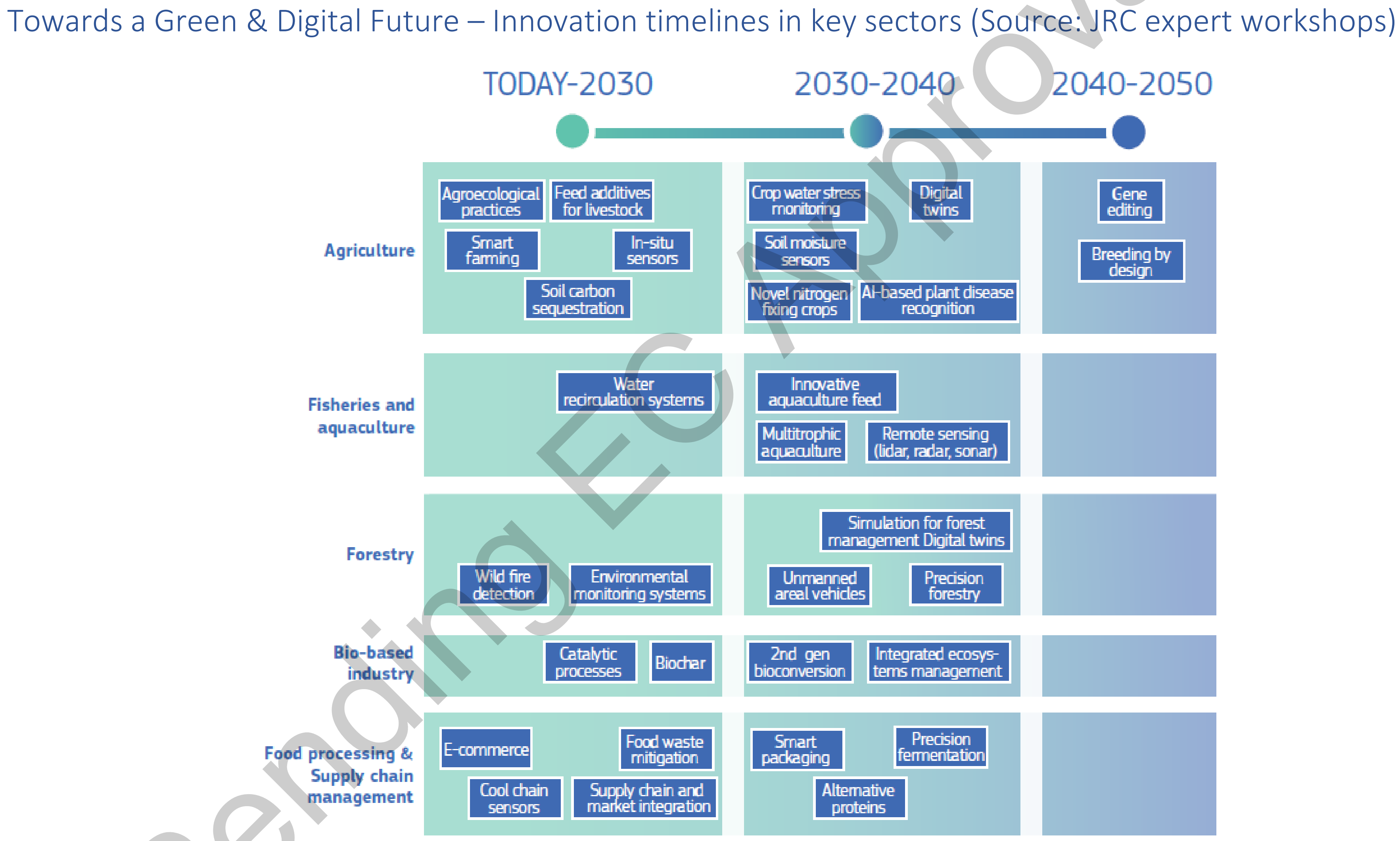

Figure 6. Green & Digital technology innovation timeline in the agriculture sector

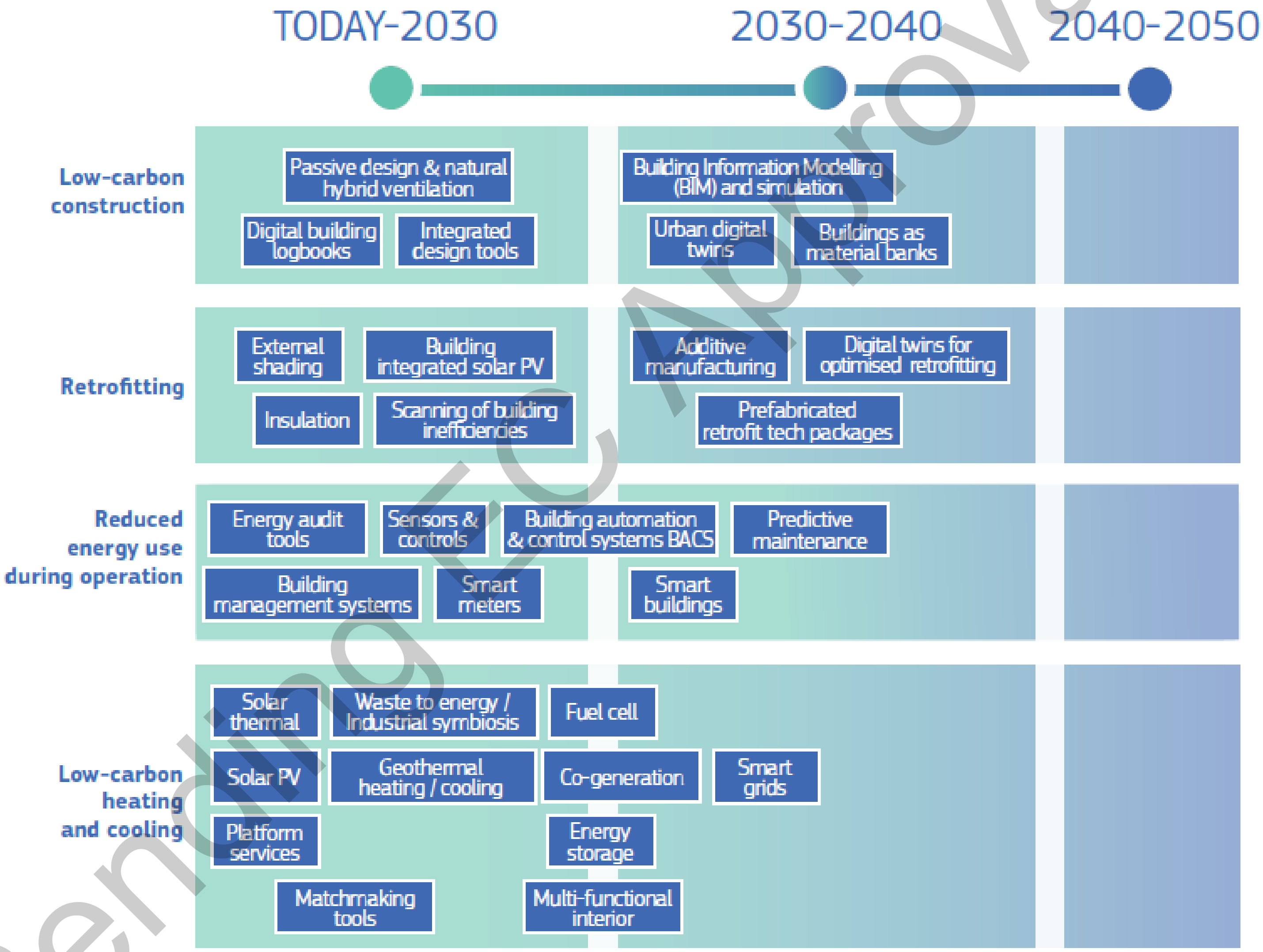

Figure 7. Green & Digital technology innovation timeline in the construction sector

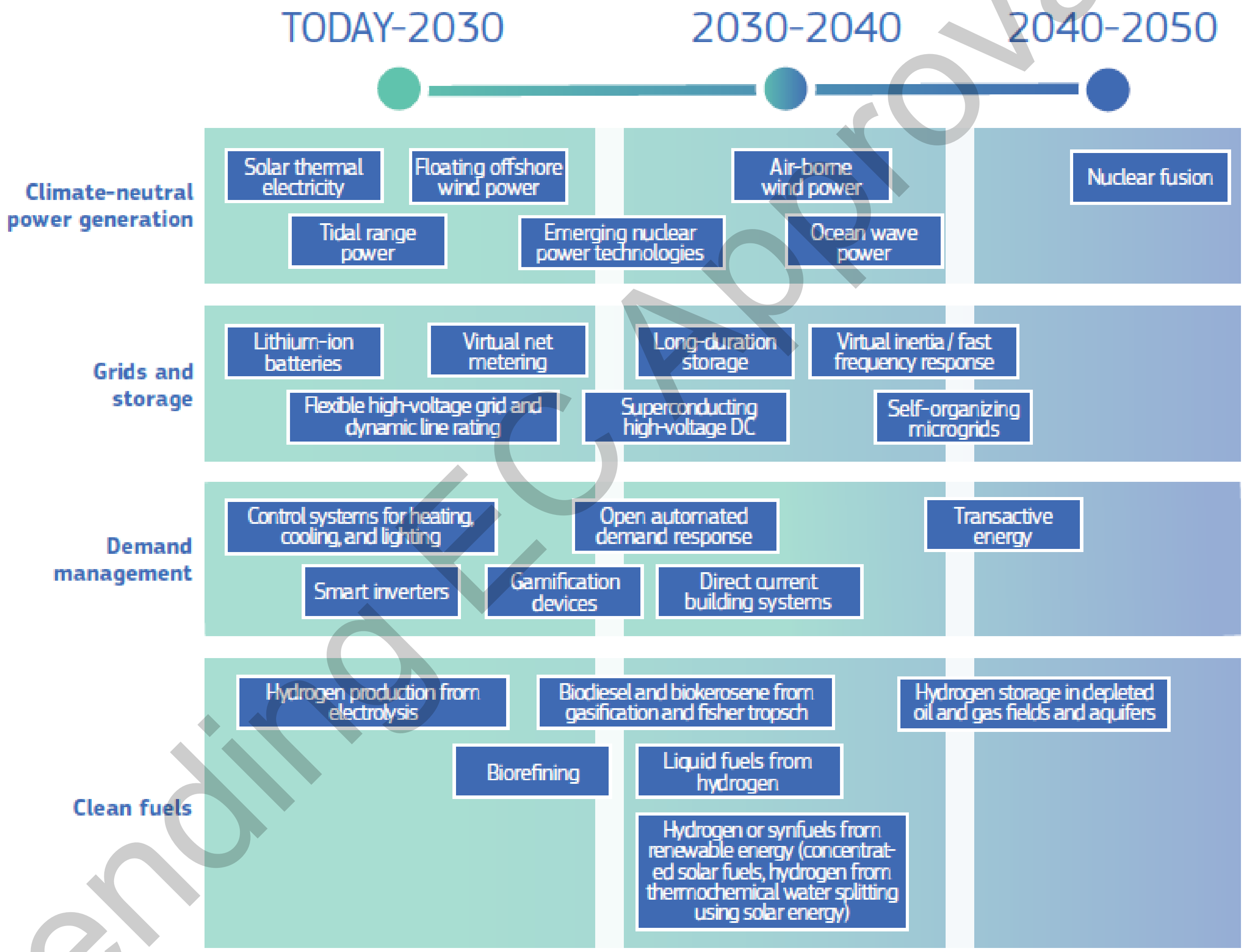

Figure 8. Green & Digital technology innovation timeline in the energy sector

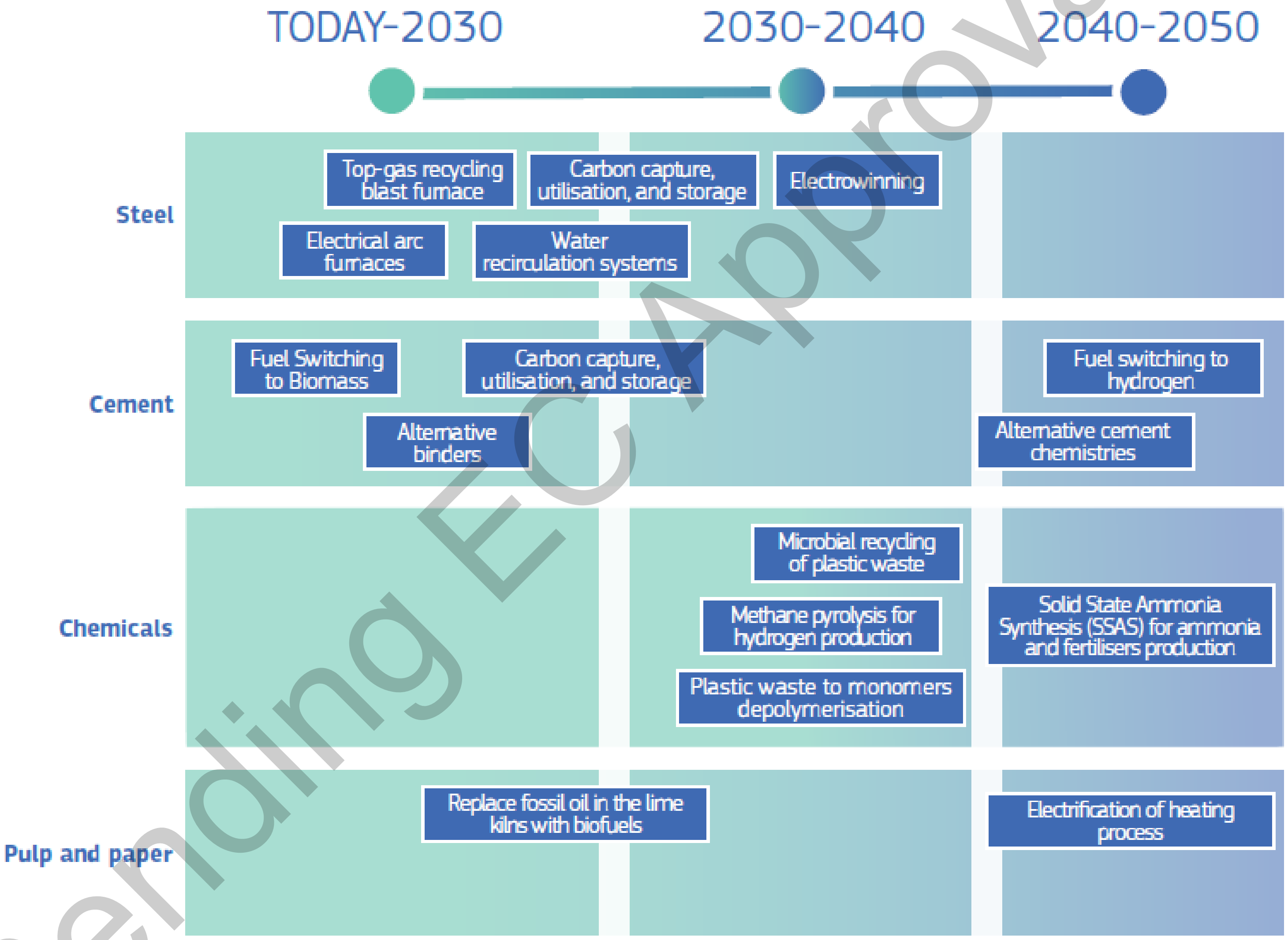

Figure 9. Green & Digital technology innovation timeline in the energy-intensive industries

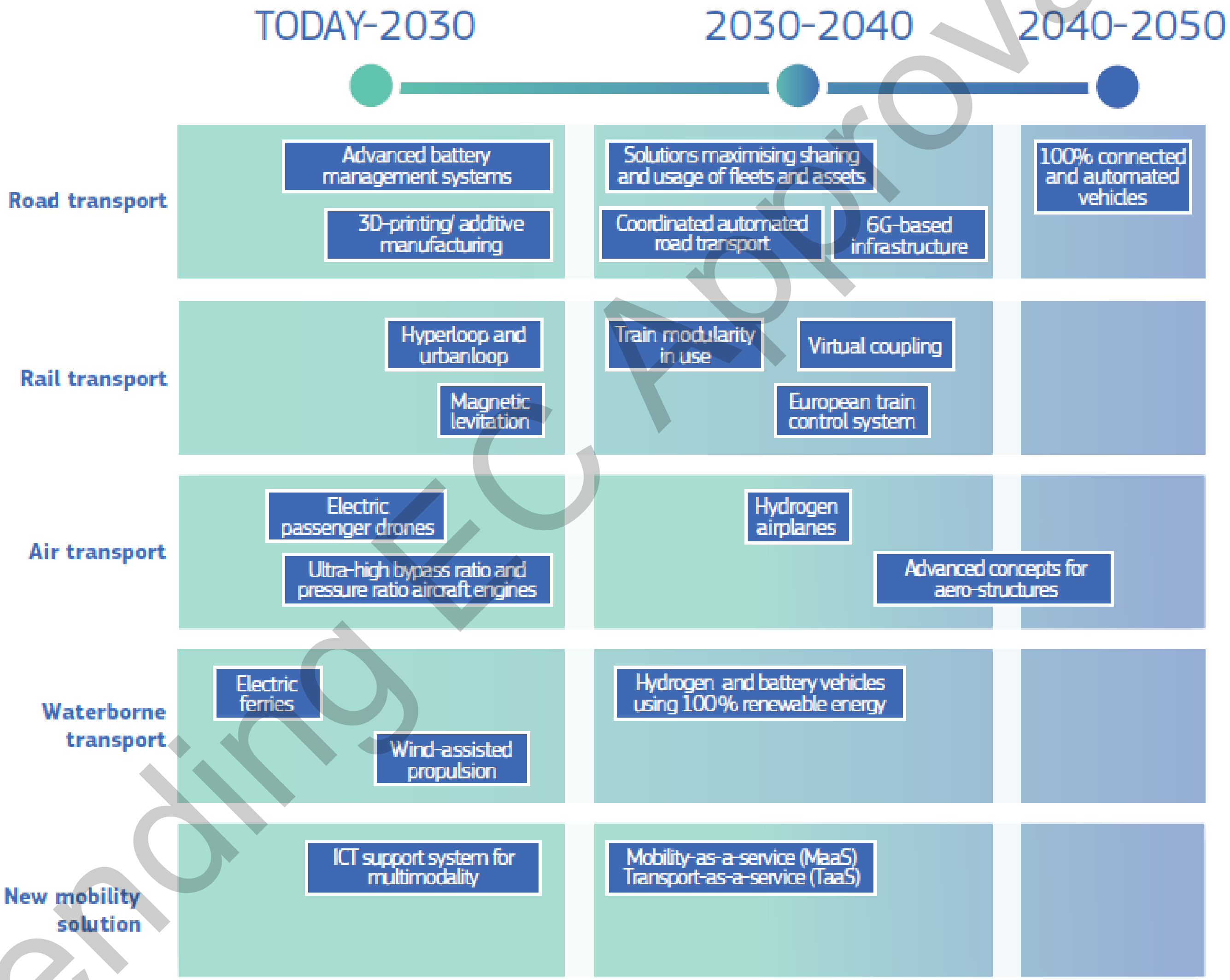

Figure 10. Green & Digital technology innovation timeline in the mobility and transport sector

4. Conceptual framing of regenerative transitions beyond sustainability

4.1. From sustainability to regeneration: the evolution of the concept

It is now more than 30 years since Brundtland defined sustainable development, broadly defined as not doing anything today to compromise tomorrow's generation, and in doing so defined sustainability for business and enterprises globally. But the prevalence of a linear and degenerative economy has weakened the planet's regenerative capacity, making it harder and harder to achieve this ambition.

Sustainability has become a necessary but insufficient condition for long-term human welfare. Next to sustaining, there is a growing need to regenerate our and the planet's ability to meet present and future needs. This has given rise to the field and idea of **regeneration**. The term essentially refers to the *ability of a system to remake or renew itself continuously*, and it has its origins in biology and natural sciences, relating to the ability of cells, organisms and ecosystems to renew themselves. As a process it is essential to biological systems and describes their capacity to bring into existence again.

The starting point for regenerative thinking is the realization that humans are embedded in, part of and fundamentally dependent on nature. We are indeed in a situation where rapid change to a healthy relationship with the planet is in order. Nowadays, the concept of "regeneration" and "regenerative economy" moves our frame of discourse from "doing things to nature" to "participate as partners with and as nature".

By taking a regenerative worldview, we can radically change the concept of sustainability. The question in *sustainable development* was "How can the economy work in such a way that we sustain or do not hurt the underlying ecological and social support systems?" Now, the question in *regenerative development* becomes "How can the economy work in such a way that we improve the capacity of the underlying support systems?"

Regenerative organizations take a more holistic view of their business practices and aim to regenerate the natural and societal spaces in which they operate, promoting the self-renewable capacity of natural systems that have been damaged or overexploited, through a co-evolutionary process, where organizations align their activities with the living systems that surround them. Their business model asks to deliver a **net positive environmental and social impact**, which is achieved when the benefits created by an organization's product or service (*handprint*) are bigger than the negative impact that this same product or service creates along its life cycle (*footprint*).

In practice, "regenerative" and "net positive" can be considered equivalent attributes: for a business activity to qualify as regenerative it is no longer enough not to do harm by neutralizing its own impact on the environment and society (*net-zero*), it needs to do good by delivering an eventually positive impact (*beyond net-zero*), as illustrated in Figure 11 below.

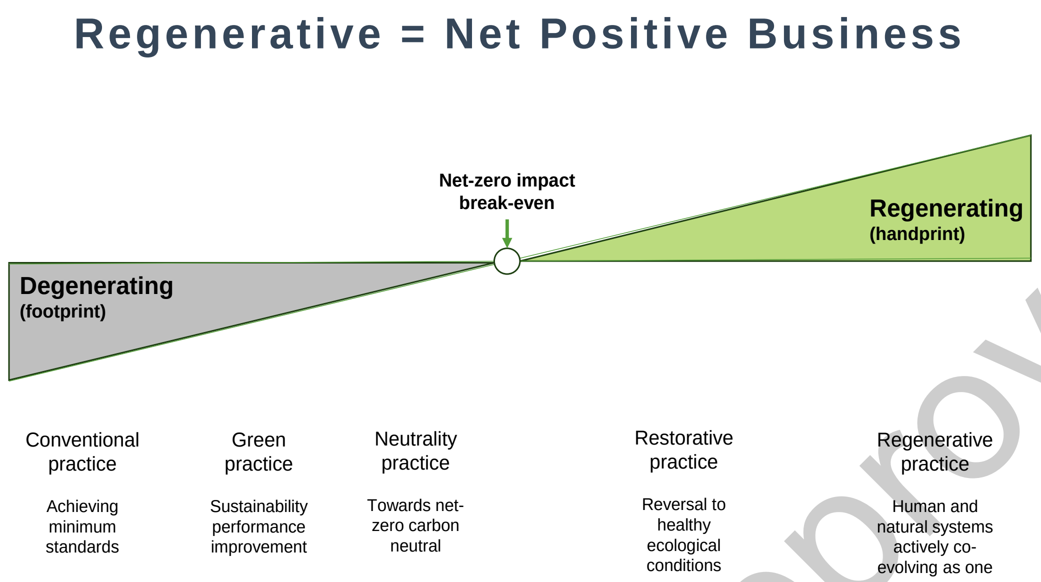

Figure 11. Shifting towards regenerative practices

The figure is conceptual, with the vertical axis representing some measurement of the whole economic and social impact of the economy and showing a gradient from negative impact on the left to positive impact on the right[12]. It conveys a key message: we no longer have the luxury of just **doing less bad** – driving the conventional linear economy model towards sustainable (green) and even circular models to neutralize the impacts on the environment and society (Net-Zero break-even target) – we need **doing more good** to deliver positive impacts on the people well-being and planet health, beyond the Net-Zero break-even. In a nutshell, the concept of sustainability is expanded to include the shift to restorative and regenerative economic systems, adopting the following definitions:

- **SUSTAINABILITY:** Limiting impact, to achieve the balance point where we give back as much as we take
- **RESTORATIVE:** Restoring social and ecological systems to a healthy state
- **REGENERATIVE:** Enabling social and ecological systems to maintain a healthy state and to co-evolve with a regenerative economy which creates conditions supporting life in all its forms.

To better understand what regenerative economy is, it is useful to highlight the differences from two other neighbouring concepts: sustainable and circular economy. Differences and overlaps among the three concepts of sustainable, circular and regenerative economy are presented in Figure 12 below.

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[12] Measuring total social and environmental impacts of an economic system is obviously complex and can be undertaken for specific contexts and using appropriate assessment methodologies. The intention of the graphic is only to visualize the rationale underpinning the definitions of sustainability, restorative, regenerative economies.

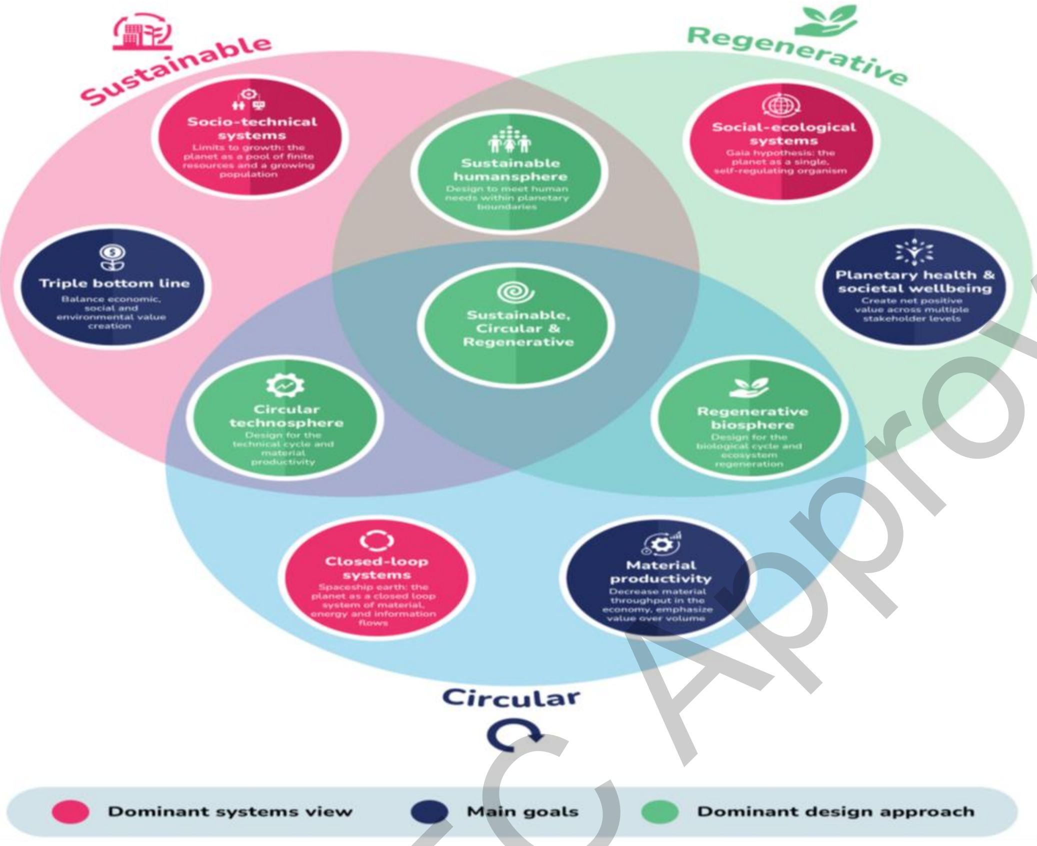

Figure 12. Intersections between sustainable, circular and regenerative business models

As explained by the authors of this figure "we frame the differences and overlaps in terms of dominant systems views, main goals, as well as the design foci. In their dominant systems view, we find that sustainable business models focus primarily on socio-technical systems, circular business models on closed-loop economic systems, and regenerative business models on social-ecological systems. In terms of their main goals, sustainable business models focus on the triple bottom line (i.e. achieving a balance between economic, social and environmental value creation), circular business models on material productivity, and regenerative business models on planetary health and societal wellbeing." (Konietzko et al., 2023, p. 377).

The elements which help to distinguish sustainable, circular and regenerative business models – their main target, strategy and design approach - are summarized in Table 6 below.

Table 6. Overview of sustainable, circular and regenerative business features

BUSINESS			
Model	**Target** **(making profit by)**	**Strategy**	**Design approach**
Sustainable	Balancing economic, social and environmental value creation (triple bottom line)	Mitigate negative impact on nature and communities	Sustainable design for meeting human needs within planetary boundaries
Circular	Increasing material productivity	Organize closed-loop economic systems to minimize material and energy throughput, while maximizing value creation	Circular design for recycling manmade materials and durable products
Regenerative	Enhancing health and well-being in socio-ecological systems	Focus on integrated and interdependent systems and human society, ecological health and human well being	Regenerative design of nature based solutions contributing to ecosystems restoration and human well being

Still another way to visualize the differences between sustainability, restorative and regenerative is classify established concepts that can be found in the broad field of "sustainable development" according to how they fit with the three stages of sustainability, restorative or regenerative impact, as it is exemplified in Figure 13 below.

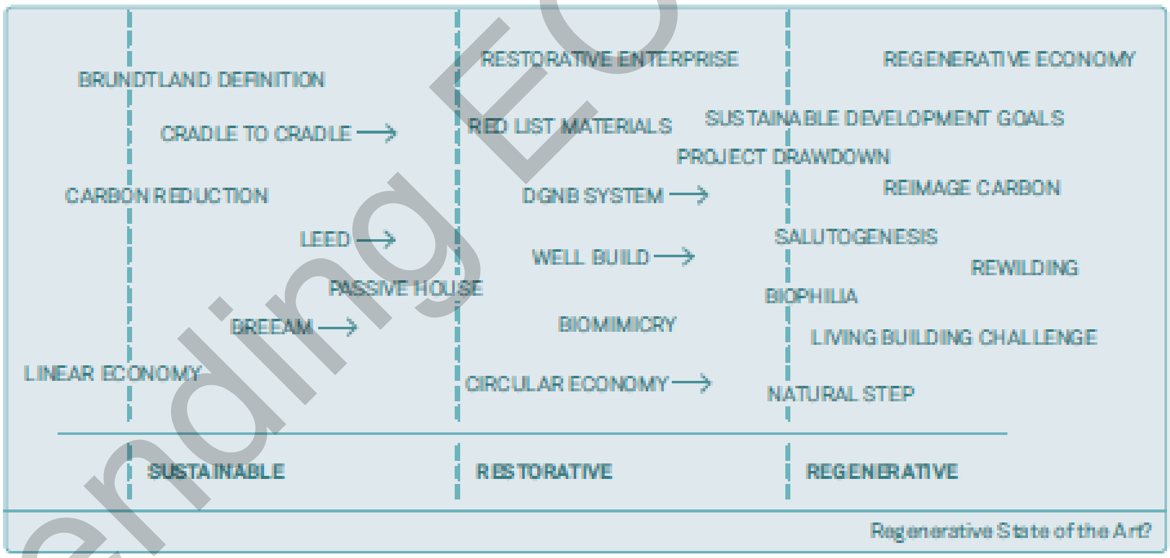

Figure 13. Sustainable, restorative and regenerative concepts

Finally, the most empirical way to define regeneration is to describe concrete examples of *regenerative practices*. These can be increasingly found in fields such diverse as agriculture, design, conservation, tourism and built environment.

The most dominant industry in the regeneration literature is food and agriculture, which occupies large areas of land and has more than 50 % of the estimated overall pressure on nature and biodiversity (Kurth et al., 2021). The literature contains extensive reference to regenerative agriculture and its potential to improve species abundance, soil health and fertility, or store carbon through agroforestry. Another important legacy industry for regenerative thinking in business is the built environment (including infrastructure), because it is material intensive and co-occupies vast areas of land with nature (Robinson and Cole, 2015; Mang and Reed, 2020). There is a direct opportunity for organizations in this industry to source materials from regenerative sources, create more biodiverse habitats for other living species in cities and surrounding areas, and align buildings and infrastructure more closely with water, air, soil, carbon, and nutrient cycles.

A useful comprehensive collection of regeneration practices can be accessed on the www.regeneration.org website. This is based on the recent Paul Hawken book "Regeneration. Ending the Climate Crisis in one generation", and it is an organized cornucopia of information, ideas, groups, videos, books' references, and people who are implementing regeneration worldwide and who welcome support and involvement. The information is organized using the concept of "nexus" to identify regeneration practice challenges and/or solutions. Nexus are large, complex issues that intersect multiple institutions, geographies, cultures, and people, but which do not fall under a single category of action or impact. For each nexus category, the website provides: clear descriptions of the issues, history, players, and impacts; the specific parties actively causing degradation and damage; lists of NGOs, activists, affected populations, and other institutions that are addressing the issue; contact information of CEOs, politicians, or other people who are key decision-makers; useful links to videos, conferences, documentaries, articles and papers.[13]

4.2. Framing sustainable, restorative, regenerative twin transition pathways

Tacking stock from the concepts of sustainable, restorative and regenerative development presented in section 4.1, we translate them in this section into a schematic frame of transition pathways to 2050, useful to feed the strategic foresight framework for the co-creation of twin transition scenarios with the stakeholders, in WP6.

Again, we suggest a schematic description, in a nutshell, of the three concepts:

SUSTAINABLE

Core logic: *Do less harm; stay within limits.*

Sustainability focuses on reducing negative impacts and improving efficiency so that human activity does not exceed ecological and social carrying capacity. Systems are optimized to reach a balance point where extraction and emissions are offset by mitigation and substitution. The underlying structures of production and consumption largely remain intact; the emphasis is on incremental improvement, control, and compliance.

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[13] The website is open source, and participation is welcomed to help improve, add and update the information on regeneration practices.

Typical question: *How can we meet today's needs with fewer resources and lower emissions?*

RESTORATIVE

Core logic: *Repair damage; bring systems back to health.*

Restorative approaches go beyond limiting harm by actively reversing degradation in ecosystems, infrastructure, and social systems. The goal is to return systems to a functional, healthy state, often by rebuilding natural capital, social trust, or degraded assets. Digital technologies are used to diagnose, target, and accelerate recovery, but the reference point is usually a past or baseline "healthy" condition.

Typical question: *How can we fix what has been damaged or depleted?*

REGENERATIVE

Core logic: *Create conditions for ongoing vitality and co-evolution.*

Regeneration shifts the focus from outcomes to systemic capability: enabling social and ecological systems to self-renew, adapt, and co-evolve over time. Humans are not external managers but participants in living systems. Digital technologies become enablers of learning, feedback, coordination, and collective intelligence, supporting diversity, resilience, and emergent value creation rather than optimization around fixed targets.

Typical question: *How can human activity increase the capacity of life-support systems to thrive?*

Taking stock of these three concepts, we can define the sustainability, restorative, regenerative potential of green and digital technologies as follows:

- **Sustainable** technologies primarily **optimize and constrain.**
- **Restorative** technologies **intervene and repair.**
- **Regenerative** technologies **enable learning, adaptation, and mutual flourishing**.

In practice, many twin green–digital technologies start as sustainable, are deployed restoratively, and only become regenerative when embedded in governance, culture, and long-term stewardship frameworks. Technological capability is rarely the limiting factor; the intent and system design are.

Moving one step further, we suggest below a frame to connect **twin green–digital technologies** explicitly to **2050 climate-neutrality pathways**, sharpening the distinction between technologies that primarily **reduce**, **neutralize**, or **create net-positive impacts**. The framing aligns well with long-term pathway thinking (efficiency → balance → regeneration), including three pathway logics towards (and beyond) 2050:

A. Footprint-reduction pathways (SUSTAINABLE)

Climate role: Bend the emissions curve downward fast
System logic: Efficiency, substitution, optimization
Carbon framing: *Less negative (reduce harm)*
2050 function: Necessary precondition, but insufficient on its own

These pathways focus on reducing gross emissions across energy, mobility, buildings, industry, and food systems. Digital technologies act as control and optimization layers, accelerating diffusion and performance of low-carbon solutions. However, they largely preserve current system structures and therefore approach—rather than reach—climate neutrality.

B. Neutralisation pathways (RESTORATIVE / NET-ZERO)

Climate role: Close the gap to net-zero
System logic: Balancing, circularity, repair
Carbon framing: *Zero net impact*
2050 function: Core condition for climate neutrality

Here the objective is to neutralize remaining emissions by restoring carbon sinks, closing material loops, and repairing degraded systems. Digital technologies support measurement, verification, coordination, and circular flows, enabling credible net-zero pathways at system level (cities, regions, sectors).

C. Net-positive pathways (REGENERATIVE)

Climate role: Go beyond neutrality
System logic: Co-evolution, resilience, living systems
Carbon framing: *Positive contribution*
2050 function: Safeguard long-term human and planetary welfare beyond neutrality

Regenerative pathways aim to increase the capacity of social–ecological systems to absorb carbon, support life, and adapt. Digital technologies here function less as optimizers and more as enablers of collective intelligence, learning, and stewardship, supporting continuous improvement rather than fixed targets.

Considering now these three transition pathways categories and an indicative typology of twin green and digital technologies, we can construct the following matrix filled with examples of potential sustainable, restorative and regenerative future impacts (Table 7):

Table 7. Classification of twin transition technologies by environmental impact:

Twin green–digital technology	**Reduce footprint *(SUSTAINABLE)***	**Neutralize impact *(RESTORATIVE / NET-ZERO)***	**Create net-positive impact *(REGENERATIVE)***
Smart energy & grids (AI + renewables)	Optimize demand–supply, reduce losses, accelerate	Balance residual fossil use with storage, sector	Enable local energy ecosystems that strengthen resilience

Funded by the European Union

	renewables integration.	coupling, and grid flexibility.	and social value creation.
Digital twins (cities, regions, industry)	Simulate efficiency gains and emissions reduction scenarios.	Identify pathways to net-zero and monitor progress in real time.	Support continuous experimentation and adaptive territorial transformation.
Industrial AI & smart manufacturing	Improve energy and material efficiency per unit of output.	Enable circular production, remanufacturing, and closed-loop supply chains.	Foster industrial ecosystems that regenerate skills, regions, and resource bases.
Precision agriculture & food systems	Reduce emissions from inputs and logistics.	Restore soils as carbon sinks and close nutrient cycles.	Enable regenerative agriculture that enhances biodiversity, resilience, and rural livelihoods.
Carbon monitoring, MRV & digital carbon markets	Improve accounting and transparency of emissions reductions.	Verify removals and balancing mechanisms for credible net-zero.	Enable place-based carbon stewardship linked to ecosystem and community regeneration.
Nature-based solutions + digital sensing	Protect existing carbon sinks more efficiently.	Restore degraded forests, wetlands, and peatlands to neutralize emissions.	Build living landscapes that co-evolve climate stability, biodiversity, and social value.
Mobility platforms (digital + clean transport)	Reduce emissions through modal shift and efficiency.	Balance residual emissions via urban redesign and circular mobility systems.	Support human-scale, low-energy living patterns that improve wellbeing and inclusion.
Digital governance & participation platforms	Improve policy coherence and implementation efficiency.	Enable collective decisions needed for net-zero transitions.	Build long-term societal capacity for learning, foresight, and regenerative governance.

Summing up, we can make a sharp distinction between:

- **Sustainable twin green–digital technologies**
  → *Help us emit less while doing largely the same things*.
- **Restorative (net-zero) twin green–digital technologies**
  → *Help us balance what we still emit by repairing and closing loops*.

- **Regenerative twin green–digital technologies**
  → *Help us redesign how we live, produce, and govern so that human activity strengthens life-support systems*.

and draw the following implications for 2050 sustainable, restorative and regenerative pathways:

1. **All three are required**, but **not equally at all times**:
    - 2020s–2030s: dominance of **sustainable (reduction)**
    - 2030s–2040s: scaling of **restorative (neutralization)**
    - Post-2050: consolidation of **regenerative (net-positive)**
2. **Technology maturity ≠ pathway role**
   The *same* digital technology can serve all three pathways depending on:
    - Governance design
    - Ownership and participation
    - Spatial and temporal scale
3. **Climate neutrality is a threshold, not an endpoint**
   Without regenerative pathways, net-zero risks becoming a **fragile equilibrium** rather than a **stable future condition**.

We eventually translate these implications into the following visual pathway diagram (Figures 14 and 15):

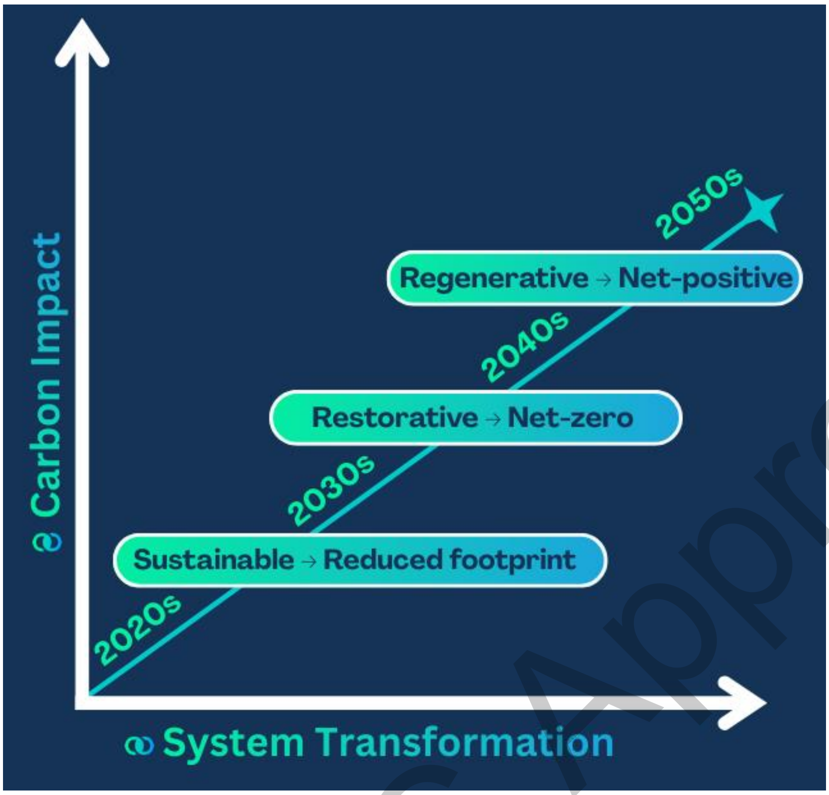

Figure 14. Sustainable, restorative and regenerative pathways

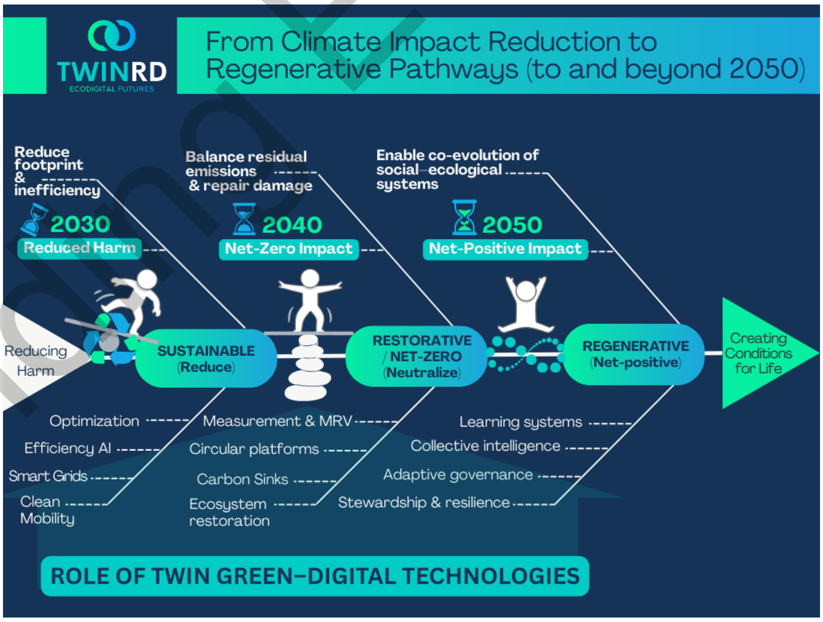

Figure 15. From climate impact reduction to regenerative pathways (to and beyond 2050)

4.3. Exploring quantitative methods to assess environmental and social impacts of regenerative transition pathways

In TWINRD we want also to explore to what extent and how sustainability (green economy), restorative (circular economy) and deeply transformative (regenerative economy) transition pathways can be simulated using the TWINRD modelling framework, producing quantitative analyses of future transition pathways with an assessment of their environmental and social impacts.

For the quantitative analysis and measuring of environmental and social impacts, TWIN-RD can stock up on existing approaches and methodologies, as the following:

- Guidelines to measure the carbon and environmental handprint (net-positive environmental impact).
- Principles for measuring systemic economic health and social outcomes (net-positive social impact).

4.3.1. Guidelines to measure the carbon and environmental handprint (net-positive environmental impact).

For many companies and organizations, the day-to-day challenge of reducing their environmental footprint—using resources more efficiently and minimizing emissions and waste – is already business as usual. Some, though, have gone beyond this and are developing products, services and technologies that also reduce the environmental impacts of their customers. The need to calculate and communicate these positive environmental benefits is clear, yet there has been a lack of effective methods of achieving this.

Environmental impacts are typically assessed by measuring and modelling the negative effects that products, services, and organizations cause to the environment. In practice, this means evaluating the used resources and the energy and emissions caused. To ensure the optimization of overall environmental performance, life cycle thinking-based methods are widely implemented.[14] However, a life cycle assessment in its current form does not assess positive environmental impacts.

VTT Technical Research Centre of Finland Ltd and LUT University have developed an approach for quantifying the environmental handprint based on standardized methods (Pajula T. et al. 2021). According to this approach, a handprint refers to the beneficial environmental impacts that organizations can achieve and communicate by offering products and services that reduce the footprints of others. In contrast to an environmental footprint, which refers to the negative environmental impacts caused throughout the life cycle of a product or service, the term handprint represents therefore the positive environmental impacts. By the same token, a carbon handprint is the reduction of the carbon footprint of others. Similarly, footprints and handprints may address other environmental aspects and impacts related to resource use or environmental emissions.

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[14] These assessment practices are thoroughly guided by the ISO standards for life cycle assessments (ISO 14040-44: 2006), the carbon footprint (ISO 14067: 2018) and the water footprint (ISO 14046: 2014).

With the footprint concept the goal is simple – to get the footprint to close to zero; but with handprints there is essentially no limit to the positive impacts that can be achieved. It is important to set targets for both: aiming to enlarge the handprint while minimizing the footprint, as shown in the Figure 16 below:

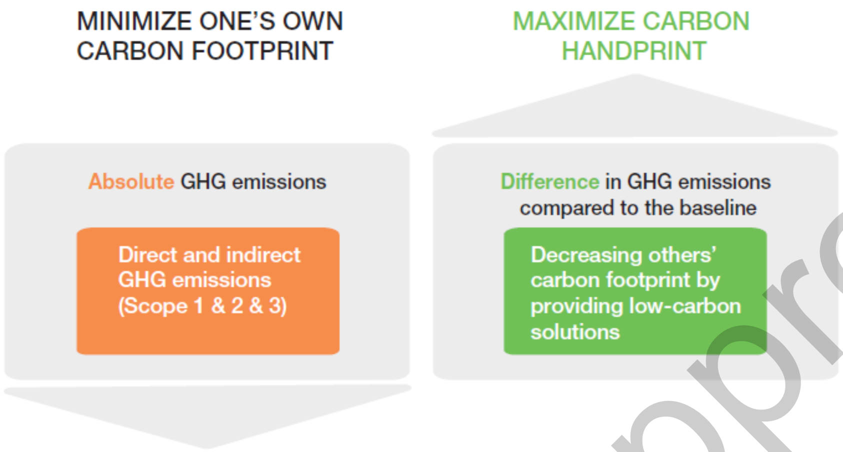

Figure 16. Footprint and handprint impacts

Moreover, a footprint is equal to the absolute emissions, whereas the size of a handprint varies based on the context and refers to a difference between two solutions: The handprint of a product or service is calculated by comparing the footprint of the baseline with that of the offered solution when used. Handprint, therefore, is a comparative indicator, which describes emissions or consumption that can be reduced or avoided using a certain product instead of a baseline product. The handprint can be created by two means: Using an offering that carries a lower environmental burden than the baseline offering (cradle to gate processes), e.g., through improved resource efficiency in manufacturing; or through the environmental impact reduction which actualizes while using the offered solution (gate to grave processes), for example through energy efficient products. Also, a combination of both means is possible to create a handprint (Pajula T. et al. 2021).

On the same vein, Norris and Phansey (2015) stated that there are two ways to create a handprint: (1) Preventing and/or avoiding footprints that would otherwise have occurred, which includes reducing the magnitude of footprints that occur, relative to what their magnitude would otherwise have been; and (2) Creating positive benefits which would have not occurred otherwise.[15]

Based on this concept, operational frameworks have been proposed in Alvarenga et al., 2020 to distinguish and classify various types of handprints, as for instance, (i) direct handprint, (ii) indirect handprint, (iii) relative handprint.

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[15] Norris and Phansey (2015) introduced also the more generale definition of the term "Net-Positive", which is the result of a positive balance between handprint and footprint, i.e., if the handprint is larger than the footprint for a given impact category, the system becomes Net-Positive for that impact category.

The *Direct Handprint* is defined as *the (absolute) positive impacts that a product can bring to its intended user, due to the product's functionality and/or due to the service flows*. A few examples of Direct Handprint, with the specific impact category between brackets, are:

- Benefits to the intended user due to ingestion of certain food (human health);
- Benefits to the intended user (patient) from taking a certain drug (human health);
- Benefits to the intended user from using a bicycle as means of transportation (human health; well-being);
- Benefits to the intended user (a paraplegic person) by making use of a wheelchair (well-being).

The *Indirect Handprint* is defined as *the (absolute) positive impacts that a product can bring to unintendedly affected subjects, due to the product's functionality and/or due to the production flows*. A few examples of footprint-consistent Indirect Handprint, with the specific impact category between brackets, are:

- The absorption of NOx when using TiO2 as coating material in buildings (generating a benefit for terrestrial acidification);
- Carbon sequestration during production phase of biofuels (generating a benefit for climate change);
- Increase in pollination during honey production (generating a benefit for ecosystem services);
- Increase in local biodiversity from offshore wind turbines (generating a benefit on local biodiversity), during electricity production.

The *Relative Handprint* is defined as the (relative) positive impacts that a product can bring in comparison to a benchmark, for the intended user and/or the *unintendedly affected subjects*, due to the product's functionality and/or the production flows.[16]

A few examples of Relative Handprint, considering the suggestion from the previous paragraph and based on footprint-consistent indicators, with the specific impact category between brackets, are:

- High-efficient batteries, in comparison to low-efficient ones, to be used for electric cars (benefits in several impact categories);
- Benefits from wind power, in comparison to other sources of power, for the electric mix of a certain region (benefits in climate change, amongst others);
- Compostable plastic, in comparison to traditional plastic, for short-life plastic bags (benefits in climate change, amongst others);
- Algae for fuel, in comparison to other fossil sources, for transportation (benefits in climate change, amongst others);

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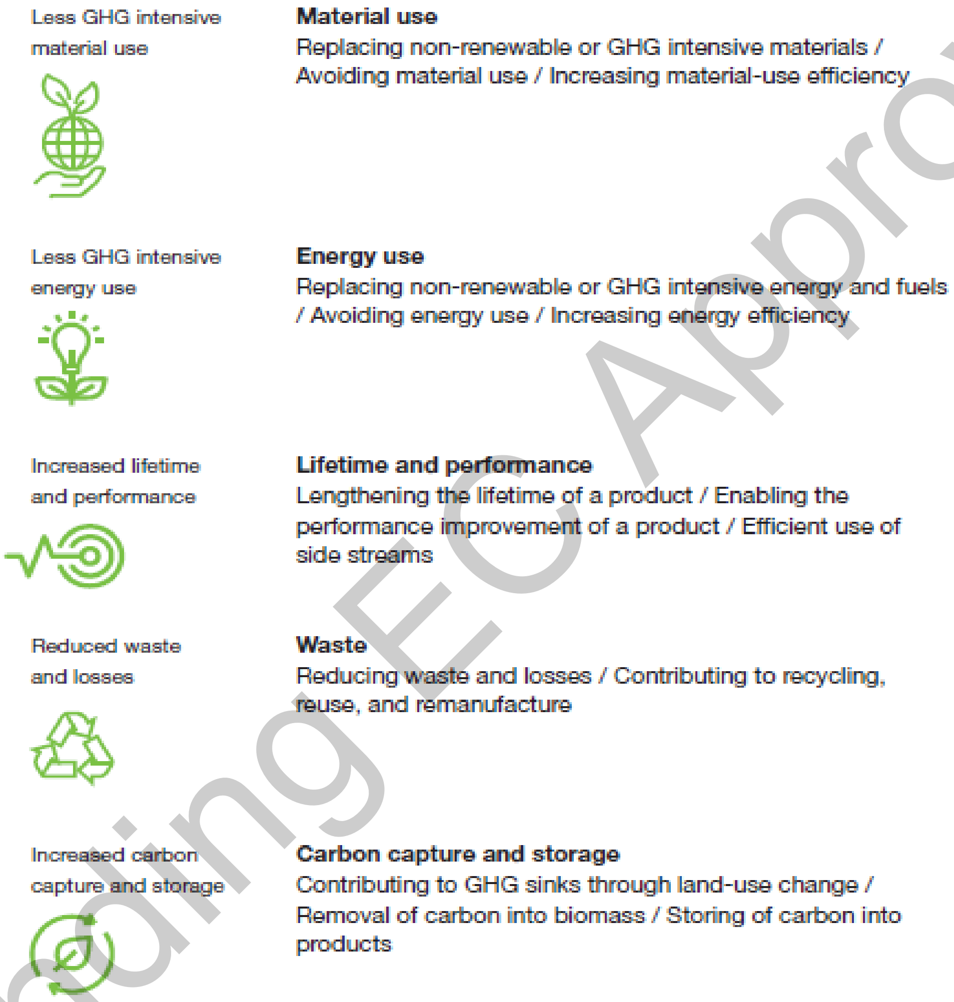
[16] This definition matches with the comparative indicator discussed in Pajula T. et al. 2021

- Double-glass, in comparison to single-glass, to improve energy efficiency in buildings (benefits in several impact categories).

Several different mechanisms can contribute to a handprint. For a carbon handprint these contributors are typically more efficient material and energy use, replacing or avoiding unwanted materials, reducing waste, extending service life and reuse – or any combination of these. Carbon capture and storage may also be of growing importance as a carbon handprint contributor, as it is shown in the Figure 17 below.[17]



Less GHG intensive material use	**Material use** Replacing non-renewable or GHG intensive materials / Avoiding material use / Increasing material-use efficiency
Less GHG intensive energy use	**Energy use** Replacing non-renewable or GHG intensive energy and fuels / Avoiding energy use / Increasing energy efficiency
Increased lifetime and performance	**Lifetime and performance** Lengthening the lifetime of a product / Enabling the performance improvement of a product / Efficient use of side streams
Reduced waste and losses	**Waste** Reducing waste and losses / Contributing to recycling, reuse, and remanufacture
Increased carbon capture and storage	**Carbon capture and storage** Contributing to GHG sinks through land-use change / Removal of carbon into biomass / Storing of carbon into products

Figure 17. Rethinking value creation through a system lens

The consideration of the handprint concept and life-cycle based framework of analysis is suggested here to explore – at least theoretically if empirical evidence on positive environmental spillover is not available - to what extent and how the TWINRD modelling

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[17] Handprint can be calculated with a similar logic for other environmental resources – water, air, land – considering specific categories of impacts and indicators (e.g. for water: scarcity, eutrophication, acidification, toxicity)

framework can be applied to simulate deeply transformative scenarios of twin transition scenarios towards a regenerative economy paradigm. As opposed to the classical extractive economy concept – where usually the impacts of economic activities on the environment and society are considered negative externalities – the regenerative economy concept claims for investing in economic activities that produce positive environmental and social externalities by means of the products that deliver on the market. Restorative (circular) economy scenario variants may be considered as well. Indeed, both restorative and regenerative innovation value chains contrast the traditional linear/extractive value chains, with the circular economy being targeted to reduce the energy and materials footprints, while to be truly regenerative an innovation shall produce economic value together with positive impacts on the environment (increasing carbon and other resources handprints) and society (improving people well-being)

We suggest to further explore the handprint concept and life cycle assessment as an approach to internalize environmental and social impacts in the functioning of the economic system. For instance, one idea could be considering **circular chains** as opposed to linear supply chains for a same product/industry as the way to reduce own carbon footprint (direct and indirect GHG emissions in the supply chain/vertically integrated sector), while **regenerative chains** are qualified by the capacity of decreasing other sectors carbon footprints by providing low-carbon solutions (Pajula T. et al. 2021). In a certain sense, the former would be a “backward” interindustry positive (benefits) spillover analysis looking the upstream impacts of a product, while the latter would be a form of “forward” spillover analysis looking to the downstream impact of the product in the use sectors.

4.3.2. Principles for measuring systemic economic health and social development (net-positive social impact)

In the last few decades advances in non-equilibrium thermodynamics (i.e., self-organizing, open, dissipative, far-from-equilibrium systems), and nonlinear dynamics, network science, information theory, and other mathematical approaches to complex systems have produced a new set of concepts and methods, which are powerful for understanding and predicting behaviour in socio-economic systems.

In a seminal research paper, for example, B. D. Fath et al (2019) used research from the new Energy Network Science (ENS) to show how and why systemic ecological and economic health requires a balance of efficiency and resilience be maintained within a particular a “window of vitality”. From this approach, they derived principles of systemic, socio-economic health and the quantitative metrics that go with them, demonstrating in the socio-economic system dimension how regenerative economics requires investment in human, social, natural and physical capital.

The “energy flow network” research is a continuation of the far-from-equilibrium open systems work[18]. Here, self-organizing processes naturally give rise to what researchers call flow systems or flow networks. A flow network is any system whose existence arises from and depends on circulating energy, resources, or information throughout the entirety of their being.

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[18] Flow networks are also called “open systems” because, in contrast to the closed “conservative systems,” which are the main focus of classical thermodynamics, open systems are characterized by ongoing transfers of matter, energy and/or information into and out of the system's boundary.

Your body, for example, is an integrated network of cells kept healthy by the circulation of energy, water, nutrients, and internal products. Ecosystems are interconnected webs of plants and animals (including decomposers) that add to and draw from flows of oxygen, carbon, nitrogen, etc. Economies are interlinked networks of people, communities, and businesses, which depend on the circulation of information, resources, money, goods, and services.

Robust, timely circulation of critical resources is essential to support a system's internal organization and processes - and the more organization there is to support, the more nourishing circulation is needed to support it. This thought applies as much to human organizations as to ecosystems. Network flow also ties directly to systemic health and development because, if critical resources do not adequately nourish all sectors or levels, then we can expect the undernourished segments of the economy to become necrotic. Like necrosis in living organisms, poor cross-scale circulation erodes the health of large swaths of economic “tissue” - typically specializations at the periphery, which in turn undermines the health of the whole.

Combining the fact that energy processes (such as circulation) are behind causal factors (such as nourishment and necrosis) which directly impact system functioning, and the fact that optimal patterns appear to follow mathematical rules, means we can use universal patterns suggesting a framework of **10 quantitative measures and targets for systemic health** (health, here, refers to the sustained, self-supporting performance and behaviour of the system in question). Such measures are vastly more effective than traditional outcome metrics or statistical correlations because they assess root causes, i.e., ones that directly impact systemic health. The ten Energy Network Science principles summarized below capture the phenomenology of the deep root causes looking for specific attributes that may show signs of imbalance or ill health. These can be called “intrinsic” measures because, where most traditional social, economic, and environmental metrics assess symptoms of socioeconomic health or dysfunction, they examine underlying causal dynamics.

The B. D. Fath et al. framework of 10 regenerative economics principles (REPs), measurement rationales and operational indicators is presented in the tables below. While it is beyond the TWIN-RD scope to apply these operational indicators, some of the principles can help to focalize regenerative aspects while analysing the evolution of socio-economic systems, green and digital technologies and twin transition scenarios. For instance, questions can be raised about how twin transition pathways can benefit from regenerative re-investment patterns (REP2), or help to maintain the reliability of critical resources (REP3), produce healthy outputs (REP4), maintain sufficient diversity (REP7) and healthy balance of small, medium and large organizations (REP5), balance economic efficiency and resilience of the economic system (REP6), promote mutually-beneficial relationships and common values (REP8), limit overly extractive and speculative processes (REP9), and, last but not the least, promote effective, adaptive, collective learning (REP10).

Table 8. Quantitative measures and targets for systemic health

Regenerative Economy Principles	Measurement Rationale	RE Intrinsic indicators
REP1: Maintain robust, cross-scale circulation of critical flows including energy, information, resources and money	*Cross-scale circulation* can be measured using ENS by how rapidly and thoroughly resources circulate inside the organization. Flows can be tracked and analyzed for money and information in socio-economic networks, and for energy, water and carbon in ecosystems networks	Ratio of total system through-flow to the total input into the system
REP2: Regenerative re-investment	*Regenerative re-investment* can be measured using ENS by the percentage of money and resources the system invests in building and maintaining its internal capacities and infrastructure. Again, the same measures and principles apply to studies of essential ecosystem services responsible for regenerative, sustainable supplies of energy, water, food and all biological needs of people and economies	Fraction of total through-flow cycled in the network
RP3: Maintain reliable inputs	*Input reliability* can be assessed by how much risk attends critical resources such as energy, information, resources, and monetary flows upon which the system depends.	sustainability indicators of renewability such as energy share from renewable sources and declining energy-return on energy invested.

Regenerative Economy Principles	Measurement Rationale	RE Intrinsic indicators
REP4: Maintain healthy outputs	Healthy outputs can be assessed by how much damage outflows do both inside and outside the system	index of human impacts (e.g., cancer rates) and environmental impacts (e.g., pollution and carbon levels).
REP5: Mantain a healthy balance and integration of small, medium and large organizations	Healthy balance can be assessed using the distribution of sizes, incomes, or resources within the system.	Flow-network data can be plotted using a weighted distribution of stocks and flows, compared against power-law distributions found in nature, and checked for indications of imbalance
REP6: Maintain a healthy balance of resilience and efficiency	A healthy balance of resilience and efficiency can be measured using the window of vitality metric introduced by Ulanowicz, the range of balance between the factors which contribute to efficiency (large size, high-capacity, streamlining) and those which contribute to resilience (small size, diversity, dense connectivity).	Balance between efficiency (fraction of energy distributed in an efficient manner) and resilience (the array of useful parallel pathways for exchange)
REP7: Maintain sufficient diversity	The laws of sufficient diversity for populations of a given size are known to follow certain mathematical rules, which can be assessed by measuring the number and diversity of players in activities critical to system functioning.	Metrics mesuring the number of roles needed in a specific network.

Regenerative Economy Principles	Measurement Rationale	RE Intrinsic indicators
REP8: Promote mutually-beneficial relationships and common-cause values.	The degree of mutualism can be determined by a matrix of direct and indirect relational-pairings, which may be categorized as: exploitative (+,-); exploited (-, +); mutualist (+, +); and competitive (-, -) based on its flow relationships. Robust ecosystems display a greater number of mutualistic relations than competitive ones. A healthy economy should also display a greater degree of mutualism.	The number of positive signs is an indication of the overall benefit a node receives by participating in that network.
REP9: Promote constructive activity and limit overly-extractive and speculative processes	The balance of constructive vs extractive/ speculative activity can be assessed as a ratio of value-add and capacity-building activities to extractive ones.	Categories of value-add vs extractive activities must be specified on a case by case basis
REP10: Promote effective, adaptive, collective learning	A society's ability to learn as a whole is the most important regenerative principle, and the hardest to measure. Relatedly, remaining adaptive is critical to address novel and changing circumstances.	Since there is no network-formula for effective learning and adaptive management, these cen be assessed by creating a composite ofexisting indicators of 1) poorly addressed human needs, 2) underutilized human resources, 3) poorly addressed environmental issues, 4) educational priority, and 5) levels of community involvement.

The energy flow system of regenerative economics principles and measurement of systemic health is useful to monitor the intrinsic, systemic health of the socio-economic systems in different stages of the twin transition process. For measuring the well-being outcomes, we suggest adopting the doughnuts framework of indicators as main reference. The Doughnut conceptual framework, originally developed by the economist Kate Raworth, delineates a “safe and just space” for human activities, located between a social foundation and an ecological ceiling (Recordon J. et al., 2025).

In her original article in 2012, Kate Raworth builds on the first version of the Planetary Boundaries (Rockstrom et al., 2009a) to draw her now famous Doughnut-shaped conceptual framework, and combines it with a social foundation, to define a *safe and just operating space for humanity.* The framework is visually represented by two concentric circles, where the outer boundary outlines the space within which human activities must operate to avoid destabilizing the Earth system.

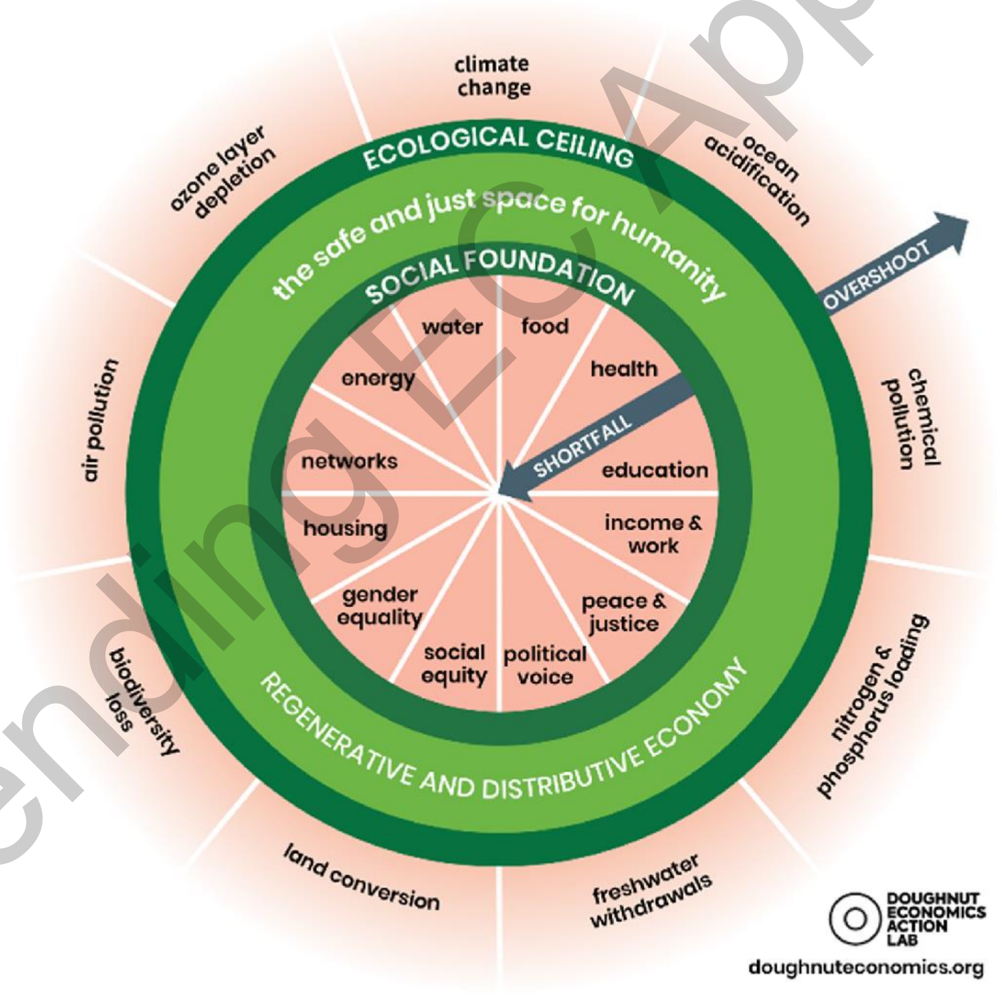

Figure 18. Safe and just operating space for humanity

Funded by the European Union

Meanwhile, the inner circle, representing its social foundation, delineates the minimum social standards necessary for individuals to escape severe deprivation and meet their essential needs. As emphasized by Raworth herself, the inner circle represents only the bare minimum required for the survival and dignified existence of the planet's populations (Raworth, 2012; Raworth et al. 2017). The aim is to eradicate extreme poverty and deprivation globally, but societies can and must aspire to more, that is enabling their people to thrive (Raworth, 2012).

Unlike the ecological ceiling, that appears to be grounded in well-established scientific facts (although there are multiple normative assumptions built into the Planetary Boundaries), the social foundation represents a political consensus. This could be interpreted either as a strength, since the dimensions of the social foundation enjoy a high level of political legitimacy, or as a weakness since it appears to be less grounded in science than the ecological ceiling.

In any event, by reaffirming the idea of limits, both environmental and social, the Doughnut framework aligns with theories of *strong sustainability*. Unlike *weak sustainability*, which presupposes an extended substitutability between natural and human-made capital (economic, social or technical), *strong sustainability* recognizes that the processes behind the planetary boundaries cannot be substituted by economic or technical capital since they are the most fundamental regulating processes of the Earth system. Nor can under (social) or over (environmental) shoots of the boundaries be justified by more economic development. Within this framework, both ecological and social objectives need to be achieved jointly. In the regenerative perspective net-positive impacts can add some flexibility, helping socio-ecological systems to evolve within – or in case of under or overshoot return to – the safe and just operating space.

5. Conclusions

The key results of the taking stock exercise, to take away for the next stages of the TWINRD project, include:

- A cross-cutting analysis of the EU policy frameworks related to the Twin Transition reveals several challenges and implications for the macro-economic modelling, including policy fragmentation and integration deficits, skill development coordination needs, regional convergence vs divergence dynamics, coordination of the consumers behaviour dimension and demand-side measures across multiple policy domains and, as it concerns the implications for the macro-economic models, the issue of capturing the interdependencies between green and digital technologies, not just parallel development directories.
- After taking stock of the existing methodologies for estimating knowledge spillovers and the evidence on R&I impacts, the deliverable describes the specific technology flow matrix approach and methodology used in TWINRD based on patent counts for the period 2020-2021, using the PATSTAT database as primary source of data. Overall summaries and trends for the number of green and digital patents are shown, discussing the overlap of green patents with digital patents (as a signal of potential integration). Using the two primary ways for identifying digital patents – J-tag and WIPO-tagging – two different types of digital technologies have been detected: "new digital", including new technologies such as AI, big data, cloud computing and autonomous systems (4th industrial revolution technologies), and "old digital" including all other digital technologies. The green and digital patents have been split and allocated to the NACE sectors, and the most prominent

NACE/Green field combinations of green and digital technologies are show in summary tables. Finally, first results and the methodology used to construct the TWINRD technology flow (or citation) matrix are presented.

- Taking stock from past applications and reports related to the NEMESIS and GEM-E3 models, the current features of the models and the mechanisms used to embody technological change and innovation dynamics are described in detail.
- Tacking stock from the literature related to the effects of ICT technologies on energy consumption, a taxonomy of ICT energy effects is presented. This is useful to analyse the scope of the impact for different typologies of twin green and digital solutions.
- Considering the new macro-economic modelling developments that are being implemented in TWINRD, a box provides the list of critical methodological limitations common to NEMESIS, GEM-E3 and other large scale macro-economic models, the list of R&I policy impacts that are often poorly captured by the models, and the priorities for the forthcoming TWINRD models upgrade.
- Tacking stock from the most comprehensive foresight study on the future of the Twin Transition in the EU (JRC Report – Muench, S. et al. 2022), goals, contextual factors, the emerging digital technologies and of green and digital solutions in key sectors (agriculture, building and construction, energy, transport and mobility) that contribute to shape the future of the twin transition are described. From the same study we have excerpted and shown the digital innovation timelines to 2050 for the four key sectors, as they are an useful example and base for upgrading them for the own TWINRD strategic foresight forthcoming exercise, focusing on most relevant combination of green and digital solution and sectors of application revealed from the technology flows analysis.
- Tacking stock from the relevant literature, we have introduced the concept of sustainability, restorative (circular), and regenerative transformation from the currently “extractive” linear economy model that leaves a negative “footprint” on the ecological and social systems towards a new “regenerative” economy model which can deliver a positive “handprint”, regenerating the natural and social spaces in which the economy operates. The distinction between the “circular” and the “regenerative” economy paradigms is also discussed, showing how the latter is more directly driven by the purpose of delivering net-positive environmental and social impacts, creating conditions to support people well-being and planetary health. This concept will be useful to frame alternative twin transition scenarios in the forthcoming TWINRD strategic foresight exercise, contrasting more “business as usual” scenarios - where digital technologies are used to increase the efficiency and even the circularity of energy and materials to extend a still inherently carbon-intensive development path - with transformative scenarios of “paradigm shift” towards a radically different, deep-decarbonized system (a Net-Zero and beyond – i.e. Net Positive – scenario).
- The concepts of regenerative value creation, the existing experiences and guidelines to measure net-positive environmental impact (handprint), the principles to measure net-positive social outcomes by using indicators of systemic economic health (as a result of an intrinsic good balance of efficiency and resilience of the economic system) and the well-established Doughnut-shaped conceptual framework of indicators to keep humanity within a *safe* (i.e. avoiding the overshoot of planetary boundaries) and *just* (i.e. avoiding the shortfall of social foundations) operating space are all discussed. Especially the methods to assess the environmental handprint are worth to be explored to upgrade the capacity of

the current Impact Assessment Models (IAMs) – and of the new TWINRD modelling framework – to measure positive carbon and environmental spillovers of regenerative green and digital innovations. About the social impact, the Doughnut framework is already a consolidated method with several application (at global and local level) that can be used to measure especially social foundation aspects, while the 10 principles and quantitative measures and targets for systemic economic health can help to shift the attention from only looking to the extrinsic outcomes of socio-economic evolutions to taking care of the intrinsic stability and health of the socio-economic systems.

All these "take aways" can be used to feed the next steps of TWINRD, together with other elements that can still be found from the collected stock-tacking documents, which are listed and classified in the selected bibliography section depending on their pertinence for different twin transition fields: policy, green and digital technology, macro-economic modelling, transition scenarios building.

6. Selected bibliography

To scan relevant literature, the stock-taking task 5.1 required to define its boundary and structure, connecting the concepts of sustainable, restorative (circular) and regenerative economy with the scope of the TWINRD project focusing on green and digital technology trajectories, the embodiment of technological change in background macro-economic modelling studies and in the foreground TWINRD applications, and the production of twin transition scenarios (as the stock-taking is also aimed to feed the WP6 scenarios co-creation workshops). This entailed first delimiting the specific fields and then identifying the relevant documents (reports, papers, etc.), starting by reading the most insightful ones and selecting the most pertinent for the TWINRD purpose through a cascade process, which required in-depth reading of key papers to excerpt relevant information.

The documents considered in the TWINRD taking stock exercise are listed in the following sub-sections, divided into four "landscape" categories: Twin transition policy, green and digital innovation, macroeconomic modelling evolution, transition scenarios.

6.1. Twin Transition Policy Landscape

European Commission (2019). The European Green Deal. COM(2019) 640 final. Brussels. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission (2020). Shaping Europe's Digital Future. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2020) 67 final. Brussels. https://digital-strategy.ec.europa.eu/en

European Commission (2022). REPowerEU: Joint European Action for more affordable, secure and sustainable energy. COM(2022) 230 final. Brussels. https://www.consilium.europa.eu/en/policies/repowereu-plan/

European Commission (2023). A Green Deal Industrial Plan for the Net-Zero Age. COM(2023) 62 final. Brussels. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_en

European Commission (2020). Europe fit for the Digital Age. Policy priorities 2019-2024. Brussels. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age_en

Draghi, M. (2024). The Future of European Competitiveness. Report prepared at the request of the President of the European Commission. Brussels. https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en

6.2. Green and Digital Technological Innovation Landscape

Amoroso S., Aristodemou L., Criscuolo C., Dechezleprêtre A., Dernis H., Grassano N., Moussiegt L., Napolitano L., Nawa D. Squicciarini M., Tübke A. (2021). World Corporate Top R&D investors: Paving the way for climate neutrality. A joint JRC and OECD report. EUR 30884 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-43373-6, doi:10.2760/49552, JRC126788

Anderson P., Tushman M. L. (1990) Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. Administrative Science Quarterly, Vol. 35, No. 4 (Dec., 1990), pp. 604-633 http://www.jstor.org/stable/2393511

Ando, Y., Bessen, J., and Wang, X. (2025). The rising returns to R&D: Ideas are not getting harder to find. US Census Bureau CES Working Paper CES-WP-25-29. https://www2.census.gov/library/working-papers/2025/adrm/ces/CES-WP-25-29.pdf

Auerbach, A.J., and Gorodnichenko, Y. (2012). Measuring the output responses to fiscal policy. American Economic Journal: Economic Policy 4(2): 1-27. https://doi.org/10.1257/pol.4.2.1

Beier, G.; Niehoff, S.; Xue, B. More Sustainability in Industry through Industrial Internet of Things? *Appl. Sci.* **2018**, *8*, 219. https://doi.org/10.3390/app8020219

Benson C.L., Magee C.L. (2015) Quantitative Determination of Technological Improvement from Patent Data. PLoS ONE 10(4): e0121635. doi:10.1371/journal.pone.0121635

Bitzer, J., Geishecker, I. (2005) : What drives trade-related R&D Spillovers? Decomposing knowlege-diffusing trade flows, Diskussionsbeiträge, No. 2005/26, ISBN 3938369256, Freie Universität Berlin, Fachbereich Wirtschaftswissenschaft, Berlin

Bresnahan, T. F., Trajtenberg, M. (1995). "**General purpose technologies 'Engines of growth'?**," Journal of Econometrics, Elsevier, vol. 65(1), pages 83-108, January.

Brynjolfsson E., Eggers F., Gannamaneni A. (2018). "**Using Massive Online Choice Experiments to Measure Changes in Well-being**," NBER Working Papers 24514, National Bureau of Economic Research, Inc.

Cappelen, Å., Raknerud, A., Rybalka, M., & Skjerpen, T. (2021). R&D, innovation and productivity: Evidence from a threshold panel model. International Journal of Innovation Studies, 5(3), 113–126. https://doi.org/10.1016/j.ijis.2021.06.002

Ciaffi, G., Deleidi, M., and Mazzucato, M. (2024). Measuring the macroeconomic responses to public investment in innovation: Evidence from OECD countries. Industrial and Corporate Change 33(2): 363-382. https://doi.org/10.1093/icc/dtae005

Cohen, W.M., and Levinthal, D.A. (1990). Absorptive capacity: A new perspective on learning and innovation. Administrative Science Quarterly 35(1): 128-152. https://doi.org/10.2307/2393553

Deleidi, M., and Mazzucato, M. (2021). Directed innovation policies and the supermultiplier: An empirical assessment of mission-oriented policies in the US economy. Research Policy 50(2): 104151. https://doi.org/10.1016/j.respol.2020.104151

Dong, K., Zeng, S., Wang, J., and Taghizadeh-Hesary, F. (2024). Assessing the role of green investment in energy efficiency: Does digital economy matter? Energy Exploration & Exploitation 42(4): 1157-1176. https://journals.sagepub.com/doi/full/10.1177/01445987231216763

Epicoco, M., Jaoul-Grammare, M. & Plunket, A. Radical technologies, recombinant novelty and productivity growth: a cliometric approach. *J Evol Econ* **32**, 673–711 (2022). https://doi.org/10.1007/s00191-022-00768-5

Farmer D., Lafond F. (2016). How predictable is technological progress? Research Policy Volume 45, Issue 3, April 2016, Pages 647-665. https://doi.org/10.1016/j.respol.2015.11.001

Favot M., Vesnic L., Priore R., Bincoletto A., Morea F.. Green patents and green codes: How different methodologies lead to different results. Resources, Conservation & Recycling Advances 18 (2023) 200132. https://doi.org/10.1016/j.rcradv.2023.200132

Foster-McGregor, N., Nomaler, O., Verspagen, B. (2019). "**Measuring the creation and adoption of new technologies using trade and patent data**," MERIT Working Papers 2019-053, United Nations University - Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT).

Frontiers (2025). Spatial spillover of fintech innovation on green economic growth based on 30 provinces in China. Frontiers in Environmental Science 13: 1514403. https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2025.1514403/full

Frontier Economics (2014). Rates of return to investment in science and innovation. Report for UK Department for Business, Innovation and Skills. https://www.frontier-economics.com/media/015adtpq/rate-of-return.pdf

Frontiers in Energy Research (2021). Impact of green innovation on firm value: Evidence from listed companies in China's heavy pollution industries. Frontiers in Energy Research 9: 806926. https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2021.806926/full

Gonçalves, E., Perobelli, F.S. & de Araújo, I.F. Estimating intersectoral technology spillovers for Brazil. *J Technol Transf* **42**, 1377–1406 (2017). https://doi.org/10.1007/s10961-016-9528-x

Gross, R., Hanna, R., Gambhir, A., Heptonstall, P., and Speirs, J. (2018). How long does innovation and commercialisation in energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. Energy Policy 123: 682-699. https://www.sciencedirect.com/science/article/pii/S0301421518305901

Hall, B.H., Mairesse, J., and Mohnen, P. (2010). Measuring the returns to R&D. In B.H. Hall and N. Rosenberg (eds.), Handbook of the Economics of Innovation, Vol. 2, pp. 1033-1076. Elsevier. https://doi.org/10.1016/S0169-7218(10)02008-3

Haščič, I. and M. Migotto (2015), “Measuring environmental innovation using patent data”, *OECD Environment Working Papers*, No. 89, OECD Publishing, Paris, https://doi.org/10.1787/5js009kf48xw-en.

Horner, Nathaniel C., Shehabi, Arman, and Azevedo, Ines L. Known unknowns: indirect energy effects of information and communication technology. United States: N. p., 2016. Web. doi:10.1088/1748-9326/11/10/103001.

Jaffe, A., Trajtenberg, M., 2002. Patents, citations, and innovations: A window on the knowledge economy. MIT Press, Cambridge, MA.

Jindra, B., Leusin, M. (2022), The Development of digital sustainability technologies by top R&D investors, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/150239, JRC130480.

Jindra, B. and Leusin, M.-E. (2024). Digital Technologies for Climate Change Mitigation and Adaptation: Evidence From the European Union. *Journal of Innovation Economics & Management,* 45(3), 123-157. https://shs.cairn.info/journal-of-innovation-economics-2024-3-page-123?lang=en.

Johnstone,N., Haščič,I., Popp,D. (2010).Renewable energy policies and technological innovation: evidence based on patent counts. Environ.Resour.Econ.45 (1), 133–155.

Liang, X., Zhang, J., & Wang, S. (2025). The impact of resource misallocation on green technology innovation: evidence from 288 cities in China. Humanities and Social Sciences Communications. https://www.nature.com/articles/s41599-025-05225-9

March J.G, 1991. "**Exploration and Exploitation in Organizational Learning**," Organization Science, INFORMS, vol. 2(1), pages 71-87, February.

Martinelli A., Mina A., Moggi M. (2019). "**The Enabling Technologies of Industry 4.0: Examining the Seeds of the Fourth Industrial Revolution**," LEM Papers Series 2019/09, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy.

Metcalfe, J. S. (1994). Evolution, Technology, Policy and Technology Management. *Prometheus*, *12*(1), 29–35. https://doi.org/10.1080/08109029408629375

Montresor, S., Vezzani, A. (2023). Digital technologies and eco-innovation. Evidence of the twin transition from Italian firms. *Industry and Innovation*, *30*(7), 766–800. https://doi.org/10.1080/13662716.2023.2213179

Moser, P. (2013). "Patents and Innovation: Evidence from Economic History." Journal of Economic Perspectives 27 (1): 23–44. DOI: 10.1257/jep.27.1.23

Mokyr, J. (2002). “The Gifts of Athena: Historical Origins of the Knowledge Economy.”.

Nelson, R. (2003) : Physical and social technologies, and their evolution, LEM Working Paper Series, No. 2003/09, Scuola Superiore Sant'Anna, Laboratory of Economics and Management (LEM), Pisa

Nomaler, Ö. & Verspagen, B. (2021). "**Patent landscaping using 'green' technological trajectories**," MERIT Working Papers 2021-005, United Nations University - Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT).

Pangallo, F. (2026)R&D and Innovation and Its Impact on Firm Performance and Market Value: Panel Evidence from G7 Economies, Economies. https://www.mdpi.com/2227-7099/13/9/254

Pasimeni F., Fiorini A., Georgakaki A. (2019). Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. World Patent Information 59 (2019)101927 https://doi.org/10.1016/j.wpi.2019.101927

Pichler, A., Lafond F., and Farmer J.D. (2020) "Technological interdependencies predict innovation dynamics." *arXiv preprint arXiv:2003.00580*.

Rouvinen, P. (2002). R&D-productivity dynamics: Causality, lags, and 'dry holes'. Journal of Applied Economics 5(1): 123-156. https://doi.org/10.1080/15140326.2002.12040573

Schoenmakers, W., Duysters, G. (2010). The technological origins of radical inventions. Research Policy 39, 1051–1059.

Spreng, D. (2015). The Interdependency of Energy, Information, and Growth. In: Hilty, L., Aebischer, B. (eds) ICT Innovations for Sustainability. Advances in Intelligent Systems and Computing, vol 310. Springer, Cham. https://doi.org/10.1007/978-3-319-09228-7_25

Tahereh S., Mohamad D., Tayebeh S. (2022), Artificial intelligence for sustainable energy: A contextual topic modeling and content analysis, Sustainable Computing: Informatics and Systems, Volume 35, 2022, 100699, ISSN 2210-5379, https://doi.org/10.1016/j.suscom.2022.100699.

Thompson P., (2012). "**The Relationship between Unit Cost and Cumulative Quantity and the Evidence for Organizational Learning-by-Doing**," Journal of Economic Perspectives, American Economic Association, vol. 26(3), pages 203-224, Summer.

Tushman M.L., and Anderson P. (1986). Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly.* 1986. Vol. 31(3):439. DOI: 10.2307/2392832

Ugur, M., Awaworyi Churchill, S., and Luong, H.M. (2020). What do we know about R&D spillovers and productivity? Meta-analysis evidence on heterogeneity and statistical power. Research Policy 49(1): 103866. https://doi.org/10.1016/j.respol.2019.103866

Funded by
the European Union

Verspagen, B. (1997): Measuring Intersectoral Technology Spillovers: Estimates from the European and US Patent Office Databases, *Economic Systems Research* 9, 47–65.

Verspagen, B., De Loo, I., Technology Spillovers between Sectors, Technological Forecasting and Social Change, Volume 60, Issue 3, 1999, Pages 215-235, ISSN 0040-1625, https://doi.org/10.1016/S0040-1625(98)00046-8.

Verspagen, Bart & Schoenmakers, Wilfred, 2000. "**The Spatial Dimension of Knowledge Spillovers in Europe: Evidence from Firm Patenting Data**," Research Memorandum 016, Maastricht University, Maastricht Economic Research Institute on Innovation and Technology (MERIT).

Ziesemer, T.H.W. (2021). Mission-oriented R&D and growth. Journal of Applied Economics 24(1): 460-477. https://doi.org/10.1080/15140326.2021.1963395

Ziman, J. (ed.) Technological Innovation as an Evolutionary Process. Cambridge University Press (2000) ISBN 0-521-62361-8

6.3. Macroeconomic Modelling Evolution Landscape

Aghion, P., Howitt, P. (1998). Endogenous growth theory. Cambridge, MA: MIT Press.

Aghion, P., Howitt P. (2006). Appropriate growth policy: A unifying framework. Journal of the European Economic Association 4(2-3): 269-314.

Akcigit U. et al. (eds.) (2022), Macroeconomic Modelling of R&D and Innovation Policies, International Economic Association Series, https://doi.org/10.1007/978-3-030-71457-4_5

Alvarenga R.A.F., Huysveld S., Taelman S.E., Sfez S., Préat N., Cooreman-Algoed M., Sanjuan-Delmás D., Dewulf J. (2020). A framework for using the handprint concept in attributional life cycle (sustainability) assessment. Journal of Cleaner Production, Volume 265, 2020, 121743, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.121743.

Andersen, E. S. (1997). The Schumpeterian Trade-off in an Evolutionary Model of Economic Growth and Development. Department of Mechanical Engineering, Aalborg University.

Axtell, R. L., and Farmer J.D.. (2025). "Agent-Based Modeling in Economics and Finance: Past, Present, and Future." Journal of Economic Literature 63 (1): 197–287. DOI: 10.1257/jel.20221319

Ayres, R. U, (2001). "**The minimum complexity of endogenous growth models:**," Energy, Elsevier, vol. 26(9), pages 817-838.

Balint T., Lamperti F., Mandel A., Napoletano M., Roventini A., Sapio A., 2016. "**Complexity and the Economics of Climate Change: a Survey and a Look Forward**," LEM Papers Series 2016/29, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy.

Beinhocker, E. (2007). The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics. Cornerstone

Bianchini S., Damioli G., Ghisetti C., 2023. "**The environmental effects of the “twin” green and digital transition in European regions**," Environmental & Resource Economics, Springer;European Association of Environmental and Resource Economists, vol. 84(4), pages 877-918, April.

Blanco, L., Prieger, J., Gu, J. (2013), "The Impact of Research and Development on Economic Growth and Productivity in the US States". Pepperdine University, School of Public Policy Working Papers. Paper 48. https://digitalcommons.pepperdine.edu/sppworkingpapers/48

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M. (2008): “International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization”, Energy Economics 30, 2912-2929.

Ciarli T., Lorentz A., Valente M., Savona M. (2017). "**Structural Changes and Growth Regime**," Working Papers of BETA 2017-19, Bureau d'Economie Théorique et Appliquée, UDS, Strasbourg.

Ciarli, T., Savona, M. (2019). Modelling the Evolution of Economic Structure and Climate Change: A Review. Ecological Economics. 158 51 64 0921-8009 https://doi.org/10.1016/j.ecolecon.2018.12.008

Charalampidis, I.; Karkatsoulis, P.; Capros, P. A Regional Economy-Energy-Transport Model of the EU for Assessing Decarbonization in Transport. *Energies* **2019**, *12*, 3128. https://doi.org/10.3390/en12163128

Dopfer, K., Foster, J., Potts, J., Micro-Meso-Macro. Available at SSRN: https://ssrn.com/abstract=721599

Dosi, G., Fagiolo, G., Roventini, A. (2010). "**Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles**," Journal of Economic Dynamics and Control, Elsevier, vol. 34(9), pages 1748-1767, September.

Dosi G., Napoletano M., Roventini A., Treibich T. Micro and macro policies in the Keynes + Schumpeter evolutionary models. 2014. hal-03429896

Dejuán O., Portella-Carbó F. & Ortiz M. (2022) Economic and environmental impacts of decarbonisation through a hybrid MRIO multiplier-accelerator model, Economic Systems Research, 34:1, 1-21, DOI: 10.1080/09535314.2020.1848808

European Commission (2017). A technical case study on R&D and technology spillovers of clean energy technologies. Technical Study on the Macroeconomics of Climate and Energy Policies. Prepared by Paroussos Leonidas, Fragkos Panagiotis, Vrontisi Zoi, Fragkiadakis Kostas (E3-Modelling) & Pollitt Hector, Lewney Richard, Chewpreecha Unnada (Cambridge Econometrics).

Foster J., 2011. "**Evolutionary macroeconomics: a research agenda**," Journal of Evolutionary Economics, Springer, vol. 21(1), pages 5-28, February.

Fouquet R., 2018. "**Consumer Surplus from Energy Transitions**," The Energy Journal, , vol. 39(3), pages 167-188, May.

Gabardo, F. A.; Porcile, G.; Pereima N., João B. (2020) : Sectoral labour reallocation: An agent-based model of structural change and growth, Economia, ISSN 1517-7580, Elsevier, Amsterdam, Vol. 21, Iss. 2, pp. 209-232, https://doi.org/10.1016/j.econ.2019.03.003

Idenburg A. M. Technological Choices and the Eco-efficiency of the Economy: a dynamic input-output approach. Paper presented at the Twelfth International Conference on Input-Output Techniques New York, 18-22 May 1998

Idenburg, A. M., Wilting, H. (2000). DIMITRI: a Dynamic Input-output Model to study the Impacts of Technology Related Innovations

Holland, J. H. (1992) Complex Adaptive Systems. Daedalus, Vol. 121, No. 1, A New Era in Computation, pp. 17-30. The MIT Press on behalf of American Academy of Arts & Sciences URL: http://www.jstor.org/stable/20025416

Klaassen,G., Miketa, A., Larsen K., Sundqvist, T. 2005. The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics 54(2–3), 227–240.

Lamperti F., Dosi G., Napoletano M., Roventini, Sapio A, 2017. "**Faraway, so Close: Coupled Climate and Economic Dynamics in an Agent-Based Integrated Assessment Model**," LEM Papers Series 2017/12, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy.

Lange, S. & Pohl, J. & Santarius, T., 2020. "**Digitalization and energy consumption. Does ICT reduce energy demand?**," Ecological Economics, Elsevier, vol. 176(C).

Le Mouël, P., Le Hir, B., Fougeyrollas, A., Zagamé, P., & Boitier, B. (2016). Towards a macro-modelling of European innovation union: The contribution of NEMESIS model. In 9th Conference on Model-based Evidence on Innovation and Development (MEIDE) the 16–17 June 2016 in Moscow, Russia.

Mandel A., 2012. "**Agent-based dynamics in the general equilibrium model**," Université Paris1 Panthéon-Sorbonne (Post-Print and Working Papers) halshs-00732823, HAL.

Metcalfe J.S., Foster J., Ramlogan R. 2006. "**Adaptive economic growth**," Cambridge Journal of Economics, Cambridge Political Economy Society, vol. 30(1), pages 7-32, January.

Nomaler, Ö., Spinola, D., Verspagen, B., 2021. "**R&D-based economic growth in a supermultiplier model**," Structural Change and Economic Dynamics, Elsevier, vol. 59(C), pages 1-19.

Nomaler Ö, Spinola D, Verspagen B. Evolutionary Selection and Keynes–Schumpeter Macroeconomics. Cambridge University Press; 2025.

Norris, G., Phansey, A., 2015. Handprints of Product Innovation: A Case Study of Computer-Aided Design in the Automotive Sector.

Pan, H., 2006. "**Dynamic and endogenous change of input-output structure with specific layers of technology**," Structural Change and Economic Dynamics, Elsevier, vol. 17(2), pages 200-223, June.

Pasinetti L., 1983. "**Structural Change and Economic Growth**," Cambridge Books, Cambridge University Press, number 9780521274104

Pajula, T., Vatanen, S., Behm, K., Grönman, K., Lakanen, L., Kasurinen, H., & Soukka, R. (2021). Carbon handprint guide: V. 2.0 Applicable for environmental handprint. VTT Technical Research Centre of Finland.

Pichler A, Pangallo M, Del Rio-Chanona RM, Lafond F, Farmer JD. Forecasting the propagation of pandemic shocks with a dynamic input-output model. J Econ Dyn Control. 2022 Nov;144:104527. doi: 10.1016/j.jedc.2022.104527. Epub 2022 Sep 13. PMID: 36117523; PMCID: PMC9472492.

Pindyck R.S., 2013. "**Climate Change Policy: What Do the Models Tell Us?**," Journal of Economic Literature, American Economic Association, vol. 51(3), pages 860-872, September.

Poledna, S., Miess, M. G., Hommes, C., Rabitsch, K., 2023. "**Economic forecasting with an agent-based model**," European Economic Review, Elsevier, vol. 151(C). DOI: 10.1016/j.euroecorev.2022.104306

Rubin, E. S., Azevedo, I. M.L., Jaramillo, P., Yeh, S. (2015). A review of learning rates for electricity supply technologies. Energy Policy, 86C, pages 198-218

Silverberg G., Verspagen B., 1995. "**Evolutionary Theorizing on Economic Growth**," Working Papers wp95078, International Institute for Applied Systems Analysis.

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review, 18*(4), 501–531. https://doi.org/10.1002/sdr.261

Tesfatsion, L., 2006. "**Agent-Based Computational Economics: A Constructive Approach to Economic Theory**," Handbook of Computational Economics, in: Leigh Tesfatsion & Kenneth L. Judd (ed.), Handbook of Computational Economics, edition 1, volume 2, chapter 16, pages 831-880, Elsevier.

Vasconcelos-Garcia, M., Carrilho-Nunes, I., 2024. "**Internationalisation and digitalisation as drivers for eco-innovation in the European Union**," Structural Change and Economic Dynamics, Elsevier, vol. 70(C), pages 245-256.

Verspagen B., 2002, Evolutionary Macroeconomics: A synthesis between neo-Schumpeterian and post-Keynesian lines of thought, The Electronic Journal of Evolutionary Modeling and Economic Dynamics, n° 1007, http://www.e-jemed.org/1007/index.php

Wolf S., Fürst S., Mandel A., Wiebke L., Lincke D., Pablo-Marti F., Jaeger C., 2013. "**A multi-agent model of several economic regions**," Université Paris1 Panthéon-Sorbonne (Post-Print and Working Papers) halshs-00825217, HAL.

Funded by
the European Union

Volodymyr R. (2006). A dynamic input–output model with explicit new and old technologies: an application to the UK. Economic Systems Research, Volume 18, Number 2, June 2006, pp. 183-203(21). Routledge, part of the Taylor & Francis Group. DOI: https://doi.org/10.1080/09535310600653040

6.4. Transition Scenarios Landscape

Bell K. (2015) Can the capitalist economic system deliver environmental justice? *Environ. Res. Lett.* **10** 125017**DOI** 10.1088/1748-9326/10/12/125017

Bergek, A., Hellsmark, H., Karltorp, K. (2023). Directionality challenges for transformative innovation policy: lessons from implementing climate goals in the process industry. Industry and Innovation, 30(8): 1110-1139. http://dx.doi.org/10.1080/13662716.2022.2163882

Centola D. et al. (2018). Experimental evidence for tipping points in social convention. Science 360,1116-1119. DOI:10.1126/science.aas8827

David, P.: The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox, *American Economic Review* 80, 355–361 (1990).

Fath B.D., Fiscus D.A., Goerner S.J., Berea A., Ulanowicz R.E. (2019). Measuring regenerative economics: 10 principles and measures undergirding systemic economic health, Global Transitions, Volume 1, 2019, Pages 15-27, ISSN 2589-7918, https://doi.org/10.1016/j.glt.2019.02.002.

Floridi L. (2016). The Fourth Revolution: How the Infosphere is Reshaping Human Reality. Oxford. Oxford University Press.

Fouquet R. & Hippe R., 2022. "**Twin Transitions of Decarbonisation and Digitalisation: A Historical Perspective on Energy and Information in European Economies**," Working Papers 08-22, Association Française de Cliométrie (AFC).

Fox, N. J. (2022). Green capitalism, climate change and the technological fix: A more-than-human assessment. *The Sociological Review*, *71*(5), 1115-1134. https://doi.org/10.1177/00380261221121232 (Original work published 2023)

Fullerton, J. (2015). *Regenerative capitalism: How universal principles and patterns will shape our new economy*. Capital Institute, https://cbey.yale.edu/event/regenerative-capitalism-how-universal-principles-and-patterns-will-shape-our-new-economy.

Future-Fit Foundation (2019), *Future-Fit Business Benchmark. Positive Pursuit Guide: Pursuing outcomes that contribute to a Future-Fit Society*. Release 2. October 2019.

Geels F.W., Pinkse J., Zenghelis D. (2021) Productivity opportunities and risks in a transformative, low-carbon and digital age. Working Paper No. 009, The Productivity Institute.

Goerner, S. (2015) *Regenerative Development. The Art and Science of Creating Durably Vibrant Human Networks*. The Capital Institute.

Hawken, P. (2023) *Regeneration. Ending the Climate Crisis in one generation*. London. Penguin Books

Hippe R. & Fouquet R., 2018. "**The Knowledge Economy in Historical Perspective**," World Economics, World Economics, 1 Ivory Square, Plantation Wharf, London, United Kingdom, SW11 3UE, vol. 19(1), pages 75-108, January.

Konietzko, J., Das, A., Bocken, N., 2023. *Towards regenerative business models: a necessary shift?* Sustainable Production and Consumption 38, 372–388. https://doi.org/10.1016/j.spc.2023.04.014.

Kurth, T., Wübbels, G., Portafaix, A., Zielcke, S., Meyer Zum Felde, A., 2021. *The Biodiversity Crisis Is a Business Crisis.* Accessed 11 December 2022 at. BCG. https ://web-assets.bcg.com/fb/5e/74af5531468e9c1d4dd5c9fc0bd7/bcg-the-biodiversit y-crisis-is-a-business-crisis-mar-2021-rr.pdf.

Lenton T.M. 2020 Tipping positive change. Phil. Trans. R. Soc. B 375: 20190123. http://dx.doi.org/10.1098/rstb.2019.0123

Lenton T.M. et al. (2022). Operationalizing positive tipping points towards global sustainability. Global Sustainability 5, e1, 1–16. https://doi.org/10.1017/sus.2021.30

Mang, P., Reed, B., 2020. *Regenerative development and design*. Sustainable Built Environments 115–141.

Mathews J. A., 2012. "**The renewable energies technology surge: A new techno-economic paradigm in the making?**," The Other Canon Foundation and Tallinn University of Technology Working Papers in Technology Governance and Economic Dynamics 44, TUT Ragnar Nurkse Department of Innovation and Governance.

Millward-Hopkins J., Steinberger J.K., Rao N. D., Oswald Y., Providing decent living with minimum energy: A global scenario, Global Environmental Change, Volume 65, 2020, 102168, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2020.102168.

Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M. and Scapolo, F. (2002). Towards a green and digital future, EUR 31075 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-52451-9, doi:10.2760/977331, JRC129319.

Nelli, L., Virgillito, M. E., Vivarelli, M. (2026). A twin transition or a flagship policy? Emergent constellations and dominant blocks in green and digital technologies. Energy Policy 209114954 SN - 0301-4215 https://doi.org/10.1016/j.enpol.2025.114954

Perez C., 2009. "**Technological revolutions and techno-economic paradigms**," The Other Canon Foundation and Tallinn University of Technology Working Papers in Technology Governance and Economic Dynamics 20, TUT Ragnar Nurkse Department of Innovation and Governance.

Perez C., 2016. Capitalism, Technology and a Green Global Golden Age: The Role of History in Helping to Shape the Future, in Jacob M. and Mazzucato M. (eds) Rethinking Capitalism: Economics and Policy for Sustainable and Inclusive Growth. Wiley-Blackwell.

Polman, P & Winston, A. (2022). *Net Positive: How courageous companies thrive by giving more than they take.* Boston: Harward Business Review Press.

Porter M.E. and Kramer M.R. (2011) Creating Shared Value. How to reinvent capitalism—and unleash a wave of innovation and growth. Harward Business Magazine. January-February 2011.

Raworth, K., 2012. A Safe and Just Space for Humanity. Can we live within the Doughnut? https://doi.org/10.1163/2210-7975_HRD-9824-0069 [Oxfam Discussion Paper]. Oxfam

Raworth, K. (2017): *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Vermont, USA: Chelsea Green Publishing. 320 p. ISBN-13: 978-1603586740

Recordon J., Gilloots C., Brunner D., Fragnière A. (2025), The Doughnut framework: From theory to local applications in Switzerland—literature review & practical lessons. Journal of Cleaner Production, Volume 505, 2025, 145440, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2025.145440.

Reed, B. (2007). *Forum. Shifting from "sustainability" to regeneration.* Building Research and Information. Taylor & Francis.

Robinson, J., Cole, R.J., 2015. *Theoretical underpinnings of regenerative sustainability*. Build. Res. Inf. *43* (2), 133–143.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A. (2009): *A safe operating space for humanity*. Nature, 461. 7263. 472-475. p. doi: 10.1038/461472a

Sandberg, A., Armstrong, S., Gorman, R., England, R. (2021). Sigmoids Behaving Badly: Why They Usually Cannot Predict the Future as Well as They Seem to Promise. Available at SSRN: https://ssrn.com/abstract=3926169

Sharpe S., Lenton T.M. (2021): Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope, Climate Policy, DOI: 10.1080/14693062.2020.1870097

Schot, J., Kanger, L., 2018. "**Deep transitions: Emergence, acceleration, stabilization and directionality**," Research Policy, Elsevier, vol. 47(6), pages 1045-1059.

Sovacool, B. K., How Long Will It Take? Conceptualizing the Temporal Dynamics of Energy Transitions (August 30, 2016). Energy Research & Social Science 13 (2016) 202–215, Available at SSRN: https://ssrn.com/abstract=3445386

Swilling, M, (2013). Economic crisis, long waves and the sustainability transition: An African perspective. Environmental Innovation and Societal Transitions. Volume 6 96-115. https://doi.org/10.1016/j.eist.2012.11.001

Vermeulen, B. (2024). The twin digital and green transition: paradigm shift or tech fix? Working Paper Nr. 231, Universität Bremen, Forschungszentrum Nachhaltigkeit (artec)

Funded by
the European Union

Veugelers R., Faivre C., Rückert D., Weiss C., 2023. "**The Green and Digital Twin Transition: EU vs US Firms**," Intereconomics: Review of European Economic Policy, Sciendo, vol. 58(1), pages 56-62, January.