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Leveraging Twin Transformation

Digital Infrastructures to Advance Decarbonisation at the Nexus of Energy and Mobility

FRAUNHOFER INSTITUTE FOR APPLIED INFORMATION TECHNOLOGY FIT,
***BRANCH* BUSINESS & INFORMATION SYSTEMS ENGINEERING**

LEVERAGING TWIN TRANSFORMATION
DIGITAL INFRASTRUCTURES TO ADVANCE DECARBONISATION AT THE NEXUS OF ENERGY AND MOBILITY

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Content

Executive Summary

»Annual infrastructure investment gaps for European climate change mitigation exceed €406 billion.«
Institute for Climate Economics

/ The ambitious plans of the Commission of the European Union (EU) to achieve climate neutrality by 2050 require fast and extensive decarbonisation efforts in all sectors. The green **electrification** of the mobility, industry, building, and agriculture sectors plays a crucial role in achieving sustainability goals and quickly reducing the carbon emissions of the respective sectors. Electrification connects these sectors closely with the energy sector. Consequently, extensive investments in the interconnection of sectors are necessary to comply with the European 'Net Zero by 2050' objective and accelerate the transition towards sustainability at a large scale.

/ The annual **infrastructure investment gaps** of the EU to mitigate climate change accumulate to over €406 billion. Such infrastructure gaps impede the progress of decarbonisation efforts. Hence, closing these infrastructure gaps is imperative to enable the green transition through cross-sectoral use cases, e.g., bidirectional charging. These emerging cross-sectoral use cases have the potential to enhance the effective use of Renewable Energy Sources (RES) and contribute to much-needed flexibility in the energy system. In a future energy system characterised by a high share of volatile RES and increased electricity demand by all sectors, cross-sectoral interconnections are essential to master decarbonisation successfully.

/ By leveraging advanced digital technologies for decentralised intelligence across sectors, the **Digital Spine** aims to bridge the infrastructure investment gaps in the short to mid-term. In doing so, the Digital Spine enables the cross-sectoral integration of existing infrastructure employing digital solutions to enhance efficiency, sustainability, and competitiveness on a European level. The resulting digital infrastructure layer enables an optimised use of RES across sectors and mitigates the need for extensive investments in physical infrastructure, e.g., transmission lines. The Digital Spine further aims to facilitate communication and standardisation of digital infrastructure, especially at the interfaces of different sectors. By streamlining the deployment of renewable energy solutions and energy flexibility measures, the Digital Spine enables the effective utilisation of available resources, accelerating progress towards sustainability goals while ensuring long-term economic competitiveness across Europe.

/ While explicitly focusing on the nexus of the energy and mobility sector, this study presents four key **Building Blocks** that leverage the potential of digital technologies to contribute to the successful implementation of cross-sectoral use cases vital for facilitating the green and digital transformation of industries (c.f. Figure 1). Enabled by the Digital Spine, the four Building Blocks represent actionable and promising starting points to connect relevant stakeholder groups and facilitate cross-sectoral collaboration – a critical aspect and prerequisite for developing scalable solutions that advance decarbonisation and unleash the potential of digital technologies on a European level. Otherwise, there is a high risk that sustainability efforts will result in fragmented and small-scale solutions that fail with cross-sectoral dependencies and yield only a limited contribution to decarbonisation.

Digital Spine – The Concept

The Digital Spine aims to bridge infrastructure investment gaps by leveraging digital technologies for decentralised intelligence across sectors, e.g., at the nexus of the energy and mobility sectors.

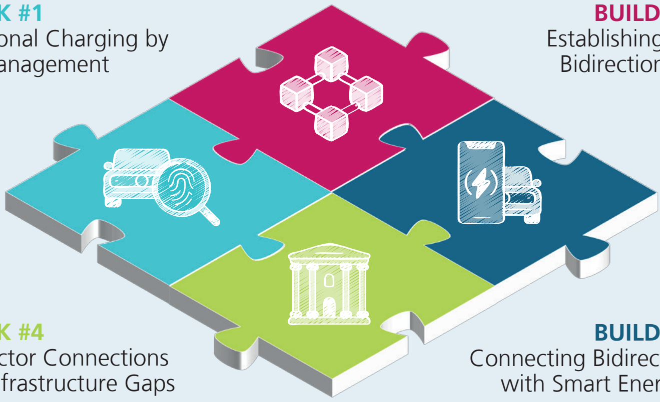
/ Immediate action on a European level is needed to advance the adoption of these Building Blocks, which rely on digital technologies such as digital identity management, data ecosystems, artificial intelligence, and edge computing. Therefore, recommendations include channelling infrastructure investments towards actionable initiatives that support the development of a cross-sectoral Digital Spine based on the presented Building Blocks. Policymakers should also define key performance indicators regarding the Digital Spine to monitor its adoption. Further, the EU Commission should drive forward the enhanced collaboration between public (e.g., EU and Member State institutions) and private institutions (e.g., companies, NGOs) to accelerate the development of digital infrastructures – since the digital infrastructure is both public and private. Continued research and development are necessary to refine and expand digital solutions for sustainable and competitive outcomes. Policymakers should prioritise investments in digital infrastructures to advance long-term economic prosperity and environmental sustainability.

Digital Spine – The Potential

The solutions that operate on a Digital Spine could be deployed on the existing grid infrastructures in less than five years at greater value and lower costs.

BUILDING BLOCK #1
Enabling Bidirectional Charging by Digital Identity Management

BUILDING BLOCK #2
Establishing Cross-Country Bidirectional EV Charging Infrastructure



BUILDING BLOCK #4
Building Cross-Sector Connections to Close Digital Infrastructure Gaps

BUILDING BLOCK #3
Connecting Bidirectional Charging with Smart Energy Applications

Figure 1. *Key Building Blocks of the Digital Spine.*

1

Spotlight: The Future of Electric Vehicles in Mobility and Energy

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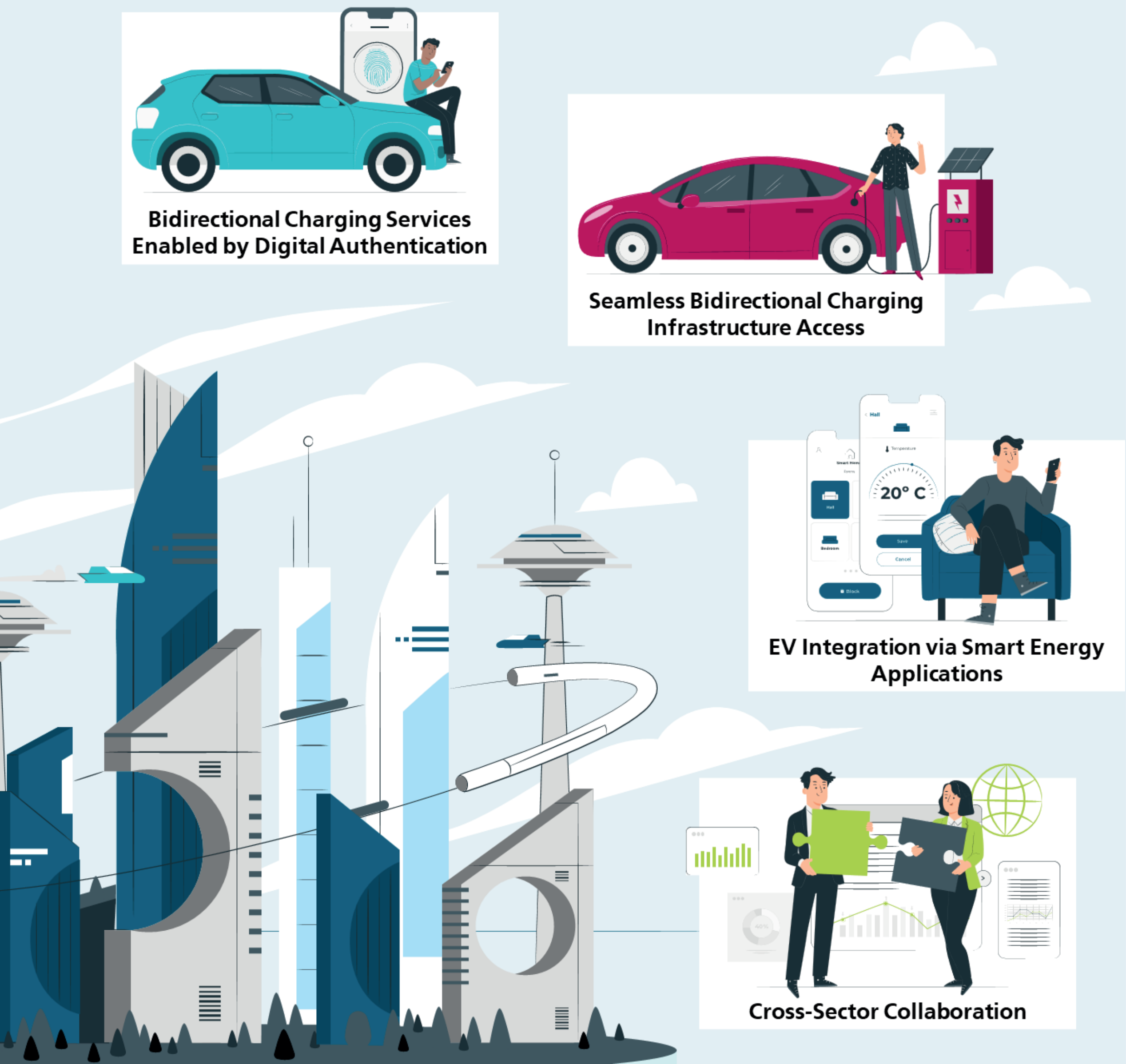
/ In the quest for a sustainable future, the cross-sectoral convergence of digital solutions is pivotal. At the heart of this transformative journey lies the deployment of digital infrastructures, orchestrating a seamless transition towards electrification and sustainability in all sectors. The following chapter casts a spotlight on four key activities of future sustainable energy and mobility solutions in Europe (cf. Figure 2). It aims to illustrate the critical role of digital infrastructures in the success of the green transition towards sustainability, specifically focusing on the nexus of energy and mobility.

Figure 2. *Driving tomorrow's sustainability: Uncovering the transformative impact of bidirectional charging leveraged by digital infrastructures.*



Bidirectional Charging Services Enabled by Digital Authentication

Bidirectional Charging

From Obstacle to Opportunity: Bidirectional charging allows EVs to charge from and supply power to the grid. Smart, bidirectional charging can mitigate the impact of e-mobility for distribution grid operations by allowing flexible charging and discharging times.

Figure 3. Bidirectional charging services enabled by digital authentication.

/ In our vision for a smart, sustainable future, we imagine Electric Vehicle (EV) users will seamlessly engage in bidirectional charging services, actively contributing to grid stability and maximising the utilisation of decentralised generation from Renewable Energy Sources (RES).

/ A digital wallet linked to the EV's digital identity serves as the gateway to bidirectional charging services at private, semi-public, and public charging infrastructure, e.g., as Elia Group (2023) recently suggested. With a mere tap on their (mobile) screen, EV users as owners of decentralised assets within the energy sector have the chance to provide their EV's storage capacity, offering flexibility services to the electricity grid and profiting both from revenues associated with the provision of flexibility services and charging services that comply with their individual mobility needs.

/ Such a digital machine identity allows user-centric authentication of EVs, ensures secure data exchange, and facilitates real-time coordination of bidirectional charging services across different charging networks and service providers. Furthermore, the users regain sovereignty over whom they want to share their personal data with and for what purposes.

/ Further, bidirectional charging points in parking houses or multi-tenant houses of private-public spaces may entail a digital orchestration element with core functionality to shift load dynamically away from peak hours based on real-world, real-time conditions. This may relief strain on distribution networks during peak loads from EVs or heat pumps. Such digital orchestration may aggregate power consumption in parking spaces and avoid peaks during EV charging during rush hours. A reasonably modest investment into the electricity infrastructure of buildings may facilitate grid-friendly connections and fast scale-up of EV charging infrastructure.

Seamless Bidirectional Charging Infrastructure Access

/ Electric vehicles are inherently decentralised – in motion to meet users' mobility needs and stationary when not in use. In our vision of a pan-European bidirectional charging infrastructure, EV users can seamlessly navigate international charging services while using EVs as "floating batteries," enhancing grid stability and energy storage across Europe. The opportunity to resort to any charging service or provide any flexibility service within the European Union (EU) relies, among other things, on the interoperability of different digital infrastructures.

/ Hence, interconnected asset registries serve as a linchpin to establishing a cross-country infrastructure and connecting both identity management of EVs and EV users. Interfaces between different European registries allow the secure and dynamic exchange of crucial master data of decentralised energy assets and make a repeated effortful asset registration of EVs abundant. Further, the interplay of machine identity management related to EVs with individual identity management related to EV user data allows, e.g., to base charging services on individual tariffs and charging preferences. This advancement of identity management, in turn, enables bidirectional charging services to unleash the full potential of distributed, small-scale assets, bolstering grid stability and RES utilisation from a European perspective.

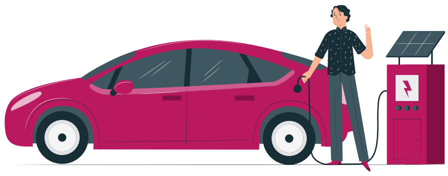


Figure 4. Seamless bidirectional charging infrastructure access.

EV Integration via Smart Energy Applications

/ Electrification not only strongly connects the energy with the mobility sector but also with building infrastructure. Given smart home systems and buildings equipped with Photovoltaics (PV), (bidirectional) charging predominantly occurs in a decentralised residential context.

/ In our vision for a sustainable energy future, a smart energy application provides individuals with comprehensive insights, e.g., regarding their bidirectional charging operations (e.g., vehicle-to-grid, vehicle-to-building), solar rooftop electricity generation on a multi-tenant building, or heat pump operation. Such a smart energy application allows consumers to use advanced decision support and real-time energy control, providing new opportunities. For example, residents may use a smart energy application with Artificial Intelligence (AI)-supported recommendations and switch between self-supply, ancillary services, and markets with their battery storage – in line with multi-criteria optimisation of electricity costs and sustainability criteria like emission intensity. Further, smart energy applications may facilitate the establishment of energy communities where individuals can share and trade electricity locally.

/ Various data streams from different assets (e.g., heating, vehicle, electric devices) converge in smart energy applications to facilitate scenarios such as local energy trading. There, users receive (price) signals for their current energy consumption that incites behavioural change, e.g., according to the current grid constraints or the availability of renewably generated electricity. Thus, a smart energy application serves as a key interface for individuals to access real-time data on energy consumption, grid conditions, renewable energy availability, and charging schedules. This, in turn, enables consumers to fully control their energy consumption and the corresponding carbon emissions in real-time. Through seamless integration and data sharing, smart homes and buildings become the cornerstone of sustainable energy practices at the nexus of the energy and building sector.

Figure 5. EV integration via smart energy applications.

Cross-Sector Collaboration

/ Finally, we envision strengthened collaborative efforts on a European level – explicitly referring to the European Commission's departments and executive agencies – to jointly pave the way for innovation and novel approaches that facilitate the transition towards sustainability. There is no energy transition towards sustainability without decentralisation and sector coupling, which strains the physical legacy infrastructure and requires cross-sector and -domain collaboration and coordination. By leveraging AI insights, legislation and political activities converge, fostering a harmonised approach towards sustainability.

/ The illustrated spotlight depicts how a smart and sustainable future could look like – one in which digital technologies play a vital role in the sustainable provision of energy and mobility services. However, some of the illustrated aspects of the green transformation are still a long way off and require substantial investments in digital infrastructures and bold action by policymakers, industry leaders, researchers, and civil society alike.

Figure 6. Cross-sector collaboration.

2

Cross-Sectoral Decarbonisation and Required Infrastructure Advancements

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RePowerEU

According to the 'REPowerEU' initiative, the EU committed to increase its RES capacity for 2030 to 42.5%, aiming to reach 45%. This would almost double the share of renewable energy in the EU as of 2022 (European Commission, 2022a).

Smart Digital Solutions

Implementing grid infrastructure upgrades with smart digital solutions bridges investment gaps, especially in the context of flexibility provision for balancing the grid. Digital technologies help utilities to achieve reliability targets at reduced costs and ensure consumer confidence.

Imperative of Cross-Sectoral European Decarbonisation

/ Complying with the ambitious global and European targets for mitigating climate change requires a comprehensive and cross-sectoral decarbonisation strategy. At the heart of this European transformation towards sustainability lie key sectors such as energy, mobility, buildings, and agriculture, which are among the primary contributors to Greenhouse Gas (GHG) emissions. Accelerating decarbonisation in these sectors requires a significant shift towards RES and a substantial increase in electrification. Consequently, the electricity system faces profound implications, and strong transformational efforts are needed to achieve net zero GHG emissions by 2050 (International Energy Agency, 2023). Notably, there is a pressing need to speed up the green transition and promote massive investment in RES. Considerable electrification efforts in the mobility sector accompany these changes. By 2030, at least 30 million zero-emission vehicles should operate on European roads (European Commission, 2020a). With a surge in decentralised RES, energy systems will increasingly boast a multitude of distributed energy resources, ranging from household devices like heat pumps and solar panels to expansive on- and off-shore wind farms, all contributing to the development of more sustainable, renewable energy systems with significantly reduced carbon emissions.

/ These developments introduce novel challenges for the operation of the pan-European energy system, including the critical task of maintaining grid stability as well as balancing energy supply and demand to optimise the utilisation of RES (Elia Group, 2023). Addressing these challenges requires a substantial increase in flexibility, which entails aligning energy supply and demand with the intermittent availability of RES. Otherwise, renewable energy development and electrification will fail to unfold their full potential for decarbonisation. Advancing flexibility in increasingly sustainable energy systems will, therefore, become a critical determinant for the success of climate policies, particularly amidst the interplay of sectors, substantially driven by the electrification of the mobility sector at the intersection with the energy sector (Elia Group, 2023; Smart Energy Europe, 2023).

Infrastructure Gaps

/ The EU has significantly strengthened its climate policies (primarily through the Fit-for-55-Package) to reach its 2030 targets (European Commission, 2021b). In the context of this strengthened EU climate policy framework, consistent gaps concerning required infrastructures across the energy, transport, building and agriculture sectors hinder the adoption of outlined cross-sectional use cases for decarbonisation (European Scientific Advisory Board on Climate Change, 2024).

/ The European Climate Investment Deficit report highlights a significant gap in annual investment needs for climate change mitigation, projecting a total of €819 billion between 2024 and 2030 (c.f. Figure 7).

It's 67 billion euros or lights out,« warned Eurelectric secretary-general Kristian Ruby. These are the annual investment needs that Eurelectric estimates for Europe's distribution grids until 2040.

Ross (2024)

Despite substantial investments totalling €407 billion in 2022, there remains a considerable shortfall of approximately €406 billion annually in infrastructure investments (Institute for Climate Economics, 2024). However, this may still be a conservative estimate, as it may not fully incorporate the substantial investments required to address the flexibility gap, particularly concerning decentralised small-scale flexibility assets in the expanding renewable energy markets. In the subsequent sections, we offer a more nuanced analysis of the primary investment needs across key sectors for decarbonisation, contextualised within broader sustainability endeavours.

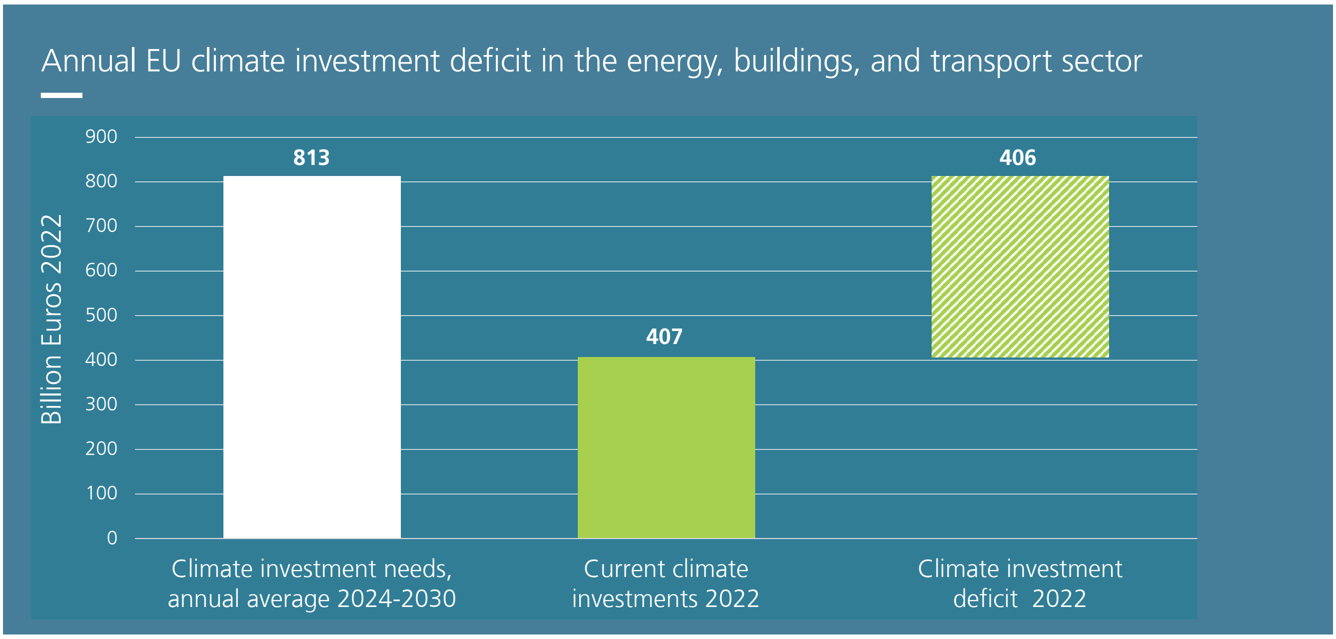


Figure 7. *Annual European climate investments (Institute for Climate Economics, 2024).*

Energy

/ On a global level, current estimations suggest that successfully reaching the agreed-on climate targets would require at least tripling global investments related to the energy transition towards sustainability to more than $4 trillion each year until 2030 in order to reach net-zero emissions by 2050, well beyond what governments can handle alone (United Nations, 2023). As a target, the energy sector's output in terms of RES generation would need to increase considerably to enable the electrification of end-use sectors (e.g., households).

/ On a European level, energy investment needs to double from the past decade to more than €400 billion a year in this decade to meet the EU objective of reducing GHG emissions by at least 55% by 2030 compared to 1990. These annual investments include some €300 billion for energy efficiency and some €120 billion for renewable energy plants and electricity grids (European Investment Bank, 2023). The ageing distribution grid is less prepared to deliver electricity at peak hours, i.e., where and when it is demanded, e.g., by EVs and heat pumps. The state of the distribution grid increases the need for costly grid investments.

Aging Grid

The ageing distribution grid is not yet prepared to deliver electricity at peak hours – where and when new energy assets like EVs or heat pumps require it.

/ The 'REPowerEU Plan' supports investments in RES and, thus, contributes to the transformation of the electricity-mix (European Commission, 2022e). Notwithstanding, the plan focusses mainly on the deployment of RES and a change in energy consumption through saving energy but not on the integration of RES. An accelerated energy transition, however, also requires a shift towards a decentralised, digitalised, integrated, and flexible energy system, with the expansion of both the transmission and distribution grids. Grid investments are urgently required to help reduce gas emissions and energy costs for consumers since cross-border energy infrastructure projects can decrease generation costs by EUR 9 billion annually until 2040 (European Commission, 2023a).

/ In this regard, the 'EU Action Plan for Grids' represents a comprehensive strategy to facilitate the deployment of electricity grids across the EU to enable large-scale integration of RES (European Commission, 2023b). Around 40% of Europe's distribution grids are over 40 years old and need modernisation (European Commission, 2023a). Therefore, the Commission estimates that around €584 billion in investments are necessary for electricity grids this decade alone, with a substantial part needed in distribution grids (European Commission, 2023a).

Mobility

/ In the mobility sector, the lack of available charging infrastructure for EVs, in general, has been identified as a critical bottleneck to achieving rapid and large-scale electrification and decarbonisation (European Commission, 2020a). With an expected surge to 40 million EVs on European roads by 2030, necessitating approximately 250 TWh of electricity, the critical role of digital technology becomes evident (Luca de Meo, 2024).

/ The 'Regulation on Alternative Fuels Infrastructures' requires the installation of fast recharging stations of at least 150kW for vehicles every 60km along the EU's main transport corridors. Recharging stations for heavy-duty vehicles with a minimum output of 350kW need to be deployed every 60 km along the core Trans-European Transport Network (TEN-T) and every 100 km on the more extensive TEN-T comprehensive network from 2025 onwards, with complete coverage by 2030 (European Commission, 2023c).

/ In its 'Sustainable and Smart Mobility Strategy', the European Commission clarified that additional investments (compared to the previous decade) of EUR 130 billion per year for renewable and low carbon fuels infrastructure deployment and an additional EUR 100 billion per year to address the 'green and digital transformation investment gap' for infrastructure. Over the next ten years, EUR 300 billion in investments are necessary to complete the TEN-T core network and build it as a genuinely multimodal system (European Commission, 2020a).

Industry

/ Europe is determinedly driving its industrial sector towards decarbonisation to combat climate change and sustain global competitiveness. Meeting this ambitious goal requires significant investments. According to the European Commission, an estimated EUR 41 billion is needed to effectively transition the industry from fossil fuels to RES between 2021 and 2030. Such investments include implementing energy-efficient machinery, adopting cleaner production processes, installing renewable energy generation systems on-site, upgrading infrastructure for energy storage, and adopting information systems that embrace energy flexibility and the toolkit for comprehensive carbon accounting and management. Regulatory initiatives such as the proposal for a revised 'Ecodesign Regulation' additionally drive the efficient use of energy and resources and the tracing and calculation of carbon and environmental footprints (European Commission, 2022f).

/ However, as highlighted by the Institute for Climate Economics (2024), comprehensive data on investment requirements in the industry sector remains lacking. Assessing the needed investments and gauging the current state of decarbonisation is challenging, especially with the reliance on emerging technologies to achieve net-zero emissions by 2050 (e.g., technological advancements that facilitate the substitution of fossil fuels in the steel industry). Closing persistent data gaps is crucial for effectively monitoring the progress of decarbonisation in the industrial sector, which calls for urgently gaining comprehensive insights on the status quo and future pathway of industrial decarbonisation in Europe.

Buildings

/ In the building sector, the EU should strongly encourage a reduction in demand for energy and materials by promoting sufficiency in the pre-use phase. This may be achieved through urban and territorial spatial planning as well as circular economy concepts to reuse building parts after the use phase. During the use phase, (home) energy management systems play a pivotal role in providing flexibility in heating and the usage of other appliances. Hence, investments are necessary to provide corresponding digital solutions as well as the data basis for these systems and their (automatically executed) recommendations for appliance usage.

/ Due to current monitoring gaps, the total number of prosumers in the EU Member States and the EU is unknown. However, the fragmented available data suggests that prosumers are increasing rapidly in some EU Member States. Regarding prosumer-driven demand response, in 2022, only 9 EU Member States had given aggregated residential end users access to the wholesale, balancing and ancillary electricity markets. Reasons include, among others, the inadequate national implementation of the EU laws and persisting market participation barriers.

/ The European Commission's Joint Research Centre (JRC) estimates that between 2012 and 2016, on average, EUR 127 billion per year was invested in energy renovations in the residential sector (European Commission, 2021c). For the non-residential sector, the JRC estimated EUR 56.7 billion per year 17 in the same period. For the renovation rate to increase from 1% to 3%, there would be a need not only for a significant scaling-up of investments, new financing instruments and schemes, and a significant increase in private capital. In 2020, the European Commission estimated that to reach the EU's 2030 target, an additional EUR 275 billion would be needed annually to close the investment gap, most of it going towards energy efficiency (European Commission, 2020b).

Prosumers

Prosumers in the building sector are households or commercial buildings that both produce and consume energy, often through RES, like solar panels. This flexibility in taking on both roles contributes to a more resilient and sustainable energy grid.

Agriculture

/ Food systems utilise 70% of the world's water (Food and Agriculture Organization of the United Nations, 2021). Additionally, the energy sector draws 15% of water resources (International Energy Agency, 2014). This interconnection between water, energy, and food systems is essential for modern life on Earth.

Most importantly, climate change has disrupted water cycles, threatening food production and human health. An ongoing shift in priorities from the hierarchy of usage to the allocation of scarcity raises a crucial question: Utilise the ample opportunities in rural areas to generate renewable energy like solar and wind or biogas at farming locations or for food production.

/ As the global demand for more efficient energy use rises and reducing GHG emissions in food production becomes a significant challenge, it places increasing pressure on our interconnected resource systems. Agriculture emissions have remained unchanged since 2005, and reductions are necessary to align the agriculture sector with the EU's climate objectives. Based on national projections, only a modest EU-level decline of 4% is expected by 2030 compared with 2005 levels. If planned additional measures are implemented, an 8% reduction is expected, highlighting the need for further action to reduce non-carbon emissions in the agriculture sector (European Environment Agency, 2023). On the road to reducing emissions, opportunities are sought through the decentralised generation from RES alongside strengthening biogas, solar- and wind energy at farming sites. Land surface use does not need to be a critical point of discussion, as solutions like Agri PV and electric tractors illustrate. The continued promotion of first-generation biofuels in EU energy policy, on the other hand, represents a policy inconsistency in applications where electrification offers a lower-emitting route to decarbonisation.

Cross-Sectoral Use Cases to Leverage Decarbonisation

/ The outlined infrastructure investment needs lay the foundation to leverage ross-sectoral use cases, which play a pivotal role in navigating the path towards decarbonisation, as they contribute considerably to increased utilisation of RES and unlocking flexibility potentials on the demand side.

One notable example of such a cross-sectoral use case is the growing adoption of bidirectional charging for EVs, which inherently bridges the energy and mobility sectors. In the following, exemplary cross-sectoral use cases illustrate how novel solutions and approaches at the intersection of various sectors will contribute to the transition towards sustainability and decarbonisation:

- **Intersection of Energy and Mobility:** Bidirectional charging for EVs not only helps mitigate harmful emissions from combustion engines but also harnesses the decentralised electrical storage capacity of EVs to enhance grid stability and maximise the utilisation of RES. Electric vehicle users can generate additional returns to reduce overall charging costs by feeding excess energy back to the electricity grid.

- **Intersection of Energy and Industry:** Energy efficiency and demand-side management strategies can help industries reduce their energy consumption and increase their flexibility in response to the availability of RES. This contributes to reducing energy-related costs for industrial consumers and improves the carbon footprint associated with business operations.

- **Intersection of Energy and Building:** Energy-efficient building design and technologies, such as smart heating and cooling systems, can help buildings reduce their energy demand and increase their flexibility to accommodate renewable energy fluctuations.

- **Intersection of Energy and Agriculture:** The concept of Agrivoltaic involves using farmland to install solar panels, enabling the coexistence of agricultural uses and energy production. Agrivoltaic allows for the simultaneous generation of energy and food without expanding the total area used and provides energy for agricultural activities.

/ These use cases highlight the importance of advancing the implementation of cross-sectoral solutions to address the complexities of modern sustainable energy systems. Despite notable progress, significant challenges persist in realising such cross-sectoral use cases. Issues such as the absence of smart metering infrastructure, inadequate bidirectional charging infrastructure, and lacking consumer engagement continue to impede implementation efforts. In addition, the underlying administrative effort necessary to realize the aforementioned developments poses a further obstacle to fast and competitive decarbonisation measures.

Digital Technologies to Bridge Infrastructure Gaps and Leverage Cross-Sectoral Use Cases

/ The progress of climate policies on a European level reveals significant gaps in infrastructure investments, which, in turn, results in substantial data gaps (e.g., in the context of real-time information on the state of decentralised assets such as EVs). Addressing these gaps offers a significant opportunity to enhance sustainability and operational efficiency. The effective use of digital technologies plays a vital role in successfully bridging infrastructure gaps and enabling the implementation of cross-sectoral use cases. Against that background, integrating advanced digital technologies and data-driven solutions into traditional infrastructure, smart infrastructure solutions can enhance efficiency, sustainability, and overall functionality and, thus, mitigate some of the imminent investment needs (e.g., in grid infrastructure). Therefore, we conclude that there is an urgent need to leverage decentralised intelligence to get the best out of the existing and developing infrastructures to enable and leverage the implementation of cross-sectoral use cases. In doing so, strengthening cross-sectoral collaboration is imperative. A holistic perspective that integrates the viewpoints of various sectors is essential for the success of climate policies, and policymakers must recognise the cross-sectoral nature of these challenges and work cohesively to coordinate efforts across traditionally siloed domains.

Sustaining European Competitiveness

/ Investing in a digital orchestrator at the nexus of the energy and mobility sectors may create promising opportunities to **sustain European competitiveness** in the future. Building up Europe's capacity to produce and use clean energy is essential to ensuring that the EU remains competitive in the global clean energy technology market, benefiting the European economy and citizens.

/ The EU currently faces technological and non-technological challenges, such as high energy prices, critical raw materials supply chain disruptions and shortages in skilled personnel. Strengthening the competitiveness of the EU's clean energy and mobility sectors will help shape a more resilient, independent, secure, and affordable energy system and, consequently, contribute to a prosperous European economy.

/ In the past, the EU has already demonstrated how the green transition can strengthen competitiveness. The phase-out of Russian fossil fuels has accelerated a new industrial revolution to end the age of fossil fuels and associated supply chain risks. A wide range of new net-zero technologies is being developed and deployed across our economy: in transport, buildings, manufacturing, energy, and even creating entirely new markets. **EU's net-zero ecosystem was worth over EUR 100 billion in 2021**, doubling in value since 2020. Finally, sufficient digital infrastructures are key to the conducive net-zero business environment the Green Deal Industrial Plan seeks to establish (European Commission, 2023d).

3

Digital Technologies as Key Enablers for Cross-Sectoral Decarbonisation

Digital Technologies as Key Enablers for Cross-Sectoral Decarbonization

/ Digital technologies are one of the key enablers for achieving fast, cross-sectoral decarbonisation and addressing the existing gaps outlined in the previous chapter. Especially regarding increasing electrification via the deployment of RES, the current landscape in the EU reveals gaps in the existing digital infrastructure that hinder an efficient integration of sector activities – for example, at the interface of the energy and mobility sector. However, emerging digital technologies have proven to offer significant opportunities and untapped potential to enhance the sustainability and operational efficiency of the EU's respective regulative instruments. Generally, the EU has already recognised the need to drive digitalisation forward and align the digital agenda with the one for the green transition – the most prominent example being the 'Digital Decade' policy programme (European Commission, 2021a, 2023f). Further programmes include, e.g., the 'EU Action Plan' to digitalise the energy system (e.g., via digital services to engage consumers), the 'Digital Europe Programme' to fund projects bringing digital technology to businesses, citizens and public administrations, or the 'Sustainable and Smart Mobility Strategy' (e.g., deploy digital services to make multimodal mobility seamless) (European Commission, 2020d, 2021d, 2022h, 2022i, 2022j).

/ These programmes highlight the need to address the hardware foundations necessary to realise digital services, i.e., a substantial increase in connectivity via high-capacity and high-speed networks, the need for growing semiconductor production, and a new paradigm for data processing in the form of edge and quantum computing. However, not only the physical components, i.e., the device layer, but also the digital ecosystem above it is highly relevant to connecting different sectors. The digital infrastructure encompasses, for example, the design of communication and information networks, the creation of appropriate functions, applications, and services based on data, and the presentation of data and information.

Digital Decade and the 2030 Digital Compass

The Digital Decade policy programme aims to advance the digital transformation of the EU and its Member States. Therefore, the Digital Decade policy programme defines four cardinal pillars to guide the digital transformation of the EU (cf. Figure 8):

- **Skills**
- Digital transformation of **businesses**
- Secure and sustainable digital **infrastructures**
- Digitalisation of public services and **government**

These pillars consist of specific targets for 2030 and are accompanied by national Key Performance Indicators (KPIs) to analyse the progress towards the stipulated targets. The Member States have to realise and evaluate roadmaps in a two-year cycle to achieve the stipulated targets (European Commission, 2023h).

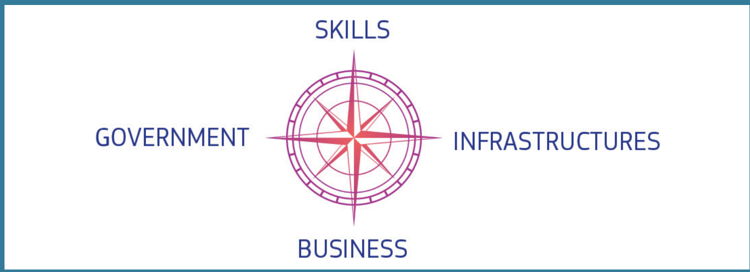


Figure 8. *2030 Digital Compass (European Commission, 2023h).*

Understanding Digital Infrastructure

/ Figure 9 highlights that it is 1) necessary to develop the hardware infrastructure in close connection to the digital layers and 2) that the digital layers of existing and upcoming architectures is complex – for example, regarding the interconnection of the physical data exchange, the semantic considerations on top of the physical communication infrastructure, and, finally, the utilisation of data and resulting information itself. In the remainder of this study, »digital infrastructure« refers to the digital layers and information systems closely integrated into the physical hardware (e.g., sensors, charging infrastructure, etc.)

A Digital Spine Connecting the Digital Infrastructure

/ The fast development of an appropriate digital infrastructure that can support electrification and the increasing number of cross-sectoral use cases is necessary to drive the development of successful decarbonisation (European Commission, 2022b, 2022c). The need to leverage decentralised intelligence is evident to both policymakers and companies to get the best out of the integration of an electricity grid increasingly based on RES with emerging smart EV-charging, smart building infrastructures, and further advances in other sectors. By integrating advanced digital technologies and data-driven solutions into traditional energy infrastructure, the digital infrastructure can enhance efficiency and sustainability (European Commission, 2023b, 2023e). Furthermore, investments in developing a digital infrastructure at the nexus of energy and mobility may broaden the existing infrastructure's overall functionality and drive the EU's competitiveness by mitigating other imminent investment needs.

/ As such, the development of a fitting digital infrastructure in the form of a "Digital Spine" (cf. Figure 10) is not only a lever but also a necessity to cope with the demand for seamless services amid staggering infrastructure investments and support critical interdependencies between sectors, e.g., the mobility and energy sector. The Digital Spine operates at the nexus of various sectors – with the energy sector at heart – and contributes to increasing the adoption of digital solutions to make infrastructures smart(er). Digital connections between sectors will reduce the short-term urgency of structural investments, e.g., concerning distribution grid infrastructure. Enabling seamless connections to the energy sector from other sectors to reduce congestion strains to the electricity grid may, in turn, reduce the need for investments in the distribution and transmission grids. By supporting an increasingly decentralised organisation of energy sources, prosumers, and consumers, an intelligent Digital Spine may reduce CAPEX and OPEX in the short and long term. As the Digital Spine represents essential connections, such digital infrastructure should be based on an open ecosystem, boosting innovative services and applications across key sectors like e-mobility, energy and buildings.

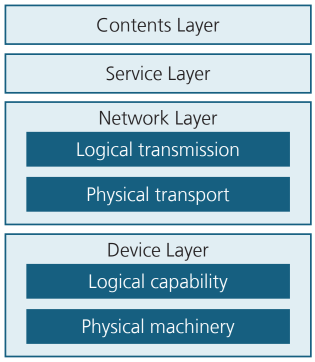


Figure 9. *The layered architecture of digital technology.*

Introducing the Digital Spine

The Digital Spine aims to leverage digital innovation and technology adoption via smart infrastructure investments at the nexus of energy and mobility. The Digital Spine builds on agreements to spur a digital-enabled infrastructure and encompasses also corresponding digital technologies for decentralised intelligence and integration of previously isolated sector activities. This concept integrates the view of minimising adverse operational risks and reducing the risks of stranded assets as well as negative impacts on users in their transition to a lower carbon footprint of living and in their transition to e-mobility. The essence of the Digital Spine is that its solutions could be deployed on the existing grid in under five years at greater value and lower costs – thus, enabling the efficient use of an emerging charging and electricity grid infrastructure.

/ In essence, the Digital Spine encompasses the digital infrastructure and corresponding digital technologies for decentralised intelligence and integration of previously isolated sector activities to enable the efficient use of an emerging charging and electricity grid infrastructure and accelerate decarbonisation in the mobility and energy sector. To better understand the need for a Digital Spine as an essential component for achieving the green

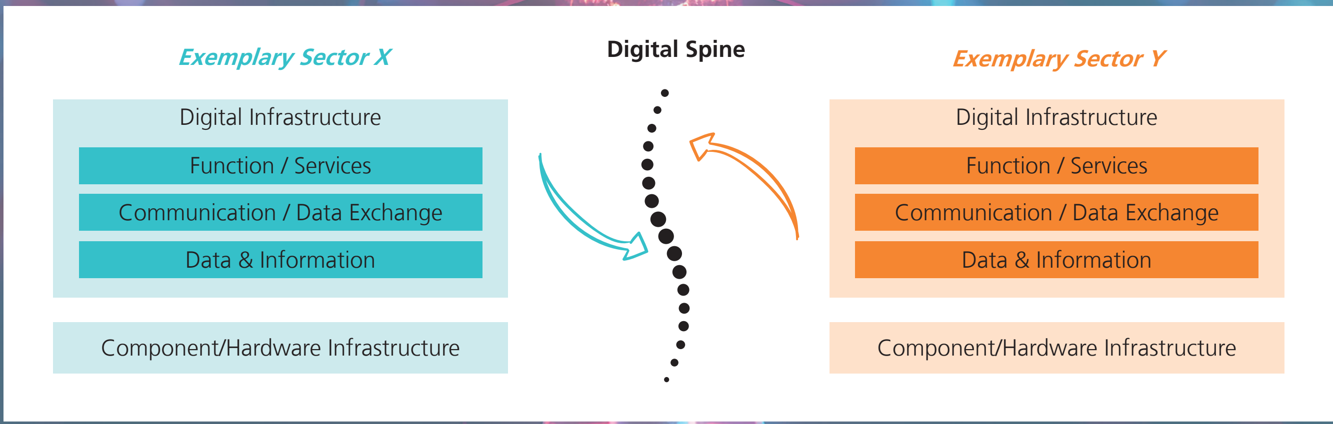


Figure 10. *The Digital Spine as orchestrator between sectors.*

Digital Spine – The orchestrator

The Digital Spine serves as a digital orchestration interface, built on the exchange of flexibility signals and/or an energy operating system, to control energy flows and minimise the carbon footprint.

transformation at the interface of the different sectors, one has to think about green electrification as one of the critical elements to achieve decarbonisation. By substituting fossil-fuel-based energy sources in the industry, mobility, building, and agriculture sectors, these sectors become much more intercoupled with the energy sector. Therefore, the Digital Spine is essential to achieving the green transformation. The Digital Spine has the vast potential to provide rapid solutions to relax urgent public investments into the grid and charging infrastructure by more efficient use of available resources. At the same time, it incentivises private investments and allows accelerated deployment of charge points, heat pumps as well as the capacity of RES integration. For example, with at least 90 GW of peak demand growth expected within the next decade, the Digital Spine could be an essential bridge to address near-term needs while new grid infrastructure is built. It will further contribute to monitoring progress towards decarbonisation targets set for 2030 of key sectors – ensuring coherence and coordination for policies and programmes to fully contribute to the European green and digital transition.

/ The Digital Spine acts as a digital orchestrator between the sectors and their specific digital infrastructure (cf. Figure 10). Thus, the Digital Spine builds the bridge between the specific infrastructures, standards, operations, and understandings of one sector to another. With the focus on renewable energy use, such a Digital Spine for translating and communicating between the sectors becomes an increasingly necessary part of the (digital) infrastructure in general – especially with respect to (energy) flexibility. In the case of providing and utilising energy flexibility, each sector has a different database, definition, and conception. For flexibility to be leveraged seamlessly between the sector interfaces, the Digital Spine aims to even out the current status quo of each sector. Agreements on flexibility functions could be settled to orchestrate energy usage, agreements on data and information exchange or energy operating systems for minimising the carbon footprint, basically with harmonised interfaces and Application Programming Interfaces (APIs). However, since the Digital Spine has first to be established by bringing the sectors together (e.g., for working on a joint understanding of flexibility and relevant data parameters), it is necessary to invest in establishing the appropriate digital infrastructure to enable cross-sectional use case and address the identified investment gaps and challenges.

Introducing Relevant Emerging Technologies for the Digital Spine Digital

/ Several emerging digital technologies build the solution space for addressing current challenges with appropriate digital infrastructure (i.e., the Digital Spine) at the nexus of different sectors. In the following, relevant digital technologies are briefly introduced – especially with respect to their characteristics that provide the potential to contribute to the Digital Spine.

DATA SPACES & ECOSYSTEMS

/ A data space or ecosystem is an interconnection of organisations, individuals, and technologies collaborating to collect, share, and analyse data for mutual benefit. These concepts have in common that they enable efficient data exchange by incorporating data privacy and security rules (cf. Figure 11). This entails previously agreed-upon and explicitly implemented data reference frameworks and governance for sharing data between two or more parties (Strnadl & Schöning, 2023). Consequently, data spaces/ecosystems foster data-driven decision-making and promote collaboration via target-oriented data sharing and data compatibility across diverse systems.

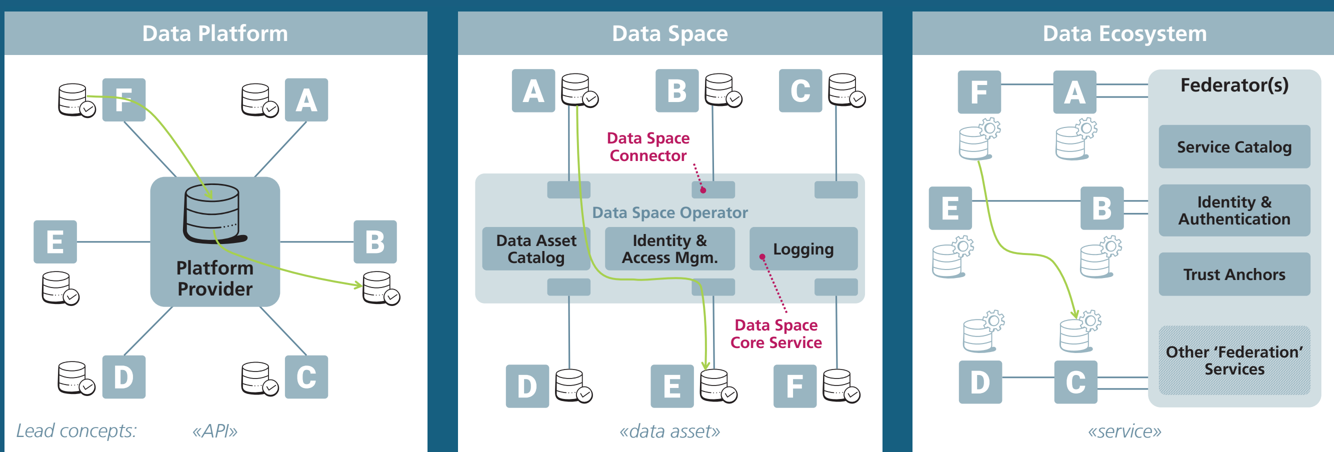
/ The sectoral data spaces, a key component of the EU's data strategy, are intended to form repositories for pooling, accessing, sharing, and processing data from within the respective sectors across the EU (European Commission, 2024). The energy data space, in particular, will have interfaces for exchanging information and interoperable open standards between grid operators, energy assets, and consumers (e.g., European Commission – DG Energy, 2023). The primary value of a data space stems from the size of the ecosystem supporting it. Common European data spaces combine relevant data infrastructures and governance frameworks to facilitate data pooling and sharing (e.g., European Commission – DG Energy, 2023). The EU and its Member States actively foster the development of such digital infrastructure via legislative initiatives (e.g., 'Data Governance Act', 'Data Act'). The creation of EU-wide common, interoperable data spaces in strategic sectors like manufacturing and energy may support overcoming existing legal and technical barriers to data sharing and, as such, unleash the enormous potential of data-driven innovation (European Commission, 2022g). The advancement of data spaces at the EU level is supported under the 'Digital Europe Programme', which especially fosters the design and development of data spaces for energy and mobility.

DIGITAL IDENTITY MANAGEMENT

/ Currently, most identities are managed in a centralised way. Centralised parties, such as administrators, define and manage a centralised identity at the system level. However, with centralised identity management, users are not able to maintain control over their identity across all identification services. To achieve autonomy in the management of identification services, identity management ideas have developed from user-centric to federated and to self-sovereign (cf. Figure 12). Self-Sovereign Identities (SSI) are an approach to digital identity management where individuals (i.e., identity holders) control their identity data and actively decide with whom to share which information of their identity (Tobin & Sovrin Foundation, 2018). This concept may be enhanced towards machines in the form of digital machine identities (Strüker et al., 2021). Because individuals or machines control their data, reliance on centralised identity providers is reduced. Thus, SSI enhances privacy and security (Clauß & Köhntopp, 2001). The EU and its Member States support the development of digital identities and corresponding identity management concepts (e.g., eIDAS).

DISTRIBUTED LEDGER TECHNOLOGIES

/ Digital and Distributed Ledger Technologies (DLT) represent a network of decentralised nodes/computers that have to agree on every transaction and state within the network (cf. Figure 13). The design of DLTs, like blockchains, offers tamper-proof record-keeping and facilitates secure and trustless transactions without relying on central authority (i.e., an intermediary). However, these solutions have to be designed and used appropriately to ensure data privacy, scalability, and low energy consumption (Schlatt et al., 2016). Hence, to leverage the potential of the features of the blockchain technology (e.g.,



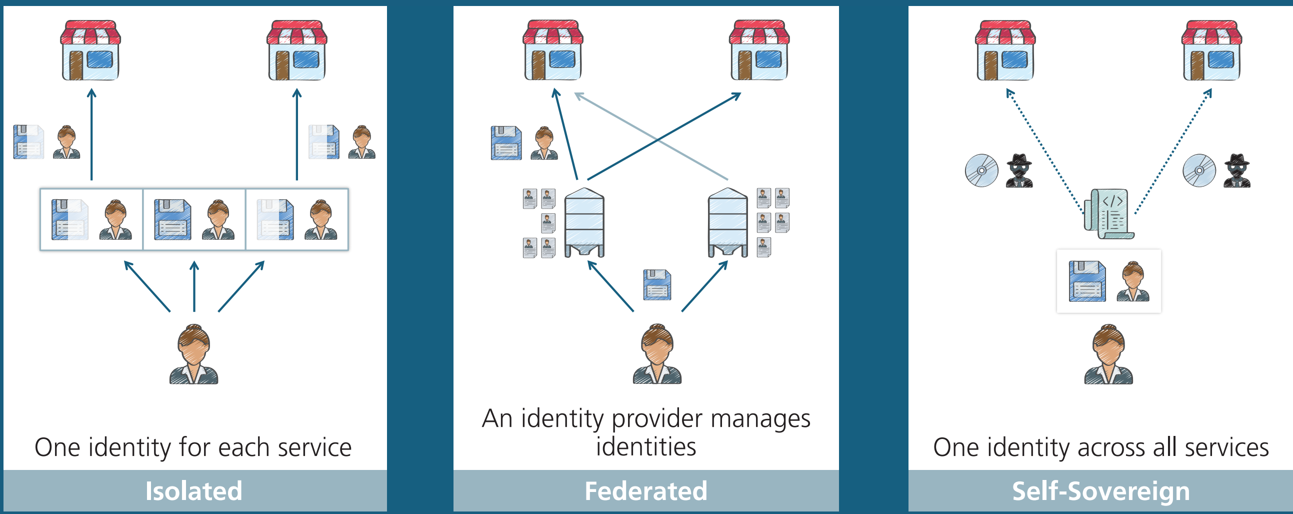


Figure 12. *From central to self-sovereign identity management (Strüker et al., 2021).*

for traceability of products and data), an important aspect is to decide what kind of record is stored on the blockchain and which data should stay off-chain for privacy and/or scalability reasons. To minimise the energy consumption of blockchains, it is also relevant to take a close look at the consensus mechanism that takes place for every transaction on the chain. The EU and its Member States actively support the development of this digital technology via legislative initiatives (e.g., Regulation 2022/858) and funding of research projects (e.g., European Blockchain Services Infrastructure (EBSI)).

ARTIFICIAL INTELLIGENCE

/ Artificial Intelligence (AI) is the intelligent use of data and self-learning algorithms that mimic and simulate human behaviour, decision-making, and interactions. AI is, therefore, a toolbox of applications that were previously performed mainly by humans and not machines (e.g., specific predictions, decision-making, automation, optimisation and solving complex tasks). AI presents multifaceted opportunities in the energy sector, such as optimising grid management and enhancing renewable energy integration. Further, AI offers cross-sectoral solutions for decarbonisation, including predictive load scheduling for industrial processes and advanced simulation methods to inform decision-making. With the advancement and operationalisation of AI solutions in recent years (e.g., in the form of large language models), the number of use cases where the utilisation of AI brings added value has increased tremendously (Schoormann et al., 2023). However, for the responsible development of AI systems as well as ethically sound and trustworthy results from their deployment, the database for the algorithms is vital, especially surrounding data bias, fairness, and transparency (Bostrom & Yudkowsky, 2018). The EU and its Member States actively support the development of this digital technology via legislative initiatives (e.g., the first law on the use of AI, i.e., the AI Act) and funding of research projects (e.g., project STAR).

EDGE COMPUTING

/ Edge Computing represents a distributed computing paradigm where data processing and analysis happen at the network's periphery, closer to where the data is generated (cf. Figure 14). Edge computing builds on advances in processing

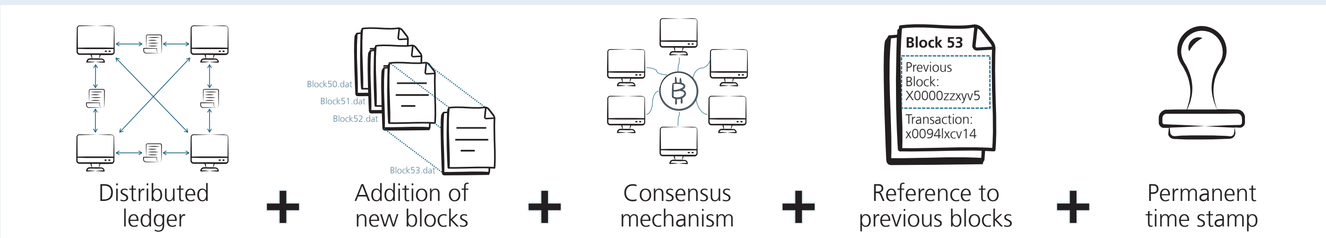


Figure 13. *Functioning of distributed ledgers (Schlatt et al., 2016).*

MetaOS in edge computing

A MetaOS can adapt dynamically to the specific needs and characteristics of each scenario and provide the appropriate functionality and interfaces through hardware virtualisation and software 'over-the-air' deployments.

power at the device level and may, thus, reduce latency and the risk of network data leakage (Wand et al.). With increasing user data security and privacy by keeping data local and minimising data transfer, edge computing may enable more real-time data processing and decision-making, especially for applications in autonomous systems. Novel abstraction paradigms at the edge, like virtualisation and containerisation, allow system developers to separate software from hardware. In particular, a so-called meta operating system (MetaOS) takes on a central role, forming the foundation for the entire edge application infrastructure (European Commission, 2022d; NEMO, 2024). It significantly influences the performance and integration of edge applications. Further, a MetaOS enables 'over-the-air' updates and interoperability between different edge computing platforms and systems.

/ Edge computing is transforming the way we manage energy systems. Referring to grid edge, for instance, the control of energy flows is reverted close to the energy end-consumers (i.e., their homes, businesses, or distribution systems) rather than at central power plants or along transmission operation lines. A MetaOS in the context of energy systems, i.e., an energyOS, may be attached to physical assets like solar panels, advanced metering infrastructure, smart inverters, energy storage systems, smart thermostats, charge points, and other smart appliances. An energyOS may tackle automated price-responsive demand response, real-time grid, data analytics, and integrated distribution system planning systems (an approach focusing on modernising utility interconnection, planning, sourcing and data sharing processes). Real-time grid optimisation would allow for a better balance between factors like reliability, availability, efficiency, and cost. Integrating energyOS with distribution system planning would support the modernisation of utility interconnection, planning, sourcing and data-sharing processes. Business innovations at the grid edge provide new opportunities like consumer analytics, third-party application interfaces and control, and aggregation for wholesale market participation.

/ To ensure interoperability between different edge computing platforms and address potential resource limitations at the edge, the EU and its Member States are active in supporting the development of the emerging edge paradigms with a budget of more than 300 million € under Horizon Europe CL4 Destination 3, section 'From cloud to edge to IoT' as well as under CL5 Destination 3, section 'Sustainable, secure and competitive energy supply' (European Health and Digital Executive Agency, 2022; European Climate, Infrastructure and Environment Executive Agency, 2022).

/ These introduced emerging digital technologies may build essential components of the future Digital Spine. As with all digital technologies, it is necessary to create the digital infrastructure and deploy it in close analysis with the requirements from a use case perspective. Only this makes it possible to leverage the properties of the respective technology to address the needs at the intersection of different sectors.

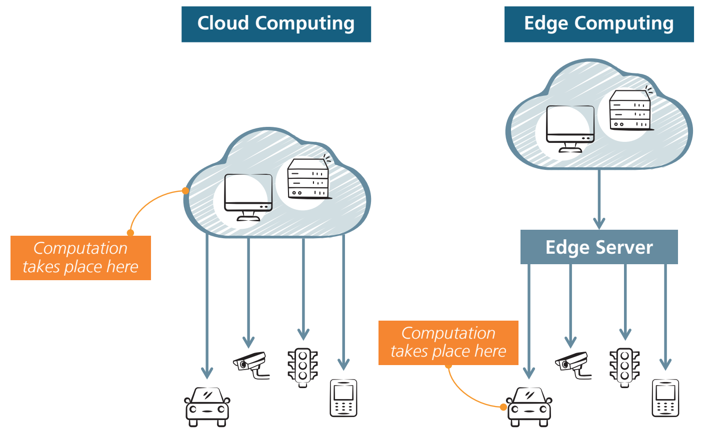


Figure 14. *Cloud vs edge computing (Wand et al.).*

4

Key Building Blocks of the Digital Spine

Key Building Blocks of the Digital Spine

/ To leverage digital technologies and information systems as an enabler to remove current investment gaps and simultaneously reach stipulated goals – especially in the realms of the 'Green Deal' – the characteristics of the technologies need to fit the problem they address. Goals may be reached faster by matching current challenges and investment gaps in realising the Green Deal with appropriate digital technologies. Moreover, digital technologies may work as enablers for the green and sustainability transition and vice versa. As such, the aim to close investment gaps within the sustainability transformation may also foster the efficient deployment of digital technologies to integrate certain sectors and specific use cases. Figure 15 illustrates the solution landscape that entails the 'matches' between digital technology solutions and current challenges and investment gaps. Within this solution space, we highlight four essential Building Blocks that represent such a 'match' and are critical elements to the spotlight vision of bidirectional EVs.

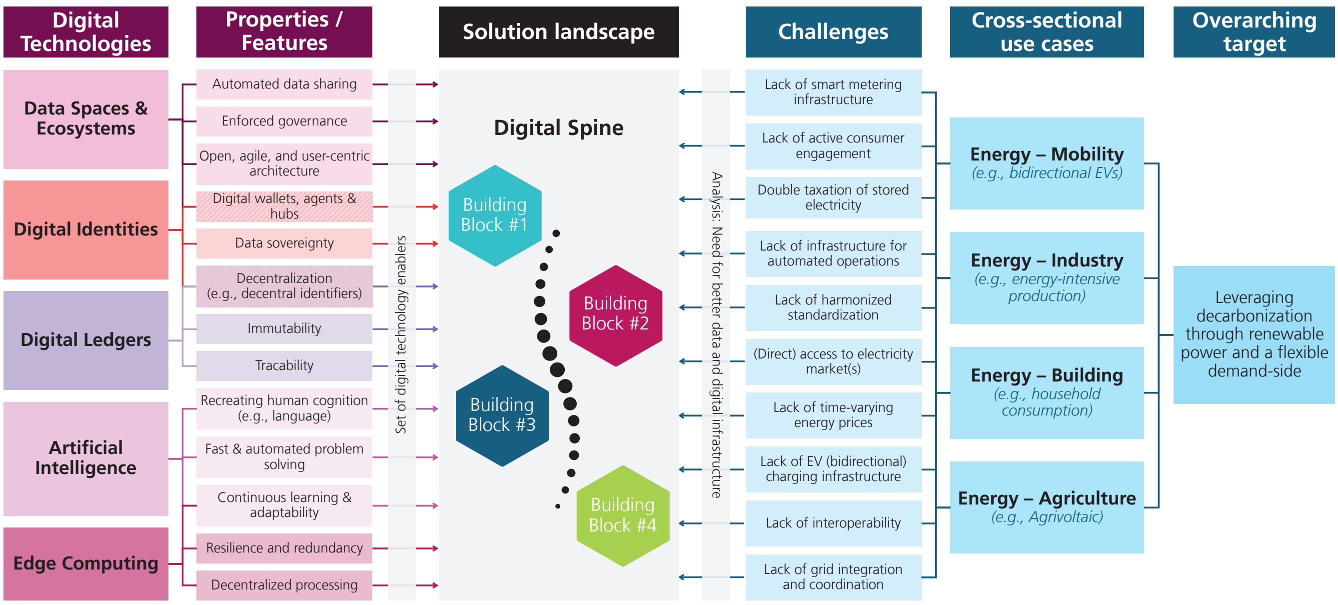


Figure 15. The solution landscape for leveraging digital technologies

/ These four key Building Blocks entail the subsequent investments:

- **Building Block #1:** Enabling Bidirectional Charging by Digital Identity Management
- **Building Block #2:** Establishing Cross-Country Bidirectional EV Charging Infrastructure
- **Building Block #3:** Connecting Bidirectional Charging with Smart Energy Applications
- **Building Block #4:** Building Cross-Sector Connections to Close Digital Infrastructure Gaps

Building Block #1: Enabling Bidirectional Charging by Digital Identity Management

CHALLENGES & INVESTMENT GAPS

/ With the electrification of the mobility sector, specifically personal vehicles, and the advancements of EVs and their batteries for discharging to connected grids, these EVs may provide services to the energy system. As such, EVs are not only a new cohort of small-scale electricity consumers but also provide electricity flexibility in two directions (i.e., time and amount of charging as well as discharging). However, for EVs to be integrated closely into the energy sector, the challenge of defining the appropriate characteristics to register an EV or similar assets within the energy system has to be overcome. It is challenging to integrate new assets like EVs that are not primarily energy assets and, hence, are not known to existing identification processes in the energy system. As such, there is a lack of "translation" tools that identify an EV within the energy system. Identifying EVs as vehicles with their specific characteristics relevant to the energy market (e.g., the state of charge) is not possible today. That is partially the case because the data relevant to identifying the vehicle within the energy sector differ from those identifying the vehicle within the classic automative value chain. Hence, identity management has to be advanced in such a way that an EV can identify itself within different sectors, i.e., as a car within its function as a vehicle (e.g., for general registration, taxes), as locally flexible storage within its function of the energy sector, and more. Current identity management does not provide interoperability between these different registers (e.g., between the general vehicle register and energy market register) or between different countries. Standardized communication protocols for identification in new areas or sectors are also lacking. Furthermore, identifying a vehicle as a machine is not sovereign in the sense of holding and managing the various identity information itself or through the owner.

DIGITAL SOLUTION APPROACH

WHAT / Digital (machine) identities, in combination with decentral identity management, have characteristics that enable the sovereign identification of a vehicle within the different sectors. Decentral and digital identity infrastructure allows entities like EVs to have control over their identities without going through central authorities for identification services. Self-Sovereign Identities (SSI) is one of the most known and established concepts in this context. SSI uses verifiable credentials to identify the entity or asset by a single or a set of characteristics. This set of characteristics may vary from sector to sector, from identification process to identification process, and even from country to country. For example, for tax purposes, the vehicles need to be identified with the help of a vehicle license, its model and fuel type, and similar characteristics. For providing services within the energy sector, other characteristics like battery capacity are relevant identifiers of the vehicle.

IMPACT ON THE CHALLENGES DESCRIBED

WHY / Digital identity management addresses challenges associated with cross-sectoral use cases, especially bidirectional charging. Such identity management with verified master data may enable seamless and trusted integration of decentralised assets in energy markets to provide grid services. Enabling EVs to manage their identity themselves can increase interoperability between different systems and sector boundaries. Hence, digital, self-sovereign (machine) identities build the foundation to securely identify actors, ensure secure data exchange between an increasing number of different stakeholders, and enable real-time coordination through end-to-end digitalisation. It is also one of the main prerequisites for providing additional grid services like emissions accounting and reporting, e.g., through digital product passports. If digital product passports are developed so that the allocated data is highly time- and volume-granular, identifying assets (e.g., within the same batch) becomes essential for differentiation. Therefore, enabling new paradigms of digital identities and their management may increase the attractiveness of demand response measures due to the possibility of verifying corresponding emission reductions. Especially for use cases like a digital product passport where characteristics like a carbon footprint should be traced along a value chain, identifying the relevant preliminary products and energy streams becomes an essential component. This may be substantially facilitated with new identity management paradigms.

MEASUREMENT OF SUCCESSFUL ENABLING OF DIGITAL, DECENTRAL IDENTITY MANAGEMENT

KPI / There are multiple ways in which a successful establishment of digital identities for identity management may be measured. Relevant KPIs should be closely aligned with the finalisation of the framework of eIDAS 2.0. Some key figures may include:

- Number of asset identities/wallets registered
- Level of interoperability achieved with other systems and platforms.
- Frequency of authentication and access requests based on digital (machine) identities.

WHO SHOULD PROVIDE SSI SOLUTIONS AND INFRASTRUCTURE COMPONENTS

WHO / To enable self-sovereign identity management, essential solution components (e.g., digital wallets) should be developed in a competitive market but with solid guidance by the EU. The regulatory framework and development support should focus on enabling the interoperability of such solutions. This may also entail investments in combination with supporting the development of certification schemes for industry solutions to ensure compliance with established standards and security requirements.

HOW CAN THE EUROPEAN COMMISSION GOVERN THE DEVELOPMENT

HOW / The EU Commission should govern the development of digital, decentral identities and corresponding solutions by the industry to drive the Commission agenda. As such, the Commission should define a regulatory framework that defines standards as well as security and privacy requirements to ensure responsible and secure deployment of identity management for assets. This may be in close collaboration with eIDAS 2.0 setting the framework for identifying people and businesses. Further, the Commission should encourage open-source initiatives that contribute to the development of interoperable and transparent solutions as well as provide funding and resources for pilot projects that demonstrate the practical applications and benefits of digital machine identities across various sectors (e.g., in real labs). Particular attention should be paid to the semantics of identities and the agreement on relevant attributes that compile the master data of an asset (i.e., a minimal set of definitions).

Key building blocks

The building blocks represent digital infrastructures that imperatively enable the green and digital transformation of industries and, therefore, constitute the solution landscape to leverage decarbonisation through renewable power and a flexible demand-side.

Building Block #2: Establishing Cross-Country Bidirectional Charging Infrastructure

CHALLENGES & INVESTMENT GAPS

/ Today, only a very limited portion of the existing EV charging infrastructure supports bidirectional charging, which prevents the increasing electrification of the mobility sector and ensures grid stability as the EV market share grows. Beyond the physical hardware, such as charging stations, a significant gap exists in the digital infrastructure necessary to support bidirectional charging. This digital layer is crucial for integrating EVs into the energy system as flexible small-scale and decentralised storage units that can both draw from and feed energy back into the grid.

/ For the successful and targeted use of bidirectional EVs and the establishment of new business models deploying the energy flexibility potential of EVs, it becomes increasingly relevant to integrate data contained in different (asset) registries. Interconnecting registries across countries, e.g., is imperative to allow EV users to engage in bidirectional charging services seamlessly. A lack of connected registries (e.g., the MaStR in Germany, RNIP in France, GSE in Italy and other registers for guarantees of origin, flexibility, etc.) may inhibit the integration of EVs into the grid as flexible energy resources, limiting their ability to support grid stability and accommodate fluctuations in generation from RES.

Registries for installed power capacity

Across the EU, the Member States keep track of the installed generation capacity and other market participant information in various registries - for example, in the 'Marktstammdatenregister' (MaStR) in Germany, the 'Registre National des Installations de Production' (RNIP), and the 'Gestore dei Servizi Energetici' (GSE) in Italy.

DIGITAL SOLUTION APPROACH

WHAT / To ease access to bidirectional charging infrastructures for EV users, interfaces between (national) registries and cross-sectoral registries (e.g., in the energy or building sector) are a prerequisite. Formulating interoperable interfaces based on agreed data exchange protocols would enable registries to communicate with each other and exchange data in a standardised format. In combination with the integration of new forms of identity management (cf. Building Block 1), this would increase access to bidirectional charging services for EV users.

IMPACT ON THE CHALLENGES DESCRIBED

WHY / Establishing digital connections between different registries across sectors is paramount for advancing sustainability efforts and optimising resource utilisation in various industries. Organisations can enhance efficiency and coordination by seamlessly integrating and sharing data across sectors such as energy, transportation, and industry. One significant advantage of this integration is the prevention of double spending and the accurate tracking of certificates, especially concerning sustainable properties like emission intensity or aggregated carbon footprints. This ensures the integrity of environmental certifications and incentives, minimising fraud and misrepresentation. Moreover, real-time monitoring of energy consumption, production, and demand across different sectors enables better control and optimisation of energy resources. This dynamic monitoring capability allows for more effective management of carbon intensity, contributing to improved environmental outcomes. Furthermore, integrated registries facilitate holistic planning by considering the interdependencies between sectors. Connecting registries across sectors and countries promotes transparency, efficiency, and innovation, laying the groundwork for a more resilient and interconnected European energy system that incites energy flexibility and utilises such potential in the context of bidirectional EV charging.

MEASUREMENT OF SUCCESSFUL CROSS-COUNTRY INFRASTRUCTURE INTEGRATION

KPI / Successfully establishing interoperable connected registries involves actors from different sectors at the Member State level (cross-sector connections) on the one hand and actors from different Member States on the other (cross-country connections). The following KPIs may provide insights into the progress of associated efforts:

- *Number of Interconnected Registries:* Track the number of registries across sectors and countries that are successfully interconnected. This metric indicates the level of progress in establishing digital connections and promoting cross-sectoral data exchange.
- *Data Exchange Volume:* Measure the volume of data exchanged between interconnected registries over a specific period. This KPI provides insights into the frequency and extent of information sharing, highlighting the effectiveness of interoperable interfaces and data exchange protocols.

WHO SHOULD ESTABLISH INTEROPERABLE REGISTRIES

WHO / The responsibility for providing interoperable registers should be shared among stakeholders in policy and industry. By engaging in dialogue, defining clear responsibilities, and fostering collaboration, stakeholders can overcome barriers and incentivise the development of interconnected digital infrastructure that benefits all parties involved. Public authorities and regulatory bodies (on Member State and EU level) play a crucial role in defining standards, regulations, and frameworks for interoperable registers. They can facilitate stakeholder collaboration, set data exchange protocol requirements, and ensure compliance with legal and privacy regulations. Industry associations can contribute by developing industry-wide standards and best practices for interoperable registers. They can foster collaboration among companies, promote knowledge sharing, and advocate for standardised data exchange formats and protocols.

HOW CAN THE EUROPEAN COMMISSION GOVERN THE DEVELOPMENT

HOW / The European Commission can set common data exchange and communication standards to ensure interoperability among different registries and systems. By defining uniform protocols and formats, the Commission can facilitate seamless integration and data sharing across sectors and countries. Further, it is necessary to actively promote the integrated design of new registries, such as those for hydrogen, by ensuring their connection to other relevant registries, such as those for electricity or guarantees of origin. This approach fosters coherence and synergy among different infrastructure initiatives, maximising their effectiveness and value. Finally, the Commission can facilitate stakeholder discussions to define the necessary interconnections between registries and clarify the responsibilities of various stakeholders. This includes engaging with various political bureaus to ensure horizontal and vertical integration and fostering dialogue among policymakers, industry representatives, and other relevant stakeholders. The Commission may create a conducive environment for developing interconnected infrastructure and governance frameworks by promoting collaboration and consensus-building.

Building Block #3: Connecting Bidirectional Charging with Smart Energy Applications Based on Advanced Data Sharing

CHALLENGES & INVESTMENT GAPS

/ Despite the availability of digital identity management and connected registries facilitating bidirectional charging services for EV users, there remains a need for user-centric digital applications. These applications should enable invoicing and payment services tailored to individual tariffs while providing an integrated energy management perspective. This includes harnessing energy flexibility potentials in smart homes and buildings and integrating external data sources related to grid congestion or renewable energy feed-in. Currently, bidirectional charging and smart home management systems operate within separate data ecosystems, resulting in siloed data and limited communication channels (Smart Energy Europe, 2023). This fragmentation hampers the realisation of decentralised flexibility provision, which is crucial for optimising RES utilisation and enhancing grid stability. To unlock the full potential of decentralised flexibility provision, novel digital approaches for data sharing (e.g., data spaces) are imperative to enable cross-sectoral interoperability (European Commission – DG Energy, 2022; European Commission – DG Energy, 2023; OFGEM, 2023). These solutions should facilitate seamless communication between bidirectional charging infrastructure, smart energy management systems, and external data sources. By integrating real-time signals and actionable insights, these solutions can prompt consumers to make informed decisions and adjust energy consumption behaviour accordingly. However, the current market landscape offers only a limited array of interoperable solutions at the intersection of the mobility, energy, and building sectors. This highlights the need for further investment and innovation to develop comprehensive and user-centric digital applications that bridge the gap between bidirectional charging and smart energy management.

DIGITAL SOLUTION APPROACH

WHAT / A smart energy application allows for integrating external data (grid conditions, renewable energy availability) with data on bidirectional charging and data related to smart home appliances. External data can be provided by Transmission System Operators (TSOs), Distribution System Operators (DSOs), or other commercial providers (c.f. Figure 16). Transferring external data (e.g., via API) to smart energy applications results in signals that may influence consumer behaviour. The received information allows consumers to monitor and control their energy consumption behaviour in real time while receiving external information that incentivises dynamic load management and demand response. A transparent, user-centric application interface is one of the key elements for users to engage in such smart energy services.

IMPACT ON THE CHALLENGES DESCRIBED

WHY / As (bidirectional) charging predominantly occurs in direct connection to smart homes, buildings, and districts, a smart energy application provides individuals with insights regarding their bidirectional charging operation (vehicle-to-grid, vehicle-to-building relation) and allows real-time energy management and control. Advanced data sharing lays the foundation to prompt consumers with signals that incentivise active consumer participation in energy markets and the effective use of energy flexibility potentials.

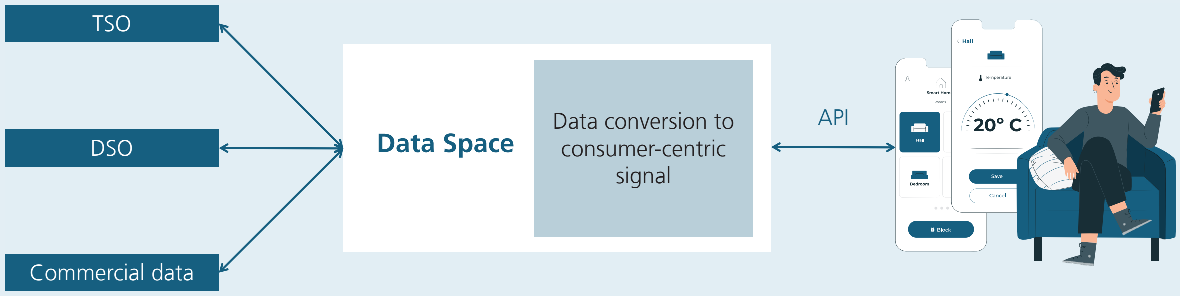


Figure 16. Consumer with smart energy application

MEASUREMENT OF SUCCESSFUL DATA SHARING AND CONSUMER INTEGRATION

KPI / There are various KPIs that may help monitoring a successful consumer integration via data sharing, especially in smart energy applications:

- *Smart meter roll out:* Tracking the number of smart meters is functional to assess the progress of energy efficiency initiatives, identify areas with high energy consumption, and implement targeted interventions to promote energy conservation and reduce carbon emissions.
- *Number of users:* Users of a smart energy application, e.g., acting as prosumers in this context, play a vital role in driving sustainable practices and leveraging digital innovations within the building environment. Accurate data on the number of users helps understand the scale of distributed energy and consumption, market demand and trends, and facilitates resource allocation.

WHO SHOULD LAY THE FOUNDATION FOR ADVANCED DATA SHARING

WHO / The European Commission can drive interoperability initiatives and set guidelines for flexibility requirements, providing a regulatory framework that encourages private investments in smart metering infrastructure. However, collaboration with industry stakeholders is vital to ensure that these standards and investments align with the practical needs and capabilities of the energy sector. DSOs and TSOs, as operators of the energy distribution and transmission networks, play a pivotal role in implementing advanced data-sharing mechanisms. Their expertise in managing grid operations and handling large volumes of data is essential for integrating smart energy applications effectively. Energy retailers and technology providers bring valuable insights and resources to the table, contributing to the development and deployment of innovative solutions. They can leverage their market knowledge and technological expertise to create user-friendly smart energy applications that meet the evolving needs of consumers and grid operators.

HOW CAN THE EU COMMISSION GOVERN THE DEVELOPMENT OF SMART ENERGY APPLICATIONS

HOW / In this regard, the Commission has developed a 'Common European Reference Framework' for energy-saving applications (European Commission, 2023g). The Commission should invest in prototypes for realising smart energy applications under this common framework that additionally incorporate bidirectional charging services and utilise external data to transmit pricing signals (e.g., in the context of the Digital Europe Programme). The resulting prototypes can demonstrate the feasibility and benefits of active load management, encouraging further innovation and adoption in the market. Further, the Commission can advocate for and support the rollout of smart meter gateways at the national level. This initiative promotes the collection of real-time energy consumption data, which is essential for enabling advanced functionalities in smart energy applications.

Building Block #4: Building Cross-Sector Connections to Close Digital Infrastructure Gaps

CHALLENGES & INVESTMENT GAPS

/ The use of digital technologies is leading to a convergence of topics across sectors. However, political frameworks are still primarily developed in silos, with traditional sector perspectives dominating decision-making processes. Political frameworks, however, are still mainly developed in silos (i.e., taking traditional sector perspectives). Insufficient collaboration and communication may result in potential inefficiencies, missed opportunities, and conflicting policies. This is especially problematic when addressing cross-cutting issues such as climate change mitigation and adaptation. Decisions and investments in one sector may inadvertently limit options and flexibility in others, leading to path dependencies and lock-ins. This can hinder the adoption of innovative solutions and impede progress towards green and competitive transformations. Instead, green and competitive transformation requires the creation of Win-Win use cases by integrating transformations and leveraging the strong effect at sector interfaces. The political structure to develop new regulatory frameworks needs to adapt accordingly. Otherwise, there is a high chance that the developed law does not fit the practical need or results in "double" legislation (e.g., more than one law addresses certain cases from different perspectives).

DIGITAL SOLUTION APPROACH

WHAT / A comprehensive solution approach can be adopted to foster cross-sectoral integration on a European level. Advanced quantitative modelling techniques can be employed to identify urgent needs for collaboration between sectors represented in the EU Commission. By analysing data and trends, these models can pinpoint opportunities for sector coupling initiatives, facilitating cross-sectoral integration and alignment of policies. AI methods can be crucial in uncovering digital infrastructure gaps and identifying policy interrelations across sectors. By processing vast amounts of data, AI algorithms can detect patterns, correlations, and potential areas for improvement. Therefore, to ensure accuracy and reliability, it is essential to base AI analysis on unbiased data sources, such as law drafts, industry insights, and other relevant information.

IMPACT ON THE CHALLENGES DESCRIBED

WHY / The digital solution approach holds the potential to strengthen cross-sectoral integration, enhance climate policy implementation, and promote comprehensive regulation. By leveraging advanced technologies and data-driven insights, the EU can address complex challenges more effectively, driving sustainable and inclusive growth across sectors. By utilising advanced quantitative modelling and AI, the EU can foster closer collaboration between different sectors represented in the EU Commission. This collaboration strengthens cross-sectoral integration, particularly concerning sector coupling initiatives. Identifying synergies and opportunities for joint action can mitigate the risk of path dependencies and lock-ins, enabling more flexible and adaptive policymaking. Digital solutions can help identify areas where coordinated action across sectors is necessary to achieve climate targets. By leveraging AI to uncover digital infrastructure gaps, the EU can ensure that climate policies are implemented cohesively, minimising duplication and maximising impact.

MEASUREMENT OF SUCCESSFUL ENABLING OF DIGITAL, DECENTRAL IDENTITY MANAGEMENT

KPI / The following KPIs can be considered to measure policy progress on the outlined digital solution approach:

- *Cross-Sector Collaboration Index:* This KPI measures the level of collaboration between different sectors represented at the European Commission or Member State level. It can be assessed through surveys or stakeholder interviews to gauge their perceptions of collaboration and communication across sectors.
- *Digital Infrastructure Gap Reduction Rate:* This KPI tracks the progress in reducing digital infrastructure gaps identified through AI analysis by measuring the percentage reduction in identified gaps over time, indicating improvements in digital connectivity, data-sharing capabilities, and interoperability across sectors.
- *Regulatory Efficiency Score:* This KPI evaluates the efficiency of regulatory efforts in addressing cross-sectoral challenges. This can be measured by assessing the time and resources required to develop and implement cross-sectoral regulations and their effectiveness in achieving intended goals.

WHO SHOULD INTEGRATE POLITICAL BUREAUS AND WORK SILOS

WHO / The primary responsibility for integrating political bureaus and breaking down work silos lies with the political players within the EU institutions and Member States. These actors play a crucial role in fostering collaboration and coordination across different sectors by promoting a culture of cross-sectoral engagement and shared objectives. By actively engaging with stakeholders, promoting communication channels, and facilitating knowledge sharing, political leaders can drive the integration of policy development and ensure that decisions are made with a holistic understanding of interconnected issues.

HOW CAN THE EUROPEAN COMMISSION GOVERN THE DEVELOPMENT OF CROSS-SECTORAL COLLABORATION

HOW / The European Commission can utilise advanced quantitative methods, such as AI, to systematically identify potential interactions between legislation and office activities across sectors. By leveraging data analytics, predictive modelling, and decision support systems, the Commission can more effectively pinpoint infrastructure investment gaps, opportunities for synergies, and cross-cutting challenges:

- *Cross-Sectoral Administrative Coordination:* The Commission can develop a systematic approach for cross-sectoral collaboration within the Commission, particularly within the Commissioners' offices. This entails establishing mechanisms for administrative coordination, information sharing, and alignment of objectives to ensure coherence and consistency across different policy domains.
- *Cross-Sectoral Institutional Coordination:* Initiating cross-sectoral and transdisciplinary platforms for research, collaboration, discourse, and decision-making can enhance institutional coordination. These platforms facilitate knowledge exchange, foster innovation, and promote integrated problem-solving by bringing together experts, stakeholders, and policymakers from various sectors.
- *Cross-Sectoral Formulation of Objectives:* Formulating objectives based on common indicators, such as emissions reduction targets, can promote cross-sectoral alignment and coherence in policy development. By establishing shared goals and metrics, the Commission can ensure that policies are mutually reinforcing and complementary.

5

Outlook: A Holistic Vision for Digital Infrastructure on a European Level

Outlook:

A Holistic Vision for Digital Infrastructure on a European Level

Decarbonisation accelerated by verified carbon information

Establishing digital infrastructures will be critical in enabling digital data ecosystems to trace and verify GHG emissions – a critical prerequisite for the success of carbon markets in effectively achieving GHG emission reductions.

On the Road to Bridging Infrastructure Investment Gaps for the Sustainability Transformation

/ Bridging infrastructure investment gaps that currently restrict European transformative efforts towards sustainability requires a holistic approach towards leveraging the potential of digital technologies across industries and sectors. Digital technologies can contribute to overcome lacking infrastructure prerequisites for decarbonisation in short to mid-term (e.g., enabling the pilot of bidirectional charging services). However, short-term infrastructure projects mainly stem from private investments, whereas the development of public infrastructure represents particularly medium- to long-term projects. Since it can take years to build up appropriate public infrastructure for specific use cases like bidirectional charging, the Commission should foster that the current infrastructure developments do not lead to lock-ins but rather support the integration of future capabilities. Thus, the Commission may provide a clearer vision of future infrastructure and reduce uncertainties for public and private investments through the availability of apparent targets. Simultaneously, such a development of digital infrastructure may significantly reduce overall infrastructure investment needs in the long term (e.g., by reducing electricity grid capacity requirements through employing intelligent control of decentralised energy assets).

/ Cross-sectoral use cases for decarbonisation illustrate how digital technologies can add economic, ecological, and societal value. The four key Building Blocks proposed in this study represent the technological foundation for such use cases. Even though cross-sectoral use cases are good starting points to increasingly implement digital infrastructures as an enabler for the green transition, the global interconnectedness and dependencies within value chains require an integrated perspective on digital technologies and their effective use in decarbonisation efforts. This, in particular, refers to the overarching need for end-to-end tracing of GHG emissions across sectors and value chains. Digital infrastructures and technologies play a crucial role in enabling end-to-end digitalised tracing of GHG emissions by providing the necessary tools, frameworks, and capabilities for data collection, monitoring, analysis, and sharing – which inherently occurs at the nexus of industries and sectors. By leveraging such opportunities, stakeholders can enhance the effectiveness and efficiency of emissions reduction efforts.

/ Today, however, we still observe a substantial lack of standardised schemes, policies, and technological solutions to provide end-to-end transparency on the origin and attribution of GHG emissions. Addressing this gap requires a comprehensive policy mix and a range of digital solutions, from establishing digital registries for certificates and enabling digitally verified primary data to fostering data sharing along value chains and designing evidence-based cross-sectoral climate policies. This, in turn, may enable companies as well as individuals to use and process verifiable carbon emission data and facilitate carbon-adaptive behaviour and management.

The Role of the Digital Spine in Advancing Digital Infrastructures across Sectors

/ The Digital Spine adds a cross-sectoral perspective on advancing the integration of digital technologies in existing infrastructures and accelerates the development of key Building Blocks for decentralised intelligence, which enables the successful implementation of cross-sectional use cases. In other words, the Digital Spine works as the orchestrator within specific sectors and between sectors. To derive a common governance framework for how this orchestrator works and how it 'translates' (e.g., in the sense of data sharing rules) between the different stakeholders, we suggest that the European Commission drives the formation of clusters that elaborate the common understanding in close collaboration with national policymakers.

/ Hence, as the institution responsible for the overarching governance framework, the EU may foster the digital interconnectedness and development of the Digital Spine by …

- identifying roles and responsibilities for various stakeholders (EU Commission, Member States, private organisations) regarding different aspects of the digital infrastructure,
- taking a closer look at infrastructure needs to foster sector coupling,
- establishing a nuanced strategy on the private vs public development of (digital) infrastructure,
- enhancing regulatory harmonisation across Member States to prevent fragmented digital infrastructure development and lock-in effects,
- promoting open standards and interoperability principles to ensure seamless integration and compatibility across various digital infrastructure components.

/ The elaboration of a Digital Spine at the heart of the energy and mobility sector may benefit not only these two sectors but also others. For example, regarding the interfaces to the agricultural sector, a Digital Spine is a pivotal opportunity to monitor resource consumption at the nexus of energy, water, and food production. Thus, a digital orchestrator may foster the reduction of emissions stemming from agriculture and the management of often-competing interests of water, energy, and food security while ensuring ecosystem preservation and promoting equitable societal development. The fruitful combination of the presented building blocks of a Digital Spine can already be seen in the approaches to designing digital product passports. The upcoming developments regarding the battery product passport will especially highlight the relevance of connecting different aspects of a digital orchestrator (e.g., identification, registration, secure data sharing, etc.).

Leveraging Digital Infrastructures and Turning Tomorrow's Sustainability into Reality

/ Realising progress on digital infrastructure advancements enabled by the Digital Spine will be essential to pave the way for future sustainable energy and mobility solutions in Europe, as illustrated in the introductory spotlight of this study. Specifically, the Digital Spine has the potential to substantially contribute to the successful establishment of user-centric identity management for EVs, interconnecting registries across sectors and countries, advanced data sharing at the intersection of smart mobility and smart energy applications, as well as to break up institutional siloed thinking and foster collaboration and communication.

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Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
DLT	Distributed Ledger Technologies
DSO	Distribution System Operator
EBSI	European Blockchain Services Infrastructure
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
GSE	Gestore dei Servizi Energetici (eng. Manager of Energy Services)
JRC	Joint Research Centre
KPI	Key Performance Indicator
MaStR	Marktstammdatenregister (eng. Market Master Data Register)
PV	Photovoltaics
RES	Renewable Energy Sources
RNIP	Registre National des Installations de Production (eng. National Registry of Production Installations)
SSI	Self-Sovereign Identities
TEN-T	Trans-European Transport Network
TSO	Transmission System Operator

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