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Decarbonization Through Digitalization in the Transport and Habitat Sectors

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E4C Fellows:
Alexander Eckervogt, Dalitso Kuntambila, Pradyumna Rao, Rica Schulz

Managing Fellow:
Martín Ignacio del Pino

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Executive Summary

As the push towards achieving deep decarbonization escalates worldwide, the role of digital technologies, with the rapid innovations and advances in the sector, towards aiding these efforts are particularly interesting. The opportunity is unique: carbon intensity reduction of 5.6 units for every unit increase in digital input in the habitat sector (Huang & Lin, 2023) shows the promise of digital applications driving towards decarbonization. With institutions in both the European Union and US pushing for greater climate action, the habitat and transport sector, jointly accounting for approximately 34% of total global greenhouse gas emissions, have been identified as primary targets. Various decarbonization strategies, ranging from net-zero, carbon neutral to carbon negative have been targeted for implementation in these sectors.

However, as 2030 and 2050 climate goals loom, achieving them involves rapid decarbonization of legacy and safety critical infrastructure. As sectors such as banking find the enablers and drivers of digitization, digitalization and digital transformation, whether digital technologies can achieve economic, social and technical levers while maintaining reliability of these dependency-heavy systems in the transport and habitat sectors remains unanswered. Motivated by this, the following Engineering for Change Impact Project aims to explore potential fields for climate action towards meeting the 1.5 degree warming target identified in the Paris Agreement.

By reviewing existing literature, conducting interviews with experts spanning various fields in both the US and Germany, and synthesizing the quantitative and qualitative data collected through a PESTEL framework, this report identifies key actions that can be taken by stakeholders from industry professionals and policy-makers to educators. Additionally, this report covers the existing state of decarbonization efforts, further challenges involved and key hardware and digital technologies. Finally, potential futures of digitalization are surveyed to curate recommendations focused on equipping stakeholders with capabilities for the present and future of digital technologies.

This report finds several outcomes of interest. Firstly, the historic trends surrounding improvements in computing power and capabilities show no sign of abating. With projected improvements at algorithmic, hardware and platform levels, there are potential digital futures that suggest rates of “doubly exponential” growth. This directly impacts the digital initiatives for decarbonization. Flexibility in revenue streams, advanced workflows, hardware utilization and open source development have not been fully realized in industries with deep decarbonization initiatives, and could potentially explode with improved computing power. However, to leverage digital technologies, educational profiles and skillsets of policy makers to interdisciplinary engineers are currently insufficient. Requirements for interdisciplinary skill sets for solving complex decarbonization problems have grown, and building cross-disciplinary skill sets for digital work needs to be explored. Finally, an inhibitor for digital transformation for decarbonization is building reliable technologies that don’t compromise the reliability of high dependency infrastructures. Additionally, the way current venture models finance climate tech is insufficient to disrupt safety critical infrastructure.

From these findings, seven primary recommendations were curated for the partners of this research, which could be adapted by other interested stakeholders, with five further areas of exploration defined. These recommendations and future research areas are key in helping achieve decarbonization pathways using digital technologies.

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1 Decarbonization Through Digitalization in the Transport and Habitat Sectors

1.1 Research Objective

Recent forecasts and climate reports point out insufficiency of current climate measures and the urgency to take action. To actually achieve the goals of the Paris Agreement, limiting global warming to 1.5°C reductions of greenhouse gas emissions by 45% are required until 2030. Thus, UNEP suggests a system-wide transformation approach, aiming at decarbonizing all sectors, including electricity supply, industry, transport, buildings and food systems (United Nations Environment Programme (UNEP), 2022, Foreword - XV).

Considering two of the largest contributors to global greenhouse gas emissions, the transport and habitat sectors represent decisive levers for climate action. As Figure 1 shows, the habitat sector (in the following predominantly including energy use in buildings and industry) is responsible for 42% of total global emissions and is composed of residential buildings (11% of global emissions), commercial buildings (7% of global emissions) and the energy use in industry (24% of global emissions). Furthermore, the transport sector constitutes another severe emitter, causing 16.2% of total global greenhouse gas emissions (Figure 1).

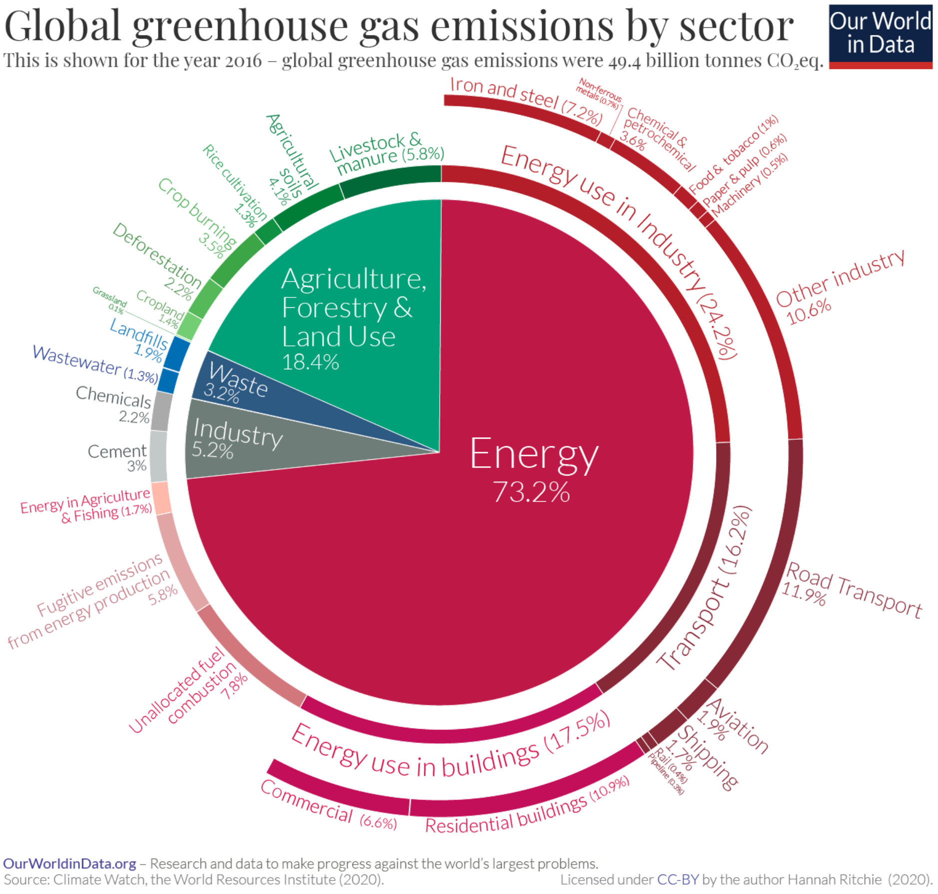


Figure 1. Share of global greenhouse gas emissions by sector, Source: Climate Watch, the World Resources Institute, 2020. *Licensed under CC-BY by the author Hannah Ritchie.*

As major contributors, there is also enormous potential for emission reductions and efficiency improvements. Thus, this report envisions the decarbonization of the transport and habitat sector. Moreover, (digital) technologies are identified as well as various workforce skills, which are considered to be vital for today's climate challenges. The target regions of this investigation are Germany and the US given their economic significance, emission profiles, share of fossil fuels (Figure 2) and the framework of the supporting international collaboration program.

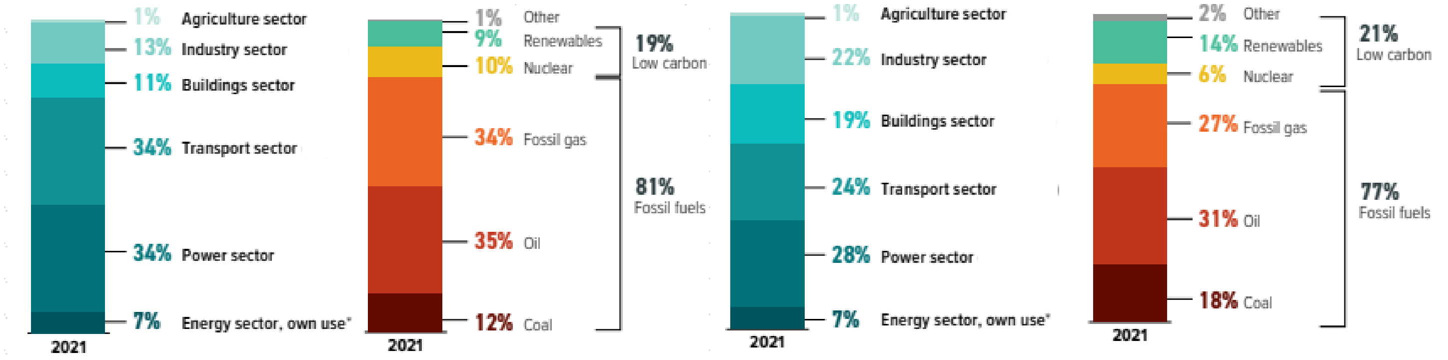


Figure 2. Energy use by sector and sources in the US (left), and Germany (right). Source Report: Climate Transparency Reports: Germany, USA, 2022. Source Data: Enerdata.

1.2 Research Scope

The **transport sector**, as defined by the International Transport Forum, encompasses all activities related to the movement of goods and people from one place to another, via various transportation modes including road, rail, air, water, and pipeline. The sector plays a vital role essential for economic and societal development, but it is heavily dependent on fossil fuels and consequently has a negative environmental impact that includes greenhouse gas (GHG) and air pollutant emissions, noise, and landscape fragmentation. Global emissions from the transport sector alone account for 23% of the total emissions, 28.5% in the US (EPA, 2023), and 23% in Germany (Energiebedingte Emissionen Von Klimagasen Und Luftschadstoffen, 2023). The ITF Transport Outlook report estimates global transport volumes to continue expanding, and if left unchecked, the emissions could increase by 60% by 2050 from 2015 levels (International Transport Forum, 2019).

The **habitat sector** encompasses the planning, design, and management of human settlements, including urban and rural areas. The sector plays a fundamental role in shaping the quality of life of all life-forms and is vital for economic growth and human well-being. Particularly, cities account for more than half of the global population, over 75% of the global energy consumption and 70% of the global carbon emissions. UN Habitat estimates the share of urban population to rise to 70%, representing an unprecedented increase in resource consumption. Consequently, if left unchecked, this could potentially have devastating negative environmental impact that includes GHG and air pollutant emissions, biodiversity loss, deforestation, soil degradation, and increased waste production (IEA, 2022).

Both sectors are exemplified by the United Nations (UN) Sustainable Development Goals (SDGs), aiming to improve human lives and protect the environment (United Nations, n.d.). This research is sustained by SDG 11, envisioning sustainable cities, communities, and respective UN Habitat programs dedicated to creating livable environments that foster well-being, social inclusion as well as sustainability. These programs tackle critical challenges such as housing availability and affordability, land use planning, infrastructure development, and environmental conservation (UN Habitat, 2020).

As the pace of urbanization intensifies, the challenge of creating sustainable settlements amplifies the need for an equally sustainable transport infrastructure, exemplifying the interplay between the habitat and transport sectors. Integrated efforts in the decarbonization of the habitat and transport sectors are crucial to achieving the UN SDGs in promoting high quality of life for people while minimizing ecological harm. The decarbonization of the transport and habitat sectors has become a global imperative to mitigate the effects of climate change. Digitalization, in the form of advanced technologies and data-driven solutions, has emerged as a promising avenue to achieve sustainability and efficiency in both sectors.

This research report explores current trends, main drivers, key technologies, challenges, and presents insights and recommendations for standards organizations like the American Society of Mechanical Engineers (ASME) and Verein Deutscher Ingenieure (VDI - Association of German Engineers) to facilitate the transition to a decarbonized transport and habitat sector.

Germany represents one of the most significant emitters in the EU with the 6th-highest per capita emissions in 2020 (Clean Energy Wire, 2023). The transport and habitat sector, as illustrated in Figure 3, account for a substantial amount of GHG emissions in that context. With more than 140 Mt of CO2 equivalents in the transportation sector and 125 Mt in the building sector, Germany represents the 6th largest emitter on a global scale (ClimateTrade, 2021).

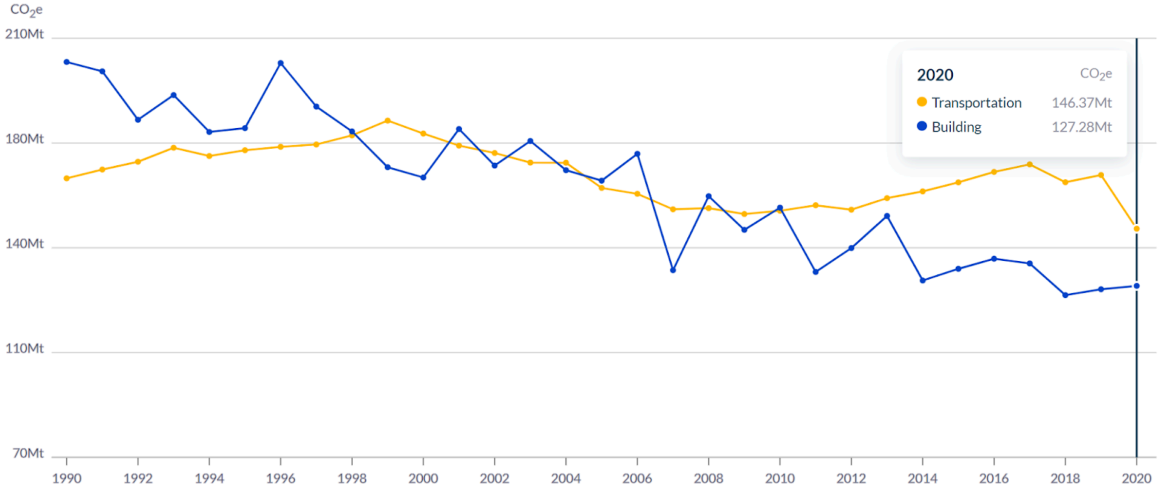


Figure 3. Historical greenhouse gas emissions transportation and building sector in Germany, Source: Climate Watch. 2022. Washington, DC: World Resources Institute. Available online at: https://www.climatewatchdata.org

The US is the second biggest carbon polluter worldwide, accounting for approximately 14% of total global emissions (ClimateTrade, 2021). As can be observed in Figure 4, US CO2 equivalents amount to 1.5 Gt in the transport sector and 515 Mt in the building sector. With respect to transportation emissions, the US is the largest polluter worldwide.

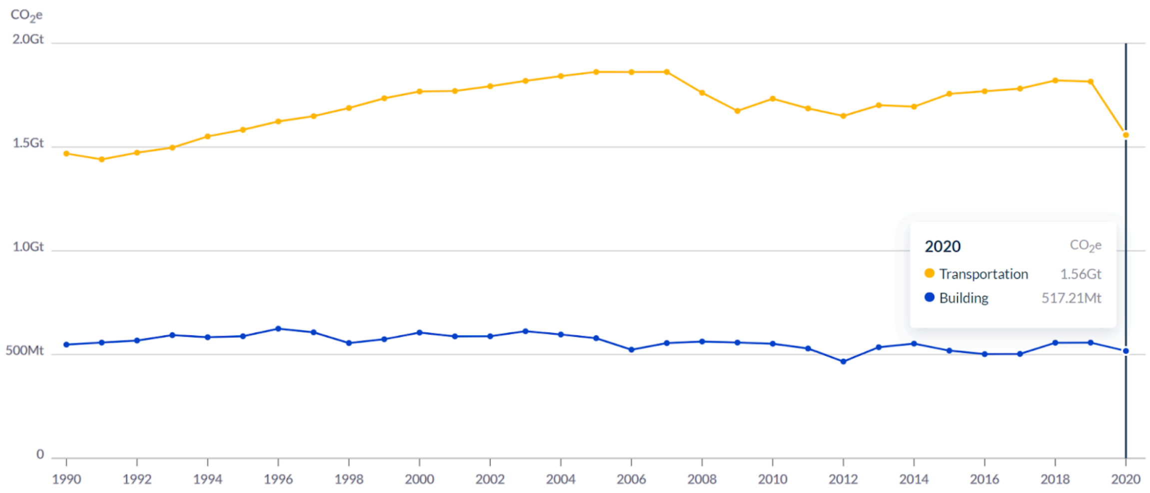


Figure 4. Historical greenhouse gas emissions transportation and building sector in the United States, Source: Climate Watch. 2022. Washington, DC: World Resources Institute. Available online at: https://www.climatewatchdata.org

1.2 Theoretical Foundations

1.2.1 Digitization, Digitalization and Digital Transformation

The primary focus of this report is to explore the ways in which digitalization can aid the transition to a low carbon economy. As such, this section seeks to define the terminology that the report shall use.

A key distinction must be made between digitization, digitalization and digital transformation. Digitization, made popular in the 20th century with the advent of the personal computer and the internet, refers to the process of converting analog information into digital. Digitalization, refers to the process of using digital technology to improve processes, in most cases leveraging digitized data, and creating value for customers. Digital transformation is where digital technologies are leveraged to transform the core competencies of an institution, transform the business model and, to a certain extent, change markets itself (Gobble, 2018).

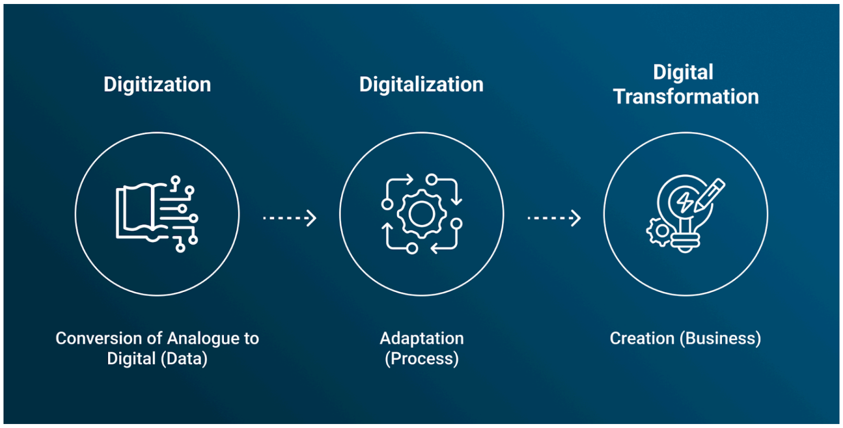


Figure 5. The process from digitisation through digital transformation

1.2.2 Motivations for Exploring Digital Spaces

In application to the decarbonization efforts in the habitat and the transport sectors, both sectors have been slow to adopt digital technologies (Digit. of built environment, 2021). Within the habitat sector, carbon intensity was found to lower by 5.6 units for every unit increase in digital input and predicted to have a scale effect (Huang & Lin, 2023), giving rise to interesting possibilities with applications of digital technologies. In the European Union, significant emphasis has been placed on using digital technologies to modernize traditional industrial sectors.

As the potential of digital technologies has been widely covered across literature, this paper seeks to expand on the work with the view of making both general recommendations as well as specific recommendations for our partner programs. Our specific recommendations will be based on evaluation of current and future key technologies in digital spaces.

2 Methods to Investigate the German and US State of Digitalization and Decarbonization

2.1 Interviews

As part of the research, 16 interviews with different companies and organizations related to digitalization and decarbonization were carried out (Table 1). The interviews were conducted by using a semi-structured interview technique.

The selection of interviewees for this research project aimed to encompass a diverse range of perspectives and insights about the transport and habitat sector, with participants hailing from both Germany and the United States. This geographical diversity was purposefully chosen to provide a comprehensive overview of the subject matter by tapping into the distinct experiences, approaches, and viewpoints present in these two regions. The interviewee pool was curated to represent a broad spectrum of stakeholders, including start-ups, international organizations, universities, industry, political representatives, and research institutes.

2.2 Desk Research

In tandem with the interview process, the research methodology also includes desk research. This complementary approach was undertaken to delve deeper into the existing literature, reports, and academic studies, helping to contextualize and cross-verify the insights gained from the interviews and address any information gaps and inconsistencies.

2.3 Data Synthesis Methodology

This research employs a systematic and structured approach to data synthesis, utilizing a top-down methodology. This involves aggregating and organizing the vast array of data collected from interviews and desk research into cohesive theme groups. By clustering data points according to their common themes and overarching concepts, complex and diverse information were put into manageable categories, facilitating a more comprehensive analysis. Additionally, a PESTEL analysis was conducted, which examined the political, economic, social, technological, environmental and legal factors of each sector (Figure 6).

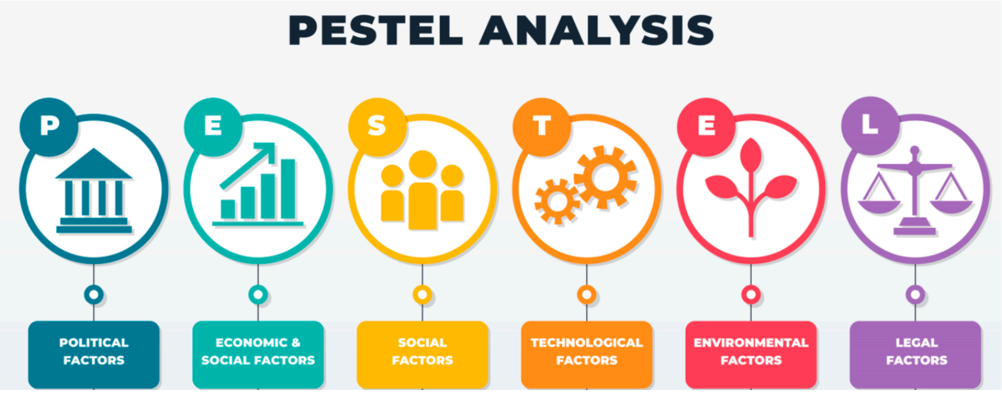


Figure 6. PESTEL analysis elements. Source: Image by freepik

This analytical framework was used to explore the external macro-environmental influences impacting the digitalization and decarbonization process in the US and Germany. The combination of these methodologies ensured that the findings were not only data-driven but also strategically contextualized to draw meaningful conclusions and recommendations.

3 Current State of Decarbonization through Digitalization and Recommendations

3.1 Decarbonization of the Transport Sector

3.1.1 Ecosystem and Current Trends

In the US and Germany, several key trends are driving efforts to reduce GHG emissions in the transport sector, with a focus on energy efficiency, electrification, alternative fuels, smart mobility, and data analytics.

Energy Efficiency: Both countries are making strides in improving energy efficiency within the transport sector. This includes the development of more energy-efficient propulsion systems, advancements in aerodynamics, and lightweight materials. Additionally, retrofitting and modernizing public transportation fleets to optimize energy use and reduce emissions are becoming more common.

Electrification: Electric mobility is gaining significant traction in both countries (Figure 7). In the United States, an expanding network of electric vehicle (EV) charging infrastructure and supportive government policies are fostering the adoption of EVs. Germany, being home to renowned automakers, is at the forefront of electric vehicle development and production.

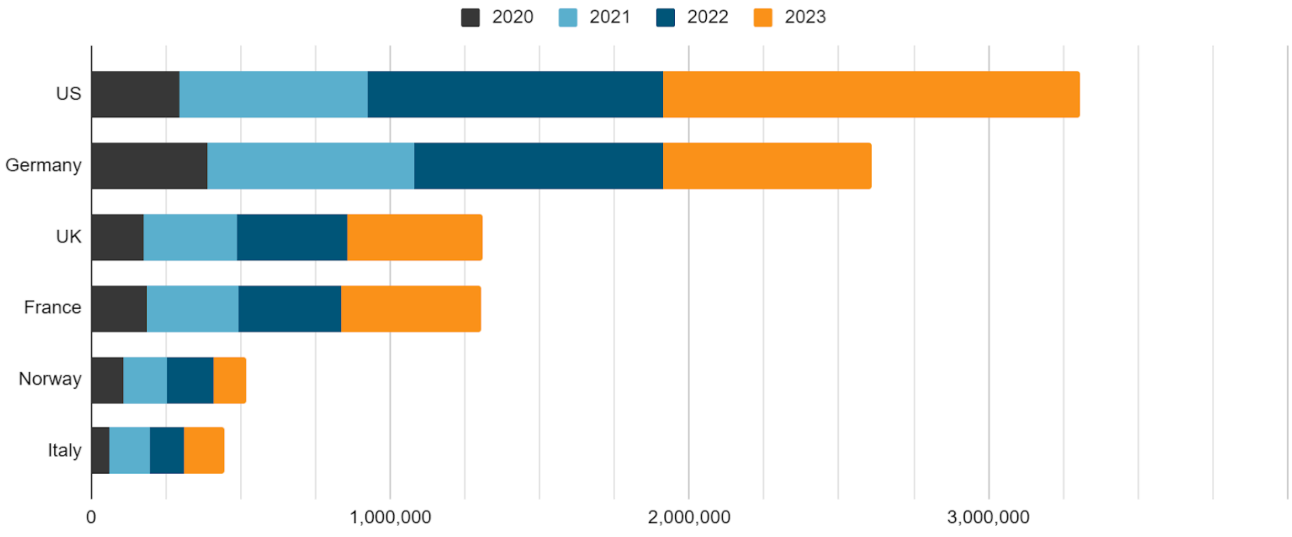


Figure 7. Plug-in and plug-in hybrid EV sales in selected countries, source data: iea.org

There is a notable push towards electrifying not only passenger vehicles but also public transit and commercial fleets. In the US and the EU an electric truck market diffusion dominance of 70% is expected from 2035 (Strategy&, 2022).

Alternative Fuels: Both countries are exploring alternative fuels to diversify energy sources and reduce emissions. Hydrogen fuel cell technology is gaining attention, especially in Germany, where initiatives like the National Hydrogen Strategy aim to promote the use of hydrogen in various transportation modes (Bundesministerium für Bildung und Forschung, 2023). The US is also investing in alternative fuels such as natural gas and biofuels.

Smart Mobility: The integration of smart mobility solutions is revolutionizing transportation in both nations. From ride-sharing and carpooling apps to autonomous vehicle development, smart mobility is improving efficiency and reducing emissions. Initiatives promoting multimodal transportation and urban planning that encourages non-motorized travel options are also becoming prevalent.

Data Analytics: The collection and analysis of transportation data are being leveraged to optimize routes, reduce congestion, and minimize emissions. Both countries are investing in data-driven solutions, including intelligent traffic management systems and predictive maintenance for fleets. Data analytics play a critical role in optimizing energy usage and enhancing transportation efficiency.

These trends reflect a shared commitment to sustainable and eco-friendly transportation solutions, acknowledging that reducing greenhouse gas emissions is not only an environmental imperative but also an economic and technological opportunity. As the transport sector continues to evolve in response to these trends, it is poised to play a pivotal role in the broader efforts to combat climate change in both the US and Germany.

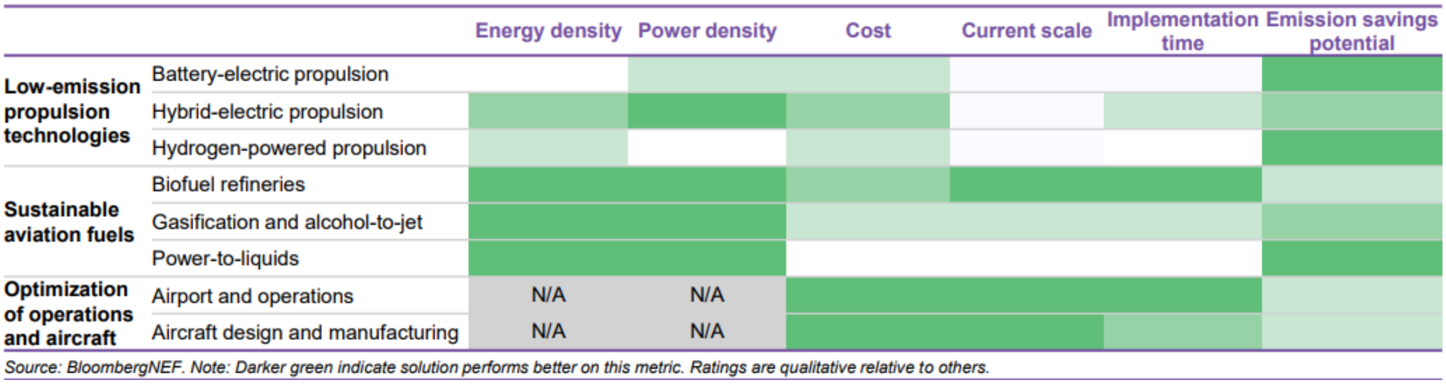
3.1.2 Key Technologies

3.1.2.1. Drive Systems: Batteries, Fuel Cells & Alternative Fuels

Electric propulsion has emerged as a sustainable alternative to the traditional internal combustion engine (ICE). Electric motors powered by batteries, and fuel cells are the key enablers to accelerate the transition from fossil fuels, enabling the transport sector to significantly reduce emissions. Battery technology is at its infancy and faces a myriad of image issues including fire risks, range anxiety, lack of infrastructure, embodied and operating carbon footprint, supply chain resilience and sustainability of battery materials, an energy intensive manufacturing process and recyclability. Despite the issues, battery technology continues to evolve and improve, providing better energy efficiency, and over 50% reduced GHG emissions as compared to ICE vehicles. Battery electric vehicles (BEVs) produce zero tailpipe emissions, eliminating harmful pollutants and particulate matter, and when integrated with renewable energy sources, BEVs have a near-zero operational carbon footprint over their lifetimes. (Bieker, 2021).

Other modes of transportation, including aviation, maritime, and heavy-duty long-haul vehicles, are exploring alternative fuels as substitutes for conventional fossil fuels. Electrification in aviation or ships presents a big challenge due to weight limitations. Traditional fuels like heavy oil and liquefied natural gas (LNG) offer high energy densities (40-55 MJ/kg) vital for long sea voyages. In contrast, lithium-ion batteries, the primary electric vessel power source, have lower energy densities (0.2-0.9 MJ/kg). This energy density gap poses a significant hurdle for electric propulsion so alternatives need to be considered.

Sustainable Aviation Fuels (SAF) often referred to as aviation biofuels, offer an opportunity for the aviation industry to reduce its environmental impact significantly. These renewable jet fuels can lower greenhouse gas emissions by up to 80% when compared to traditional jet fuels, making them a potent tool for decarbonization. SAFs possess properties akin to conventional jet fuels and can be employed as drop-in replacements without necessitating costly aircraft modifications or infrastructure changes. Globally, airlines and aviation authorities are increasingly incorporating SAF into their operations, driven by government incentives and international agreements that promote SAF development and deployment. (Holladay et al., 2020).



		Energy density	Power density	Cost	Current scale	Implementation time	Emission savings potential
Low-emission propulsion technologies	Battery-electric propulsion		░	░			▓
	Hybrid-electric propulsion	▒	▓	▒		░	▒
	Hydrogen-powered propulsion	░		░			▓
Sustainable aviation fuels	Biofuel refineries	▓	▓	▒	▓	▓	░
	Gasification and alcohol-to-jet	▓	▓	░	░	░	▒
	Power-to-liquids	▓	▓				▓
Optimization of operations and aircraft	Airport and operations	N/A	N/A	▓	▓	▓	░
	Aircraft design and manufacturing	N/A	N/A	▓	▓	▒	░

Source: BloombergNEF. Note: Darker green indicate solution performs better on this metric. Ratings are qualitative relative to others.

Figure 8. Qualitative ranking of decarbonizing aviation technologies, Source: BloombergNEF, 2022

The world's oceans host about 100,000 large vessels responsible for 90% of global trade. These ships mainly rely on heavy fuel oil, a byproduct of crude oil refining, contributing to 3% of global greenhouse gas emissions. International organizations aim to cut shipping emissions by 50%, but the path to decarbonizing maritime transport is uncertain. Experts are exploring alternative fuels like LNG, hydrogen, ammonia, and methanol, each with unique emissions, safety, feasibility, and cost considerations.

Biofuels derived from organic materials such as crops, algae, or waste biomass, are emerging as a viable alternative to gasoline and diesel fuels, offering a path for significant reduction in GHG emissions. For instance, PepsiCo is embarking on a pilot project to recycle and transform waste oil into biodiesel for its fleet, potentially leading to a reduction of up to 90% in carbon emissions (Biofuels International, 2023). Biofuels are very adaptable and can be blended with traditional fuels or used in pure form, providing consumers and industries with flexibility. However, ensuring their sustainability is vital. Factors such as feedstock selection and production methods play pivotal roles in avoiding adverse environmental impacts, such as deforestation or the diversion of food crops (Ryste et al, 2019).

3.1.2.2. Smart Mobility

Smart mobility encompasses a broad range of innovations and strategies that leverage digital technologies to optimize the efficiency, safety, and sustainability of transportation systems. These innovations include connected and autonomous vehicles, intelligent transportation systems, Mobility as a Service (MaaS), real-time traffic management, and integrated multi-modal transportation networks. Smart mobility, driven by digital technologies and innovative transportation concepts, is central to decarbonizing the transportation sector. Smart mobility leverages data-driven decision-making, seamless connectivity, advanced analytics, and artificial intelligence. (Biyik et al, 2021).

Digital technologies, particularly **data analytics and the Internet of Things (IoT)**, have revolutionized the way we monitor and optimize transportation. They offer unprecedented insights into vehicle performance, traffic patterns, and environmental conditions. Their deployment across various modes of transport is improving overall efficiency, reducing congestion, and minimizing the environmental impact of transportation (iMOVE, 2023).

MaaS, exemplified by the business models of start-up companies Uber and Lyft, contributes to decarbonization efforts by promoting shared and efficient transportation options. MaaS platforms enable users to seamlessly plan and pay for multi-modal journeys, combining various transportation options such as ride-sharing, public transit, and bike-sharing into a single, user-friendly app. This concept leverages integrated transport systems to simplify urban mobility, reduce reliance on private car ownership, and promote sustainable transportation choices. Similarly autonomous vehicles hold the potential to significantly reduce accidents and traffic congestion while offering a convenient and efficient mode of transportation with lower carbon footprints. Companies like Waymo and Cruise are pioneering a new wave of ride-sharing autonomous EVs.

Blockchain technology plays a pivotal role in advancing smart mobility by enhancing the security, transparency, and efficiency of transportation systems. The integration of blockchain in smart mobility solutions enables secure and tamper-proof record-keeping for transactions, data sharing, and vehicle identities. Vehicle data encryption safeguards sensitive information, such as location data and driver preferences, protecting user privacy while enabling data-driven decision-making for improved transportation efficiency and safety. Additionally, blockchain can ensure secure and transparent transactions that facilitate V2X (Vehicle to Everything) communication including public EV charging infrastructure and peer-to-peer transactions within MaaS platforms, ensuring the authenticity of payments and agreements between users and service providers (Oladimeji et al., 2023).

3.1.2.3. Energy Efficiency

Lightweighting and energy recovery techniques help improve the energy efficiency of vehicles.

Lightweighting strategies involve the use of advanced materials and design techniques to reduce the weight of vehicles and so require less energy to operate. Careful material selection affords associated reduction in cost while maintaining or even increasing overall strength. Substituting conventional cast iron and steel with lightweight materials like aluminum, composite plastics, and carbon fiber can reduce the vehicle's base structure by half (Zhang & Xu, 2022).

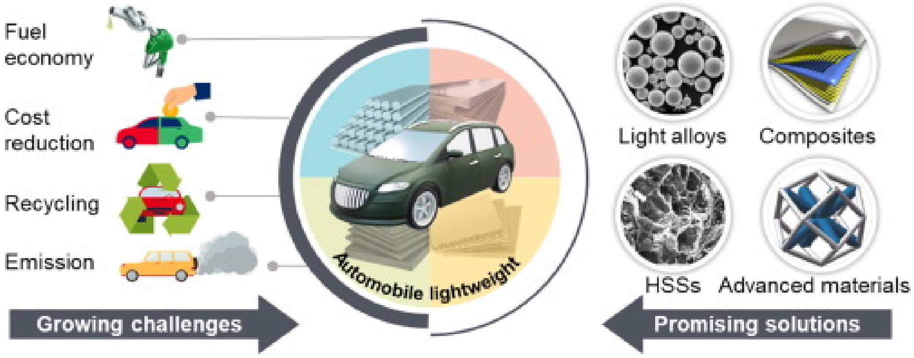
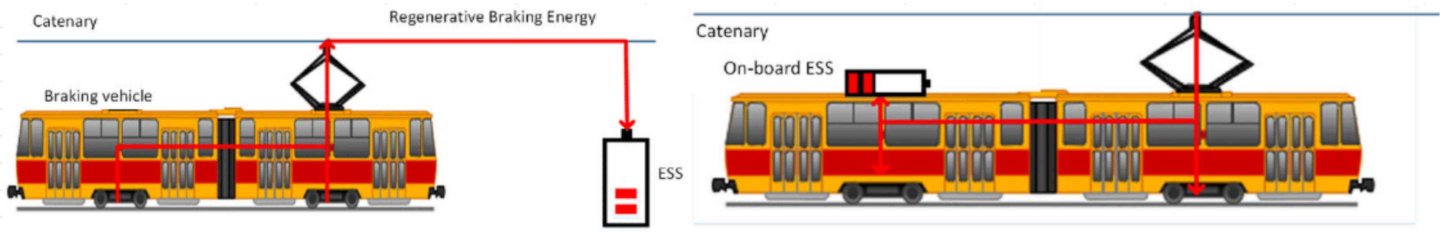


Figure 9. Advanced lightweight materials for automotive, Source: Zhang & Xu, 2022 / CC BY 4.0

Energy recovery involves the capturing, storing, and reuse of energy that would otherwise be wasted or lost as heat or other forms of energy. Regenerative braking is a key energy recovery technique in the transport sector.

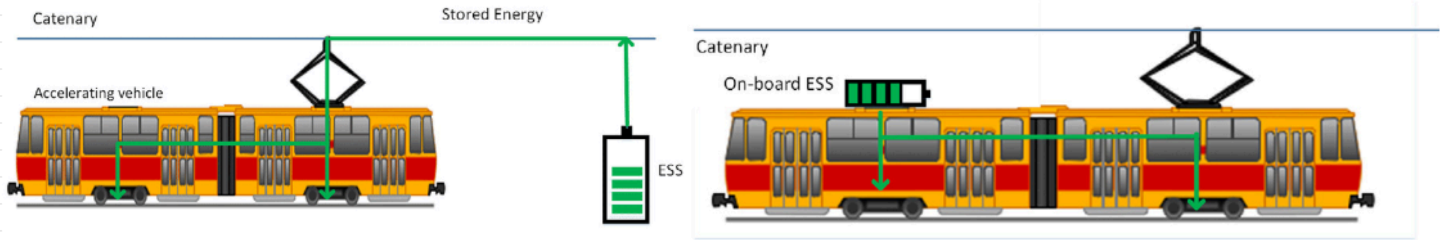
In hybrid EVs and EVs, the vehicle's electric motor captures the kinetic energy of a decelerating vehicle and uses it to recharge the battery, recovering up to 40% of the braking energy with a proportional range extension and improving the overall efficiency of an EV by up to 70% (Energy5, 2023).

Similarly, in electrified rail systems, regenerative braking energy can be recovered by train timetable optimization and onboard (OERS) or wayside energy recovery systems (WERS). The MTA in New York, for example, captures regenerative braking energy by train timetable optimization where the energy from a braking train is fed back to a third rail for use by a neighboring train. However the uncertainty in the timing and matching of the available energy source and sink means that excess energy may need to be dumped as heat to avoid over-voltage in the power supply section (NY interview). Southeastern Pennsylvania Transportation Authority (SEPTA) subway and elevated systems capture regenerative braking by using a 10.75 MW WERS, the largest of its kind in the US (SEPTA, 2020).



(a) Energy recovery in braking phase

(a) Under catenary operation



(b) Energy delivery in traction phase

(b) Catenary-free operation

Figure 10. Operation schematic of WERS (left) and OERS (Right) in a railway system, Source: Liu & Li, 2020 / CC BY

3.1.3 Challenges

		Challenges	Potential Strategies
Political / Legal	01	Political polarization, threatening to obstruct climate policies and regulations and rise of populists parties advocating returning to conventional technologies.	1. Educational work by politicians and schools. 2. Creating balanced regulatory frameworks consisting of deterrents and incentives. 3. International agreements to reduce emissions. 4. Inflation reduction acts and action programs.
	02	Lack of standardization for measuring GHG emissions.	1. Establishing a common framework for consistent tracking and reporting of emissions by policies and supporting institutions. 2. Obliging industries to report and monitor emissions aiming to reduce them.
Economic	03	Insufficient investments and budgets to develop efficient electric vehicle infrastructure.	1. Oblige industries to enhance corporate social responsibility and to create strategies to mitigate emissions by introducing respective policies.
	04	Disrupts in automotive business models, workforce adjustments, global competition.	1. Support transition of workforce and business models by promoting trainings and enabling qualification. 2. Create incentives by introducing policies creating benefits for sustainability efforts.
	05	Socio-economic inequalities regarding access to “green” transportation solutions	1. Balancing stimulating growth and ensuring a just and equitable transition. 2. Governmental incentives, subsidies and policies supporting lower income groups.
Social	06	Rising inequality with accelerating transition towards sustainable transport technologies.	1. Encourage, empower, incentivize, lower income groups. 2. Enhance awareness about sustainable technologies and long-term (financial) benefits.
	07	Changing job requirements and shift in job markets.	1. Engage in upskilling, reskilling and adapting to changing industrial requirements. 2. Providing appropriate education and training. 3. Promote lifelong learning.
Technological / Environmental	08	Workforce readiness and changing qualification requirements to create, deploy and maintain (new) technologies	1. Engage in upskilling, reskilling and adapting to changing industrial requirements. 2. Providing appropriate education and training.
	09	Seasonality and fluctuations of renewable energy generation.	1. Enhance and expand grid infrastructure to increase reliability and resiliency. 2. Deploy efficient energy storage systems and steer transportation networks to reduce resource consumption.
	10	Infrastructure gaps.	1. Implement real-time data analytics to monitor and optimize energy consumption and forecast potential outages. 2. Deploying “Internet of Things” supported vehicles, optimizing efficiency and consumption.

Illustration 1: Summary of Challenges and Recommendations for the Transport Sector, Source: authors

Political

Decarbonization through digitalization in the transport sector in Germany is confronted with various political challenges. The challenges vary from local to trans-regional challenges involving the European Union. The most prominent among these challenges is the **escalating political polarization**, which threatens to obstruct the passage of comprehensive climate policies and regulations (Marschall & Klingebiel, 2019). This polarization is particularly concerning due to the rise of populist parties advocating for a return to traditional technologies like combustion engines and opposing the electrification of the transport sector (Laconde & Lah, 2019). The ideological divide between these factions and those pushing for sustainable, digital solutions may intensify the struggle to implement effective decarbonization measures.

Another significant political challenge is the **lack of standardized methodologies** when it comes to measuring whole life carbon assessments. The absence of uniform international methodologies for calculating emissions across full systems, from their material production, installation, maintenance, repair, and end-of-life, hampers the ability to accurately assess progress and compare results across regions and industries (Alger et al., 2023).

Even though some standardized metrics are inter alia proposed by International Organization for Standardization Technical Committees (International Organization for Standardization, 2008), their uniform application by industries is not ensured. This lack of standardization not only complicates regulatory efforts but also hinders transparency and accountability in the transportation sector's efforts to reduce its carbon footprint. Addressing this issue is crucial for establishing a common framework that allows for consistent tracking and reporting of emissions, facilitating the development and adoption of effective mitigation strategies, and ensuring a more cohesive global approach to combating climate change in the realm of transportation.

Economic

The transition towards sustainable, digitally driven transportation systems demands **significant financial investments**. The magnitude of these financial commitments raises concerns about straining both public budgets and private sector resources. Additionally, there are intricate economic repercussions associated with the transformation of traditional industries, such as the automotive manufacturing sector. As Germany pivots towards electric and digital technologies, established players may experience **disruptions in their business models**, workforce adjustments, and global competitiveness. Managing this transition while safeguarding jobs and economic stability is a multifaceted challenge.

Furthermore, the up-front costs of adopting advanced digital systems and sustainable transportation options can be prohibitive for many individuals and businesses, especially small and medium-sized enterprises (Approved - A DeWitt Company, 2022). This **economic disparity in access to green transportation** solutions could exacerbate socio-economic inequalities and limit the broader adoption of eco-friendly mobility options. Striking a balance between stimulating economic growth and ensuring a just and equitable transition to a low-carbon transport sector is paramount. Government incentives, subsidies, and targeted policies will be necessary to bridge these economic gaps and make sustainable transportation more accessible to all segments of society. Ultimately, overcoming these economic challenges is essential to realizing the long-term benefits of decarbonization through digitalization and fostering a more environmentally and economically sustainable future for Germany's transport sector.

Social

It is imperative to recognize and address the social challenges, including the widening **inequality gap**. As the transition towards sustainable transportation technologies accelerates, there is a risk that certain segments of society, such as elderly people and low-income households, may be left behind (Gewiese & Rau, 2023). Lower-income individuals and marginalized communities may find it more challenging to access the benefits of green transportation solutions, potentially deepening disparities in mobility options and environmental justice.

Moreover, the **shift in employment patterns,** particularly in sectors undergoing transformation, could disrupt traditional job markets and necessitate upskilling or reskilling for affected workers. Consequently, comprehensive policies that prioritize social equity, accessibility, and affordability must be woven into the fabric of decarbonization efforts to ensure that the advantages of a cleaner, digitally-enhanced transport sector are accessible to all, thereby mitigating the risk of exacerbating societal inequalities.

Technological & Environmental Factors

The sector also encounters a multifaceted array of technological and environmental challenges, including workforce readiness, the seasonality and fluctuations of renewables, and infrastructure gaps, each requiring focused attention. Workforce readiness remains a significant issue as the sector rapidly embraces new technologies like electric and autonomous vehicles, necessitating a workforce skilled in these emerging fields. To overcome this challenge, investment in education and training programs is essential.

Seasonality and the intermittent nature of renewable energy sources like wind and solar pose a challenge for sustainable transportation (Deutscher Wetterdienst, n.d.). Electric vehicles heavily reliant on renewables may experience limitations during periods of low energy production. Developing efficient energy storage solutions and grid management systems to mitigate this variability is crucial to ensuring reliable and sustainable transportation.

Infrastructure gaps are also prominent hurdles. Expanding charging networks for electric vehicles, upgrading roads and bridges to accommodate autonomous vehicles, and enhancing public transportation systems require substantial investments. Addressing these gaps is critical for enabling the transition to more eco-friendly transport options. It is estimated that, hardware, planning and installation of public charging in the US will cost more than $35 billion through 2030 (McKinsey & Company, 2022).

3.1.4 Enablers and Externalities Driving Change

The transition to a more sustainable and environmentally responsible transport sector provides a path to reduce harmful emissions and consequently mitigate the impacts of climate change. Several key elements are playing vital roles in steering the transition: environmental externalities, heightened consumer awareness and demand, corporate social responsibility, regulatory frameworks acting as both deterrents (sticks) and incentives (carrots), and technological innovations driven by data analytics and advanced sensor technologies.

Political & Legal

The role of regulations, both on the global and national levels, is paramount in driving decarbonization through digitization. Policymakers are enacting regulations and incentives that encourage the adoption of sustainable transport technologies and practices. This multifaceted approach employs both sticks and carrots. On one hand, regulatory measures and stringent emissions standards act as sticks, compelling industries to reduce emissions and invest in sustainable technologies. On the other hand, financial incentives, subsidies, and favorable policies serve as carrots, encouraging consumers and companies alike to embrace digital technologies and invest in sustainable transportation. These comprehensive approaches harmonize regulations, incentives, and digital innovations, creating an environment conducive to environmentally responsible, digitally enhanced transport in the US and Germany.

International agreements, exemplified by the Paris Agreement, have established ambitious targets for reducing emissions in the transport sector. These agreements serve as a foundation for national policies and actions aimed at decarbonization. By aligning with international standards, governments can harmonize their efforts with the broader global commitment to combat climate change and achieve environmental sustainability.

The Inflation Reduction Act and Bipartisan Infrastructure Law in the US represent the largest investment in climate action in history and are aimed at reducing net GHG emissions 40% below 2005 levels by 2030. In Germany, the Climate Action Programme 2030 and the Climate Action Act, the world's first Climate Action Act, are aimed at reducing GHG by 55% by 2030.

Economic

The corporate sector is playing a pivotal role in advancing the decarbonization agenda. Many forward-thinking companies are taking proactive measures to reduce their carbon footprint and adopt sustainable practices. For instance, General Motors (GM) has committed to making its global products and operations carbon neutral by 2040. As part of this commitment, GM aims to eliminate tailpipe emissions from their new US light-duty vehicles by 2035, use renewable sources to power 100% of electricity for US sites by 2025, and globally by 2035. GM's dedication to sustainability not only aligns with environmental goals but also reflects the growing corporate responsibility towards eco-friendly practices. This corporate-driven approach complements regulatory efforts and further accelerates the transition towards a more sustainable and environmentally responsible transport sector (Gilliam & Walker, 2023).

Social

Consumers are becoming more conscious of their environmental footprint and the sustainability of their choices. An emerging awareness of the environmental consequences of traditional transportation modes has spurred a demand for cleaner, more sustainable alternatives. This consumer-driven shift is not only influencing individual choices but also shaping corporate strategies and public policies.

Furthermore, ensuring the inclusion of all income groups and generation in the transition to digital technologies represents a vital task which should not be neglected by companies or policies. For that reason, initiatives like the European Union funded project DIGNITY aims to address these gaps and safeguard the integration of all stakeholders (DIGNITY, 2021).

Technological & Environmental

The transport sector has evident environmental externalities including: air pollution and climate impact. These externalities cast a pressing mandate to reduce the environmental footprint of transportation. The SDGs, particularly Goal 13 ("Climate Action"), emphasize the global commitment to combat climate change. Achieving the SDGs requires collective efforts to reduce emissions, transition to sustainable energy sources, and promote eco-friendly practices in all sectors, including transportation. As a result, there is a growing recognition that decarbonization of the transport sector is essential for meeting the challenges and digitization can be a potent enabler.

3.2 Decarbonization of the Habitat Sector

3.2.1 Ecosystem and current trends

The habitat sector is significantly affected by growth of population. In particular, urban regions experience strong population increase, leading to high population density in cities. Also, Germany and the US experience high urbanization rates of more than three quarters (Figure 11).

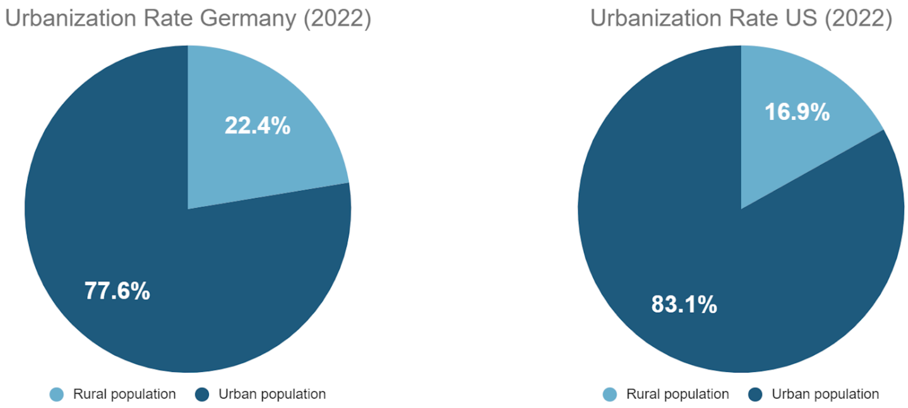
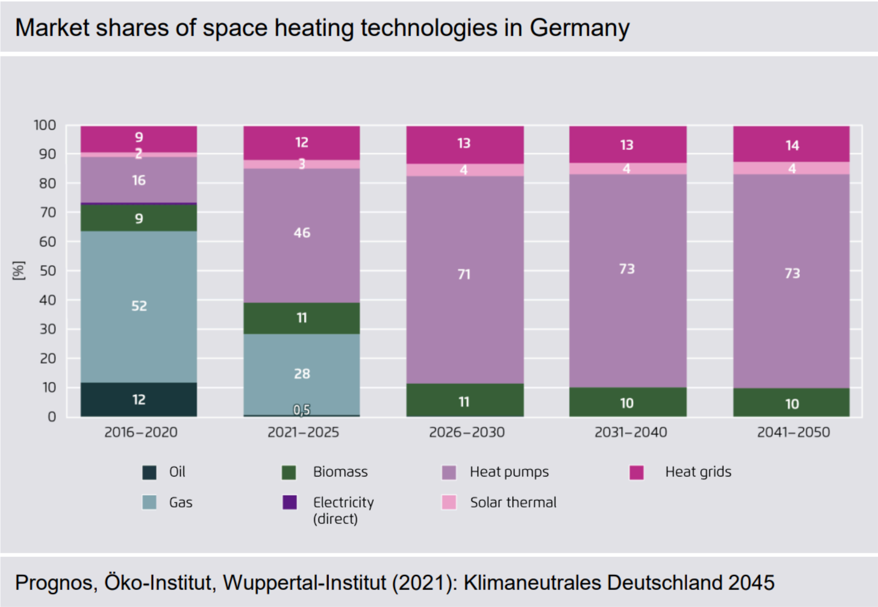


Figure 11. Urbanization Rates Germany and US (2022). Source data: World Population Review, n.d.

According to United Nations "World Population Prospects 2022", by 2050 a global population of approximately 10 billion people can be expected (UN, 2022). This growth entails a rise in energy demand, resource shortages, leading to price increases (OECD, 2011, 9-13). Moreover, existing grid infrastructure will be challenged by enhanced need for energy as well as the ever-growing demand for electrically driven solutions.

Germany

In particular, within the past two years, the German habitat sector has been shaped by political and economic developments. Challenges like the Russo-Ukrainian war led to a strong demand for renewable energy supply and autonomous technologies from the customer and political perspective (Schuh, 2023). These technologies include heat pumps, solar, thermal and hybrid solutions, which have been increasingly subsidized by the state of Germany (Amelang et al., 2023).


Market shares of space heating technologies in Germany

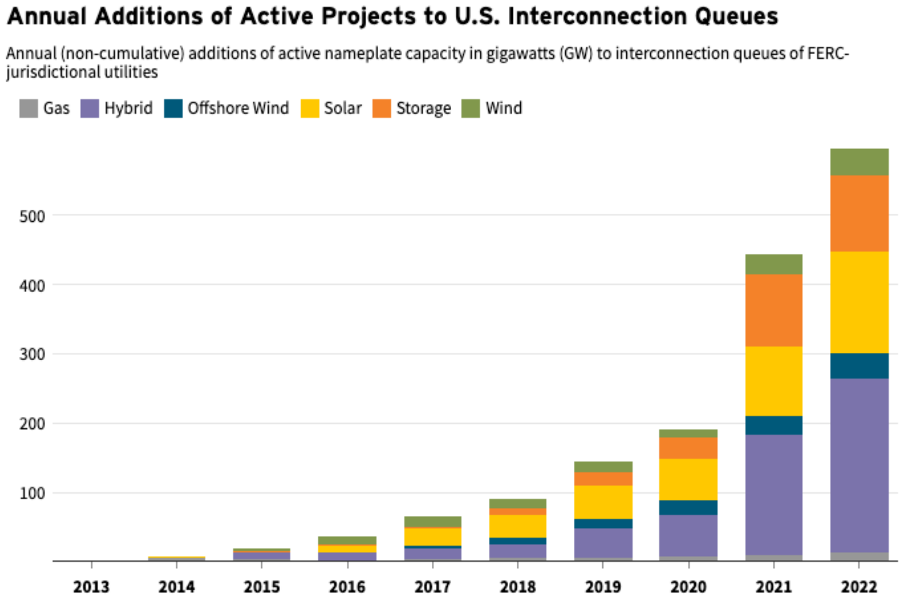
Prognos, Öko-Institut, Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045

Figure 12: Market Shares of space heating technologies in Germany, Source: Prognos, Öko-Institut, Wuppertal-Institut, 2021

With respect to current discussions regarding new legal requirements in the building sector, aiming to agree on a new Building Energy Act (Gebäudeenergiegesetz, GEG), criticism towards the implementation of new energy systems has been raised ("Sparen Wir Nicht Massiv Energie, Wird Dieses Gesetz Zum „Wachstumskiller"," 2023). As of September 2023, after months of political discussions, German policy makers have agreed upon the phase out of fossil fuels and powered boilers, covering more than 80% of current heat supply in buildings. The new law claims that heating systems of new buildings from 2024 onwards need to utilize at least 65% of renewable energy, but implementation still needs to be proven.

United States

With around 50% of carbon emissions originating from what is traditionally defined as the habitat economic sector, deep decarbonization of the sector is considered a top priority. Within the sector, the power grid is seen as the linchpin to decarbonization at rural and urban levels because it enables the deployment of clean technologies such as electric heat pumps ("1.5°C NDC Climate Leadership by US", 2021).



Data excludes ERCOT, as ERCOT is not FERC jurisdictional. Hybrid resource totals are underestimates, as they include the nameplate capacity of only the primary resource.

Chart: Claire Wayner • **Source:** Lawrence Berkeley National Laboratory

Figure 13. Current interconnection queue size and complexion, Source: Interconnection queue reform, 2023. Source: Lawrence Berkeley National Laboratory.

The current habitat sector has several safety critical dependencies, and reliability issues or energy crises result in public health crises or food crises. For those from underdeveloped and underserved communities, these are particularly devastating (Marsh, 2022). In 2021, the winter storms in Texas resulted in the loss of 250 lives from loss of power, demonstrating the need for care in how transitions for the habitat sector are handled (Scott, 2022).

Future applications of digitalization may provide solutions towards improving the speed of adoption of renewable technologies. However, as will be covered later in this report, these techniques and technologies will need to adopt safety critical standards in order to maintain and improve reliability standards.

3.2.2 Key Technologies

Technologies aiming to reduce carbon emissions of the habitat sector are distinguished into hardware and digital solutions. Whereas hardware technologies emphasize the actual generation, supply and use of energy, software envisions to increase efficiency by utilizing and monitoring data, steering digital products, implementing AI and machine learning models as well as telemetry.

3.2.2.1 Key Hardware Technologies

3.2.2.1.1 Renewable Energy Generation

Due to the rising need to reduce carbon emissions in the event of climate change, the application of renewable energies becomes increasingly important. In that regard, technologies like wind, solar, hydropower, and geothermal energy are considered to be a more sustainable option to generate energy.

The US as well as Germany emphasize on expanding public energy generation infrastructure, for example, by investing in large-scale solar fields, wind turbines and hydropower systems (Vaishnav, 2023; Schuh, 2023). Figure 14 reflects the focus on these energy sources, particularly pointing out the importance of photovoltaic (PV), solar and wind energy (more details in Annex I) .

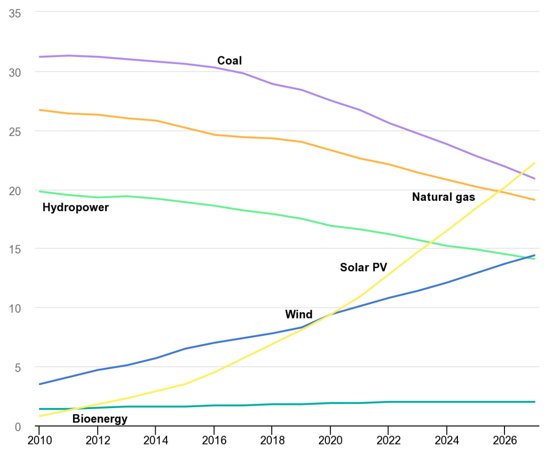


Figure 14. Share of cumulative power capacity by technology, 2010-2027, Source: Fossil fuel capacity from IEA (2022), World Energy Outlook 2022. (IEA, 2022)

3.2.2.1.2 Building Technologies/ HVAC Systems

The **grid** represents a connector between energy generation and the actual consumption of energy in the habitat sector. With the aim of decarbonizing energy usage and supply, technologies like heat pumps, buffer storage, and smaller PV systems gain great attention in private households in the US and Germany (Vaishnav, 2023).

Heat pumps can be used for heating and cooling households as well as water heating. The heat pump is powered by a relatively small amount of electricity (on average 0.5 kW) to transport and compress a refrigerant (cooling fluid). The refrigerant absorbs heat from its surrounding air, geothermal or water heat, catalyzes the energy and consequently supplies buildings with the generated heating energy. Heat pumps, just like a reversed refrigerator, create a closed cycle as the refrigerant can absorb new heat after releasing the previously generated heat to the building. The heat pump can be combined with (existing) boiler systems, solar panels or storage systems (International Energy Agency, n.d.).

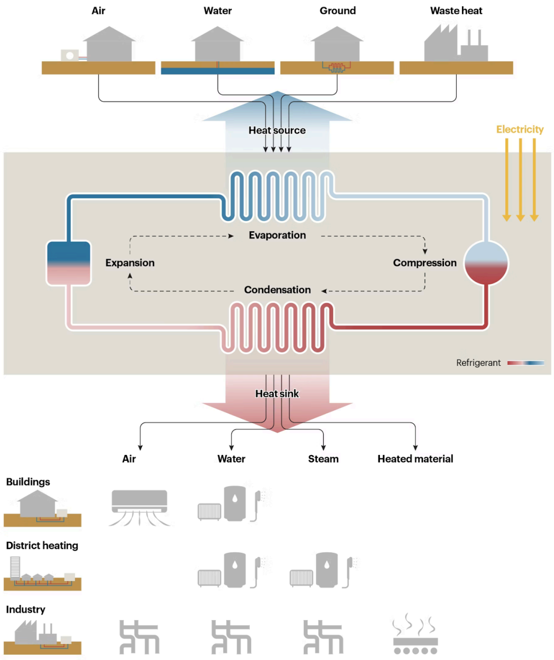


Illustration 2: Operating principle of heat pumps, Source: (IEA, 2022), n.d. Available online at: https://www.iea.org/reports/the-future-of-heat-pumps. Licence: CC BY 4.0

To store overproduced amounts of renewable energy (e.g. from solar/wind peaks), **storage systems** are considered to be vital. In that context, it is distinguished between kinetic (e.g. used for regenerative braking in vehicles), thermal, chemical, electrical storage systems (e.g. batteries, utilizing electrochemical reaction cells) (Tester et al., 2012, 817-827).

According to one of the leading heat pump suppliers, Viessmann, an extensive application across **Germany** is considered to be realistic (Roman, 2023). An enabler for successfully implementing the technology is solid insulation and an efficient building envelope to keep generated heat inside the building (McGee et al., 2023). In contrast, US households are leaky (Vaishnav, 2023) and thus, would require retrofits or new building envelopes to facilitate the useful application of heat pumps. The US showcases a significant variation in climate conditions, whereas Germany consists of one rather homogenous climate zone. Consequently, the US places more complicated requirements on the grid and general infrastructural elements, which is why technologies like heat pumps are scarcely implemented (Roman, 2023). This effect is even more enhanced by current climate change effects like temperature fluctuations and the increasing likelihood and severity of natural catastrophes (Smith, 2023).

An option to incrementally shift towards more sustainable technologies is to apply hybrid systems in older buildings (Bosch Home Comfort Group, n.d.). This trend can also be observed in Germany, where existing heating systems like gas boilers are complemented by a heat pump and / or solar panels.

However, considering individual building requirements and preconditions, the maintenance of (efficient) conventional boilers might be even more reasonable and opportune, e.g. for large buildings or institutions, if the technology is more efficient (Reed, 2023). In these cases it is vital to update less efficient conventional technology and also retrofit fossil systems accordingly (Thompson, 2023). Yet, in Germany, Viessmann considers 90% of all buildings to be suitable for heat pumps or other less carbon-intense technologies. By doing so, scale effects like price reductions, increased affordability and minimized use of material can be achieved (Roman, 2023). In reality, the current share of heat pumps in Germany only amounts to 6% of implemented HVAC technology, even though at least 50% would be required to switch to similar technology to achieve the 1.5 degree target of the Paris Agreement (Schuh, 2023).

Critics of heat pumps argue that refrigerants, which are required to absorb, transfer and release energy, contain toxic and persistent gasses. However, refrigerants like propane (R290) have become more sustainable and efficient, leading to a reduction of these gasses, complying with an upper limit of 150 g inside buildings (Schuh, 2023).

In addition, using **hydrogen** to supply HVAC technologies is being investigated and tested. In the course of testing, companies like Vaillant replace gas with hydrogen, using existing gas pipeline infrastructure. Results show that hydrogen can be used with existing gas infrastructures and only require minor changes to grid and technologies. By research and testing, Vaillant elaborates on safety requirements before starting to produce hydrogen boilers on a large scale (Vaillant Group, n.d.)

The conversion of existing gas pipelines for the use of hydrogen has the advantage of small switching costs and efforts. As 54% of German houses are connected to the gas line, hydrogen would be a realistic alternative to the fossil energy sources (Schuh, 2023).

Despite heat pumps being considered as one of the most promising technologies and have been mentioned by all interviewees from this area, experts consider a mix of described options as crucial to drive sustainability. Thus, the best case scenario for the future would be a mixture of, for example, geothermal, (air source) heat pumps, PV, storage and energy management systems (Roman, 2023; Reed, 2023). In that regard, “flexible buildings”, composed of an individual set of solutions that can be repeated/transferred to similar building types, are required (Reed, 2023).

Furthermore, efforts to reduce existing carbon contamination by carbon capture can be part of the strategy to limit damage of emissions already exposed to the atmosphere (Vaishnav, 2023). Current research in that regard, though, shows controversial perspectives on the effectiveness and sustainability of carbon capture techniques.

3.2.2.2 Digital penetrations in the habitat sectors

With both the EU and the US focusing on initiatives such as Industry 4.0 (“McKinsey 4IR”, 2022), this section of the report seeks to explore and define the application of digital technologies within the habitat sector.

An interest of this report, and a key lens which this topic is approached by, is how legacy infrastructure systems integrate with, or can be disrupted by, digital ecosystems (Chester & Allenby, 2023), particularly in the habitat sector. From the exploration conducted, this report is able to narrow down key use cases and capabilities enabled by digital technologies.

3.2.2.2.1 Advanced design workflows and connected ecosystems

Advanced software product development methodologies such as **Agile, Waterfall, Evolutionary, Spiral** have given rise to the rapid delivery of dynamic, complex projects. The ability of the software industry to recognize the pros and cons, adopt and modify methodologies according to the problem statement has allowed for delivery of solutions that tackle complex issues with high dependencies and network effects (“Choose software dev methodology”, n.d.). The iterative nature of these methodologies have enabled data based insights that allow for building of user focused products.

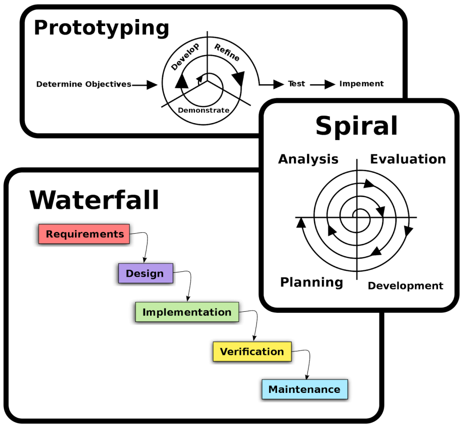


Illustration 3: Common software development methodologies. Source: wikimedia.org

Meanwhile, hardware design processes have continued to embrace classical lifecycles (Huang et al., 2012), siloing them from advanced workflows that allow data to be leveraged in the decision making process.

Smart hardware technologies, such as smart grid and smart building solutions, are now trending towards becoming standardized technologies in the habitat sectors. From **Battery Management Systems** to **Building Management Systems**, the ability to leverage data to enhance lifecycle design and development is a customer requirement. New ventures such as Energy Storage Safety Products International at Newlab Detroit, now find that having connected hardware is a commonly accepted base design requirement.

Digital penetrations through connected hardware enable faster product improvement lifecycles as they are able to leverage advanced digital workflows. These capabilities are key in decarbonization efforts, as we look towards hardware technologies to help deep decarbonization efforts to achieve 2030 and 2050 climate goals.

3.2.2.2.2 Visualization and Monitoring

Another key use case within the habitat sector is visualization and monitoring capabilities, an important aspect of data utility ("Data Visualization importance", 2020). Technologies such as digital twins have key capabilities that enable the visualization of complex data and patterns to users, as well as real-time monitoring (Botín-Sanabria et al., 2022). This report identifies visualization and monitoring digital tools as critical in building user comfortability in complex data decisions, which aid speed up the product development process.

Illustration 4: The abilities offered by digital twins enable users, stakeholders and engineers to visualize, monitor and improve performance.

A key technology for this use case are **digital twins** ("McKinsey Digital Twin Technologies", 2023). A real world example that this report found was WSP using digital twins for developers and building managers to make investment decisions based on life cycle assessments. This had previously been a pain point, as bridging diverse stakeholders from building developers to managers was difficult due to their siloed interests. Visualizing life-cycle operations of the building through digital twins helped align stakeholders to commit to decisions that improved life cycle operations, and increased sustainability value.

The use case of visualization and monitoring using digital technologies like digital twins is a key capability that is crucial to making life-cycle based decisions. In considering implementation of decarbonization models such as **circular economies**, which involve complex streams and design decisions, technologies such as digital twins are key value drivers to create and manage products and supply chains with circular designs (Preut et al., 2021).

As both the European Union ("EU Action Plan Circular Economy", 2015) and the US("White House Circular Economy", 2023) commit to targeted action towards circular economy models in the habitat sector to improve resource adequacy, digital technologies that enable visualization and monitoring will play critical roles.

3.2.2.2.2 Computing capabilities through advanced simulation and modeling

Powering key technologies such as digital twins are advanced simulation and modeling methods and softwares. These techniques are increasingly valuable when transforming complex systems with significant dependencies, an example being exploring deep decarbonization of the power grid.

Design, Analysis and Optimization Modeling

Modeling and simulation products offered by ANSYS and Autodesk have been widely used in the hardware industry for design, analysis and optimization for physical behaviors (Wang & Nelson, 2015). The ability to predict and improve performance through advanced simulation is key to unlocking value drivers that hardware technologies tackling deep decarbonization need (Reehten, 2023).

As bringing technologies that drive towards Net Zero becomes more immediate, front-loaded and capital intensive (Krishnan et al., 2022), the importance of reducing product costs and time-to-market becomes paramount to the success of the hardware in the habitat space. The resultant of this has been the rapid rise of **Simulation-Driven Product Development (SDPD)** (Johansson & Sätterman, 2012).

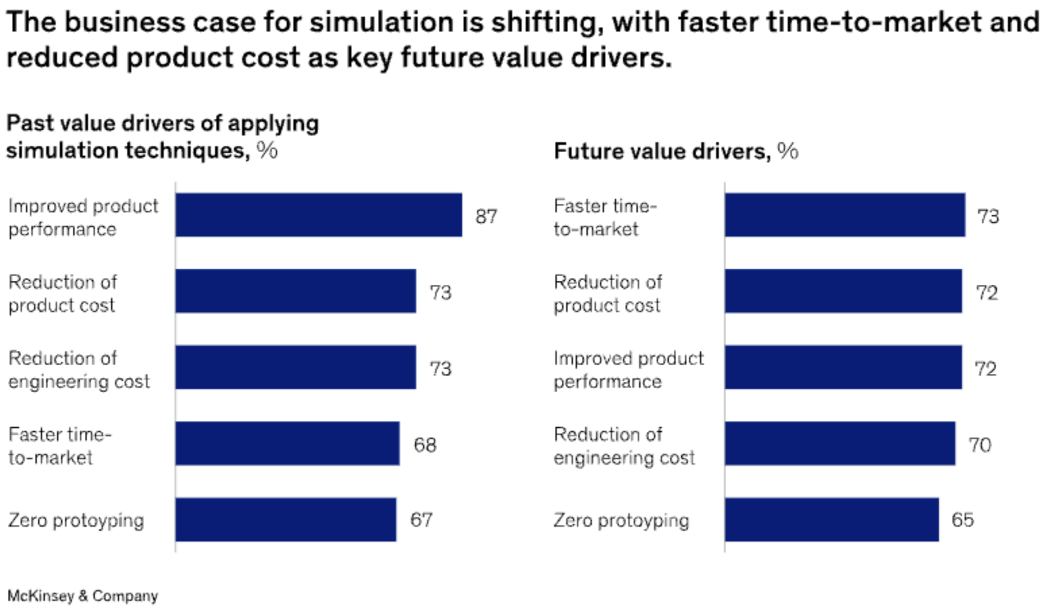


Figure 15: Value drivers of simulation, which is giving a rise to Simulation-Driven Product Development ("McKinsey next frontiers of simulation", 2023)

With the simulation industry estimated to grow by compound annual growth rate of 14% from 2023 to 2030 ("Simulation Market Research", 2023), advanced SDPD have turned to **Analysis Led Design (ALD)** principles (Khot & Tripathi, 2019) to capitalize. These techniques enable greater integration and leverage of performance data across the supply chain, with the emergence of **Multi-disciplinary Optimization (MDO)** and **Simulation Process and Data Management (SPDM)** ("MDO and SPDM in commercial and defense aviation", 2023). As we observe the increased penetrations of simulation technology, validated by experimental datasets, algorithms such as Machine Learning help improve their capabilities (Perez et al., 2020).

Gearing these digital techniques towards optimizing designs for sustainability value are key in accelerated decarbonization efforts, especially as hardware in safety critical sectors such as the power grid and buildings are targeted.

Deep Decarbonization, Energy and Scenario Modeling

High-fidelity energy and **Deep Decarbonization Modeling (DDM)** are key techniques in modeling markets and informing data-driven policies. As decarbonization efforts depend on the adaptation of safety critical systems in the USand Germany such as the power grid, modeling effects on these systems is critical (Plazas-Niño et al., 2022).

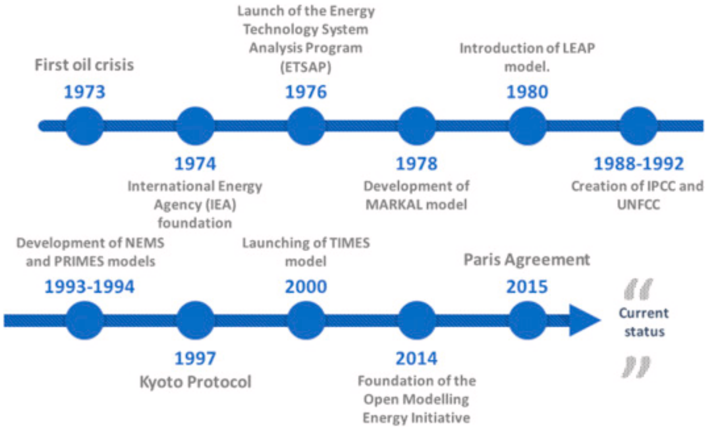


Illustration 5: Timeline of the history of energy and decarbonization modeling (Plazas-Niño et al., 2022)

The foundation of the **Open Modelling Energy Initiative** was part of a drive towards leveraging open-source scientific research towards policy decisions. Techniques such as **Capacity Expansion Modeling** are already being used as references to model build outs of the power grid (van Ouwerkerk et al., 2022). These **agent based simulations** and **lifecycle analysis capabilities**, enabled by initiatives such as **EnergyPlus**, **OpenStudio**, **ReEDS** and **NREL-Sienna**, provide policymakers with tools to model their decisions.

The effectiveness of these models are still unclear. This report also identifies a key gap as when modeling for scenarios, many of these models maintain legacy systems in their operations. Bridging the technical proficiency gap and ease of use of these models and platforms for policymakers is key to speed up decision making.

Considering the rapid pace of development of digital platforms that this section explores, a safe assumption to make is that Deep Decarbonization Modeling and tools will continue to grow in capabilities. As most of these initiatives are open-source, contribution to and adoption of them by policymakers, engineers, entrepreneurs and industry leaders is key in achieving climate goals.

3.2.2.2.4 Value of Open Source

Since the 1960s, the **open source community** has spurred scientific and industry development in the digital and software spaces. From languages such as Python, technologies such as Geographical Information System (GIS) and Linux to the early stages of OpenAI, open source has made a sizable contribution to the digital systems running today. In hardware, apart from robotics and mechatronics, the adoption and creation of open source development has been largely underutilized, which has often capped product development avenues and sustainability value (Pearce, 2019).

This report finds that, as we move towards rapid, deep decarbonization, two avenues that the open source community will need to be emphasized. Firstly, using, developing and maintaining open source software infrastructure that focuses on decarbonization design, management and modeling. From modeling and design capabilities enabled by **OpenStudio**, **NREL-Sienna**, valuation platforms such as **[C]Worthy**, AI platforms such as **PyTorch** and **TensorFlow**, to battery management systems such as **foxBMS**, open-source capabilities will help maximize the scale effect of digitalization in decarbonization spaces (Huang & Lin, 2023). Secondly, supporting and scaling open-source hardware efforts, especially those that focus on contributing to, or disrupting safety critical systems, is a vital priority. To this extent, further developing or scaling the efforts of the **E4C Solution Library**, or **OSHWA**, is an immediate next step in ongoing decarbonization efforts. Building and nurturing an open source developer community, reliable version control and standardizing the development inputs i.e. standardized CAD and analysis files within these existing platforms will be key to starting a wave of open source development.

Additionally, efforts such as the creation of **carbon dioxide removal (CDR) markets**, which are key in valuing products of carbon negative technologies such as carbon sequestration and capture, depend on the existence of reliable data and data sources (Gili & Marañón, 2022). These markets have attracted the attention of tech giants such as Microsoft (“”Microsoft CDR Report FY23”, 2023) and Google, which have invested in these markets and technologies as part of their commitments to their climate pledges.

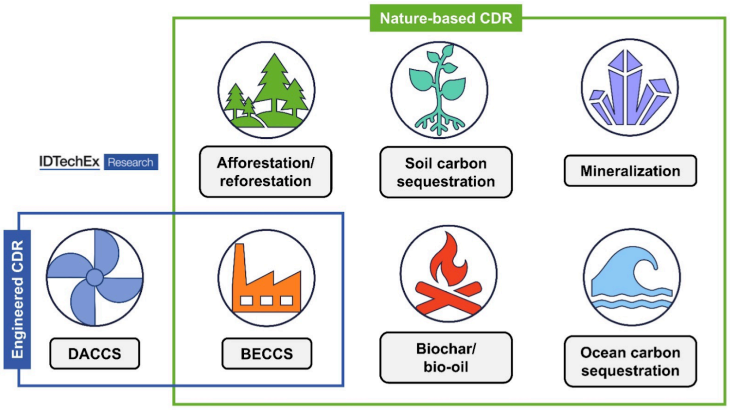


Figure 16: Examples of potential CDR markets that are projected to grow over the next 20 years (Plazas-Niño et al., 2022)

Vital to the growth and success of these markets are accurate quantification of carbon capture and sequestration, more widely known as **Monitoring, Reporting, and Verification** or **MRV** (“OECD MRV”, n.d.). Building and maintaining MRVs pose significant technical challenges, as most of the modeling techniques cannot precisely quantify carbon removal loads. However, through leveraging open-source **Data Platforms** and **API’s**, independent non-profits like [C]Worthy are able to model carbon removal with discounts to account for uncertainties. These capabilities are able to build markets, by building a single source of truth for valuation of carbon and its data.

The functions that open-source data platforms have to standardize data sets and valuation and accounting mechanisms are key in enabling market creation and maintenance. As the creation of digital carbon markets grows, the necessity for standardizing the technologies that power and leverage them will be necessary to build market confidence.

3.2.3 Challenges

		Challenges	Potential Strategies
Political / Legal	01	Innovation and implementation of sustainable technologies depends on political decisions and (insufficient) utility bill earnings.	1. Include sustainability enhancement plans in policies and enforce measures by policy. 2. Reduce political dependencies (e.g. resources like gas from other countries) without providing backup solutions or alternatives. 3. Increase autonomy with long-term focus of trade agreements and investments.
	02	Political discussions and emotions about expensive market prices affect individual decisions (particularly in Germany).	1. Introduce price caps and subsidize lower income groups. 2. Communicate transparently correct information and educate about potential benefits and returns of sustainable investments 3. Implement market mechanisms like taxes to influence consumer behaviour and finance sustainability.
Economic	03	Lack of workforce and expertise due to new market requirements and insufficient training respectively.	1. Create attractive trainings and education programs to acquire (young) professionals. 2. Enhance reputation of technical professions e.g. by including technicians in decision-making. 3. Design sustainable (re-) training and education to cater individual needs.
Social	04	Inability to use and unavailability of consumption data.	1. Promote benefits of using data by industries and politicians. 2. Enhance communication and education about data analytics to reduce personal fears and doubts about exposing data.
	05	Resistance towards change and unawareness of society about urgency to act.	1. Communicate the urgency to act and individual meaningfulness of day-top-day actions. 2. Use market mechanisms and instruments to steer behaviour (e.g. by introducing taxes). 3. Providing the right mix of "sticks and carrots".
	06	Short-term view on investments (e.g. focusing on initial cost).	1. Communicating the importance of long-term perspective and respective benefits and return on investments. 2. Provide financial (sustainable) education to show benefits of investments.
Technological / Environmental	07	Unoccupied and oversized building space.	1. Consolidate work spaces to decrease powered empty building spaces. 2. Monitoring energy consumption of buildings.
	08	Insufficient grid and pipeline conditions.	1. Expand and improve grid infrastructure to enhance resiliency and ensure sufficient amounts of energy.
	09	Disadvantageous building preconditions and expensive retrofits.	1. Showcase positive impacts and potential energy savings after retrofitting.
	10	Seasonality and fluctuations of renewable energy generation.	1. Enhance and expand grid infrastructure to increase reliability and resiliency. 2. Deploy efficient energy storage systems/ energy management systems to steer energy consumption of buildings and reduce resource consumption.
	11	Hydrogen technologies and resources are immature, as there are not exclusively sustainable sources.	1. Engage in research in the area of hydrogen. 2. Implement (green) hydrogen technologies where possible. 3. Control and select sources of imported hydrogen.
	12	Affordability.	1. Deploy public owned solutions like wind parcs or solar fields to avoid private investments. 2. Provide governmental subsidies and incentives.
	13	Embodied carbon.	1. Assess the entire product life cycle (LCA-analysis) for a holistic view. 2. Implement a mix of technologies.

Illustration 6: Summary of Challenges and Recommendations for the Habitat Sector, Source: authors

Political

To begin with, the political environment of the habitat sector consists of inter alia governmental activities and fiscal policies. Thus, the political factor of this analysis examines which role politics play with respect to decarbonization through digitalization.

In the **US**, most financial investments stem from revenues generated from the utility bill. Thus, consumers strongly depend on state decisions regarding funding or subsidizing renewable technologies and are limited to the earnings from the utility bill. Also, regulations passed by the government determine whether renewable energies are desired or not (Reed, 2023). This can result in building owners being restricted in transitioning away from fossil fuels and their scope of action is limited.

Furthermore, electricity prices in the US can be five times as expensive as gas prices, leading to less lucrativeness of renewable electric solutions (Reed, 2023). To actually foster "green" technology, subsidies and lower prices are necessary. Thus, the US market is predominantly dependent on state initiatives and efforts towards decarbonization. Despite the urgency to provide essential infrastructure and incentives to become more "green", governments are not in line with these goals and efforts to achieve decarbonization are insufficient (Thompson, 2023).

The **German** market is shaped by its history of polypolies. Polypolies are characterized by a high number of suppliers covering demand for a high number of customers. Thus, this market condition is not marked by real competition that would lead to price reductions. As a consequence, Germany records one of the most expensive energy markets (Schuh, 2023).

Furthermore, policy makers currently try to counteract the climate crisis by introducing a new Energy Act in Germany. The objective is to oblige building owners to invest in renewables and cease the initial commissioning of fossil fuels. A ban of fossil fuel burning technologies for new buildings is intended from 2024 onwards. This goal of the Energy Act leads to controversial discussions in Germany. While activists require politicians to take even more strict measures, critics fear future investments in e.g. heat pumps, which can be financially intense. Thus, side-objectives like subsidizing building owners and electricity prices are suppressed and more emphasis is being placed on potential financial burdens. This development even has led to increasing unpopularity of heat pumps, which have been strongly demanded in the course of gas supply uncertainties (Norddeutscher Rundfunk, 2023).

Consequently, political discussion impedes the actual objective to reduce emissions and the implementation of sustainable technologies. Furthermore, current policy focuses rather on firefighting and diminishing conflicts and endangered energy systems, rather than leading the way towards sustainability.

Economic

The US as well as Germany strongly rely on skilled professionals and junior staff. In both countries though, labor shortages can be observed, challenging the habitat sector. Consequently, there is a lack in workforce, particularly in technicians, responsible for installation, service and maintenance of HVAC systems (Vaishnav, 2023). Furthermore, the share of well-educated workers diminished, as less young talents enter these jobs and professional training does not suit the job requirements. To counteract this development, respective jobs need to be made more attractive and professional training needs to be designed according to the habitat sectors' needs. Thus, it is essential to actually get to know the sector and corresponding technologies (Reed, 2023).

Besides the challenge of the workforce, economic activities to increase energy efficiency and reduce carbon emissions are impeded by the lack of (consumer) data. Due to strict data regulations (in Germany: General Data Protection Regulation (GDPR)) and bureaucracy of utilities, it is almost impossible to use data to monitor, steer and forecast energy consumptions (Reed, 2023; Thompson, 2023). Particularly Germans fear the disclosure of private data and feel observed or even curtailed in privacy, if data is being used by energy suppliers or other institutions (Schuh, 2023). The inability to use data combined with the polypoly market in Germany thus lead to a lack of incentives to invest in energy efficiency measures and reduce carbon footprint.

Social

The society represents another important factor with respect to decarbonization efforts. Only if people engage in sustainability, actual results can be achieved. Thus, the mindset of society is either one of the key enablers or one of the highest barriers on the path towards a more sustainable future. Particularly cultural factors like education, political or social situation affect society's mindset as well as the attitude of individuals in politicians, managers and other decision-makers.

Furthermore, as lots of decarbonization solutions rely on electricity, respective prices are decisive for environmental-friendly investment decisions. E.g. in New York City, electricity can be five times as expensive as gas, leading to unattractiveness of operating electric alternative technologies. Consequently the general public does not have affordable access to these firms and respective expertise (Reed, 2023).

Thus, if no affordable solutions are provided by companies or incentivized by the government, the majority does not invest in sustainable solutions (Thompson, 2023).

Technological & Environmental Factors

Some technologies presented in chapter 3.1.2 also entail challenges or downsides and thus, cannot be deployed easily or without any (undesired) side effects.

For instance the majority of New York City's **buildings are 30% oversized**, leading to a huge amount of unoccupied space and overcapacity, which still requires energy. Thus, waste of energy in large buildings is immense. In addition, 80% of New York City's buildings are heated by steam, which cannot be replaced by heat pumps or other technologies, due to insufficient pipeline or grid systems (Reed, 2023). Thus, large investments in general infrastructure are required before actually deploying more sustainable HVAC technologies.

Also, with increasing use of electric solutions, **the grid load increases drastically and electricity demand might exceed current grid capabilities**. To prevent overload and potential blackouts, grid infrastructure needs to be expanded and optimized. This is even more relevant for the US, as current grid expansion and connectivity of buildings to the grid is less robust compared to Germany. As grid infrastructure is a challenge for the entire country, a central solution to cover this gap needs to be provided by the state (Roman, 2023).

New constructions or building retrofits are considered to be a huge lever for increasing energy efficiency (Vaishnav, 2023). However, **retrofitting building envelopes is accompanied by enormous investments**, which need to be funded by building operators or the government. As these efforts are immense, most building owners refrain from retrofits, despite the envelope being one of the largest levers (McGee et al., 2023).

3.2.4 Enablers and Externalities Driving Change

Political, Economic & Social

To reduce high reactivity of human behavior and rather focus on long-term, sustained decision-making, policy should envision long-term orientation as well. Thus, subsidies and incentives to implement more sustainable, autonomous solutions should be sustained. To reduce resistance and doubts of society, it is essential to stress the long-term benefits of sustainable solutions opposed to the short-term (expensive) investment. Especially with respect to increased autonomy of HVAC and energy generation, sustainable long-term focus aims at even higher security than short-term firefighting solutions (Schuh, 2023).

In addition, a significant share of the public still needs to become aware of the urgency to change behavior and take action as soon as possible to counteract climate change. Consequently, understanding and awareness need to be fostered by strong communication and policy, as the mindset is at least as important as the availability of technology (Schuh, 2023).

One measure suggested to achieve this mindset change could be the introduction of market mechanisms, e.g. a CO2 tax. Particularly sectors with less potential for technological innovation and efficiency improvements could make use of taxation schemes or certificate trading schemes (Fichert, 2023). By introducing price increases and taxes on environmentally harmful activities, people are educated about the impact of their behavior and which activities contribute most to climate change. As a result, behavioral change can be achieved aiming to reduce e.g. the use of private cars or aircraft. However, if the changing behavior leads to a shift from one emitter to another one, this side effect should be considered for a holistic calculation of individual carbon footprints (Fichert, 2023).

Furthermore, the implication of sustainable technologies depends on the willingness and field of competence of the building owner. Thus, building owners are required to develop technical know-how about potential systems and their application (Reed, 2023). However, as technical professionals are not necessarily the target group purchasing technologies, they could at least be incorporated in consulting building owners and decision makers for building projects.

To further increase the effectiveness and efficiency of new, more sustainable technologies, retrofits constitute a vital lever. By increasing the quality of building envelopes, heat and cold can be kept inside houses and deployed technologies work more efficiently. Consequently, less energy is required to power HVAC technologies leading to decreased energy consumption and cost, justifying respective investments. Therefore, showcasing these benefits to building operators is considered to be a political responsibility.

Moreover, using data to monitor and control energy consumption may contribute to energy efficiency and a reduction of use. However, such energy management systems require the availability of consumption data, which is a sensitive topic, particularly for private persons. To provide and analyze useful data it is essential to combat and react to individual fears and doubts about data disclosure. Politicians as well as energy management system providers thus play a key role in communicating the benefits of data utilization and reducing resistance (Schuh, 2023).

As the lack of workforce represents another critical challenge hampering the introduction and deployment of sustainable technologies and useful political measures, it is vital for policy and industries to promote technical jobs. Further, the reputation of such jobs needs to be enhanced and the workforce should be appreciated by society to attract skilled professionals. By including (technical) experts and young talents in decision making processes and shaping the future, more skilled people can be acquired. In addition, offering opportunities and incentivizing reeducation, training and continuous learning, enables staff to cater current needs of customers and the industry and keep up with recent developments.

Technological & Environmental

A systemic technological perspective is a key strategy to minimize emissions. For example, retrofits for building envelopes can be combined with energy management systems and more efficient technologies like heat pumps. By interconnecting solutions and technologies with help of IoT and steering them in the most efficient way, the overall building efficiency increases (Roman, 2023).

A vital point is the infrastructure expansions and optimization to rely on electricity. Thus, the “grid evolvement and deployment should take place as fast as the political situation allows” (Vaishnav, 2023).

In the US, grid infrastructure is less prepared to introduce solar technologies in the private sector. Furthermore, households show a rather reluctant attitude towards private investments in that regard. Thus, regions like the city of Ann Arbor focus on implementing large-scale solar fields to feed into the public grid.

To prevent potential blackouts or energy shortages due to increased electricity demand, enhancing storage capacities and technologies represents a key enabler. By storing excess energy in times of high generation rates, e.g. on summer days or during windy periods, fluctuations of energy generation can be balanced and consumption can be shifted to times where there is less renewable energy generation, e.g. at night or in winter.

3.3 Results Part 3: Intersection / cross-sector results and challenges

In the course of expert interviews and related literature research, not only transport- and habitat-specific technologies, challenges and enablers have been identified, but also cross-sector trends and similar developments can be observed. The following aims to elaborate on respective technologies, cross-sector challenges and respective enablers and recommendations for solutions.

3.3.1 Ecosystem and current trends

The following elaborates on key ecosystems and trends essential for decarbonizing the transport and habitat sectors, highlighting the significance of data platforms, service business models, venture capital models, safety critical system designs, interdisciplinary education models and open source software and hardware development.

Data Platforms and Application Programming Interfaces (APIs), are the first building block behind digital transformation. Data Platforms and APIs help easy access to distributed, cloud based or open-source software architectures. The ability to access, contribute to, and leverage software architecture through API's are now becoming commonplace practice in digital "have-more's". Data Platforms are becoming a vital element of fully capitalizing on data-driven design insights, flexibility in value streams amongst several digital benefits.

Service business models, ranging from "As a Service" (aaS) to shared services business models are transforming consumer solutions and the way ventures and businesses are able to interact with users. From Zipcar to AirBnB, service business models are becoming increasingly popular, and the potential for these models, that couple hardware and software infrastructures, to help further decarbonization efforts have been well documented. Additionally, as industry 4.0 initiatives move towards bringing greater penetrations of connected hardware, the value stream flexibility of digital platforms and data allow for a transformation of traditional industrial mechanisms.

Venture Capital Models and the risk, returns and time profile that cleantech ventures have not found synergy to help achieve climate goals. In a study conducted by the MIT Energy Initiative in 2016, which studied the initial climate tech boom and bust between '06-'11, concluded that a variety of actors are needed to facilitate the R&D of low carbon ventures. With ARPA-E and similar Department of Energy initiatives taking a greater role in providing capital to help fund climate ventures, venture models will play a role in the scaling of successful R&D, rather than early development. An example of this would be the methane monitoring venture LongPath Technologies, where proof of concept was successfully demonstrated using DOE funds, and venture capital was used to scale. Refocusing venture capital models to complement a multitude of actors and interests in developing climate tech will be key in achieving climate goals.

Safety Critical System design is a key pain point in digital technologies serving decarbonization efforts. As deep decarbonization strategies depend on systems like the power grid that have many critical dependencies, switching analysis design efforts to target safety critical design methodologies in development would significantly speed up acceptance of low carbon technologies. As seen by the latest NERC and FERC rulings, the adoption of low carbon technologies have been stalled by reliability concerns, and maintaining safety critical design targets would have helped ease integration earlier.

Interdisciplinary education models are necessitated to help integrate digital technologies onto low to zero carbon hardware. The exploration by this report found that the capability to build technical depth through the T-model is no longer sufficient when dealing with integrated hardware and software designs. As a result, new educational models must be considered, such as the Shield Model, detailed in a later section.

Open Source Software and Hardware Development will be vital towards improving the speed of product development with a low to zero carbon impact. The digital community has leveraged open source development to great effect, and in integrating digital capabilities, many such tools are already available via open source. In hardware however, no comprehensive effort has broken through, and a trend of sustained open source hardware product development will be needed to build the technology necessitated to achieve net zero targets.

3.3.2 Key technologies

The following elaborates on key technologies essential for decarbonizing the transport and habitat sectors, highlighting the significance of quantum computing, sustainable computing, AI and Machine Learning, data tracking, data analysis, forecasting, greenhouse gas inventory tools, smart grids, and fuel cells.

Quantum Computing: Quantum computing's exceptional processing power allows for complex simulations and optimizations. In the habitat sector, it aids in materials science and building design, enabling the discovery of novel materials that are more energy-efficient and environmentally friendly. In transport, it supports intricate logistics, optimizing supply chains, route planning, and traffic management, leading to reduced energy consumption and emissions.

Sustainable Computing: Sustainable computing practices encompass a range of strategies, including green data centers powered by renewable energy sources such as solar and wind. These practices also involve using energy-efficient hardware components, advanced cooling techniques, and algorithms designed for energy efficiency. By implementing sustainable computing practices, the transport and habitat sectors can significantly reduce their carbon footprint associated with digital infrastructure.

AI and Machine Learning: AI and Machine Learning have wide-reaching applications. In transport, AI-driven autonomous vehicles promise to revolutionize mobility by reducing traffic congestion and improving fuel efficiency. Machine learning algorithms can optimize traffic flow, predictive maintenance for vehicles, and even enhance public transportation efficiency. In habitats, AI is employed in smart climate control systems, which autonomously adjust heating, cooling, and lighting to minimize energy consumption while maintaining occupant comfort.

Data Tracking and Analysis: Data tracking involves real-time monitoring of various parameters, such as emissions, energy usage, and transportation patterns. In the habitat sector, data-driven insights inform decisions about energy usage, building occupancy, and resource allocation. In transport, data tracking assists in optimizing routes and schedules, promoting energy-efficient driving practices, and ensuring compliance with emissions regulations.

Forecasting: Forecasting technologies in both sectors enable better preparedness for changing conditions. For habitats, these tools can predict energy demand based on historical data and weather forecasts, allowing for the proactive adjustment of heating and cooling systems. In transport, forecasting helps anticipate traffic patterns, energy demand for electric vehicles, and the availability of renewable energy sources, facilitating optimized planning and resource allocation. With the help of satellite data, weather prediction and forecasting can be achieved in order to make informed decisions and early warnings in case of natural catastrophes (International Telecommunication Union (ITU), 2019). Thus, using radiocommunication technologies may lead to enhanced resiliency and risk assessment (Ubeda, 2023).

Greenhouse Gas Inventory Tools: These tools are critical for quantifying emissions accurately. They assist organizations and governments in tracking their carbon footprint, assessing progress towards emission reduction targets, and formulating policies and strategies to achieve sustainability goals. In both sectors, transparent emissions reporting is essential for accountability and climate action.

Smart Grids: Smart grids play a crucial role in optimizing energy distribution and management. In habitats, they enable real-time communication between energy producers and consumers, allowing for the efficient integration of renewable energy sources, load balancing, and demand response programs. In transport, smart grids ensure efficient charging infrastructure for electric vehicles and grid stability, facilitating the transition to clean energy solutions.

Fuel Cells: Fuel cells offer efficient and low-emission energy solutions in both sectors. In transport, hydrogen fuel cells power zero-emission vehicles, offering longer ranges and faster refueling times compared to batteries. In habitats, fuel cells provide reliable and clean energy for heating, cooling, and electricity generation, reducing dependence on fossil fuels.

These technologies represent a sophisticated toolkit that, when strategically applied, can drive substantial reductions in greenhouse gas emissions while enhancing efficiency and sustainability in both the transport and habitat sectors. Their continued development and integration into existing infrastructures are central to achieving a sustainable and decarbonized future.

3.3.3 Challenges

Challenges			Potential Strategies
Political / Legal	01	Lengthy political discussions, slowing innovation process and not always in favor of sustainability.	1. Increase awareness and communicate urgency of climate action. 2. Promote target-oriented discussions and decision making involving technical professionals.
	02	Lack of qualification and collaboration of governance and industries.	1. International collaboration to solve problems jointly. 2. Promote (re-) education for sustainability.
	03	Ineffective choice of market mechanisms and political/economic instruments.	1. Forecast and assess potential (side) effects of "carrots and sticks".(e.g. compensation schemes or emission trading schemes). 2. Use carbon taxes to finance infrastructure and public measures.
Economic	04	Financial aid required for innovation and investments, especially due to financial instabilities.	1. Create funding structures and consult companies and individuals for sustainable building solutions.
	05	Lack of standardisation and procedures.	1. Standardise working methods, carbon reporting, calculation schemes, carbon accounting, KPIs, sustainability measures, industrial processes. 2. Require industries to commit to sustainable development by policy.
	06	Financial investments required, but short-term perspective on investments Ways for monetization lacking.	1. Financial education for long-term perspective to justify initial investments. 2. Conduct break even analysis and identify ROI. 3. Encourage investments by policies.
	07	Lack of workforce and suitable skillset due to new fields of work.	1. Enable knowledge transfer between experienced and young professionals as well as (re-) education to keep up with new trends and challenges. 2. advertise for and design of attractive, esteemed technical programs by industries. 3. NewLab concept -> create an open innovation platform
Social	08	Awareness about urgency for climate action and innovation among society and decision makers.	1. Communicate the urgency to act and individual meaningfulness of day-top-day actions. 2. Use market mechanisms and instruments to steer behaviour (e.g. by introducing taxes). 3. Providing the right mix of "sticks and carrots".
	09	Inability to use and unavailability of consumption data.	1. Promote benefits of using data by industries and politicians and enhance communication to reduce doubts and fear of data exposure.
	10	Decreasing disposable income and emotional guidance of decisions.	1. Educate about positive effects in the future and security in the long-run (e.g. in schools and news).
	11	Decreasing disposable income and emotional guidance of decisions.	1. Educate about positive effects in the future and security in the long-run (e.g. in schools and news).
Technological / Environmental	12	Limited capacity of the grid Rising demand for electricity.	1. Overthink "electricity-only" approach and apply a mix of technologies to reduce grid load. 2. Deploy storage systems, energy management systems and forecasting to prevent outages, catalyze and steer demand and capture overproduction to enhance resiliency.
	13	Embodied carbon often neglected Difficulties to quantify and identify embodied carbon.	1. Enhance and expand grid infrastructure to increase reliability and resiliency. 2. Deploy efficient energy storage systems and steer transportation networks to reduce resource consumption.
	14	Quantum computing and data server footprint.	1. Take a holistic view by conducting LCA.
	15	Immature technologies, e.g. hydrogen and carbon capture.	1. Implement a mix of technologies as there is no "one-size-fits-it-all" and maintain conventional technologies to cover transition phase. 2. Increase the efficiency and level of automation to reduce overall process energy use.
	16	Difficulty to detect failures and defects of semiconductors.	1. Improve methodology and defect detection.

Illustration 7: Summary of Cross-Sector Challenges and Recommendations, Source: authors

The transport and habitat sector face overlapping challenges as the development towards decarbonization and digitalization entail similar consequences for political, economic, social, technological, legal and environmental aspects. The following challenges have been identified during the course of this research and respective expert interviews.

Political

The political situation of the transport and habitat sector is considered to be a key determinant of developments with respect to decarbonization, as policy builds the foundation for consumer markets, economics and other aspects of life. Thus, if political discussions are lengthy, unsuccessful and controversial, policies slow the process of innovation. In fact, policies and respective legal requirements to the transport industry and the energy market may even hamper the implementation of more efficient technologies, if they are not in favor of sustainable development and do not work towards the same goals (Alger et al., 2023).

Furthermore, a lack of qualification and collaboration of governance and industries is being observed as policy makers are not necessarily experts of the sectors and real circumstances they decide about. As a result political decisions do not always suit actual market conditions and requirements of economics and consumers (Thompson, 2023). Especially with respect to increasing urgency to act against climate change and current economic challenges, it is even more important to respond to customer’s individual needs and incentivise sustainable decisions in daily life and for long-term investments.

With respect to decarbonization of industries and (public) institutions, recommendations for action and standardized procedures, strategies, methods and KPIs are required to guide the way towards climate action. This guidance and support is currently insufficient but demanded by stakeholders (Thompson, 2023).

In addition, financial instabilities and economic crises challenge politicians to take sustainable measures and respond to public fears and requirements. However, interviewees question the effectiveness of current measures and incentives for investing in digital technologies and decarbonization. Further, they claim that funding possibilities and financial aid need to be enhanced in order to be effective and yield investments for renewable technologies. In that context, the question about “carrots and sticks” usually arises and it is discussed whether policy should only create incentives or also use punishment/restrictions to enforce certain behavior.

Economic

The economic situation is marked by the need for intense investments for more sustainable solutions. Not only is it expensive to retrofit existing infrastructures and technologies but also research and development towards decarbonization and digitalization require industries to incur high investments.

As mentioned above, deficiencies in the workforce can be observed throughout the entire transport and habitat market. In particular, this concerns areas of system deployment, crafts and technical support. In the course of emerging new technologies this effect is even more sustained, as new areas like system technicians (e.g. for heat pumps) and technologies increasingly including electronics, have been developed over the last years. Thus, experts knowing mechanics as well as electrics are demanded but scarce. Additionally, especially young talents are missing in this area leading to an increasing age gap, impeding the transfer of knowledge to younger generations (Roman, 2023).

Social

The perception and mindset of the general public is one of the key levers for climate change. Not only individuals are required to take action in their daily decisions but also political and economic decision makers are vital for decarbonization efforts. As a high share of people is not aware of the urgency to counteract global warming or does not care about it, a cultural change is necessary (Thompson, 2023).

Furthermore, the implementation of sustainable technologies supposes individuals to be convinced to purchase them and to believe in their functionalities. However, as people tend to draw on well-known products, a change of behavior patterns might even be necessary. In addition, solutions aiming at energy efficiency often entail the use of data to monitor consumption and derive demand patterns. For the implementation of demand-based energy consumption steering, it is thus essential to receive and use consumer data, which does not work if people are too concerned about data privacy (Schuh, 2023).

Legal

The legal situation is an important precondition for the implementation of decarbonizing digital technologies. Laws and regulations can even require individuals or industries to invest in sustainable technologies or implement a certain share of renewables. However, these legal requirements are often controversially discussed like currently in Germany and may lead to dissatisfaction if not thoroughly elaborated and incentivized. Moreover, critics and climate activists usually claim that legal requirements to implement renewables and more efficient technologies are not strict enough to actually have a sufficient impact and meet 1.5 degree targets (United Nations, 2022).

Technological & Environmental

To enable a holistic approach towards decarbonization the entire product life cycle of “sustainable solutions” needs to be taken into account. For example, embodied carbon can be difficult to quantify (Alger et al., 2023). Thus, technologies like hydrogen, fuel cells, batteries and electric vehicles can have a negative environmental impact as well, depending on the origin of incorporated resources as well as required operating current (Vaishnav, 2023).

Also, with respect to digitalization the impact of energy use should not be underestimated. Data centers and data processing requires huge amounts of data, leading to the question which “sustainable” activities are probably more harmful than helpful (IEA, 2023). Thus “sustainable computing” vs. computing for sustainability needs to be assessed and weighted .

Additionally some efforts to develop technologies for decarbonization like e.g. carbon capture and storage systems yet not necessarily lead to an overall reduction if based on pre- or post-combustion, oxyfuel process (Papadis & Tsatsaronis, 2020, 5).

Another challenge regarding technological developments concerns the use of semiconductors. With the increased demand for technologies using software and chips, the production and supply of semiconductors is being challenged and shortages can be observed. Further, semiconductors are prone to defects on the wafer leading to system failures and thus need to be checked thoroughly. This process is relatively time-intense and requires additional efforts and capacities (Cheng & Liu, 2000, 371). Consequently, the chip and software industry needs sufficient data monitoring and semiconductor analysis tools to identify failures and track systems where chips are applied in (Thompson, 2023).

3.3.4 Enablers

Political & Legal

One of the biggest challenges of today is represented by the existing workforce gap. In particular, technical jobs and engineering lack young professionals to cover the existing age gap and enable knowledge transfer to younger generations. Thus, advertisement and designing of attractive and esteemed technical programs are vital for the future of craft industries and engineering. As a result, policy and economics need to join forces and foster the acquisition of young talents. In the course of this, it is also a political responsibility to enhance the reputation of technical jobs and point out their indispensability. To do so, respecting and appreciating junior staff is inevitable to create an attractive working environment for them.

Another enabler to tackle the shortage of workforce is the encouragement of international collaboration to jointly solve problems, create innovation and exploit potentials. In that regard, it is also meaningful to consider foreign/external perspectives and use worldwide resources and solutions (Reed, 2023). Also, funding structures to support research and development projects or start ups need to be enhanced to drive innovative force (Thompson, 2023).

For the implementation of digital decarbonization technologies high investments and changes to existing systems are required. To enable this transformation, a long-term perspective needs to be taken into account in order to justify the investment. Thus, comparing high initial cost with the long-term benefits of decarbonization and reduced cost of negative effects of climate change reveals the lucrativeness of sustainable investments. Consequently, weighting “upfront-cost vs. after-cost” (McGee et al., 2023) or conducting breakeven analysis is recommended to be incorporated into political decisions and industries as well as customers should be encouraged by politicians to take this perspective.

Showcasing the urgency to counteract climate change by enabling data utilization and to commit to sustainability in other areas of life, is vital for speeding up the shift of mindset towards change. As the city of Ann Arbor has proven, it is possible to fund and afford sustainable technologies and programs by (additional) taxes, if the majority of the population believes in climate action and is willing to invest in a more sustainable future. Incorporating an additional tax or tax raise has shown to be effective in that regard, as people do not actively invest a specific amount of money but it is deducted automatically from their gross loan. Thus, people have voted for higher taxes to afford climate change (personal interview with public sector employee, 2023). To balance “sticks and carrots”, i.e. reward and punishment systems, considering and assessing effects and potential (negative) repercussions and conducting holistic analysis is inevitable in that regard (Fichert, 2023).

In addition, especially with respect to current financial instability, funding and consulting infrastructure need to be expanded to, for example, enable carbon neutral building roadmapping for building owners (Reed, 2023). Sound advice, sustainable standards for working methods and carbon reporting thus are required to be provided by policies. To achieve these standards and political preconditions, it is essential to include technicians and other sector experts into political decision-making to facilitate reasonable policies (Brown, 2023).

Economic

With respect to economic impact on sustainability, it is important to utilize existing workforce as efficiently and effectively as possible. Thus, hiring and re-educating staff is essential for keeping up with new trends and challenges and enabling future proofness (Thompson, 2023). Also deploying modules and appliances like solar foil which are easy to install and thus require less expertise and personnel (Schmitz, 2022).

Furthermore, innovation, research and development are facilitated by skilled labor and cooperation. Thus, especially huge companies and industries are required to remain innovative and foster creativity. The concept of NewLab envisions this innovation culture and speed by pairing startups with big companies. By doing so, big market players are taught characteristics like agility, creativity and innovative strength. In addition, NewLab creates open (collaboration) spaces and emphasizes transparent offices and labs, which enables creation of new ideas. Startups at NewLab are inspired by others and thus technological development is even more accelerated (Fahle, n.d.).

This innovative culture and focus on research and development activities can be vital for the future and thus are worthwhile initial investments. Particularly, do most of these investments break even and pay-off in the long-run, which is more beneficial than avoiding investments, which need to be accounted for afterwards.

Social

To enable decarbonization through digitalization the society represents a vital contributor to the progress. Particularly the mindset and attitude towards sustainability is decisive for personal decisions to take “green” measures. According to the interviews, a high share of doubts and resistance is still being observed, leading to hampered climate action. To counteract this perspective on decarbonization, know-how needs to be increased by continuously informing about the urgency for climate action. Furthermore, encouraging and empowering individuals rather than expressing accusations are considered to be useful and actually enable a mindset shift.

This strategy can be further sustained by clarifying the impact of today’s decisions for the future and showcasing what positive but also negative effects today’s actions may have. As a result, people increasingly understand how meaningful their individual behavior is for the overall goal to become carbon neutral. In that context it is particularly essential to stress the significance of each individual and appreciate every effort contributing to sustainability.

Taking into account personal insecurities and doubts regarding current inflation trends and financial instabilities, it is also important to educate about the positive effects in the future when investing in sustainable and autonomous solutions. Pointing out that today’s efforts may be great but pay-off in the future and create even more security in the long-run, should not be neglected when establishing a sustainable mindset. To support the idea of sustainable/financial education respective subjects in school or university could be offered and calculations of break even analysis and return on investment of sustainable solutions should be communicated in public.

Legal

To guide and assist industries, institutions and individuals on their path towards sustainability, the creation of useful legal frameworks and standards should be ensured. As the majority feels insecure about “green” procedures and correct working methods, guidance is demanded by all stakeholders. This guidance may include standard calculation schemes for carbon accounting, reporting or KPIs, common sustainability measures for buildings as well as industrial processes and minimum requirements to be implemented in organizations or households. This might also include the requirement to engage in research and development and dedicate a certain amount of revenues to sustainable development.

Technology

With respect to technological challenges it becomes apparent that there are numerous digital and sustainable solutions, which all have benefits and shortcomings. Thus, a broad positioning (mixture) regarding various technologies is recommended for all stakeholders. In that context, it is important to take a holistic perspective (Alger et al., 2023; McGee et al., 2023) to design systems as efficient and carbon neutral as possible. To enable a holistic approach LCA are vital and consider all parts of a product's life cycle from extraction of resources until disposal or recycling.

This results in a variety of individual solutions, as there is "no one size fits it all" (Alger et al., 2023). Thus, a modular composition of technologies and also small solutions is recommended to be implemented in private households, industries and for public infrastructure. Even small appliances like solar foil, solar balcony appliances or batteries may contribute to the mix of technologies and can have a significant impact for reducing one's individual carbon footprint. With this mixture of technologies grid load can be minimized and energy generation for private households might be sufficient to cover household devices or charging electric vehicles at home. Furthermore, implying storage systems and batteries enable autonomy and backup supply in case of any outages and shortages of electricity supply and capture energy produced exceeding actual demand. As a result resiliency is increased and risk recovery becomes possible (Alger et al., 2023; Vaishnav, 2023).

Furthermore, smart home appliances and energy management systems can complement this mixture of technologies by monitoring and steering them in the most efficient way. Also on a large scale it is possible to use consumption data and traffic flows to forecast demand patterns and redirect energy supply to corresponding needs (Alger et al., 2023). Consequently, tools enabling data tracking and analysis enable efficient energy use and catalyze demand and e.g. consolidate traffic to increase load factors of public transportation and thereby reduce carbon footprint per passenger.

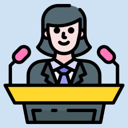
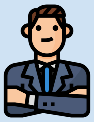
However, experts claim that the transition towards renewables will not be feasible without the use of fossil fuels and existing conventional systems, as a complete shift would require an entire infrastructure retrofit and would cause obsolescence of current technologies and systems. Furthermore, does the increased use of electronic devices and solutions lead to a stronger demand for energy, challenging current infrastructure capabilities. Thus, the maintenance of conventional power plants and fossil fuels is required to cover current energy demand and fluctuations of renewables. As these technologies have become exceedingly efficient, they even may represent one of the most efficient and effective solutions as of today (Papadis & Tsatsaronis, 2020, 5).

Education & Capabilities

As already mentioned, the workforce represents a key enabler for developing, deploying and maintaining sustainable solutions. Thus, not only policy makers but also technical professionals and managers require a specific skillset. To build these skill sets and educate professionals also schools, universities and other training programs or institutions need to convey respective content.

The following table summarizes these roles and respective capabilities and responsibilities which are considered to be essential for digitalization and decarbonization of the habitat and transport sector.

Table 1. Overview of recommendations for key roles with respect to decarbonization through digitalization, Source: authors

Role	**Skills**		
	Hard skills	**Soft Skills**	**Role regarding responsibility**
Policy-makers 	Know-how about: Sustainability, respective sector requirements and technologies, building infrastructure and preconditions for renewables	"Doer mentality", encouraging and empowering others with strong communication to showcase urgency of sustainability and importance of technologies and individual action	Providing (economic) measures to build infrastructure, incentivized funding schemes, creating social awareness, fostering international collaboration
Managers (industries) 	Know-how about: Market requirements and customer, technologies and technical implementation	Innovative and sustainable mindset, encouraging and empowering employees and colleagues, strong negotiation skills	Implementing sustainability strategies and utilizing resources in industries, fostering international collaboration
Technical professionals and engineers 	Know-how about: engineering depth, infrastructural, mechanical and electrical engineering combined (real-world scenarios), understanding interaction of PESTLE-environments, LCA calculations → interdisciplinary education including business, technical and political setup	Holistic view, being able to transfer knowledge, life-Long learning, interdisciplinary thinking, entrepreneurial skills, intercultural skills, international collaboration	Ensure development and deployment of sustainable technologies Engineering for resiliency
Education (teachers, professors, trainers, etc.) 	Know-how about: education of all aspects (financials, economics, mechanical/electrical engineering), teaching holistic view, application-based teaching (what do I do with this knowledge later in life?)	Ability to convey complex environments and respective requirements, holistic perspective and teaching sustainability as interdisciplinary topic	Designing education and training programs → interdisciplinary education including business, technical and political setup + hands-on technical training combined with economics Providing modular studies according to interest and job requirements → Exploring novel educational competency profiles that offer alternative approaches to the current industry standard T-shaped profiles need to be explored.

3.4 Future of Digitalization

In evaluating the future of digitalization, this report seeks to define it at three primary levels - algorithmic, language and hardware level. Additionally, as demand for capabilities with both digital and hardware tools increase, a rethink of the skill set models that we hold as standard is necessitated.

3.4.1 Advances in algorithms

As the amount of big datasets in the habitat and transport sectors increase worldwide (Bhattarai et al., 2019), the ability to leverage insights from them become more and more valuable. In recent years, techniques such as **artificial intelligence**, **machine learning**, **computer vision**, **natural language processing**, **neural networks** and **deep learning** have famously gained significant traction and attention.

Over the next decade, this report finds that over the next decade, these algorithmic advances may drive business and scientific computing and discovery. From more intensive integrations such as Enterprise cognitive computing, which is the enhancement of business operation using AI (Tarafdar et. al), to manufacturing, customer operations, marketing and sales, software engineering, and R&D and business productivity (Chui et al., 2023), artificial intelligence algorithms stand to unveil a new business frontier. The advances and increases in use cases of AI mean that the business value of integration rapidly increases, making building digital infrastructure to accommodate advanced algorithms undeniable..

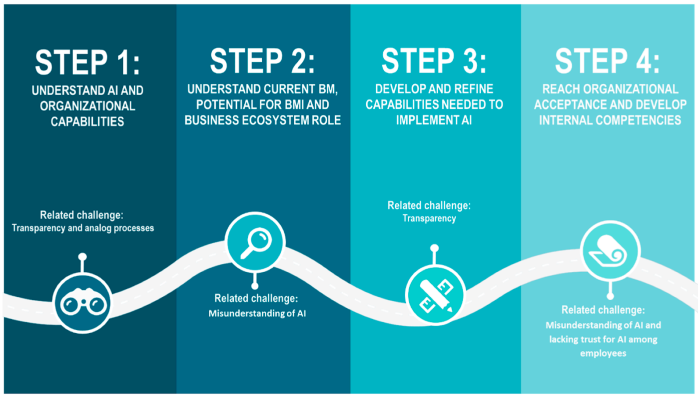


Illustration 8: Stages of business integrations of artificial intelligence. Broadly, this could be applied to digital adoption too. A Roadmap for Business Model Innovation - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Roadmap-for-AI-business-model-implementation_fig1_341127824 Source: (Reim et al., 2020)

Meanwhile, the potential applications of large scale artificial intelligence techniques such as self-supervised learning has large implications for the fields of scientific discovery. AI algorithms are becoming widely used tools for researchers by optimizing parameters and functions, automating procedures to collect, visualize, and process data, exploring vast spaces of candidate hypotheses to form theories, and generating hypotheses and estimating their uncertainty to suggest relevant experiments (Wang et al., 2023).

While this report recognizes attempting to predict the future of computing is an imprecise and inaccurate venture, the historical advances in algorithmic capabilities is likely to continue. To this effect, this report cites the potential emergence of **Quantum AI and Machine Learning**, researched at Google and IBM amongst other players, as further proof of advances in algorithmic capabilities (Biamonte et al., 2017). With improvements in precision and capabilities of these algorithms, the gap between digital have and have mores will be exacerbated further.

3.4.2 Advances in computing power

Early barriers to large scale modeling was computing power, improvements to which are now driving the artificial intelligence age ("Intel improvements in computing power", 2018). The advances of processing capabilities, predicted by Moore's Law, a techno-economic model that predicted the doubling the performance and functionality of digital electronics roughly every 2 years within a fixed cost, power and area, has driven the I.T. revolution and been one of the most important sources of national productivity growth, explaining 49%-94% of performance improvement in the sector (Thompson et al., 2022).

In late 2019, a significant breakthrough in technological capabilities of **quantum computing** was achieved at Google Quantum AI. Powered by the Sycamore processor, a niche calculation, ample one instance of a quantum circuit a million times, that a state-of-the-art classical supercomputer would take approximately 10,000 years was achieved in about 200 seconds, an effort known as **quantum supremacy** (Arute et al., 2019). Efforts at IBM mid-2023 achieved a proof-of-principle that provided evidence that quantum computers could soon beat ordinary ordinary ones at useful tasks, such as calculating properties of materials or the interactions of elementary particles (Castelvecchi, 2023).

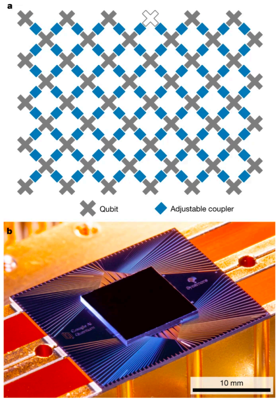


Illustration 9: The Sycamore Processor at Google AI that demonstrated quantum supremacy, Source: (Arute et al., 2019)

These capabilities sparked a potential new model to replace Moore's Law, nicknamed Neven's Law after Hermut Neven, Director of Google's Quantum Artificial Intelligence Laboratory. The law predicts the improvement in processing capabilities at a "**doubly exponential**" rate (Hartnett, 2019), a staggering improvement on Moore's Law. If computing capabilities are observed to fulfill this, the importance of and dependence on digitalization to elevating and maintaining economic productivity will be substantial.

3.4.3 Advances in programming languages and platforms

Open-source Python development has been the bedrock of digital development of the past 20 years, replacing C and Fortran despite deficiencies in computing speed and efficiency (Duranton et al., 2020). However, as computing demands increase, innovations at the programming and platform level have elevated the playing field that have furthered computing performance.

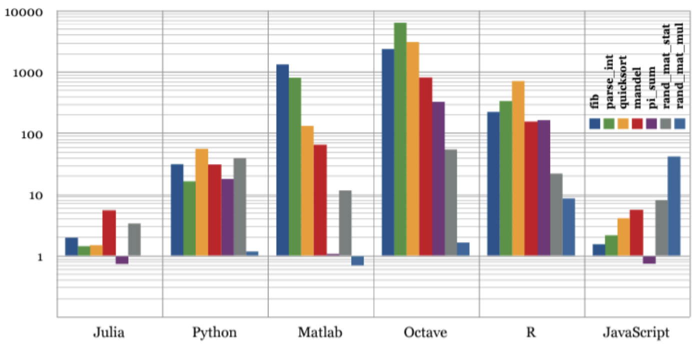
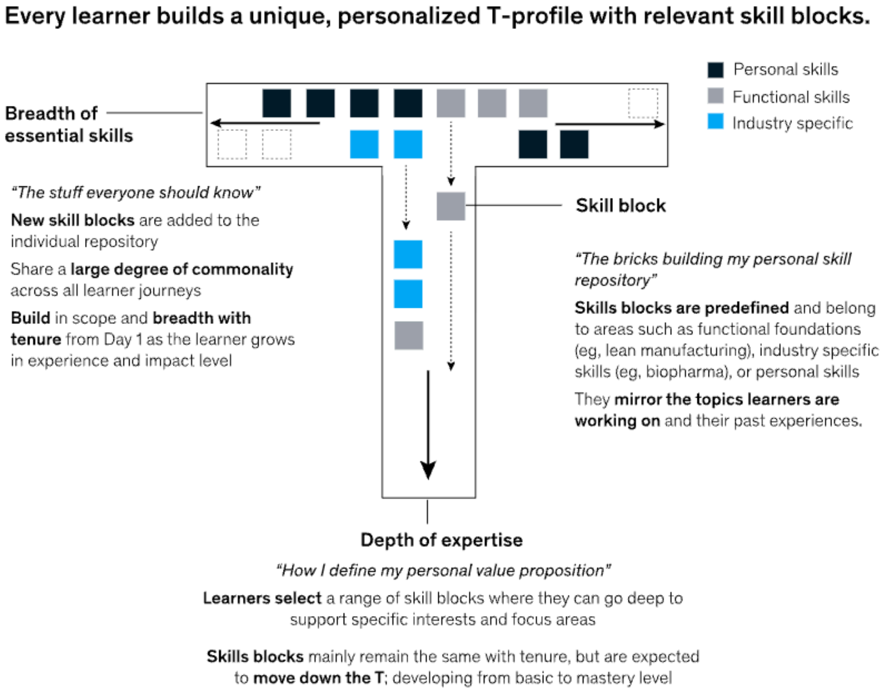


Figure 17. The quicker computational timescales that Julia is able to compute at in comparison to other languages, Source: (Bezanson et al., 2012)

Julia, a programming language built for technical and scientific computing, has the dynamic capabilities of Python, with the speed of C and Fortran (Bezanson et al., 2012). Its ability to integrate with several other packages across languages make it an attractive scientific proposition for advanced simulations (Bezanson et al., 2017). Integrated with advanced algorithms and processing hardware, the computing capabilities that are enabled are significantly enhanced.

3.4.4 Interdisciplinary skill set models

A key finding of this report pertains to the lagging interdisciplinary skill sets of those working with technologies that currently, or potentially have digital components to them. The current industry standard for skillset models is the T-profile.



Every learner builds a unique, personalized T-profile with relevant skill blocks.

"The stuff everyone should know"

New skill blocks are added to the individual repository

Share a **large degree of commonality** across all learner journeys

Build in scope and **breadth with tenure** from Day 1 as the learner grows in experience and impact level

"The bricks building my personal skill repository"

Skills blocks are predefined and belong to areas such as functional foundations (eg, lean manufacturing), industry specific skills (eg, biopharma), or personal skills

They **mirror the topics learners are working on** and their past experiences.

"How I define my personal value proposition"

Learners select a range of skill blocks where they can go deep to support specific interests and focus areas

Skills blocks mainly remain the same with tenure, but are expected to **move down the T**; developing from basic to mastery level

Figure 18: Detailed overview of the industry standard T-profile, Available online at: https://www.mckinsey.com/capabilities/operations/our-insights/operations-blog/ops-40-the-human-factor-a-class-size-of-1

However, when working in decarbonization spaces with deep digital penetrations, or even when designing or building connected hardware, this profile is insufficient to fully leverage computing capabilities. Requiring technical expertise in multiple areas, including digital capabilities, begs the question, are there other models of skill set profiles that better serve tackling complex, interdisciplinary problems such as climate change?

A novel skill set profile, called the shield model, was proposed for interdisciplinary problem solving in doctoral education (Bosque-Pérez et al., 2016). The model proposes building intermediate depth in multiple disciplines while maintaining discipline expertise in the student's area of focus. Run in collaboration with the University of Idaho and Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the model found positive outcomes in developing communication capabilities, collaborations and research spanning multiple fields.

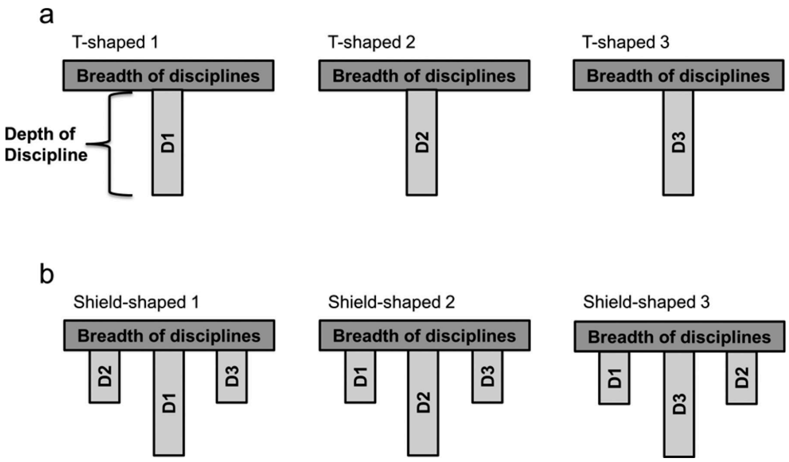


Figure 19: A possible new skill set model, the shield profile, is primed for tackling interdisciplinary problem solving, Source: (Bosque-Pérez et al., 2016) / CC BY-NC 4.0

Available online at: https://www.researchgate.net/figure/Examples-of-the-a-T-shaped-competency-model-and-b-shield-shaped-competency-model-in_fig3_301292903

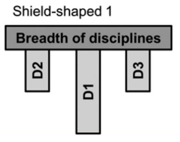
While this model proves its efficacy to an extent at a doctoral level, application to other levels of education is still unproven. Despite this, as computing capabilities increase at a potential doubly exponential rate, the importance of the shield shaped model in bridging disciplinary gaps is vital to leveraging digital advances.

4 Conclusions and Recommendations

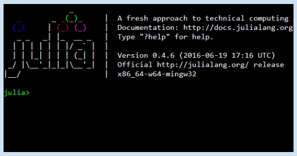
Digitalization presents a unique opportunity to accelerate the decarbonization of the transport and habitat sector. Based on the work of this report, four main takeaways

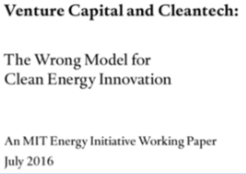
1. The exacerbating gap between digital haves and have-mores showing no signs of abating, with computing power and capabilities expected to rise over the coming decades, a rethink is necessitated for legacy infrastructure to both leverage and support this.
2. Values of digitalization such as flexibility in revenue streams, advanced workflows, hardware utilization and open source development have not been fully realized in industries with deep decarbonization initiatives.
3. Educational profiles from policy makers to interdisciplinary engineers are currently insufficient to leverage digital technologies in their work. As interdisciplinary approaches are needed for complex decarbonization problems, building cross-disciplinary skill sets for digital work needs to be explored.
4. A key pain point of digital transformation for legacy industries is building reliable technologies that don't compromise the reliability of high dependency infrastructures. Additionally, the way current venture models finance climate tech is insufficient to disrupt safety critical infrastructure.

As a starting point, the following recommendations have been curated to help improve digital futures. These recommendations, while focused towards the partners and sponsors of this report, can be easily leveraged by other institutions and interested parties.

Recommendation	Description	Potential Avenues
High impact open-source collaborations Sienna OpenStudio	Open-Source projects such as OpenStudio are the backend of several industry standard design and analysis softwares such as REVIT. Contributing to the development of platforms like OpenStudio and NREL-Sienna gives end users of standardized design softwares better capabilities to incorporate sustainable designs.	VDI, ASME and E4C could partner to provide fellowships for contributing modeling and simulation capabilities towards retro-fitting in buildings.
Re-imagining interdisciplinary education approaches 	As the lines separating engineering and STEM disciplines blur in approaching complex problems, the industry accepted T profile may no longer be sufficient to achieve breakthrough outcomes. The shield model, which has been tested for interdisciplinary outcomes in doctoral education, could provide a viable alternative.	A pilot program modeling the program by CATIE and University of Idaho to focus on cross-functional industrial technology development can be run to research the efficacy of the model in solving problems involving various professions. If effective, rapid adoption is recommended, and educational and industrial models shifted to

		reflect a new paradigm.
International decarbonization data platforms and datasets  Google Cloud State of API Economy 2021 Report	The current collaboration of ASME, VDI and Engineering For Change brings together partners that have significant infrastructure worldwide, from engineering fellows to institutional presence. As models such as Machine Learning and Artificial Intelligence, which are dependent on large datasets, become widely adopted, creating a single source of truth for international effects of decarbonization efforts is critical towards bulk modeling and planning. By creating a single Data Platform sponsored and standardized by the partners, decarbonization research collaborations across borders could be turbo-charged.	Creating a Data Platform that has standardized data on international power grid load, distribution and generation will be key in decarbonization, especially in low data environments in developing regions. A standardized data platform on carbon consumption and production globally will be key in international research efforts to MRV.

Preparing for the quantum digital world

`A fresh approach to technical computing`
`Documentation: http://docs.julialang.org`
`Type "?help" for help.`
`Version 0.4.6 (2016-06-19 17:16 UTC)`
`Official http://julialang.org/ release`
`x86_64-w64-mingw32`
`julia>`
	As scalable quantum computing promises to, in a horizon of two years, begin an age of “*doubly exponential*” growth in computing capabilities, equipping the workforce to have capabilities leveraging quantum hardware and software will be critical to reducing the exacerbating gap between digital haves and have mores. Building these models in advanced languages such as Julia will build literacy at the edge of technology.	Webinars, information sessions and lectures on quantum literacy for industry leaders and professionals. Additionally, fellowships could be focused on converting traditional algorithms and approaches towards leveraging quantum processing capabilities.

ASME ISHOW recommendation I: Long term purchase agreements for carbon negative hardware  Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation An MIT Energy Initiative Working Paper July 2016	Technologies such as carbon dioxide removal, critical to global net-zero efforts, are infeasible using traditional venture models. ASME’s IShow brings entrepreneurs across the globe focused on decarbonization efforts together. However, preparing ventures tackling legacy systems and safety critical hardware towards venture models has historically proved to be ineffective. Focusing these entrepreneurs to implement business models leveraging long-term purchase agreements that the	Creating an ASME IShow category for deep decarbonization hardware to focus on engaging customers with long term purchase agreements, like those tech companies such as Google and Microsoft have committed to, will bring a new industry dynamic.

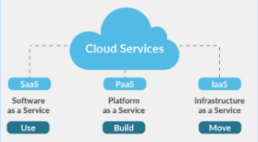
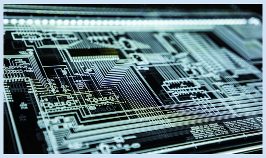
	industry is beginning to adopt will allow disruption of legacy systems.	
ASME ISHOW recommendation II: Category for hardware service business models 	Infrastructure-As-A-Service models in software such as SaaS (Software as a Service) and shared services have revolutionized the accessibility of infrastructure. Adopters are able to leverage data for product insights that allow them multitudes of advantages over competitors, and often a headstart in exploring novel fields and products. However, hardware service models have not been able to leverage this effectively, as well as fully leverage the value stream flexibility of the data insights of such models.	A key finding of this report was customer requirements for hardware ventures are shifting to necessitate connected hardware. ASME IShow category on Hardware Service Models to bring entrepreneurs that would like to improve their hardware product utility, leverage insights and use connected hardware towards decarbonization service models.
Power electronics, advanced design workflows and analytics competencies 	Quite simply, the most critical field in decarbonization efforts are power electronics. Key to power grid infrastructure, IoT devices amongst several others, Additionally, literacy in building, deploying and using Data Platforms and API's, described as the building block of digital transformation, is imperative. Finally, hardware design workflows need to be researched and reformulated from waterfall methodologies to faster iterative workflows.	Building university curriculum to have familiarity pulling from known Data Platforms and API's for all disciplines. Engineering project work undertaken in manufacturing and design should be conducted using advanced iterative workflows.

Table 2. Overview of recommendations for partners based on report's exploration, Source: authors

5 Further Research

To further elaborate on findings and aspects of this research, the following areas are relevant for supplemental investigations and exploration:

- LCA-analysis and holistic perspectives on key technologies mentioned in Chapter 3. Particularly, comparing the impact of computing for sustainability vs. sustainable computing.
- Research and implementation of industrial standards e. g. for GHG reporting, GHG and LCA calculations or the installation of specific technologies and a certain share of renewables (Thompson, 2023)
- Research and implementation of a standardized greenhouse gas emission inventory. Setting the starting point as the work of Kommission zur Reinhaltung der Luft (KRdL) would help build towards this effort.
- Efforts towards educating young engineers and designing (re-)education programs, focused on enabling a sustainable mindset and decision making. An example of this is sustainable investments required skills for the future (Alger et al., 2023)
- Sustainable education regarding professions such as technicians, installers, maintenance staff. In that context, campaigns, advertisement and further development of educational programs may be determining.

Annex I - Renewable Energy Generation details

Photovoltaic (PV) technologies (often referred to as **solar cells**) are composed of semiconductor materials and protective materials to withstand outdoor influences. By converting photons contained in sunlight into electrical energy up to 2 watts of power can be produced per PV cell. (Office of Energy Efficiency & Renewable Energy, n.d.). Combining multiple PV cells, solar energy is suitable for smaller (1-10kW) and larger scale (10-200MW) applications. Thus it represents a flexible technology for many use cases and provides energy for houses and the national grid (Tester et al., 2012, 689). Due to the high effectiveness and efficiency of solar PV, this source of renewable energy is considered to be one of the key technologies for the future (Illustration 10; IEA, 2022).

Especially in Southern states of the US solar is being considered as one of the most promising renewable energy solutions, as these regions exhibit a large amount of sunshine hours and therefore boost energy generation (McGee et al., 2023). By implementing extensive state-owned technologies grid complexity can be reduced, which also results in lower maintenance effort and cost for respective contractors. With respect to the relatively small investment in comparison to the pivotal output of technology, the application of solar is incentivised by the US Government (Reed, 2023; Thompson, 2023).

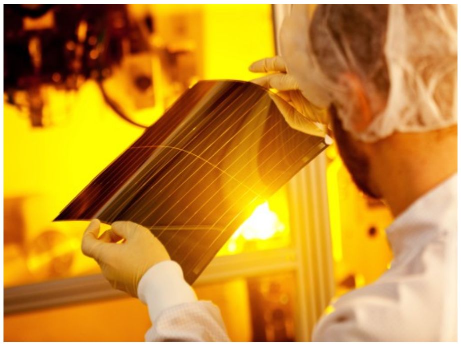


Illustration 10: Solar foil. Source: Heliatek

Wind energy utilizes a different form of renewable energy. By heating the atmosphere, irregularities of the earth's surface and its rotation, wind flow is created. This wind drives blades of a wind turbine (mechanical power), generating energy, which is being translated into electricity. Wind turbines can take a vertical and a horizontal shape. These turbines can be installed onshore and offshore.

Illustration 11: Vertical, horizontal and offshore wind turbines, Source: Dennis Schroeder (NREL 25897), Mike Van Bavel (NREL 42795), Dennis Schroeder (NREL 40484), Wind Energy Technologies Office, n.d.

Hydropower (hydroelectric power) is a renowned source of energy, which makes use of the natural flow of moving water and elevation differences. E.g. dams or run-of-river facilities enable the capture of kinetic energy produced by the force of water. For the transition towards renewables this energy source represents a promising option (Water Power Technologies Office, n.d.).

Geothermal energy is energy which is sourced from reservoirs of hot water and can be natural or artificially constructed e.g., groundwater's temperature can be utilized due to its constant temperature throughout the year and is suitable for electricity generation, heating and cooling or direct use (Vaishnav, 2023). With the help of wells and underground loops, heat can be transferred to the surface and converted to steam driving turbines (electricity generation) or to power geothermal heat pumps. Due to its low land and resource use it is considered to be a clean renewable energy source (Geothermal Technologies Office, n.d.). Especially in the US this source of energy is being considered to be path-breaking (Vaishnav, 2023).

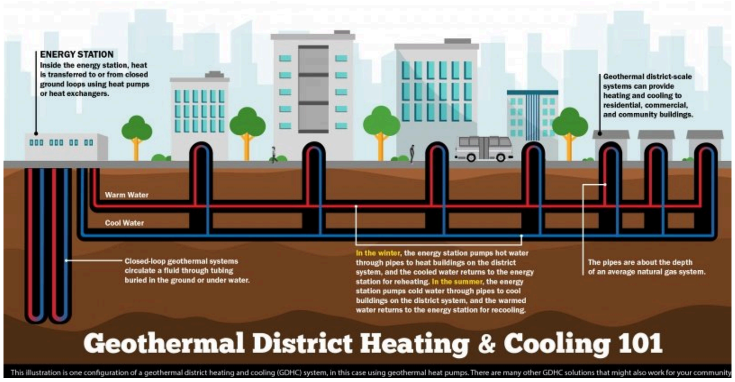


Illustration 12: Geothermal District Heating and Cooling, Source: Geothermal Technologies Office, n.d.

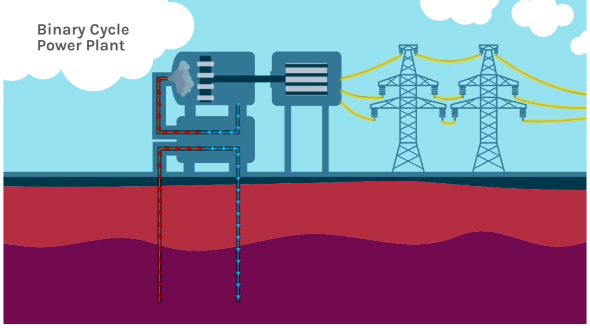


Illustration 13: Geothermal Binary Cycle Power Plant, Source: Geothermal Technologies Office, n.d.

Energy floors like Pavegen tiles capture kinetic energy from walking over a mat. One person produces 5 watts of energy when walking. This energy is captured by the tiles and stored in batteries, enabling access to off-grid energy on demand. Can be used to charge phones, power heating/cooling, light and other devices (Creighton, 2016).

However, in order to utilize the generated renewables and be able to power new electric technologies in the habitat sector, infrastructure is key (Thompson, 2023). Consequently, it is essential to build an energy grid capable of transferring the produced electricity and storing excessive amounts of energy (Thompson, 2023). In particular, battery systems are required to store generated energy during peak times and supply users during times of increased demand or even in case of outages (Vaishnav, 2023). These technologies can be complemented by matching demand and supply intelligently utilizing respective data, which will be further explained in the section "Key Software Technology".

Inverter Based Resources are the lynchpin of grid decarbonization. In order to maintain stability in a renewable energy based power grid, inverter based resources, more commonly known by the acronym IBR, will be key in helping maintain synchronized operations (Sajadi et al., 2022). As more power electronics penetrate the grid, a new set of technical challenges, particularly around islanding, cybersecurity and control sequences will arise (Kroposki, 2019). Digital modeling and design tools will play key roles in helping efforts to integrate and instantaneously control IBRs on the grid.

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