

THE EFFECT OF DIGITAL TECHNOLOGY UTILIZATION FOR MORE
EFFICIENT ENERGY PRODUCTION, TRANSMISSION AND
CONSUMPTION ON ENERGY POLICIES

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CONSUMPTION ON ENERGY POLICIES**

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ABSTRACT

THE EFFECT OF DIGITAL TECHNOLOGY UTILIZATION FOR MORE EFFICIENT ENERGY PRODUCTION, TRANSMISSION AND CONSUMPTION ON ENERGY POLICIES

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This study explores the transformative role of digital technologies in enhancing energy efficiency, optimizing energy systems, and supporting sustainable energy transitions. In light of increasing energy demands, climate change challenges, and the need for decarbonization, this study evaluates how digital technologies address inefficiencies across energy production, transmission, and consumption processes.

The research adopts a mixed-methods approach, combining a comprehensive literature review, case studies from developed economies, an assessment of emerging economies, and quantitative analysis towards digitalization's role on sustainable energy. Findings reveal that smart grids facilitate real-time energy management, enable demand response, and improve grid reliability, while AI and IoT technologies provide predictive analytics and automation to optimize energy flows. Blockchain introduces transparency and decentralization in energy markets, enabling peer-to-peer energy trading and improving renewable energy integration.

The study identifies significant barriers to the adoption of digital technologies, including high capital costs, cybersecurity risks, regulatory inconsistencies, and workforce capacity gaps. Policy recommendations emphasize financial incentives, regulatory harmonization, public-private partnerships, and skills enhancements as critical enablers for digital energy solutions. Furthermore, international collaboration is highlighted for addressing the challenges in emerging economies, whereas localized solutions can bridge infrastructure and financial gaps.

This dissertation concludes that aligning technological advancements with supportive policies can enable utilization from digitalization, leading to energy efficiency gains, emissions reductions, and sustainable economic growth. The findings contribute to the knowledge on digital energy transitions and provide practical insights for policymakers, industry stakeholders, and researchers.

Keywords: Energy Policies, Digital Energy Systems, Smart Grids, Artificial Intelligence (AI), Blockchain Energy Markets

ÖZ

DAHA VERİMLİ ENERJİ ÜRETİMİ, İLETİMİ VE TÜKETİMİ İÇİN DİJİTAL TEKNOLOJİLERDEN FAYDALANILMASININ ENERJİ POLİTİKALARINA ETKİSİ

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Bu çalışma, dijital teknolojilerin enerji verimliliğini artırmada, enerji sistemlerini optimize etmede ve sürdürülebilir enerji dönüşümlerini desteklemedeki dönüştürücü rolünü incelemektedir. Artan enerji talepleri, iklim değişikliği zorlukları ve karbon azaltımı ihtiyacı göz önünde bulundurularak, bu çalışma akıllı şebekeler, Yapay Zekâ (YZ), Nesnelerin İnterneti (IoT), dijital ikizler ve blok zincir gibi teknolojilerin enerji üretimi, iletimi ve tüketim süreçlerindeki verimsizlikleri nasıl ele aldığını değerlendirmektedir.

Araştırma, kapsamlı bir literatür taraması, gelişmiş ekonomilerden vaka çalışmaları, gelişmekte olan ekonomilerin kendilerine has zorlukları ve fırsatlarının değerlendirilmesini, ve digitalleşmenin sürdürülebilir enerjiye etkisini inceleyen sayısal bir analizi içeren karma bir yaklaşımı benimsemektedir. Bulgular, akıllı şebekelerin gerçek zamanlı enerji yönetimini kolaylaştırdığını, talebi karşılamayı mümkün kıldığını ve şebeke güvenilirliğini artırdığını ortaya koyarken, YZ ve IoT teknolojilerinin enerji akışlarını optimize etmek için analizler ve otomasyon

imkanları sağladığını göstermektedir. Blok zincir ise enerji piyasalarında şeffaflık ve adem-i merkeziyeti sağlamakta, enerji ticareti kapsamını genişletmekte ve yenilenebilir enerji entegrasyonunu artırmaktadır.

Çalışma, dijital teknolojilerin benimsenmesinde yüksek sermaye maliyetleri, siber güvenlik riskleri, mevzuat uyumsuzlukları ve iş gücü kapasitesi eksiklikleri gibi önemli engelleri saptamaktadır. Politika önerileri, dijital enerji çözümlerinin önünü açmak için mali teşvikler, düzenleyici uyum, kamu-özel sektör ortaklıkları ve iş gücü eğitiminin kritik rolünü vurgulamaktadır. Ayrıca, uluslararası iş birliği, altyapı ve finansman açıklarının yerleştirilmiş çözümlerle aşılabileceği gelişmekte olan ekonomilerin zorluklarını ele almak için önemli görülmektedir.

Anahtar Kelimeler: Enerji Politikaları, Dijital Enerji Sistemleri, Akıllı Şebekeler, Yapay Zekâ (YZ), Blok Zinciri Enerji Piyasaları

To my beloved family and friends

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AC	Alternating Current
ADR	Automated Demand Response
AI	Artificial Intelligence
AMI	advanced metering infrastructure
ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Reinvestment Act
DR	Demand Response
DOE	The US Department of Energy
DSM	demand-side management
EMS	energy management systems
ESCOs	energy service companies
ESS	energy storage systems
ETS	The EU Emissions Trading System
EV	electric vehicle
EU	European Union
FITs	feed-in tariffs
GHG	greenhouse gas
HVAC	Heating, Ventilation, and Air Conditioning
HVDC	High-Voltage Direct Currents
IEA	International Energy Agency
IMF	International Monetary Fund
IoT	Internet of Things
PPPs	Public-private partnerships
P2P	Peer-to-Peer
R&D	research and development
RECs	renewable energy certificates
REV	New York's Reforming the Energy Vision

SDGs	Sustainable Development Goals
SGIG	Smart Grid Investment Grant
YZ	Yapay Zeka

CHAPTER 1

INTRODUCTION

The world energy sector is going through a transformation to mitigate concerns regarding energy security, climate change and the excessive use of fossil fuels. Sustainable energy transition has been in the focus for many countries. The struggle to meet increasing energy demands, as well as reducing greenhouse gas emissions has been a necessity. Utilization of digital technologies is a significant driver in this transformation. These technologies enable more efficient and sustainable energy systems. Technologies such as Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and smart grids help improve the energy sector in terms of operational efficiency, resource optimization and policy implementation.

The energy industry has been operating with conventional methods for power generation and transmission. Unfortunately, inefficiencies, losses and high carbon footprints are inherent to these methods. Environmental degradation has been a significant issue due to use of fossil fuels, outdated infrastructures and low utilization of renewable energy.

Nevertheless, the digital technologies offer a variety of solutions, in terms of monitoring, analysis and optimization of activities, to mitigate these challenges. Their utilization in the energy sector provides modern management and stakeholder engagement (including consumers) opportunities. This enables smarter and more resilient energy systems.

Furthermore, the digitalization of energy systems aligns with the United Nations' Sustainable Development Goals (SDGs) as well. Goal 7, affordable and clean energy goal, and Goal 13, on climate action, defines the need for transition solutions to achieve a low-carbon economy. These technologies play an important role in enabling countries to meet their sustainability targets. However, the successful

implementation of such energy systems requires a supporting policy, infrastructure investments, collaboration among stakeholder (i.e. governments, industries, and consumers). From Figure 1.1 below, the limited progress achieved in these SDGs can be examined.

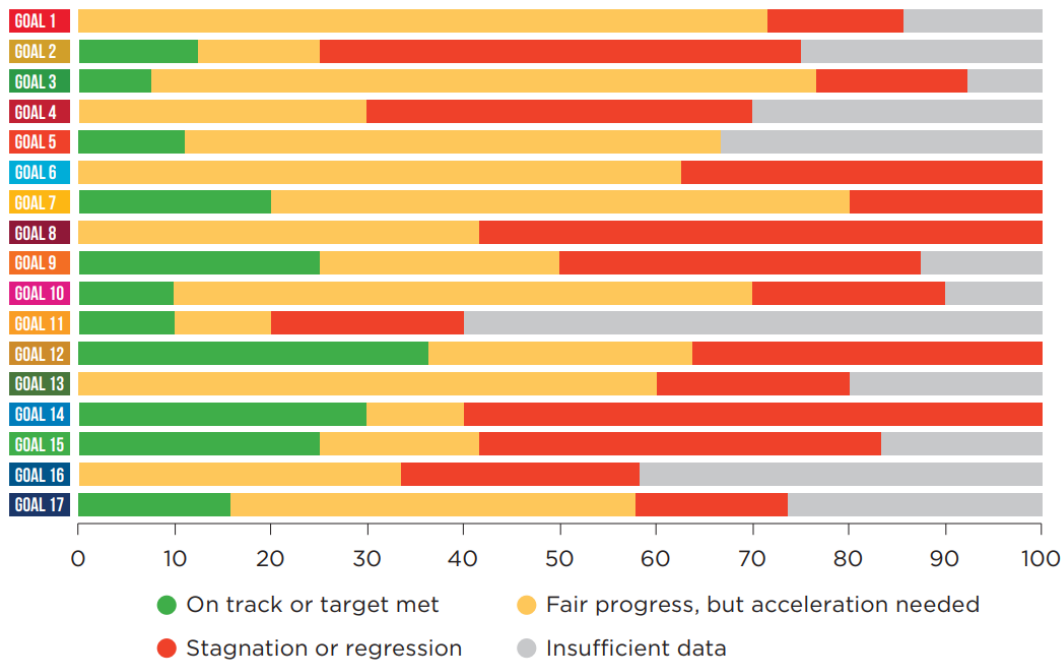


Figure 1.1 Progress assessment for the 17 Goals based on assessed targets, 2023 or latest data (percentage) (United Nations, 2023)

On the other hand the figure below shows how technology advancements towards sustainable energy contributes to the achievement of these goals:

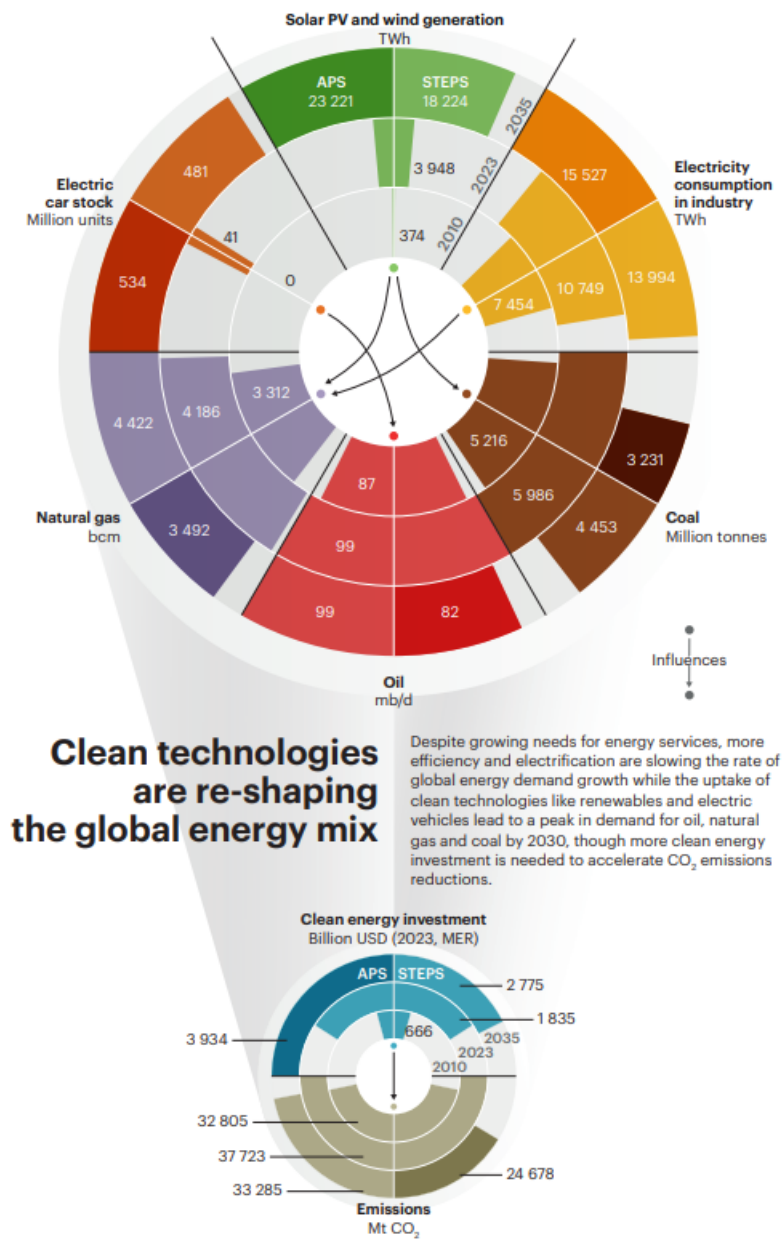


Figure 1.2. Contributions of clean energy investments (IEA, 2024)

The integration of digital solutions in the energy sector also offers opportunities for energy efficiency. Digital solutions allow for control and optimization in energy production, transmission, and consumption, hence minimize energy losses and enhance system performance. Solutions such as smart meters, automated demand response, and predictive analytics allows consumers to make more informed decisions about their energy use, which promote behavioral changes that contribute

to sustainability goals. The smart grids, along with decentralized energy production foster the increasing of the renewables in the energy mix, which improves grid stability and reliability.

Renewable energy sources are another way to mitigate the environmental challenges, caused by traditional methods used by the energy sector. Their share in the energy mix is rather limited because of financial, technical and policy-level constraints. Digital technologies have also the potential to help overcome those barriers. However, comprehensive strategies to utilize digital tools for energy efficiency and sustainability are limited, which is a critical gap.

Although there is a certain level of awareness towards benefits of digital technologies, there are challenges, faced in the energy sector in adopting them. Initial investment costs, cybersecurity and data related risks, and regulatory barriers are the main obstacles. And as in the case of other digital technologies, the digital divide between various regions and countries lead to doubts regarding equitable access. A mixed approach, consists of technological innovation, policy development and capacity-building is needed to ensure a strong and just transition modern energy systems.

This study explores the role of digital technologies in improving energy systems. It examines how energy policies can support that digitalization and how digitalization can support the implementation of energy policies to be able to address inefficiencies. The study presents findings on the challenges regarding the digitalized energy systems, including infrastructure requirements, regulatory frameworks, and cybersecurity concerns. Through an analysis of case studies from both developed and emerging economies, this research aims to provide recommendations for policymakers and stakeholders to accelerate the adoption of digital technologies in the energy sector.

The study's primary objective has been to analyze the impact of digital technologies including IoT, AI, blockchain, and smart grids on energy related sustainability. To address the identified problems, this study focuses on how digital technologies can

improve the energy production, transmission, and consumption efficiencies; the role of policies in facilitating the digital solution adoption in the sector; the challenges and barriers to implementing such energy systems; the case studies from developed and emerging economies to show the impact of digitalization on energy efficiency and sustainability; and the policy recommendations to relevant stakeholders.

The scope of this study contains a comprehensive review of relevant digital technologies, policy frameworks, and case studies. It focuses on the relation between technology and policy to address challenges in energy systems. The research uses data from academic literature, industry reports, and international organizations and institutions. By synthesizing from multiple sources, this study aims to contribute to the knowledge on sustainable energy transitions.

This study utilizes a mixed approach, which combines a systematic review of existing literature, a comparative analysis of case studies, and a qualitative analysis to determine the relation between digitalization and energy use. The research process involves the following steps:

- Literature Review: A review of academic articles, industry reports, and policy documents to identify key trends, challenges, and opportunities in energy systems
- Data Collection and Analysis: Data collection from reputable sources to analyze the role of digital technologies in energy systems
- Comparative Analysis: Examination of cases from both developed economies (e.g. European Union and United States) and emerging economies (e.g. China and India) to compare approaches to digital technology adoption
- Policy Evaluation: Policy analysis that support digital energy systems, including incentives, regulations, and innovation programs
- Synthesis and Recommendations: Merging of findings to develop actionable recommendations for policymakers and stakeholders

The methodology targets to ensure a comprehensive understanding of the research topic by combining theories with practical examples. The comparisons of case studies provide a perspective on the challenges and opportunities, while the policy evaluation highlights the role of governance.

This dissertation is composed of seven chapters. Each chapter addresses a specific aspect of the topic. Chapter 2, as the literature review chapter, reviews existing literature on digitalization in energy systems and related policies. It identifies gaps in research and highlights the need for further studies. The methodology chapter, Chapter 3, describes the design of the research, data collection methods, and study's analytical framework.

Chapter 4 aims to provides details on digital technologies' role in energy systems and the application of digital technologies such as smart grids, IoT, AI, and blockchain in energy systems. In order to provide insight to the implications of energy policies, Chapter 5 analyzes the role of these policies in supporting digital technology utilization in energy systems and lays down the barriers to implementation. This chapter also focuses on case studies and comparisons, and presents case studies from both developed and developing economies. It presents best practices and lessons learned.

Under the discussion chapter, Chapter 7, the findings are interpreted, their implications are discussed, and policy recommendations are provided. Finally, Chapter 8 summarizes the key findings, presents the contributions of the study, and suggests topics for future research as conclusion.

The study, with the abovementioned structure, aims to provide a coherent and comprehensive analysis of the role of digital technologies in energy systems and supporting sustainable energy. The study targets to contribute to the knowledge on energy transitions and offer insights for policymakers, researchers, and industry stakeholders. Figure 1.2 visualizes the aspects and relations, studied within this dissertation.

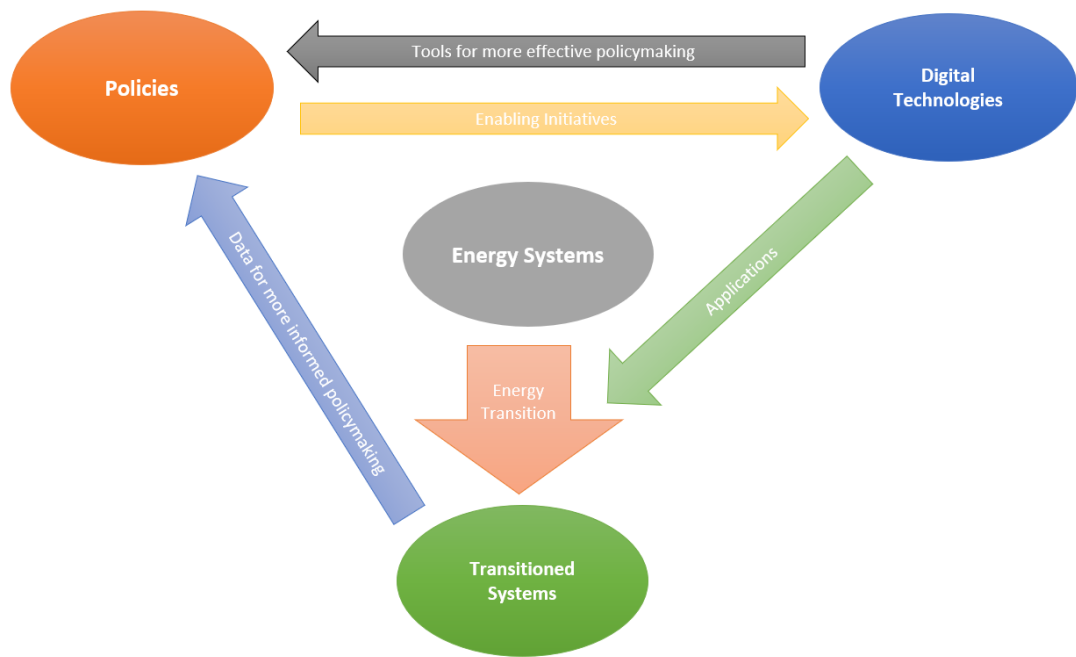


Figure 1.3 Studied aspects and relations

CHAPTER 2

LITERATURE REVIEW

Largely focusing on the main technology areas, namely AI, IoT, blockchain, digital twins, and smart grids, this chapter provides a review in terms of the analyzed role of digital technologies in the sector, as these technologies offer significant improvement opportunities through fast monitoring, predictive maintenance, and resource management.

This chapter also goes over the studied key policies, such as decarbonization strategies, carbon pricing mechanisms and renewable energy incentives, that support the sector.

2.1 Digitalization in Energy Systems

Digital technologies play an important role in addressing inefficiencies, high costs and environmental impacts. AI, the IoT, and blockchain based solutions, along with advanced tools like digital twins and smart grids, have offered beneficial changes in energy production, transmission, and consumption.

Achieving the climate goals through the integrated and controlled energy systems, the vision is drawn around abandonment of classical energy supply and demand systems and opting for more renewables-based energy production (wind, hydro, large solar and bio-energy) on both central and local levels, distributed energy storage using cold, heat and electricity, creation and use of data and flexible energy trading systems (Mlecnik, 2020). For the creation of data, as part of the digitalization trend, the total amount of devices with the internet connectivity is foreseen to be above 75 billion throughout the world by 2025 which adds up an increase of five

times in a decade. This includes smart meters, household devices along with instruments of energy production industry, which paves the way for an energy internet of things or energy internet that enables better interaction and optimization between supply and demand. A decentralized and digitalized energy sector poses as an option to create more value for all the actors and achieve a lower carbon footprint (Zhang et al., 2017).

2.1.1 Role of AI, IoT, and Blockchain

2.1.1.1 Artificial Intelligence (AI) in the Energy Sector

AI has been a very widely adopted technology compared to other digital solutions. Optimization in operations, predictive analytics have been the most prominent among the AI based solutions. AI utilizes real-time data and advanced algorithms to enable predictive maintenance, optimize energy grids, and support decision-making (El Zein & Gebresenbet, 2024).

AI based solutions have also been quite beneficial in grid management, based on their ability to analyze large datasets in short periods. Grid operators utilize these solutions to anticipate and mitigate the faults before they occur. Predictive maintenance opportunities created via AI reduces downtime and minimize losses. Moreover, through AI algorithms, solar and wind energy generation patterns can be foreseen, which addresses their variable nature and leads to their more effective integration to the grid. Both conventional and renewable energy production means largely benefit from AI in identifying inefficiencies, load forecasting and demand response management, as a result, production and transmission efficiency is enhanced (Singh et al., 2022).

2.1.1.2 The Internet of Things (IoT) for Energy Management

IoT's critical role can be summarized as facilitating more effective monitoring and control of energy systems. IoT relies on sensors and communication technologies to gather and share momentary data, which helps to improve energy efficiency, support the integration of renewable energy, and advance smart metering systems. IoT-enabled devices, which include smart meters, sensors, and automated controllers, can gather and transmit data, which allow for precise energy management and efficiency improvement. These systems are particularly effective in smart grids, since they enable automated demand response, hence better renewable energy integration (El Zein & Gebresenbet, 2024).

The use of IoT in energy management systems has empowered both consumers and operators to identify and address inefficiencies. For example, IoT-enabled smart meters provide consumers with granular data about their energy usage patterns, fostering energy-saving behaviors and reducing overall consumption. Moreover, IoT devices contribute to demand response programs, where energy consumption is adjusted dynamically based on grid conditions (Singh et al., 2022).

2.1.1.3 Blockchain for Decentralized Energy Systems

Blockchain technology has introduced secure, transparent, and decentralized energy trading solutions. Its application in the energy sector focuses on improving efficiency, promoting peer-to-peer (P2P) energy transactions, and enhancing trust among stakeholders. The use of blockchain reduces the requirement for a central point of authority, since the data is securely stored, while its shared and distributed (Hrga et al., 2020). Hence, it allows for distributed energy trading and creation of decentralized microgrids, along with effective grid and renewable energy management (El Zein & Gebresenbet, 2024).

By enabling P2P energy trading, blockchain technology reduces reliance on centralized intermediaries, enhances local energy autonomy, and increases

transparency in energy markets. Households and businesses with surplus renewable energy can trade directly with other consumers, fostering a more decentralized and resilient energy system. Blockchain further contributes to the verification and tracking of renewable energy, ensuring the credibility of green energy transactions (Singh et al., 2022).

2.1.2 Digital Twins and Smart Grids

2.1.2.1 Digital Twins: A Virtual Solution for Energy Optimization

Digital twins represent a cutting-edge solution for improving energy system reliability and sustainability. As virtual models of energy systems are created, digital twins enable operators to analyze real-time performance, identify faults, and implement predictive maintenance activities, which as a result, reduces the operational disruptions and enhances efficiency (Cali et al., 2023).

The digital twins are also applied to increase the operators' real-time monitoring and optimization and control capabilities on nuclear reactors, solar and wind farms: enhancing maintenance practices and strengthening operational resilience (Galkovskaya & Volos, 2022). These tools simulate the impact of weather variability and other external factors on energy generation, enabling operators to adjust operations in real time (Cali et al., 2023).

2.1.2.2 Smart Grids: Enhancing Grid Performance and Resilience

Smart grids combines other digital technologies such as AI, IoT, and digital twins to optimize energy distribution, integrate renewable energy, and balance grid performance. Unlike traditional grids, smart grids enable two-way communication between energy producers and consumers, allowing for real-time monitoring and control (Oluwatoyin Adegbite et al., 2023).

One of the key benefits of smart grids is their ability to reduce transmission losses and improve grid resilience. Smart grid technologies provide grid operators with real-time data, enabling them to detect faults and manage energy flows more effectively. Additionally, smart grids facilitate automated demand response, where energy consumption is adjusted dynamically to match grid conditions. “The transformation to smart grids enhances real-time decision-making, fault detection, and demand response efficiency (El Zein & Gebresenbet, 2024). Below figure shows a comparison between the traditional and smart grids.

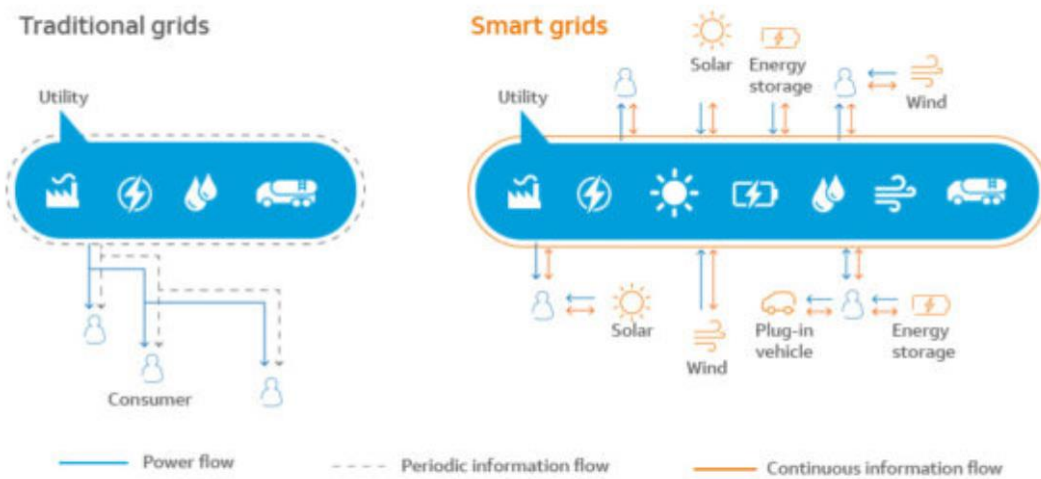


Figure 2.1. Traditional and Smart Grids (Ghofrani et al., 2018)

2.2 Energy Production, Transmission, and Consumption

2.2.1 Efficient Energy Production

Digital technologies have significantly improved energy efficiency in production by addressing operational inefficiencies, minimizing downtime, and reducing resource waste. AI-driven predictive maintenance systems, IoT-based monitoring devices, and data analytics tools are transforming traditional production methods (Yu et al., 2024).

In industrial energy production, predictive maintenance powered by AI has emerged as a critical solution for minimizing energy losses. By analyzing performance data, AI algorithms can detect potential faults in critical equipment, such as turbines and boilers, before they occur. This proactive approach reduces operational disruptions, optimizes resource usage, and extends the lifespan of production equipment (El Zein & Gebresenbet, 2024).

The IoT further enhances production efficiency by enabling real-time monitoring of energy usage and equipment performance. IoT-enabled devices collect and transmit data from sensors installed in production facilities, providing operators with insights into energy consumption patterns (Yu et al., 2024). Sensors and communication technologies used by IoT-enabled devices facilitate real-time data collection, and eventually improving energy efficiency, smart metering and minimizing environmental impacts (El Zein & Gebresenbet, 2024).

For example, in renewable energy production, IoT devices monitor the performance of wind turbines and solar panels, allowing operators to adjust operations for maximum efficiency. Additionally, IoT data supports energy optimization by identifying energy-intensive processes and implementing measures to reduce consumption (Ahmad et al., 2021).

2.2.2 Energy Efficiency in Transmission Systems

Energy transmission plays a vital role in ensuring that energy generated—whether from conventional sources or renewable sources—reaches end users efficiently. Traditionally, significant energy losses occurred during transmission due to outdated grid infrastructure and poor management. However, the introduction of digital technologies such as smart grids, IoT-enabled sensors, and advanced transmission systems has substantially improved energy efficiency across transmission networks (Cali et al., 2023). Smart grids, in particular, have emerged as a disruptive driver in enhancing transmission efficiency. Smart grids utilize real-time data and advanced

analytics to dynamically manage energy flows, integrate renewable energy sources, and reduce transmission losses. These systems allow grid operators to identify and resolve transmission inefficiencies promptly, ensuring stable energy delivery while minimizing wastage (Pereira et al., 2020).

A significant innovation within smart grids is the deployment of IoT-enabled sensors and monitoring systems. These devices collect and transmit real-time data from critical grid infrastructure, such as transmission lines, transformers, and substations which helps detecting faults, monitoring grid health, and optimizing energy flows. The adoption of advanced transmission technologies like High-Voltage Direct Currents (HVDC) systems, that are highly efficient in long-distance energy transmission, further reduces energy losses compared to traditional Alternating Current (AC) systems(Cali et al., 2023).

The integration of renewable energy sources into transmission systems has also benefitted from smart grid advancements. Smart grids use predictive analytics and AI algorithms to manage the variability of renewable energy generation, such as solar and wind power. This allows smart grids to adjust transmission operations dynamically to balance supply and demand. This capability ensures that energy generated from renewable sources is efficiently transmitted to the grid with minimal losses. For example, in wind farms, IoT-enabled devices monitor turbine performance, while AI-based analytics forecast energy output to optimize grid integration (Yu et al., 2024).

In summary, digital technologies in energy transmission systems have significantly reduced technical losses, improved operational reliability, and enhanced the capacity to integrate renewable energy sources. These advancements represent a critical step toward achieving more sustainable and efficient energy systems.

2.2.2.1 Energy Efficiency in Consumption

The world electricity consumption is expected to increase its share in the final energy consumption. In the instance of EU, it is expected to reach 30% by 2030 and 40% by 2050 (Pereira et al., 2020). Although countries have various approaches to the matter, where the share of cities in both the global energy consumption and CO2 emissions is around 60 to 80%, it is obvious that buildings have a significant role in the energy markets since they shape the demand on various energy sources (Mlecnik et al., 2020). The below figure shows changes in electricity consumptions of developed and emerging economies between 1992 and 2021:

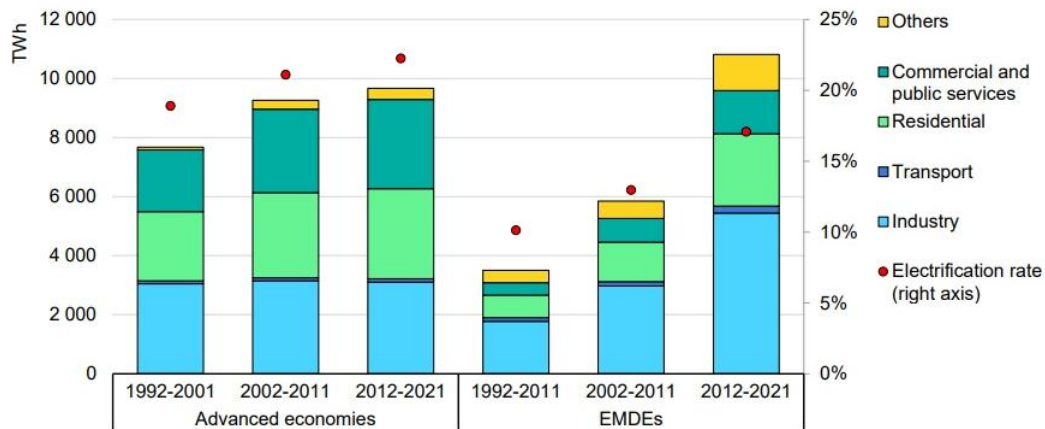


Figure 2.2. Global final electricity consumption by sector and electrification rate, 1992-2021

In mitigating these facts, the role of digital technologies in improving energy efficiency extends beyond production and transmission to include energy consumption. Consumers, ranging from households to industries, are empowered to monitor, manage, and optimize their energy use through smart meters, automated demand response systems, and energy management systems (EMS)(Kim et al., 2022).

Smart meters are one of the most significant tools in enhancing energy efficiency for consumers. These devices provide insights into their energy consumption, allowing them to identify their energy-intensive activities and adopt energy-saving measures.

Smart meters, enabled by IoT, allow real-time monitoring of energy usage, leading to optimized consumption patterns (El Zein & Gebresenbet, 2024). By offering hourly or daily granular data on energy use, smart meters enable households and businesses to adjust behavior and reduce energy waste (Kim et al., 2022).

In addition to empowering consumers, smart meters support grid stability through automated demand response (ADR) programs. ADR systems adjust energy usage during peak periods, contributing to grid stability and energy savings. ADR systems use real-time data to adjust energy consumption based on grid conditions. During peak demand periods, non-essential energy loads, such as heating, ventilation, and air conditioning (HVAC) systems, lighting, and appliances, can be automatically reduced to alleviate pressure on the grid. (Singh et al., 2022). This dynamic adjustment both enhances grid reliability and also reduces overall energy consumption.

Smart home technologies have also contributed significantly to energy efficiency in residential settings. Devices such as smart thermostats, energy-efficient lighting systems, and intelligent appliances use AI-driven algorithms to optimize energy usage. For example, smart thermostats learn user preferences and adjust heating and cooling systems accordingly, ensuring comfort while minimizing energy consumption. These technologies collectively promote energy savings and support sustainability goals (Singh et al., 2022). Below figure shows the typical data flow of residential energy use.

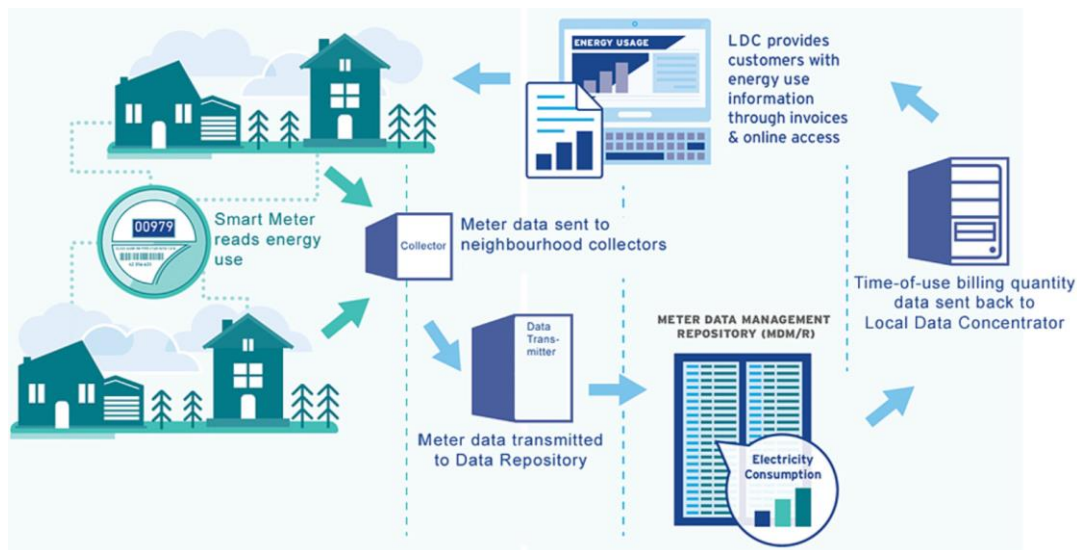


Figure 2.3. Residential energy data flow (Absolute Energy Solutions, 2022)

In industrial and commercial settings, Energy Management Systems (EMS) play a critical role in improving energy efficiency. EMS utilize real-time data from IoT sensors to monitor energy usage across facilities, identify inefficiencies, and implement energy-saving measures (Calise et al., 2018). For instance, industrial plants equipped with EMS can automate the operation of machinery, lighting, and HVAC systems based on real-time energy demand. By analyzing usage patterns and resource flows, EMS optimize energy consumption while reducing operational costs (Rajat Pusa et al., 2024).

Furthermore, advancements in electric vehicle (EV) technologies have significantly improved energy efficiency in the transportation sector. EVs, supported by smart charging infrastructure, offer a sustainable alternative to conventional vehicles powered by fossil fuels. Smart charging systems use IoT-enabled devices to optimize charging schedules based on grid conditions and energy availability. By balancing energy demand, smart charging reduces the strain on power networks and minimizes energy losses. As digital tools continue to evolve, they hold great potential for further improving energy efficiency in transportation systems (Ahmad et al., 2021).

To summarize, digital technologies such as smart meters, automated demand response systems, and energy management tools have transformed energy

consumption patterns. By providing consumers and industries with real-time insights and automated control, these technologies enable significant energy savings, reduce waste, and contribute to the overall efficiency of energy systems.

2.3 Key Policies Supporting Energy Efficiency and Sustainability

2.3.1 Decarbonization Policies

Governments worldwide have recognized the importance of policy frameworks in supporting energy efficiency and promoting the transition to sustainable energy systems. Among the most impactful policies are decarbonization strategies, which aim to reduce carbon emissions through measures such as energy taxes, carbon pricing, and renewable energy incentives. These policies play a critical role in encouraging industries and consumers to adopt energy-efficient technologies and practices (Brown, 2015).

One of the most widely adopted tools for decarbonization is carbon pricing, which assigns a cost to carbon emissions to incentivize reductions. Carbon pricing promotes awareness of energy efficiency, encourages technological innovation, and incentivizes industries to lower energy consumption costs. By creating financial incentives for industries to lower their carbon emissions, carbon pricing encourages the adoption of energy-efficient solutions and the integration of renewable energy sources (Mohammadi et al., 2023).

In addition to carbon pricing, renewable energy incentives such as feed-in tariffs and subsidies have been instrumental in driving the growth of clean energy generation. These incentives provide financial support to renewable energy projects, making them economically viable and attractive to investors (Mohammadi et al., 2023). In this sense, the supportive policies, such as R&D subsidies, carbon pricing, and feed-in tariffs, have driven significant progress in energy efficiency. The success of these

policies is evident in the European Union, where renewable energy generation has increased significantly due to targeted interventions (IEA, 2024).

These subsidizing policies also lower the market barriers for renewables and cause decreases in the real electricity prices. This is expected reach to an extent that not only risks the profitability of the production based on high-cost fuels i.e., gas, oil and hard coal but even the production based on low-cost fuels such as nuclear and lignite (Specht & Madlener, 2019). Table below shows the related policies that were analyzed for this study to understand recurring themes, best practices and present a summary of policy trends:

Table 2-1 Countries, Programmes and Policies

Country	Program	Policy
Brazil	The Energy Efficiency Program	Mandates utilities to allocate part of their revenue to efficiency. Half of the investments were directed to low-income groups, saving 15% on the electricity use.
Canada	The Greener Homes Affordability Program	Will provide USD 588 million to fund low- and medium-income households in reducing heating costs through retrofits.
Czechia	The New Green Savings Programme Light	Provides up to 100% of the costs of efficiency measures for low-income households, with a maximum of USD 6 500 per home.
Chile	The Housing and Neighborhood Improvement Programme	Provides subsidies up to 80% of the costs for home upgrades, reducing costs for low-income families.

Table 2-1 (Continued)

Country	Program	Policy
EU	The revised Energy Efficiency Directive	Raises efficiency obligations, mandating member states to prioritize energy poor, vulnerable and low-income households as beneficiaries.
France	The Renovation Mortgage	Provides mortgages to low-income groups for renovations. From 2024, a zero-interest version of this loan is available for up to USD 54 400.
Ireland	The National Retrofit Plan	Targets 500 000 upgrades by 2030, focusing on low-income households. In 2023, 6 000 energy-poor homes were retrofitted.
Mexico	The Pilot Project for Efficiency Measures	Integrates efficiency in self-built housing.
New Zealand	The Warmer Kiwi Homes	Covers up to 90% of the costs to purchase and install insulation and an efficient heater for homes built before 2008 in low-income areas.
Portugal	The Long-Term Strategy	Aims to eradicate energy poverty by 2050. It allocates USD 326 million for efficiency in for homes in 2021-2025 for low-income households.

2.3.2 Carbon Pricing and Renewable Energy Incentives

The implementation of carbon pricing has had a measurable impact on energy efficiency across industries. By internalizing the environmental costs of carbon

emissions, carbon pricing motivates businesses to invest in energy-saving technologies and reduce their reliance on fossil fuels. Facilitated by these policies, electricity generation from renewable sources in the EU has increased by 32%, driven by targeted policy interventions and carbon reduction (Mohammadi et al., 2023).

Renewable energy incentives, such as tax credits and investment subsidies, have further supported the deployment of clean energy technologies. These incentives lower the financial barriers associated with renewable energy projects, enabling industries and communities to transition toward sustainable energy sources. Countries that have implemented such incentives have witnessed significant improvements in energy efficiency and reductions in carbon emissions (Specht & Madlener, 2019).

2.4 Case Studies: Global Perspective

The adoption and integration of digital technologies into energy systems vary significantly across regions, influenced by economic development, infrastructure availability, and policy frameworks. Case studies from developed and emerging economies offer valuable insights into the opportunities and challenges associated with digitalization in energy systems.

2.4.1 Developed Economies

Developed economies, particularly in Europe and North America, have made substantial progress in implementing digital energy technologies due to strong policy frameworks, advanced infrastructure, and significant investments in research and development. The shift to a more decentralized power system can be observed in Germany example. As part of its ongoing transition to a more sustainable power sector, the decentralized electricity production in Germany exceeded the production of traditional, centralized power plants. This trend started with gas fired power plants

in 2006, went on with nuclear power plants and hard coal fired power plants in 2011 and finally the decentralized production surpassed lignite fired power plants in 2014 (Loock, 2020). The share of renewables within the power mix, which is expected to reach 60% by 2030, is already over 50% in countries like the USA, Brazil, Spain, Japan besides Germany (Güner & Turan, 2017).

One notable example is Finland's grid optimization initiative, which utilized digital twin technology to enhance energy distribution and improve maintenance strategies. Digital twins enable the creation of real-time virtual replicas of power grids, allowing operators to simulate grid performance, detect faults, and predict maintenance requirements. By exploiting digital twins, Finland has achieved improved grid reliability, reduced energy losses, and enhanced operational efficiency (Fingrid, 2024).

Similarly, the European Union has achieved significant progress due to strong policy frameworks and technological investments. The EU serves as a leading example of how supportive policies and technological investments can drive progress in energy transition. The EU has implemented a range of measures, including carbon pricing, feed-in tariffs, and renewable energy incentives, to promote the adoption of clean energy technologies. These policies have significantly contributed to the region's energy efficiency achievements (Mohammadi et al., 2023).

In the United States, the focus has been on developing smart grids and integrating renewable energy into the existing energy infrastructure. Smart grid initiatives have demonstrated the potential of digital technologies to improve sustainable energy systems. IoT, AI, and automated demand response systems have enabled these grids to have reduced energy losses, improved grid stability, and facilitated the integration of solar and wind power (Angelo & Chan, 2015). The success of these initiatives highlights the role of innovation and policy support in enabling digital energy transitions (U.S. Department of Energy, 2024).

2.4.2 Emerging Economies

While developed economies have led the way in implementing digital energy technologies, emerging economies face endemic challenges and opportunities in their energy transitions. Limited infrastructure, high implementation costs, and technological gaps often hinder the widespread adoption of digital solutions (Huang et al., 2024).

However, emerging economies also have the potential to abandon traditional energy systems and adopt innovative, renewable-based solutions. For instance, emerging economies in Asia and Africa are increasingly exploring digital solutions to address energy access challenges and improve efficiency. Smart grids, IoT-enabled devices, and decentralized renewable energy systems have shown significant potential to enhance energy access and reliability in rural and underserved areas (Sani et al., 2020).

These challenges have also created opportunities for innovation and investment. In countries such as India and China, rapid advancements in renewable energy and digitalization have paved the way for scalable solutions (Huang et al., 2024). For example, India's National Smart Grid Mission aims to modernize the country's energy infrastructure by deploying smart meters, automated demand response systems, and renewable energy integration technologies. These efforts are critical in addressing energy inefficiencies while meeting growing energy demands (Sani et al., 2020).

In addition to government initiatives, private sector investments and partnerships have played a key role in promoting digital energy solutions in emerging economies. Decentralized energy systems, supported by blockchain technology and IoT devices, are increasingly being deployed to provide reliable and affordable energy in remote regions. Such investments could allow emerging economies to transform their conventional energy systems (El Zein & Gebresenbet, 2024).

CHAPTER 3

METHODOLOGY

This chapter describes the methodology adopted for this research, including the research design, data collection process, data analysis techniques, and the framework used for evaluating digital energy innovations. Given the interdisciplinary nature of this study, a robust mixed-methods approach was employed, combining systematic literature review, empirical analysis, and qualitative evaluation. This methodology ensures a comprehensive understanding of the role of digital technologies in energy efficiency across production, transmission, and consumption ecosystems while addressing policy and economic considerations.

This chapter outlined the methodological approach used in this study, including the research design, data collection methods, and analytical techniques. The mixed-methods approach—combining systematic literature review, empirical analysis, and qualitative evaluation—ensures a comprehensive and balanced understanding of the research topic. The framework developed for evaluating digital energy innovations provides a robust method for assessing technological performance, environmental impacts, and economic viability.

By applying these methods, this study delivers an analysis of how digital technologies contribute to energy systems, while identifying the challenges and opportunities associated with their implementation.

3.1 Research Design

The research design forms the backbone of this study, providing a clear and logical structure for addressing the research objectives. A mixed-methods approach was chosen to combine the strengths of both qualitative and quantitative methods. This

approach was deemed appropriate for exploring the technological, environmental, and economic impacts of digital innovations within energy systems.

The research design comprises three key stages:

- **Systematic Literature Review:**

The study begins with a systematic literature review to establish the current state of knowledge, identify research gaps, and form the foundation for empirical analysis. The systematic approach ensures a rigorous and unbiased examination of relevant literature. Key steps included:

- **Defining the Scope:** The research focused on digital technologies (AI, IoT, blockchain, digital twins, and smart grids) and their role in improving energy efficiency.
- **Inclusion/Exclusion Criteria:** Peer-reviewed articles, industry reports, and policy documents published between 2000 and 2024 were included. Studies unrelated to energy efficiency, digital technologies, or global energy systems were excluded.
- **Keyword Search:** A comprehensive search was conducted using terms such as “digital energy systems,” “AI in energy systems,” “IoT-enabled grids,” “blockchain for decentralized energy,” and “energy efficiency policies”.
- **Data Extraction and Synthesis:** Relevant studies were analyzed for key findings, recurring themes, and emerging challenges, which were systematically categorized for later stages of the research.

- **Empirical Analysis:**

The second stage of the research involved empirical analysis using cross-sectional datasets. These datasets provided quantitative insights into the adoption and performance of digital technologies across energy systems. This step focuses on identifying measurable impacts, such as energy savings, emissions reductions, and renewable energy integration rates. Empirical methods included:

- Descriptive Statistics: To analyze and summarize quantitative data, including energy efficiency outcomes, technological adoption rates, and emissions data.
- Comparative Analysis: To compare trends and performance indicators between developed and emerging economies, providing a global perspective.
- Regression Modeling: To explore relationships between digital technology adoption and key outcomes such as energy savings and carbon emission reductions.
- Qualitative Evaluation:

Content analysis was employed to complement the quantitative findings. The qualitative evaluation focused on understanding stakeholder perceptions, technological challenges, and the policy frameworks influencing digital energy transitions.

By integrating these stages, the research design ensures a balanced and comprehensive approach to addressing the research questions. The mixed-methods approach enhances the robustness of the findings by triangulating data from multiple sources and methods.

3.2 Data Collection and Analysis

3.2.1 Data Collection

The data collection process combined sources to ensure the comprehensiveness and reliability of the research. This multi-source approach provided both quantitative and qualitative data for analysis.

Gathered data formed a critical part of the research, ensuring access to large-scale, reliable datasets and reports. The following secondary sources were utilized:

- International institutions' reports on energy transition and digitalization trends.
- Government publications detailing energy efficiency initiatives, decarbonization strategies, and digital energy programs.
- Industry publications on the deployment of digital technologies in global energy systems.

These sources provided quantitative indicators, such as energy savings, emissions data, and renewable energy integration rates, as well as qualitative insights into policy frameworks and technology trends.

3.2.2 Data Analysis

The analysis combined quantitative methods for empirical data and qualitative techniques for stakeholder insights and policy evaluation.

3.2.2.1 Quantitative Analysis

Quantitative data were analyzed to evaluate the impact of digital technologies on energy systems. The key indicators, such as energy savings, emissions reductions, and renewable energy adoption were summarized to provide a baseline understanding of the data.

Regression Analysis: Applied to explore the relationships between digital technology adoption and measurable outcomes. Regression models were used to assess how initiatives towards digital technology utilization decreased the energy use per capita.

3.2.2.2 Qualitative Analysis

Qualitative data from content analysis was analyzed to identify recurring themes, stakeholder perspectives, and emerging trends. Policy documents and reports were reviewed to extract key themes related to energy efficiency policies, technological innovations, and regulatory challenges.

Cross-comparisons between developed and emerging economies were conducted to highlight differences.

3.3 Framework for Evaluating Digital Energy Innovations

To systematically evaluate the role of digital technologies in improving energy efficiency, a comprehensive framework was examined in three key dimensions:

- **Technological Performance:** Evaluates the efficiency, scalability, and reliability of technologies like AI, IoT, digital twins, and blockchain.
- **Environmental Impact:** Measures the contribution of digital technologies to sustainability goals, such as reducing greenhouse gas emissions and increasing renewable energy integration.
- **Economic Viability:** Analyzes the cost-effectiveness and financial benefits of implementing digital energy solutions.

To understand this framework, specific metrics such as energy savings, emissions reductions, and cost benefits were analysed to measure technological impacts. Data from case studies were compared to identify best practices and lessons learned across regions.

CHAPTER 4

THE ROLE OF DIGITAL TECHNOLOGIES IN ENERGY SYSTEMS

This chapter explores how digital technologies are reshaping energy systems to improve efficiency, reliability, and sustainability. With the growing complexity of modern energy networks, technologies such as Smart Grids, Digital Twins, Internet of Things (IoT), Artificial Intelligence (AI), and Blockchain have emerged as essential tools for optimizing energy production, distribution, and consumption. The table below summarizes the trend of digital technology investments in the energy sector:

Table 4-1 Investment in digital technologies, 2015-2022

Year	Total Investment*	Smart meter s*	Automation and Management System*	Networking and Communication*	Transformers*	EV Public Charging Infrastructure*	Analytics*
2015	38	10	13	9	4	1	1
2016	43	14	14	9	4	1	1
2017	46	18	14	8	4	1	1
2018	51	19	16	8	5	2	1
2019	52	19	14	10	5	2	2
2020	53	20	14	10	4	4	1
2021	59	23	16	10	4	5	1
2022	62	22	14	9	4	11	2

* Billion USDs

To this end, smart grids and their role in balancing supply and demand, enabling automated demand response, and improving grid reliability through real-time monitoring is explored; digital twins as virtual models that optimize infrastructure management, facilitate predictive maintenance, and enhance microgrid resilience are highlighted; IoT's enabling real-time data collection and AI's provision of predictive

analytics for energy forecasting, fault detection, and grid optimization is discussed; and blockchain technology’s role in decentralized energy markets, peer-to-peer energy trading, and transparent renewable energy certification is covered.

Overall, this chapter presents how digital technologies are transforming energy systems, enabling smarter infrastructure, enhanced maintenance, decentralized trading, and real-time optimization. These innovations enable achieving energy efficiency, enhancing grid reliability, and supporting the transition to sustainable energy systems. Figure below shows the structural changes in energy systems made possible by use of digital technologies:

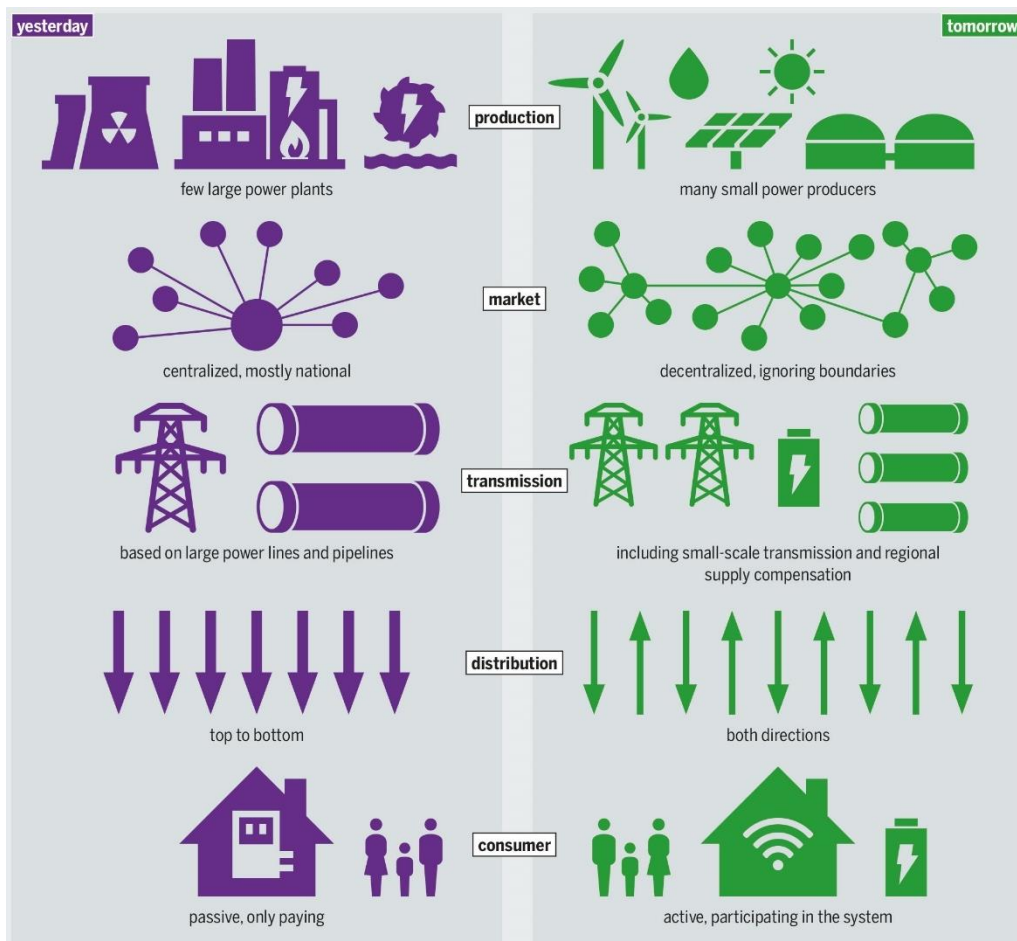


Figure 4.1. Energy systems, transitioned by digital technologies (Wikipedia, 2024)

4.1 Supply Side Applications of Digital Technologies

Although the use of digital technologies redefines the concepts of supplier and consumer, and thus supply and demand, this subsection presents solutions that serve and enhance the capabilities of traditional energy production and transmission systems. However, since the explanations are organized by major technology areas, there are references to how these specific technologies are used in decentralized systems, which will be discussed in more detail in the next subsection.

4.1.1 Digital Twins for Energy Infrastructure Management

The concept of digital twins has gained significant traction in recent years as a powerful tool for optimizing energy infrastructure and enhancing system reliability. A digital twin is a virtual replica of a physical system that uses real-time data to simulate, analyze, and optimize the performance of the system. In energy systems, digital twins enable operators to monitor infrastructure, predict maintenance requirements, and improve operational efficiency. Digital twins provide a dynamic platform for managing complex energy infrastructure by combining real-time monitoring with advanced simulation capabilities (Cali et al., 2023).

One of the primary applications of digital twins in energy systems is predictive maintenance, which involves forecasting potential equipment failures and scheduling maintenance activities proactively. Traditional maintenance practices often rely on fixed schedules, which can lead to unnecessary costs or unexpected downtimes. In contrast, digital twins use real-time data and predictive analytics to identify issues before they escalate, ensuring optimal system performance. For instance, digital twins can simulate the behavior of power generation assets, such as turbines, transformers, and transmission lines, under various operating conditions. These simulations allow operators to identify inefficiencies, optimize performance, and reduce energy losses. By minimizing unplanned outages and improving asset

reliability, digital twins contribute to the overall efficiency and sustainability of energy systems (Cali et al., 2023).

Digital twins also play a critical role in managing microgrids, which are localized energy systems that can operate independently or in conjunction with the main grid. Microgrids are essential for integrating renewable energy sources and ensuring energy access in remote or underserved areas. Digital twins enable real-time simulation and optimization of microgrid operations, improving grid stability and resilience. An example would be the digital twins' ability to model energy demand, renewable energy generation, and storage capacity within a microgrid. By analyzing these variables, operators can optimize energy flows, reduce reliance on fossil fuels, and enhance system reliability. This capability is particularly valuable for ensuring grid stability in regions with high renewable energy penetration. (Cali et al., 2023).

Besides their numerous benefits, their reliance on real-time data and connectivity introduces cybersecurity challenges for these applications as well. Energy systems utilizing digital twins are vulnerable to cyber threats, which can disrupt operations and compromise system integrity. To address these challenges, robust cybersecurity measures, such as encryption protocols and intrusion detection systems, must be integrated into digital twin platforms. Ensuring the security and integrity of data is critical for realizing the full potential of digital twins in energy infrastructure management.

Overall, digital twins represent a transformative technology for optimizing energy infrastructure, enabling predictive maintenance, enhancing microgrid resilience, and improving operational efficiency. By providing real-time insights and simulation capabilities, digital twins empower energy operators to make data-driven decisions, minimize energy losses, and enhance system reliability. The below figure summarizes the usecases for digital twin solutions within the energy systems.

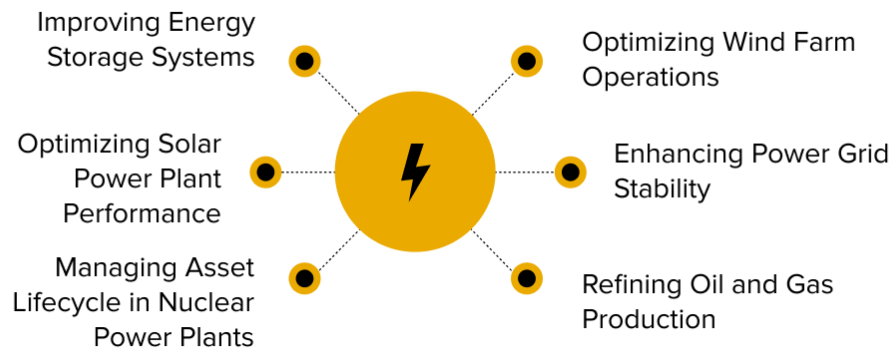


Figure 4.2 Applications of Digital Twins in the Energy Systems (Appinventiv, 2024)

4.1.2 IoT and AI Applications in Energy Production and Distribution

The integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies has revolutionized energy production, distribution, and management by enabling real-time monitoring, predictive analytics, and automated decision-making. Traditional energy systems often rely on manual processes and delayed feedback loops, which can result in inefficiencies, energy losses, and costly downtimes. IoT and AI address these challenges by transforming energy systems into intelligent, responsive, and adaptive networks.

4.1.2.1 IoT in Energy Systems

The Internet of Things (IoT) refers to a network of interconnected devices that use sensors and communication technologies to collect, process, and transmit real-time data. In energy systems, IoT-enabled devices, such as smart meters, sensors, and connected appliances, play a critical role in optimizing energy production, transmission, and consumption.

IoT devices provide continuous real-time data on energy flows, equipment performance, and environmental conditions. This data allows energy operators to detect inefficiencies, identify equipment faults, and implement corrective actions

promptly. For instance, in power generation systems, IoT sensors monitor the performance of turbines, boilers, and transformers to detect anomalies. This capability ensures early fault detection and reduces energy losses caused by equipment failures. In addition, IoT devices in renewable energy systems, such as solar panels and wind turbines, collect data on weather conditions and energy output to optimize generation efficiency (Kim et al., 2022).

Besides the benefits on consumers' enhanced ability to identify opportunities to reduce energy waste with provided data. Smart meters also facilitate dynamic pricing and demand response programs, enabling consumers to adjust energy usage during peak demand periods (Kim et al., 2022).

The integration of IoT in smart grids further enhances energy distribution efficiency by balancing supply and demand in real time. This capability reduces transmission losses and improves grid stability, especially in regions with high renewable energy penetration (Van Summeren et al., 2021). Figure 4.2 would help visualize the impact of IoT in the energy sector.

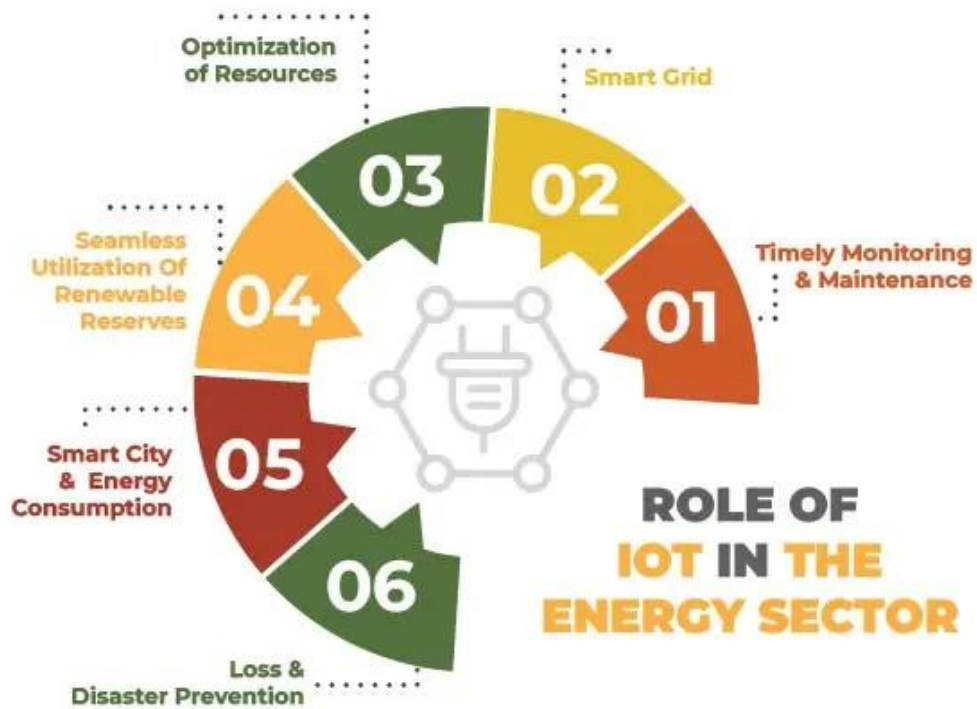


Figure 4.3. Role of IoT in the Energy Sector (Conure Technology Services L.L.C, 2022)

4.1.2.2 AI Applications in Energy Systems

Artificial Intelligence (AI) complements IoT by analyzing large datasets and providing actionable insights for energy optimization. AI-driven models use machine learning algorithms to forecast energy demand, optimize grid performance, and predict equipment failures.

Predictive maintenance is one of the most significant applications of AI in energy systems. By analyzing historical and real-time data, AI algorithms identify patterns and anomalies that indicate potential equipment failures. (El Zein & Gebresenbet, 2024). For example, in wind farms, AI models analyze data from turbine sensors to detect blade fatigue and mechanical issues. Predictive maintenance strategies reduce energy losses, extend equipment lifespan, and enhance the overall efficiency of renewable energy systems.

AI-based models play a critical role in forecasting energy demand and supply. By analyzing historical consumption patterns, weather data, and grid performance, AI algorithms predict energy demand trends with high accuracy. This capability enables grid operators to balance supply and demand dynamically, reducing transmission losses and improving grid stability (Singh et al., 2022). In addition, AI-driven optimization algorithms enhance grid resilience by managing renewable energy integration. By forecasting energy generation from solar and wind sources, AI ensures smooth grid operations and reduces reliance on fossil fuel-based power generation.

AI enables automated decision-making processes in energy production and distribution systems. Intelligent energy management systems use AI to optimize energy flows, identify cost-saving opportunities, and improve resource utilization. For instance, AI-powered systems automate load balancing in smart grids, ensuring efficient energy distribution while minimizing energy losses.

The integration of IoT and AI technologies in smart grids creates a robust, intelligent infrastructure that enhances energy efficiency, reliability, and resilience. IoT devices provide real-time data on grid performance, while AI models analyze this data to optimize grid operations. Together, these technologies enable (Singh et al., 2022):

- **Dynamic Load Management:** Balancing supply and demand in real time to reduce grid congestion and transmission losses.
- **Demand Response Optimization:** Implementing automated demand response programs based on real-time energy consumption data.
- **Renewable Energy Integration:** Managing the variability of renewable energy generation by forecasting energy output and adjusting grid operations dynamically.

The combined power of IoT and AI ensures that energy systems operate efficiently, sustainably, and cost-effectively, laying the foundation for future energy transitions. Figure below, Figure 4.3 summarizes the mentioned AI usecases.

Role of AI in Energy Sector



Figure 4.4. Role of AI in the Energy Systems (Appventurez, 2024)

4.2 Demand Side Applications and Decentralized Systems Enabled by Digital Technologies

As discussed, the traditional supplier and consumer roles only apply to a limited extent when modern energy systems are considered. In this subsection, the opportunities offered by digital technologies for the energy consumers, as well as concepts, such as smart grid, prosumer and peer-to-peer trading, which have been created via digital technologies will be analyzed.

4.2.1 Smart Grids and Demand Response Optimization

The evolution of energy systems has demanded smarter, more flexible grids to meet the growing challenges of renewable energy integration, real-time optimization, and energy efficiency. Traditional electricity grids, designed for one-way energy flow from centralized power plants to consumers, lack the capabilities to manage modern energy systems' complexities. As energy demand fluctuates and renewable energy sources introduce intermittent generation patterns, smart grids emerge as a crucial

solution. These advanced electrical grids incorporate digital technology, sensors, and provide two-way communication to monitor, optimize, and automate energy flows. Smart grids enable grid operators to detect faults, optimize energy distribution, and balance supply and demand dynamically (Majeed Butt et al., 2021).

Omni-present data, lower market barriers, higher predictability created by digital technologies lead to the the smart grids, the combined outcome of these transitions. The updated grid structure means the stepping away from traditional, one-way systems to multi-directional systems. Smart grids can be visualized as a comprehensive matrix that comprises information on any level from a specific device up to a district or a city and on any aspect from storage to generation or transmission etc. (Zhang et al., 2017). Increased share of renewables, decentralized power generation and more energy efficiency are facilitated by smart grid structures (Difiglio et al., 2021). Table below summarizes the aspects of energy systems fostered and facilitated by smart grids.

Table 4-2 Key benefits, effects and tools of Smart Grids (IEA, 2024)

Key benefits	Improving the Performance of Current Grids	Managing Demand Growth and Electrification	Improving Access and Affordability	Preparing for the Data Revolution	Preparing for the Future
Effects	<ul style="list-style-type: none"> • Reducing maintenance costs • Reducing technological losses • Reducing electricity theft 	<ul style="list-style-type: none"> • Reducing the impact of electric heating and cooling growth • Reducing the impact of EVs 	<ul style="list-style-type: none"> • Reducing the cost of Access • Reducing barriers to access 	<ul style="list-style-type: none"> • Improving data governance • Leveraging full benefits of data 	<ul style="list-style-type: none"> • Improving resilience • Improving energy system planning

Table 4-2 (Continued)

Key benefits	Improving the Performance of Current Grids	Managing Demand Growth and Electrification	Improving Access and Affordability	Preparing for the Data Revolution	Preparing for the Future
Tools	<ul style="list-style-type: none"> • Remote monitoring, control and automation • Advanced grid management • System protection and restoration • Renewable resource forecasting systems 	<ul style="list-style-type: none"> • Advanced distribution grid management • Smart EV charging • Smart Inverters • Demand-response enabled appliances • Virtual Power Plants 	<ul style="list-style-type: none"> • Better planning for access • Digital platforms and operations • Digital payment 	<ul style="list-style-type: none"> • National data frameworks • Regulatory innovations • Data management 	<ul style="list-style-type: none"> • Grid infrastructure digital records • Resilience planning • Distributed Energy Resources forecasting • Multi scale and multi-objective planning

As discussed, an initial step to incorporation of the digital technologies is creation of data. Although there are a number of applications that increases the production efficiency, this creation is based on the involvement of smart metering when the demand side and the grid operation of the energy sector are considered. Whereas there are other digital tools that can be utilized such as text-based big data analytics on the texts available on web, smart metering is considered to be the first essential application towards informed grid management system with high customer involvement. Therefore, smart meters, which are considered to shape the customers perception of smart grids, are the keys to develop customer-based business models and inclusive energy governance structures. They are also the tools, through which the future business models can learn and update themselves in the long term (Le Ray & Pinson, 2020).

The model structure of a smart grid and the fundamental role of digital technologies including smart metering can be viewed in the following figure:

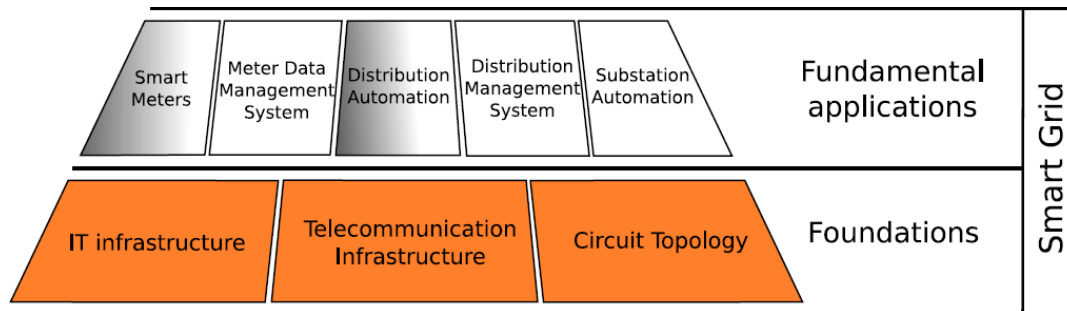


Figure 4.5. Model Structure and Role of Smart Grids (Farhangi, 2010)

On the production side of the smart grids, decentralized energy generation brings the introduction of the prosumers, consumers that also generate electricity such as via solar panels on rooftops. The excess power can be integrated to the grid and consumed by other parties within the grid, which requires means that allow reliable peer-to-peer energy contracts and trade. Cost-effective and environmentally sustainable storage capabilities also become available with the help of digital technologies (SWECO, 2019). In the context of smart grids households and electric vehicles take part in the grids, not only as consuming or producing agents but also the grid's storage units (Milchram, 2018). This capability of these agents can be further exploited in possible future business models, such as provision of access to a grid operator that controls the storage facilities for enhanced capacity to meet the supply and demand (Specht & Madlener, 2019).

Business model revision needs to adapt to smart grids is even more present for the distribution system operators. The adaptation efforts can be observed in EC JRC data, which shows that the smart grid project investments of DSOs by 2015 add up to 814 Million Euros (Pereira et al., 2020).

One of the key features of smart grids is their ability to implement Demand Response (DR) programs, which allow consumers to adjust their energy consumption based on real-time grid conditions or economic incentives. Demand response optimizes energy usage during peak demand periods, reducing the burden on the grid and enhancing energy efficiency (Majeed Butt et al., 2021). In practical terms, demand

response systems enable grid operators to communicate with consumers through IoT-enabled devices and smart meters. By analyzing grid data in real time, DR programs can automatically reduce energy loads in non-essential appliances, during peak demand periods. These adjustments help to prevent blackouts, stabilize the grid, and lower energy costs for both consumers and utilities (Rajat Pusa et al., 2024).

For example, advanced DR scheduling systems are capable of targeting optimal energy usage patterns for buildings while maintaining occupant comfort. Demand-side flexibility and bidding for flexible loads in air-conditioned buildings are essential for lowering peak demand and improving grid stability. Such systems allow building managers to balance energy efficiency goals with economic constraints, leading to significant energy savings (Kim et al., 2022).

Smart grids also improve energy management through their ability to analyze vast quantities of real-time data and automate energy flows. Energy management strategies, such as peak shaving and load shifting, are essential for balancing demand and supply within modern grids. With the help of predictive analytics, grid operators can forecast energy demand trends and optimize grid performance accordingly (Pereira et al., 2020). Additionally, smart grids enhance reliability by detecting faults and facilitating self-healing mechanisms. These systems use dynamic optimization algorithms to reroute energy flows and minimize disruptions caused by equipment failures or energy fluctuations (Majeed Butt et al., 2021).

Despite the numerous advantages of smart grids, their increased reliance on digital technologies introduces new challenges, particularly in the area of cybersecurity. The integration of IoT devices, communication networks, and automated systems makes smart grids more vulnerable to cyberattacks (Majeed Butt et al., 2021). To mitigate these risks, cybersecurity frameworks and encryption protocols are being integrated into smart grid systems. Ensuring the security of energy data and protecting critical infrastructure is essential for maintaining trust and resilience in modern energy networks.

In summary, smart grids represent a transformative solution for modernizing energy systems, enabling demand response optimization, fault detection, and grid management in real time. The ability to balance supply and demand, integrate renewable energy sources, and optimize energy flows makes smart grids an essential component of future energy systems. However, addressing cybersecurity vulnerabilities and enhancing infrastructure resilience remain key priorities for the widespread deployment of smart grid technologies. Below figure helps visualize the interrelations of the actors within a smart grid.

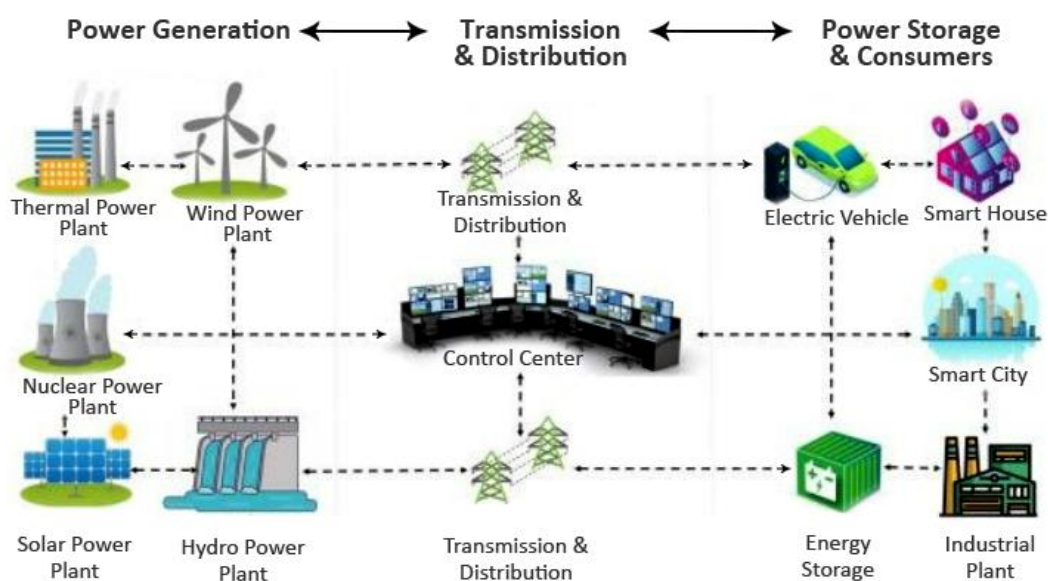


Figure 4.6. Visual Example of a Smart Grid (Circuitloop Technologies LLP, 2022)

4.2.2 Blockchain for Decentralized Energy Markets

Despite it became widely recognized with digital currencies, blockchain technology have the potential to yield wider benefits in various fields. Blockchain based digital solutions have the ability to include a number of actors in a flexible way, combine smart contracts (a series of codes that involve the agreed upon policies between parties) and the transactions, and enable secure, high speed transactions on any scale (Patil et al., 2020).

Blockchain technology has emerged in energy sector as a transformative tool for enabling decentralized, transparent, and secure energy markets. Blockchain is a distributed ledger technology that allows peer-to-peer (P2P) transactions without the need for intermediaries. In energy systems, blockchain facilitates decentralized energy trading, renewable energy certification, and transparent data management.

One of the most significant applications of blockchain in energy systems is peer-to-peer (P2P) energy trading, where consumers and producers exchange energy directly without intermediaries. This decentralized approach enables households and businesses with surplus renewable energy to sell it to other consumers, fostering energy democratization and grid flexibility. For example, blockchain-based projects such as the Brooklyn Microgrid in the United States allow residents to trade solar energy locally. Blockchain ensures that energy transactions are secure, transparent, and immutable, reducing transaction costs and enhancing trust among participants (Hrga et al., 2020).

Blockchain technology is also used to issue and manage renewable energy certificates (RECs). These certificates verify the origin of renewable energy and provide transparency in energy markets. Blockchain acts as a decentralized registry, ensuring that RECs are securely tracked and validated (Hrga et al., 2020).

The implementation of blockchain in energy systems faces challenges as well, including scalability, data privacy, and regulatory concerns. Blockchain networks require significant computational power and energy, which can limit their scalability. Furthermore, regulatory frameworks for decentralized energy markets are still evolving, creating uncertainty for widespread adoption (Hrga et al., 2020).

To conclude, blockchain technology offers a robust and transparent platform for decentralized energy markets, peer-to-peer energy trading, and renewable energy certification. By eliminating intermediaries and ensuring data integrity, blockchain fosters innovation, energy democratization, and grid flexibility. Addressing scalability and regulatory challenges will be critical for realizing the full potential of

blockchain in energy systems. The following figure visualizes the energy trading flow, enabled by blockchain technology.

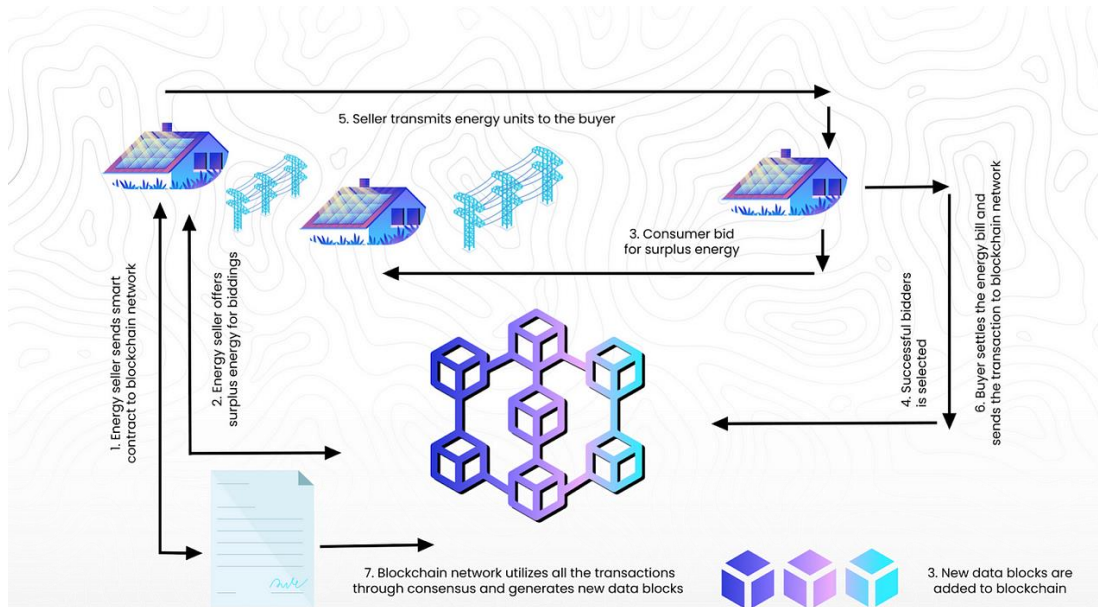


Figure 4.7. Energy Trading Enabled by Blockchain (NeoNomad, 2024)

CHAPTER 5

ENERGY POLICIES, CASE STUDIES, THEIR IMPLICATIONS AND COMPARATIVE ANALYSIS

This chapter explores the role of policies in supporting technological innovation, analyzed successful case studies from regions, and examined the barriers to digital integration in energy systems. The case studies examined in this chapter highlight the importance of integrated policies, financial incentives, technological innovation, and public-private collaboration in achieving energy efficiency and sustainability goals. While developed regions provide successful examples of smart grid deployment and renewable energy integration, emerging economies demonstrate the potential for innovation and localized solutions. Figure below presents how digital energy systems can be fostered and facilitated by initiatives.

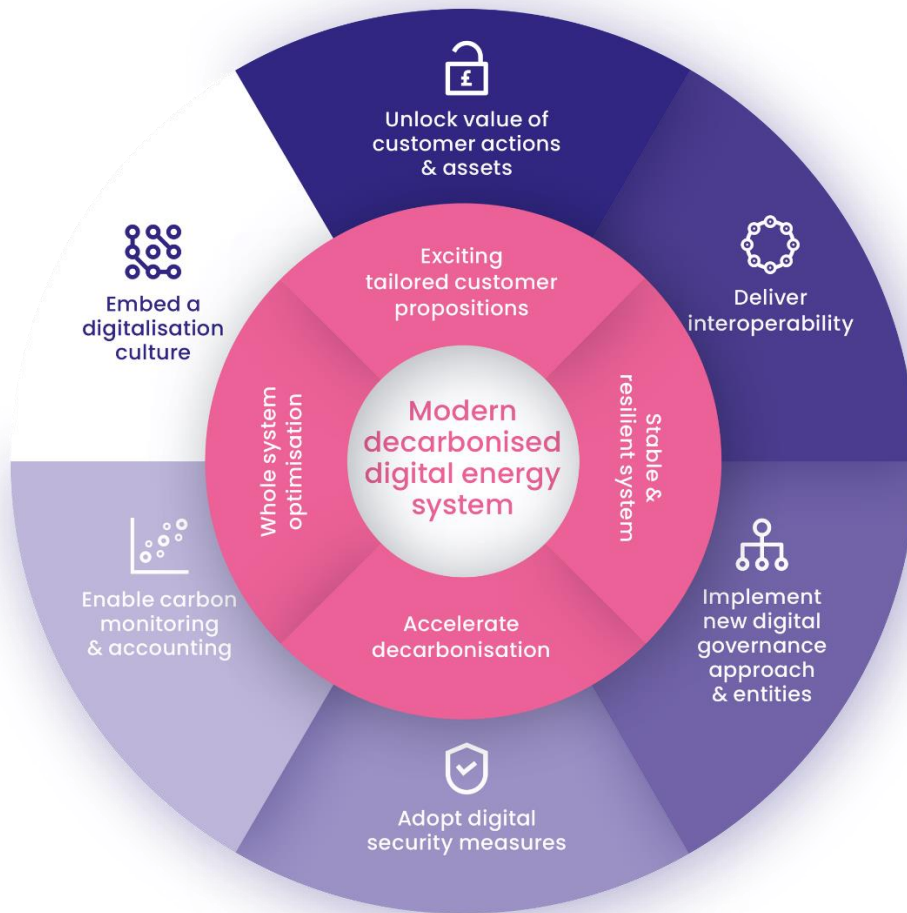


Figure 5.1. Initiatives for energy digitalization (Energy Systems Catapult, 2021)

5.1 Policies Supporting Technological Innovation

The rapid digitalization of energy systems, combined with the need for enhanced energy efficiency, has made technological innovation a cornerstone of sustainable energy transitions. Policies that support research, development, and adoption of new technologies play a vital role in facilitating this transformation (Huang et al., 2024). These policies serve as enablers of innovation by addressing financial constraints, creating supportive regulatory environments, and encouraging collaboration between public and private stakeholders. Governmental interventions such as

research and development (R&D) funding, subsidies, and tax incentives help overcome market failures and create pathways for emerging technologies to thrive. Such policies ensure that technological advancements are not prevented by initial investment costs or lack of commercial incentives (Angelo & Chan, 2015).

Investments in R&D are critical for driving innovation in digital technology utilization in energy systems. Public funding for R&D, particularly in clean energy technologies, serves as a catalyst for private sector involvement and accelerates technological breakthroughs (Van Summeren et al., 2021). Government-funded programs have demonstrated significant economic and environmental benefits. Initiatives, particularly in advanced economies like the United States and European Union, highlight the importance of supporting R&D through policy frameworks. Programs that enable technology transfer from publicly funded research laboratories to private enterprises have proven to enhance innovation spillovers (Angelo & Chan, 2015).

However, it is important for policymakers to ensure that R&D investments are aligned with the evolving technological landscape. Policies must be periodically reviewed and updated to reflect market needs and technological progress. Failure to do so may render certain policies ineffective (Brown, 2015).

In addition to R&D investments, financial incentives such as grants, subsidies, and tax breaks play a crucial role in supporting technological innovation. These incentives help lower the financial barriers to adopting energy-efficient technologies, particularly for private enterprises. For instance, subsidies for renewable energy technologies, such as solar photovoltaics and wind energy, have significantly accelerated the deployment of clean energy solutions. Governments have also implemented tax incentives to encourage industries to adopt energy-efficient practices. These incentives not only reduce upfront costs but also provide long-term economic benefits through energy savings (Eshbayev et al., 2024).

Furthermore, regulatory policies mandating energy efficiency standards have driven significant technological advancements. Energy performance standards for

buildings, appliances, and industrial processes provide a clear framework for compliance and incentivize innovation (Brown, 2015).

Collaboration between public and private sectors is critical for fostering innovation and ensuring that policies are effectively implemented. Public-private partnerships (PPPs) play a key role in driving research, sharing risks, and accelerating the deployment of new technologies. These partnerships allow governments to incorporate private sector expertise while providing financial and regulatory support for innovation. In addition, workforce training programs are essential for ensuring the availability of skilled labor required to manage and implement energy-efficient technologies (Eshbayev et al., 2024).

5.2 Case Analysis of Effective Energy Policies

This section demonstrates how effective energy policies, including carbon pricing, technology transfer, and renewable energy incentives, have driven energy efficiency and innovation in different regions. The European Union's leadership in integrating energy policies with decarbonization goals provides a model for achieving emissions reductions. In the United States, technology transfer and public-private partnerships have accelerated clean energy innovation. Meanwhile, emerging economies offer unique opportunities to adopt innovative energy solutions, provided that financial and institutional barriers are addressed. These case studies may provide insights to policymaking processes to design targeted strategies to overcome challenges, foster innovation, and achieve sustainable energy transitions.

Effective energy policies serve as the cornerstone for driving energy efficiency, fostering technological innovation, and addressing global sustainability goals. Case studies of successful policy frameworks in regions like the European Union (EU), the United States (US), and emerging economies offer critical insights into the role of governance, financial incentives, and institutional support. These examples not

only highlight policy successes but also highlight the challenges and lessons learned in implementing digital and energy efficiency solutions.

This section examines how targeted policies-such as carbon pricing, renewable energy incentives, and technology transfer programs-have contributed to energy efficiency, decarbonization, and innovation in energy systems. Additionally, it explores the challenges and opportunities in emerging economies.

5.2.1 European Union: A Model for Energy Efficiency and Innovation

The European Union (EU) stands as a global leader in advancing energy efficiency and sustainable energy transitions through its comprehensive policy frameworks and technology-driven initiatives. The EU's approach combines binding energy targets, financial incentives, and strong regulatory mechanisms to accelerate technological innovation and decarbonization. By prioritizing smart grid deployment, renewable energy integration, and digital energy solutions, the EU has established a replicable model for achieving long-term decarbonization targets while fostering economic growth and technological innovation. Their energy policy is based on three pillars, environmental sustainability, economic efficiency, and the security of power supply, all of which increases the emphasis on smart grids (Milchram, 2018).

The EU's energy transition strategy is deeply rooted in its commitment to combating climate change, as outlined in the European Green Deal and associated directives. Policies such as the Renewable Energy Directive, the Energy Efficiency Directive and Digitalizing the Energy System set clear targets for energy savings, carbon emissions reductions, and renewable energy adoption. Moreover, financial incentives, research and development (R&D) funding, and public-private partnerships have accelerated the deployment of cutting-edge technologies, such as smart grids, digital twins, and energy storage systems.

5.2.1.1 Smart Grids as a Cornerstone of EU Energy Policy

As a proactive body in terms of policy development, especially in the cases of climate and energy, the European Union plans to render its power grids “smart” to exploit the benefits of real time data to foresee and manage potential supply and demand imbalances (EU, 2019).

Smart grids represent a transformative solution for modernizing the EU’s energy infrastructure. Unlike traditional power grids, smart grids integrate advanced digital technologies, IoT sensors, and real-time data analytics to enable dynamic energy management and improve grid resilience. These grids play a critical role in addressing the challenges of renewable energy variability, peak load management, and energy transmission losses. (Pereira et al., 2020)

In many EU countries, smart grid projects have demonstrated tangible benefits in improving energy reliability and facilitating renewable energy integration. For example, Germany’s energy policy emphasizes grid modernization to accommodate increased solar and wind power generation. Under the Renewable Energy Sources Act, Germany introduced incentives for energy storage systems (ESS) by exempting them from grid tariffs and levies. This policy has encouraged the adoption of energy storage technologies, enabling renewable energy producers to store excess energy and reduce grid congestion (Sani et al., 2020). In order to empower such investments in energy systems, the EU supports the creation of digital twins of electricity grids for distribution and transmission system operators, and the establishment of common smart grid indicators and objectives for central European Agencies as well as governments (EU, 2022)

The deployment of smart grids has also facilitated the implementation of demand-side management (DSM) programs, allowing utilities to optimize energy consumption during peak periods. By using digital tools and IoT-enabled devices, smart grids provide real-time communication between grid operators and consumers, enabling automated demand response. This approach not only enhances grid

efficiency but also empowers consumers to actively participate in energy optimization. As a result, smart grids have become a cornerstone of the EU's strategy for achieving energy efficiency and decarbonization goals (Majeed Butt et al., 2021).

In order to be able to

5.2.1.2 Integration of Renewable Energy and Storage Systems

The EU's energy policy places a strong emphasis on the integration of renewable energy sources into the grid. Solar and wind energy, which are inherently variable, require advanced grid management solutions to balance supply and demand effectively. Smart grids, combined with energy storage systems, provide a robust platform for managing renewable energy variability and ensuring grid stability. Countries like Denmark and Spain have successfully implemented policies that promote the adoption of energy storage technologies. These policies include feed-in tariffs, investment subsidies, and regulatory incentives that support both large-scale and distributed energy storage projects. By storing excess energy generated from renewable sources, energy storage systems enable utilities to smooth out fluctuations in energy supply and ensure consistent delivery to consumers (Sani et al., 2020).

The European Union has also prioritized funding for energy storage research and innovation through programs such as Horizon Europe. These initiatives focus on developing next-generation energy storage technologies, including advanced batteries, hydrogen storage, and thermal storage systems. By aligning financial incentives with innovation funding, the EU has created an enabling environment for renewable energy integration and grid optimization (Alofaysan et al., 2024).

The success of renewable energy policies in the EU demonstrates the importance of combining technological advancements with supportive regulatory frameworks.

5.2.1.3 Policy Support and Financial Incentives for Innovation and Integration

The EU's leadership in energy efficiency can be attributed to its robust policy support and financial incentives for technological innovation. Policies such as the Energy Efficiency Directive and the Renewable Energy Directive set ambitious targets for energy savings, emissions reductions, and renewable energy adoption and encourages member states to implement measures such as building retrofits, appliance efficiency standards, and industrial energy audits. The integration of energy efficiency policies with broader decarbonization goals has driven significant progress in reducing greenhouse gas emissions (Brown, 2015).

These directives are complemented by a range of financial instruments that incentivize clean energy investments and technological innovation. For instance, feed-in tariffs (FITs) provide guaranteed payments to renewable energy producers, creating financial certainty and attracting private sector investment. Similarly, green bonds have been used to finance large-scale infrastructure projects, such as smart grid deployments and energy storage installations (Sani et al., 2020).

The EU Emissions Trading System (ETS), a cap-and-trade program, has also been one of the most successful policies in reducing carbon emissions. By placing a price on carbon emissions, the ETS incentivizes industries to adopt clean energy technologies and improve operational efficiency. This policy has provided a replicable model for balancing economic and environmental goals via clean energy adoption (Danish & Senjyu, 2023).

These incentives have played a crucial role in scaling up renewable energy deployment across Europe, contributing to energy security and emissions reductions. Meanwhile, EU funding programs such as Horizon 2020 and its successor Horizon Europe have supported research and development (R&D) in energy storage, smart grids, and digital energy technologies (Alofaysan et al., 2024).

The EU has established a strong innovation ecosystem through research and development funding programs like Horizon Europe and Digital Europe (Niet et al., 2022). These programs provide grants to technology developers, startups, and research institutions working on cutting-edge energy solutions, including IoT-enabled smart grids, AI-based energy management systems, and digital twins. By fostering collaboration between public and private stakeholders, the EU has accelerated the deployment of innovative technologies that drive energy efficiency and sustainability (Sani et al., 2020).

5.2.1.4 Remaining, Digitalization Focused Initiatives

Beyond these initiatives, the EU's action plan for digitalization of the energy system efforts to address remaining issues that are specific to digitalization, such as data management, cybersecurity and consumer engagement. As a foundational aspect of these efforts, EU aims to create a dedicated energy data space, which is expected to be an interoperable framework of common standards and practices that will streamline data sharing and enhance collaboration across the energy value chain. The updated energy system with shared data structure is empowered by the cybersecurity measures. Through complementing cross-sector legislation like the NIS 2 Directive, the Cyber-Resilience Act, and the proposed Council Recommendation on critical infrastructure, the EU is working on a network code addressing cybersecurity aspects of cross-border electricity flows. Future measures will include delegated acts on the cybersecurity of gas and hydrogen networks. Additionally, the establishment of the EU Smart Energy Expert Group, featuring a "Data for Energy" working group, are additional ways of commitment to secure data management in the energy sector (EU, 2022).

In order to empower its citizens and promote the adoption of sustainable energy practices, EU aims to actively engage the consumers in designing and utilizing digital tools. To this end, strategies that focus on developing guidance are being put into operation, tools, and a pioneering platform to enable energy communities to

harness digital solutions effectively. Moreover, the EU is fostering large-scale partnerships to support the digitalization of the energy value chain under the Pact for Skills initiative. This partnership emphasizes the importance of equipping citizens with the necessary skills to adapt to and thrive in a digitized energy landscape (EU, 2022).

As a final set of measures, the EU aims to address the increasing carbon footprint of digitalization via integrating sustainability into the ICT sector by targeting communication networks, data centers, and crypto-assets. Initiatives such as eco-design and energy labeling for products like computers, an EU code of conduct for the sustainability of communication networks, and environmental labeling schemes for data centers are in place. For crypto-assets, energy-efficiency labeling for blockchains is being explored to mitigate their environmental impact (Digitalising the Energy System - EU Action Plan, 2022).

The EU's success demonstrates the importance of aligning policy, innovation, and market incentives to achieve long-term energy goals.

5.2.2 United States: Driving Innovation through Technology Transfer

The United States has emerged as a significant player in driving energy innovation through the development of smart grids, the use of digital platforms, and the integration of advanced technologies such as Artificial Intelligence (AI) and Internet of Things (IoT). Unlike the European Union's centralized policy approach, the US relies on a combination of federal initiatives, state-level programs, and private sector innovation to promote energy efficiency and grid modernization. Key policies, including federal funding programs, technology transfer initiatives, and public-private partnerships, have facilitated the commercialization and deployment of clean energy innovations. Policies that facilitate the movement of technologies from research institutions to the private sector have been instrumental in country's

progress. This decentralized approach enables flexibility and encourages innovation while addressing regional energy challenges and priorities.

5.2.2.1 Smart Grids: A Pillar of US Energy Modernization

The United States has been at the forefront of smart grid deployment, with significant investments aimed at modernizing energy infrastructure and improving grid reliability. Smart grids in the US address key energy challenges, including transmission losses, grid congestion, and the integration of renewable energy sources. By incorporating real-time data analytics, IoT sensors, and automated control systems, smart grids enable dynamic load management and fault detection (Angelo & Chan, 2015).

One of the most impactful initiatives supporting smart grid deployment is the Smart Grid Investment Grant (SGIG) program, launched under the American Recovery and Reinvestment Act (ARRA). This program provided over \$4.5 billion in funding to utilities and technology providers to implement advanced metering infrastructure (AMI), demand response systems, and digital grid management tools. As a result, the SGIG program accelerated the adoption of smart grid technologies across states and demonstrated tangible benefits in reducing transmission losses, improving energy efficiency, and enhancing grid resilience (U.S. Department of Energy, 2024).

The adoption of smart grids in the US has also supported renewable energy integration. With the advantage of digital tools and predictive analytics, smart grids manage the variability of solar and wind power, ensuring a stable and reliable energy supply. Grid operators can forecast energy demand, balance supply in real time, and optimize grid operations to accommodate renewable energy sources. This capability has been critical in reducing reliance on fossil fuels and supporting the transition to a low-carbon energy system (Majeed Butt et al., 2021).

5.2.2.2 Role of Digital Platforms and AI in Energy Management

The integration of digital platforms has revolutionized energy management in the United States by enabling data-driven decision-making and automation. These platforms utilize IoT devices, AI algorithms, and real-time analytics to optimize energy production, distribution, and consumption. Artificial Intelligence plays a central role in enhancing grid performance and energy efficiency. AI-based models analyze large datasets to forecast energy demand, identify system inefficiencies, and optimize energy flows. For example, AI-driven energy management systems enable predictive maintenance by detecting faults in equipment before they escalate, reducing downtime and improving operational efficiency (Ahmad et al., 2021).

In addition to predictive maintenance, AI enhances the stability and flexibility of smart grids by automating load balancing and demand response programs. By analyzing historical and real-time energy data, AI models predict fluctuations in demand and adjust energy distribution accordingly. This capability ensures grid stability, reduces peak loads, and minimizes energy losses. IoT-enabled devices, such as smart meters and sensors, complement AI-driven platforms by providing real-time data on energy usage and grid performance. Smart meters empower consumers to monitor and manage their energy consumption, while grid operators use IoT data to optimize energy flows and detect faults. As a result, the integration of IoT and AI in smart grids has transformed the US energy sector, creating intelligent and adaptive systems that respond dynamically to changing conditions (Niet et al., 2022).

5.2.2.3 Federal Policies and Technology Transfer

The success of smart grid and digital platform adoption in the US can be attributed to supportive federal policies and initiatives that promote technology transfer and innovation. The Bayh-Dole Act has played a vital role in facilitating the commercialization of technologies developed through federally funded research

programs. By allowing universities and research institutions to retain ownership of their innovations, the Bayh-Dole Act has encouraged the transfer of clean energy technologies to private enterprises. This approach has accelerated the development of renewable energy systems, energy storage technologies, and advanced grid solution (Rosário & Dias, 2023). These federal research programs have led to the development of advanced battery storage systems, which are now being deployed at scale to support grid resilience and renewable energy integration (Angelo & Chan, 2015).

The US Department of Energy (DOE) has also implemented initiatives to reduce bureaucratic barriers and streamline technology transfer processes. Modernization programs have accelerated the commercialization of innovations in energy efficiency and digital technologies, enabling faster deployment of digital energy solutions. Through funding programs such as the Advanced Research Projects Agency-Energy (ARPA-E), the DOE supports high-risk, high-reward energy projects that drive innovation. ARPA-E has been instrumental in bridging the gap between research and commercialization, enabling the deployment of breakthrough technologies that improve energy efficiency and grid resilience (Angelo & Chan, 2015).

Public-private partnerships (PPPs) further strengthen the US approach to energy innovation by blending in private sector expertise and investment. PPPs facilitate collaboration between federal agencies, utilities, technology providers, and research institutions, ensuring that energy projects are implemented efficiently and cost-effectively. These partnerships foster private sector expertise and capital while ensuring that public policy goals, such as emissions reductions and energy savings, are achieved (Sani et al., 2020).

5.2.2.4 State-Level Initiatives and Regional Innovation

In addition to federal programs, state-level initiatives were implemented to advance energy efficiency and grid modernization in the US. States such as California, Texas,

and New York have implemented policies and pilot projects that demonstrate the potential of smart grids, digital platforms, and renewable energy integration. For instance, California's Demand Response Programs incentivize consumers to reduce energy consumption during peak periods, thereby improving grid stability and reducing emissions. These programs rely on smart meters and IoT-enabled devices to communicate real-time energy usage data to consumers and grid operators. Similarly, New York's Reforming the Energy Vision (REV) initiative promotes grid modernization, renewable energy adoption, and energy efficiency through regulatory reforms and financial incentives. State-level innovation highlights the flexibility of the US energy system, where regional policies address local challenges and priorities. This decentralized approach fosters experimentation, innovation, and the development of tailored solutions that contribute to national energy goals. The US experience with smart grids, digital platforms, and energy policies provides valuable lessons for other regions (Angelo & Chan, 2015):

- **Technology Transfer Accelerates Innovation:** Policies such as the Bayh-Dole Act demonstrate the importance of facilitating technology transfer from research institutions to private enterprises to drive commercialization.
- **Public-Private Collaboration:** Federal funding programs and public-private partnerships have enabled the successful implementation of energy projects, incorporating private sector expertise and investment.
- **Digital Platforms Enhance Grid Resilience:** The integration of AI, IoT, and predictive analytics in smart grids has improved grid reliability, reduced energy losses, and facilitated renewable energy integration.
- **State-Level Flexibility:** Regional initiatives allow states to experiment with innovative policies and technologies, addressing local energy challenges while contributing to national goals.

The US approach shows the importance of combining federal policies, regional initiatives, and private sector collaboration to achieve energy efficiency, technological innovation, and grid modernization.

5.2.3 Emerging Economies: Challenges and Opportunities

Emerging economies face particular challenges in transitioning to efficient, sustainable, and digitalized energy systems. These challenges include financial constraints, unstable energy infrastructure, institutional barriers, and limited access to advanced technologies. Despite these hurdles, emerging economies can find substantial opportunities. Given their growing energy demand and abundant renewable energy resources, emerging economies are well-positioned to leapfrog traditional energy systems by adopting innovative solutions tailored to their specific needs.

5.2.3.1 Barriers for Energy Transition

In many emerging economies, including leading ones such as India, Indonesia, Bangladesh, Chile and Taiwan, the upfront costs of digital technologies remain a significant barrier. Governments often lack the financial capacity to provide incentives or invest in large-scale infrastructure projects due to the high cost of deploying advanced energy technologies, such as smart grids, energy storage systems and IoT-enabled devices (Huang et al., 2024). Limited financial resources and underdeveloped capital markets make it challenging for governments and businesses to invest in clean energy infrastructure. Furthermore, high upfront costs of energy technologies often deter their adoption despite their long-term economic benefits. To address these financial barriers, innovative financing mechanisms, such as green bonds, concessional loans, and public-private partnerships (PPPs), are essential. Governments can utilize international funding from organizations such as the World Bank, International Monetary Fund (IMF), and regional development banks to support clean energy projects (Sani et al., 2020).

Moreover, weak institutional frameworks and outdated regulations further impede energy transitions in emerging economies. Regulatory inconsistencies and uncertainties, lack of enforcement, and insufficient technical expertise hinder the

deployment of digital energy systems and renewable energy projects. Energy markets in these regions often lack the incentives needed to encourage private sector investments in energy efficiency and clean technologies. To overcome these barriers, governments must create conducive policy environments that incentivize innovation and private sector participation. Policies such as subsidies, tax incentives, and feed-in tariffs (FITs) can reduce financial risks and encourage investments in energy infrastructure (Sani et al., 2020).

5.2.3.2 Opportunities for Emerging Economies

Despite the challenges, emerging economies have significant opportunities to transform their energy systems by leveraging renewable energy resources and energy storage technologies. Regions such as Africa, Asia, and Latin America are endowed with abundant solar, wind, and hydro resources, which can be harnessed to meet growing energy demands sustainably. Energy storage systems (ESS) play a pivotal role in addressing the intermittency of renewable energy sources. Battery storage solutions enable utilities to store excess energy generated during peak production periods and dispatch it during periods of high demand. In remote and underserved regions, off-grid solar systems combined with battery storage provide reliable and affordable energy access (Sani et al., 2020).

Emerging economies can also capitalize on localized production of renewable energy technologies, such as solar panels, wind turbines, and energy storage systems. By investing in domestic manufacturing, these countries can reduce technology costs, create employment opportunities, and build technical expertise. Localized production not only strengthens energy supply chains but also enhances energy independence and economic resilience (Eshbayev et al., 2024).

5.2.3.3 Policy Solutions and Strategic Priorities

To unlock the potential of energy innovation in emerging economies, policymakers must prioritize the following strategies (Huang et al., 2024):

- **Financial Incentives and International Cooperation:** Providing financial incentives, such as subsidies, concessional loans, and investment guarantees, can reduce the cost barriers associated with clean energy technologies. Governments must also collaborate with international financial institutions and development partners to access funding for energy projects.
- **Regulatory Reforms and Capacity Building:** Modernizing regulatory frameworks to support decentralized energy systems, renewable energy integration, and digital infrastructure is critical. Governments must also invest in capacity-building programs to develop technical expertise and strengthen institutional governance.
- **Support for Local Manufacturing and R&D:** Investing in local manufacturing and research and development (R&D) initiatives can drive innovation, reduce technology costs, and create economic opportunities. Policies that promote public-private partnerships and foster innovation ecosystems are essential for achieving long-term energy goals.
- **Grid Modernization and Energy Access:** Deploying smart grids and off-grid energy solutions can improve energy access, particularly in rural and underserved areas. Combining renewable energy with energy storage technologies ensures grid stability and reduces reliance on fossil fuels.

Emerging economies face significant challenges in implementing energy efficiency and clean energy solutions, including financial constraints, institutional barriers, and infrastructure gaps. However, these regions possess immense opportunities for renewable energy adoption, energy storage deployment, and localized technology production. By implementing targeted policies, fostering international cooperation, and investing in R&D and capacity building, emerging economies can accelerate

their energy transitions, improve energy access, and contribute to global sustainability goals.

5.3 Key Lessons from Global Case Studies

The case studies of the European Union, the United States, and emerging economies provide valuable insights into the policies, strategies, and technologies that drive energy efficiency and sustainable energy transitions. While developed regions have successfully implemented smart grids, digital platforms, and renewable energy policies, emerging economies demonstrate the potential for innovation despite financial and institutional barriers. This section synthesizes the key lessons learned from global energy initiatives as follows:

- **Integration of Policies and Technology:** One of the most critical lessons from the EU and US case studies is the importance of aligning policy frameworks with technological advancements. The EU's success in integrating renewable energy sources with smart grid technologies highlights the value of cohesive policies that address both energy efficiency and decarbonization. Similarly, US policies supporting smart grid deployment and technology transfer emphasize the role of innovation in achieving energy goals (Majeed Butt et al., 2021).
- **Financial Incentives and Innovation Support:** Financial incentives, such as subsidies, feed-in tariffs, and R&D funding, play a crucial role in driving the adoption of clean energy technologies. The EU's use of green bonds and the US's Smart Grid Investment Grant (SGIG) program illustrate how targeted financial support can reduce barriers to adoption and accelerate innovation (Huang et al., 2024).
- **Public-Private Collaboration:** Public-private partnerships (PPPs) are essential for financing and implementing energy projects, particularly in resource-constrained regions. Collaboration between governments,

industries, and technology providers enables risk-sharing, fosters innovation, and accelerates project deployment (Angelo & Chan, 2015).

- **Localized Solutions for Emerging Economies:** Emerging economies can adapt lessons from developed markets by implementing localized solutions that address their specific challenges and opportunities. Policies supporting local manufacturing, off-grid energy solutions, and workforce development are critical for achieving sustainable energy transitions (Sani et al., 2020).

The examined case studies show the importance of integrated policies, financial incentives, technological innovation, and public-private collaboration in achieving energy efficiency and sustainability goals. While developed regions provide successful examples of smart grid deployment and renewable energy integration, emerging economies demonstrate the potential for innovation and localized solutions.

5.4 Comparative Analysis and Lessons Learned

A comparative analysis of energy policies in the European Union, the United States, and emerging economies highlights several key lessons:

- **Integration of Policies:** Aligning energy efficiency measures with decarbonization goals, as demonstrated by the EU, ensures a holistic approach to sustainability.
- **Technology Transfer:** Facilitating the transfer of technologies from research institutions to private enterprises accelerates innovation and commercialization, as seen in the US.
- **Financial Incentives:** Providing financial support, such as subsidies and tax incentives, is essential for overcoming upfront cost barriers and encouraging private sector adoption.

- **Capacity Building:** Investing in workforce training and local manufacturing can drive economic growth while addressing energy access challenges in emerging economies.
- **Policy Flexibility:** Policies must be periodically reviewed and updated to reflect technological advancements and market changes.

5.5 Policy Barriers and Solutions for Digital Integration

Policy barriers such as financial constraints, outdated regulations, cybersecurity risks, and workforce gaps pose significant challenges to digital energy integration. However, these barriers can be addressed through innovative financing mechanisms, regulatory reforms, investments in R&D, and capacity-building programs. By implementing these solutions, policymakers may unlock the full potential of digital technologies to improve energy efficiency, enhance grid resilience, and support sustainable energy transitions.

While digital technologies hold immense potential to improve energy efficiency, reduce emissions, and enhance grid resilience, their widespread integration into energy systems faces significant policy and institutional barriers. These challenges include financial constraints, outdated regulations, technological limitations, and workforce capacity gaps. Addressing these barriers requires innovative financing mechanisms, regulatory reforms, and collaborative efforts between governments, industry stakeholders, and technology providers.

This section explores the primary barriers to digital integration in energy systems and highlights policy solutions that can facilitate the adoption of smart grids, IoT-enabled devices, AI-driven energy management systems, and blockchain-based decentralized energy markets.

Economic and Financial Barriers

The cost of implementing digital technologies remains a substantial challenge, particularly in emerging economies where financial resources are limited. The

deployment of digital technologies requires significant investments in infrastructure, hardware, and software. For many stakeholders, including utilities and industries, the high upfront costs can deter adoption, despite the long-term benefits of energy savings and operational efficiency. Governments in emerging economies often face competing priorities, such as energy access and poverty alleviation, which limit their ability to allocate funds for energy efficiency programs. Additionally, access to financing for clean energy projects remains uneven, particularly in regions with underdeveloped financial markets (Eshbayev et al., 2024).

Regulatory and Institutional Barriers

Outdated regulatory frameworks often fail to accommodate the complexities of digital energy systems. Traditional energy regulations were designed for centralized, fossil fuel-based grids and are not equipped to support decentralized, renewable-based systems enabled by digital technologies. For example, regulatory inconsistencies in smart grid deployment, data management, and peer-to-peer energy trading hinder the scalability of digital solutions. In addition, institutional barriers such as fragmented governance, limited policy enforcement, and a lack of systematic evaluation processes impede effective implementation. In many cases, governments lack the capacity to monitor and evaluate the outcomes of energy policies, resulting in inefficiencies and gaps in implementation (Danish & Senjyu, 2023).

Technological and Cybersecurity Challenges

The adoption of digital technologies also faces technical challenges, such as cybersecurity risks, data interoperability issues, and integration complexities. As energy systems become more interconnected, they are increasingly exposed to cyber threats, which can disrupt operations, compromise data, and undermine critical infrastructure. For instance, smart grids rely on IoT-enabled sensors, real-time communication, and cloud-based platforms to monitor and optimize energy flows. While these technologies enhance efficiency, they also introduce vulnerabilities to cyberattacks. Policies need to address these by establishing security standards and encouraging R&D in secure digital systems (Danish & Senjyu, 2023).

Workforce Capacity and Skills Development

The transition to digital energy systems requires a skilled workforce capable of managing, implementing, and maintaining advanced technologies. However, many regions face workforce capacity gaps due to inadequate education and training programs. This challenge is particularly pronounced in emerging economies, where access to technical training and digital literacy programs is limited (Danish & Senjyu, 2023).

5.6 Findings on the Relation between Digitalization and Energy Efficiency

In addition to country specific case study analyses and in order to be able to grasp the relationship between the overall digitalization level of an economy with its energy sector on an international context, two sets of data (IMD World Competitiveness Center, 2024) (Huawei, 2024) were combined and contrasted with another set of data from IEA. The combined two datasets were two separate scores for digitalization level of countries from IMD World Competitiveness Center and Huawei.

The IMD methodology is structured around four primary factors: Economic Performance, Government Efficiency, Business Efficiency, and Infrastructure. Each of these factors is further divided into five sub-factors, culminating in a total of 20 sub-factors. These sub-factors are evaluated using 336 criteria, encompassing both hard data (such as GDP) and soft data (like the availability of competent managers). Notably, each sub-factor contributes equally to the overall ranking, regardless of the number of criteria it contains. In the final assessment, hard data accounts for two-thirds of the overall ranking, while survey data represents one-third.

The Global Digitalization Index by Huawei in collaboration with IDC, provides an evaluation of digital transformation across 77 countries, representing 93% of global GDP and 80% of the world's population. The methodology is structured around four key enablers, namely ubiquitous connectivity, digital foundation, green energy, and

policy and ecosystem, which serve as the foundation for assessing a country's digital maturity. The report measures digital transformation through 42 indicators, covering aspects like fiber and mobile broadband coverage, cloud investment, renewable energy adoption, and ICT policies. The GDI framework emphasizes both the supply (ICT infrastructure and digital services) and demand (technology adoption and economic integration) perspectives, for the sake of ensuring a balanced assessment of digital economies. Their research incorporates data from authoritative sources such as the OECD, ITU, GSMA, World Bank, and various industry reports, enhancing its credibility. The GDI findings highlight a strong correlation between ICT investment and GDP growth, with a one-dollar investment in digital transformation yielding an 8.3-dollar return in the digital economy. By focusing on forward-looking infrastructure development, digital industry expansion, and talent cultivation, the GDI methodology provides a fairly robust and data-driven approach for evaluating national digitalization strategies.

The average of these data was utilized, then it was compared to each country's change in electricity consumption per capita between 2000-2022, to analyze if there is any relationship between two aspects. A fit test was conducted and higher-degree polynomial models were tested to determine if a more complex relationship existed. While these models showed slight improvements in R-squared values, they also introduced issues of multicollinearity and higher p-values, reducing the significance of individual predictors. Therefore, a linear model was chosen as a fair balance between fitness and significance. The results of the conducted fit test and the regression analysis and datasets were presented in Appendix A.

The analysis focused on Europe because countries in this region share similar geographical and geopolitical characteristics. Geographically, Europe's countries experience moderate climates and have relatively equal access to natural resources, creating less variability in energy consumption compared to regions with more extreme conditions. Politically, many European nations are part of the European Union or European Economic Area, which sets unified goals for digital transformation, energy efficiency, and sustainability. Policies like the EU's Digital

Strategy and Green Deal encourage member states to adopt similar approaches to digitalization and energy use, making Europe an ideal region to study these relationships in a more controlled context.

Unlike studies across diverse global regions, where differences in development approaches, income levels, infrastructure, or policy frameworks might obscure patterns, although limited, the relative similarity among European countries ensures that the results focus on the interplay between digitalization and energy consumption. By limiting the scope to Europe, the analysis avoids unnecessary variability, making the findings more reliable and relevant to understanding these trends.

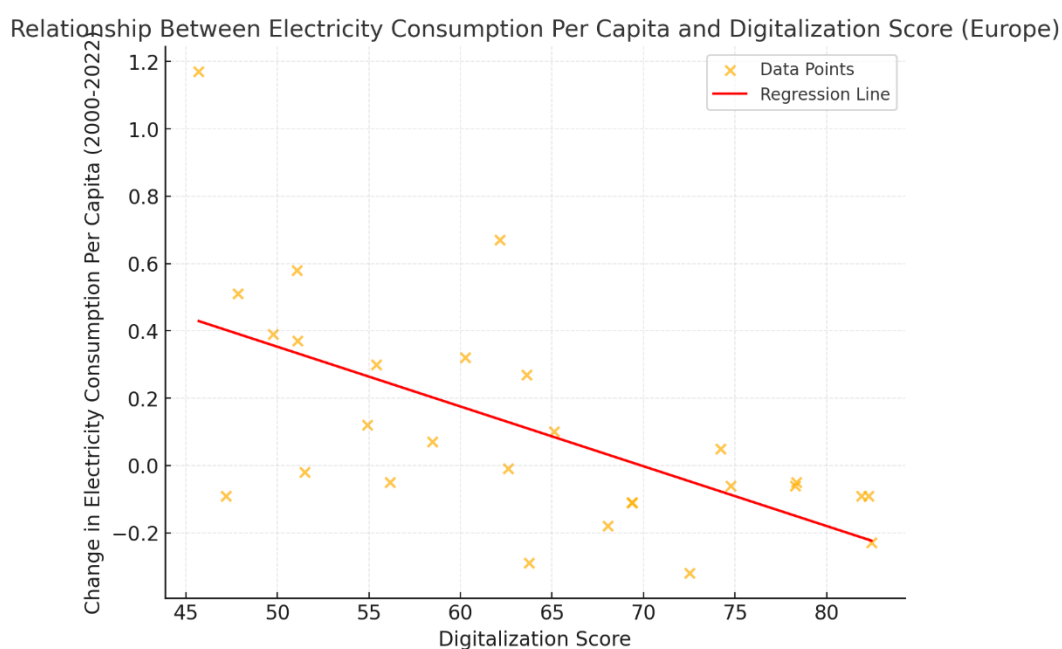


Figure 5.2. Digitalization Score - Energy Consumption per Capita Relation

The relationship between the Digitalization Score and the Change in Electricity Consumption Per Capita in Europe is illustrated in Figure 5.2. The scatter plot displays data points for individual countries, while the regression line highlights the overall trend. The analysis indicates a statistically significant negative relationship ($p < 0.001$), with an R-squared value of 0.382, suggesting that approximately 38.2% of the variance changes in electricity consumption per capita in is explained by digitalization. This negative association implies that as digitalization levels tend to

increase, electricity consumption per capita decreases, likely reflecting that greater energy efficiency is driven by digital technologies.

CHAPTER 6

DISCUSSION

This chapter explores the impact of digitalization on energy efficiency, provided policy recommendations for digital integration, and examined the challenges hindering widespread adoption. Governments can create an enabling environment for digital energy solutions through combining financial incentives, regulatory reforms, public-private collaboration, and workforce development. Addressing economic, technical, and institutional barriers is essential to ensure the successful transition to smarter, more sustainable energy systems.

6.1 Impact of Digitalization on Energy Systems

The role of digitalization in transforming energy systems cannot be overstated. By integrating advanced technologies such as smart grids, IoT-enabled systems, Artificial Intelligence (AI), and blockchain, digitalization enhances energy efficiency across production, transmission, and consumption processes. These technologies allow for precise monitoring, real-time optimization, and automated energy management, leading to significant reductions in energy waste, operational inefficiencies, and carbon emissions.

As global energy demands continue to rise, driven by industrialization, urbanization, and population growth, traditional energy systems face mounting challenges. Aging infrastructure, reliance on fossil fuels, and inefficiencies in energy transmission exacerbate environmental and economic pressures. Digitalization offers a solution to these challenges by enabling smarter, more efficient energy systems that align with global sustainability goals.

The findings of the regression analysis conducted under this study show a clear negative relationship between a country's digitalization score and the change in electricity consumption per capita. This means that as digitalization increases, electricity consumption per capita tends to decrease. The model explains 38.2% of the variation in electricity consumption, suggesting that digitalization plays a significant role in driving more efficient energy use. Overall digitalization level of a country highly likely includes aspects that increase the efficiency in consumption as much as digital technology utilization in energy systems among others. As a deduction, it can be strongly argued that this outcome aligns with the idea that digital technologies can optimize electricity usage and reduce waste.

These results highlight how digitalization can contribute to energy efficiency in practical terms. As countries adopt more advanced digital tools, they are better equipped to monitor and manage electricity use, reducing unnecessary consumption. The strong link between digitalization and energy efficiency reinforces the importance of integrating digitalization in national and regional strategies.

This section explores how digitalization has improved energy efficiency by enhancing system performance, reducing emissions, and supporting economic growth. It also highlights the role of technological integration in promoting energy sustainability.

6.1.1 Enhanced Monitoring and Optimization of Energy Systems

One of the primary benefits of digitalization is its ability to improve energy efficiency through real-time monitoring and optimization of energy flows. Technologies such as IoT sensors, smart meters, and digital platforms provide granular data on energy production, consumption, and distribution, enabling stakeholders to identify inefficiencies and implement corrective actions promptly.

In industrial processes, for example, IoT-enabled systems monitor energy usage in machinery and equipment, allowing operators to optimize performance and reduce

waste. Real-time data analytics provide actionable insights that improve operational efficiency, lower energy costs, and extend the lifespan of critical assets. As highlighted in the literature, digitalization automates processes such as heating, cooling, and electricity distribution, minimizing energy waste while maintaining performance standards. The integration of AI-driven tools further enhances optimization by enabling predictive analytics and automated decision-making. AI models analyze historical and real-time data to forecast energy demand, detect anomalies, and optimize energy flows. For instance, AI-based energy management systems can adjust heating and cooling in buildings based on occupancy patterns, reducing unnecessary energy consumption without compromising comfort. By combining IoT and AI technologies, energy systems achieve greater precision, responsiveness, and efficiency (Alofaysan et al., 2024).

6.1.2 Reduction of Greenhouse Gas Emissions and Sustainability Gains

Digital technologies play a crucial role in supporting global sustainability efforts by reducing greenhouse gas (GHG) emissions and enabling the integration of renewable energy sources. Traditional energy systems, which rely heavily on fossil fuels, are significant contributors to carbon emissions. Digitalization facilitates the transition to cleaner, more sustainable energy systems by improving grid efficiency, integrating renewable energy, and reducing energy losses.

Smart grids, for example, enable the seamless integration of variable renewable energy sources such as solar and wind into the grid. With digital tools for real-time monitoring and grid balancing, smart grids mitigate the challenges of renewable energy intermittency and ensure stable energy supply. This capability reduces reliance on fossil fuel-based power generation, leading to measurable reductions in carbon emissions. As noted, renewable energy combined with digital innovations, such as smart meters and blockchain, has demonstrated substantial gains in energy efficiency and emissions mitigation (Alofaysan et al., 2024).

Moreover, the use of AI in renewable energy forecasting has improved the accuracy of energy generation predictions. AI models analyze weather patterns, solar radiation, and wind speeds to optimize renewable energy output, ensuring efficient utilization of clean energy resources. These advancements not only enhance energy efficiency but also support long-term sustainability goals by reducing the environmental footprint of energy systems.

6.1.3 Economic Growth and Technological Advancements

Digitalization not only improves energy efficiency but also contributes to economic growth by driving technological innovation and creating new market opportunities. The deployment of smart energy solutions generates demand for advanced technologies, such as energy storage systems, digital twins, and blockchain platforms. This, in turn, stimulates innovation, creates employment opportunities, and enhances energy independence.

For example, investments in smart grid infrastructure have led to the development of technologies that optimize energy distribution, reduce transmission losses, and improve grid resilience. These innovations have significant economic benefits, including cost savings, increased productivity, and reduced operational expenditures. Countries that prioritize digital energy solutions experience enhanced competitiveness in the global market while achieving their energy efficiency targets (Eshbayev et al., 2024).

Furthermore, the adoption of digital technologies fosters the growth of clean energy industries, such as solar photovoltaics, wind energy, and energy storage. Governments and private sector stakeholders benefit from reduced energy costs, increased energy security, and a more resilient energy infrastructure. The economic gains from digitalization are further amplified by its role in reducing energy losses, extending asset lifespans, and minimizing maintenance costs.

6.1.4 Impact on Energy Resilience and Reliability

Another significant impact of digitalization is its ability to improve the resilience and reliability of energy systems. Traditional grids are often vulnerable to disruptions caused by equipment failures, natural disasters, and fluctuating energy demands. Digital technologies address these challenges by enabling predictive maintenance, real-time fault detection, and automated grid management.

For instance, smart grids equipped with IoT sensors continuously monitor grid performance and detect anomalies, such as voltage fluctuations or equipment malfunctions. By identifying issues early, utilities can implement preventive measures to avoid power outages and minimize downtime. Predictive maintenance strategies, powered by AI and digital twins, further enhance grid reliability by forecasting potential failures and scheduling maintenance activities proactively.

The integration of energy storage systems also plays a critical role in enhancing grid resilience. Storage technologies allow excess energy generated from renewable sources to be stored and dispatched during periods of high demand or grid disruptions. By providing backup power and improving load management, energy storage systems contribute to the stability and reliability of energy systems.

The digitalization of energy systems has had a transformative impact on energy efficiency, sustainability, and economic growth. By integrating advanced technologies such as IoT, AI, smart grids, and energy storage systems, digitalization enables real-time monitoring, predictive analytics, and automated optimization of energy flows. These capabilities significantly reduce energy waste, improve operational efficiency, and support the transition to cleaner, more resilient energy systems.

Furthermore, digitalization fosters economic growth by driving innovation, creating employment opportunities, and enhancing energy independence. As countries continue to adopt digital energy solutions, the benefits of improved energy

efficiency, reduced emissions, and enhanced grid reliability will play a critical role in achieving global sustainability goals.

6.2 Policy Recommendations for Digital Integration in Energy Systems

The integration of digital technologies into energy systems offers transformative opportunities for improving energy efficiency, sustainability, and resilience. However, unlocking the full potential of digital energy solutions requires targeted and well-structured policies that address financial, regulatory, and institutional barriers. Drawing insights from successful global case studies and existing research, this section provides policy recommendations that focus on creating an enabling environment for digital integration. These recommendations emphasize financial incentives, regulatory harmonization, workforce development, and collaborative approaches to accelerate adoption and scalability of digital technologies in energy systems.

6.2.1 Financial Incentives for Accelerating Digital Adoption

One of the most significant barriers to digital integration in energy systems is the high upfront cost of implementing advanced technologies such as smart grids, IoT devices, AI-driven platforms, and energy storage systems. Financial incentives are critical for reducing these costs and encouraging stakeholders—particularly in emerging economies—to adopt digital solutions.

Governments can introduce grants, subsidies, and tax incentives to make digital energy technologies more accessible and affordable. These financial tools lower the initial investment burden on utilities, industries, and households, thereby driving adoption at scale. For instance, subsidies for smart meter installations, energy-efficient appliances, and IoT-enabled systems have proven effective in regions that have prioritized energy efficiency (Eshbayev et al., 2024). Additionally, tax credits

for energy-saving technologies encourage businesses to invest in upgrades that improve operational efficiency and reduce energy consumption.

Beyond direct financial incentives, governments can incorporate performance-based incentives to reward stakeholders for achieving measurable energy efficiency gains. For example, energy service companies (ESCOs) can implement energy-saving measures under contracts where financial rewards are tied to actual energy savings. These models align incentives with outcomes, fostering innovation while ensuring cost-effectiveness.

International financial instruments, such as green bonds and concessional loans, can also play a key role in supporting digital energy projects. Green bonds allow governments and corporations to raise funds specifically for sustainable energy initiatives, while concessional loans provide low-interest financing for infrastructure projects in emerging markets. These tools are particularly valuable for addressing financial constraints in regions with limited access to capital (Eshbayev et al., 2024).

6.2.2 Regulatory Harmonization and Standardization

Outdated and fragmented regulatory frameworks are a major barrier to the integration of digital technologies into energy systems. Many existing regulations were designed for centralized, fossil fuel-based grids and do not accommodate the complexities of decentralized, digitally enabled energy systems. Harmonizing regulations and developing consistent standards across regions are essential for enabling the smooth implementation and operation of smart energy solutions.

Governments must establish clear regulatory frameworks that support digital innovation while addressing challenges such as cybersecurity, data privacy, and system interoperability. For example, developing universal standards for IoT-enabled devices, communication protocols, and blockchain-based platforms ensures seamless integration and data exchange between different technologies and systems

(Hrga et al., 2020). Standardization also reduces technical barriers for manufacturers and technology providers, enabling economies of scale and cost reductions.

In addition to technical regulations, policymakers must create legal frameworks that facilitate the adoption of decentralized energy systems. Policies that support peer-to-peer (P2P) energy trading platforms, enabled by blockchain technology, can empower consumers and producers to exchange energy transparently and securely. These platforms promote the democratization of energy systems, improve resource allocation, and incentivize renewable energy adoption.

Furthermore, regulatory reforms should prioritize the integration of cybersecurity measures into digital energy systems. Given the increasing reliance on digital tools, energy infrastructure is becoming more vulnerable to cyber threats. Governments must mandate the implementation of robust encryption protocols, intrusion detection systems, and cybersecurity best practices to protect critical infrastructure and ensure data integrity.

6.2.3 Public-Private Collaboration and Multi-Stakeholder Approaches

Collaboration between governments, the private sector, and technology providers is essential for overcoming barriers to digital integration. Public-private partnerships (PPPs) enable the pooling of resources, expertise, and innovation to implement large-scale energy projects while mitigating investment risks.

Governments can incentivize private sector participation by offering financial guarantees, reducing bureaucratic hurdles, and streamlining approval processes for energy projects. Successful case studies, such as smart grid deployments in the United States and renewable energy programs in the European Union, highlight the importance of public-private collaboration in achieving energy goals (Eshbayev et al., 2024).

Moreover, governments should foster multi-stakeholder approaches that involve utilities, technology companies, research institutions, and civil society organizations

in policy design and implementation. This inclusive approach ensures that policies are responsive to the needs of stakeholders and address real-world challenges effectively.

6.2.4 Workforce Development and Capacity Building

The transition to digitalized energy systems requires a skilled workforce capable of implementing, managing, and maintaining advanced technologies. However, many regions—particularly in emerging economies—face workforce capacity gaps due to insufficient technical training and digital literacy programs. Addressing these gaps is critical for the successful integration of digital solutions.

Governments must invest in education and workforce training programs that equip workers with the technical skills needed to support digital energy systems. Specialized training initiatives in areas such as smart grid management, IoT deployment, AI-based analytics, and cybersecurity are essential for building a capable workforce.

Collaborative efforts between governments, academic institutions, and private sector organizations can provide hands-on training opportunities, apprenticeships, and certification programs. For instance, public-private partnerships can support the development of vocational training programs and capacity-building initiatives tailored to the energy sector.

In addition to technical training, promoting digital literacy among consumers and energy users is essential for fostering acceptance and adoption of digital solutions. Consumer education campaigns can raise awareness about the benefits of smart energy technologies, such as energy savings, cost reductions, and environmental sustainability.

Implementing digital energy solutions requires a coordinated approach that addresses financial, regulatory, and workforce-related challenges. Governments play a central role in creating an enabling environment through financial incentives, regulatory harmonization, and targeted investments in workforce development. Public-private collaboration and multi-stakeholder approaches further strengthen policy implementation by exploiting innovation, resources, and expertise.

By adopting these policy recommendations, countries can accelerate the integration of digital technologies into energy systems, improving energy efficiency, enhancing grid resilience, and supporting long-term sustainability goals.

6.3 Challenges in Adoption and Scalability and Solutions

While digital technologies such as smart grids, IoT-enabled systems, Artificial Intelligence (AI), and blockchain have revolutionized energy systems, their widespread adoption and scalability face significant obstacles. These challenges arise from financial constraints, cybersecurity risks, technological limitations, and institutional barriers. For emerging economies, these barriers are further compounded by resource shortages, weak infrastructure, and competing developmental priorities. Overcoming these hurdles requires comprehensive policy reforms, innovative financial mechanisms, and collaborative approaches to ensure the successful integration of digital energy solutions at scale.

This section explores the key challenges hindering the adoption and scalability of digital technologies and highlights potential pathways to address these issues.

6.3.1 Economic Barriers and High Capital Costs

One of the most prominent challenges in adopting digital technologies is the high upfront cost of upgrading legacy energy systems and implementing new infrastructure. Smart grids, IoT networks, AI-driven platforms, and blockchain

systems require significant financial investments in hardware, software, and workforce training. For many regions, especially emerging economies, these costs represent a substantial barrier to entry.

The implementation of smart grids, for instance, necessitates extensive infrastructure upgrades, including the installation of advanced metering systems, communication networks, and control systems. While the long-term benefits—such as reduced energy losses and improved grid efficiency—are well-documented, the initial capital investment required can deter utilities, governments, and private investors (El Zein & Gebresenbet, 2024).

In emerging economies, financial constraints are exacerbated by limited access to capital and competing development priorities. Governments often prioritize basic infrastructure, such as healthcare and education, over energy system modernization. Moreover, underdeveloped financial markets and lack of investment incentives further hinder the adoption of clean energy technologies (Alofaysan et al., 2024).

To overcome financial constraints, governments must implement innovative financing mechanisms that reduce the economic burden on stakeholders. These mechanisms include:

- **Green Bonds:** Issuing bonds specifically for energy efficiency and smart energy projects can attract investment from institutional investors and international development organizations.
- **Public-Private Partnerships (PPPs):** PPPs enable governments to share investment risks with private companies, blending in their expertise and resources to implement large-scale digital energy projects. PPPs have been instrumental in financing smart grid infrastructure and clean energy innovation in both developed and emerging economies.
- **Feed-in Tariffs (FITs) and Incentives:** Financial incentives such as feed-in tariffs, tax credits, and performance-based subsidies encourage industries and households to adopt energy-efficient technologies. FITs provide guaranteed payments to producers of renewable energy, ensuring project viability.

For emerging economies, concessional loans and grants from international financial institutions, such as the World Bank and International Monetary Fund (IMF), can provide much-needed capital to kick-start digital energy initiatives.

6.3.2 Cybersecurity and Data Vulnerabilities

The increasing reliance on digital technologies in energy systems introduces significant cybersecurity risks. Digital tools, such as IoT sensors, smart meters, and AI-driven platforms, rely on real-time data collection, storage, and communication. While these tools enable dynamic grid management and energy optimization, they also expose critical infrastructure to cyber threats. Cyberattacks on energy systems can have severe consequences, including grid disruptions, data breaches, and compromised energy security. Many utilities lack the technical capacity and resources to implement robust cybersecurity measures, leaving energy systems vulnerable to attacks. Furthermore, the absence of standardized cybersecurity protocols exacerbates these risks, particularly in decentralized energy systems where data is exchanged across multiple platforms and stakeholders.

Measures to address cybersecurity challenges:

- **Cybersecurity Standards:** Developing robust cybersecurity frameworks and encryption protocols is critical for protecting digital energy systems. Governments should establish regulations mandating cybersecurity requirements for utilities and technology providers.
- **Interoperability Research:** Supporting R&D efforts to develop universal standards for IoT, smart grids, and blockchain platforms ensures integration and system interoperability. This ensures consistency across regions and reduces vulnerabilities in interconnected energy systems.
- **Digital Resilience Programs:** Governments should invest in programs that enhance the resilience of digital energy systems against cyber threats, natural disasters, and technical failures. Strategies to identify, prevent, and respond

to cyberattacks, including regular security audits and penetration testing can be adopted.

Policies may also promote collaboration between governments, technology providers, and cybersecurity experts to develop and implement best practices for secure digital energy systems.

6.3.3 Technological Integration and Interoperability Issues

The integration of digital technologies into existing energy systems poses technical challenges, including interoperability issues and infrastructure limitations. Many energy systems, particularly in developing regions, rely on outdated infrastructure that is incompatible with modern digital tools. Upgrading legacy systems to accommodate smart grids, IoT devices, and blockchain platforms requires significant investments and technical expertise.

Interoperability issues arise when different technologies, platforms, and devices are unable to communicate or exchange data seamlessly. This lack of standardization hampers the scalability of digital solutions and creates inefficiencies in energy management.

To address interoperability challenges, policymakers must prioritize the development of universal standards for digital energy systems. These standards should cover:

- **Communication Protocols:** Ensuring that IoT-enabled devices, smart meters, and grid control systems can communicate effectively.
- **Data Management Frameworks:** Establishing guidelines for data collection, storage, and sharing to improve system integration and operational efficiency.
- **Compatibility with Legacy Systems:** Supporting the gradual modernization of energy infrastructure while ensuring compatibility with existing technologies.

Investments in research and development (R&D) are essential to drive innovation and develop scalable solutions that address technical barriers. Collaborative efforts between governments, technology providers, and research institutions can accelerate the deployment of interoperable, cost-effective digital energy systems.

6.3.4 Institutional and Governance Challenges

Institutional barriers, such as fragmented governance structures, lack of policy coordination, and limited technical capacity, hinder the implementation of digital energy solutions. In many regions, energy policies are outdated, inconsistent, or poorly enforced, creating uncertainty for stakeholders and investors.

Moreover, weak institutional frameworks in emerging economies often result in fragmented decision-making, with responsibilities distributed across multiple agencies and levels of government. This lack of coordination delays project implementation and reduces policy effectiveness.

To address these challenges, policymakers may focus on:

- **Developing Interoperability Standards:** Establishing universal communication protocols and technical standards ensures seamless integration of smart grids, IoT devices, and blockchain systems. Standardization improves system interoperability and enables different technologies to interact efficiently.
- **Streamline Regulatory Processes:** Simplify approval processes for digital energy projects to reduce bureaucratic delays and encourage private sector participation.
- **Streamlining Policy Enforcement:** Governments must strengthen institutional capacity to enforce energy efficiency regulations and monitor compliance. This includes investing in digital infrastructure for real-time monitoring and evaluation.

- **Supporting Decentralized Energy Systems:** Regulatory reforms should encourage the adoption of decentralized energy markets, such as peer-to-peer trading platforms enabled by blockchain. These reforms create an enabling environment for innovation while protecting consumer interests.
- **Enhance Policy Coordination:** Establish centralized agencies or task forces to oversee the implementation of energy efficiency and digitalization programs.
- **Build Technical Capacity:** Invest in training programs and technical assistance to strengthen the capabilities of government agencies and institutions.

6.3.5 The Environmental Effect of Digitalization

When the relationship between digital technology adoption and carbon emission intensity is analyzed, both direct and indirect effects of digital technology on carbon emissions are observed, which vary depending on the industry and country context. While the digital technologies industry itself may not be inherently environmentally friendly, it contributes to reducing carbon emission intensity through cross-industry and cross-border technology spillovers. The overall impact of digital technology innovation combined with technological spillover is a reduction in carbon emission intensity. Among the factors influencing carbon emission intensity, domestic backward and forward spillover effects are the most significant contributors to emission reductions. However, the reduction effects of international technology spillover are not as robust as expected. Overall, digital technologies seem to offer a net benefit in terms of reducing carbon footprint (Wang et al., 2021). To improve this net outcome, policies' focus can be on increasing investments in research and development (R&D) and introducing intellectual property to improve the technological sophistication; adjusting the industrial and energy consumption structures for lower carbon emitting means; and transitioning from heavy industry to a service-oriented industrial structure.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Summary of Findings

This research aimed to examine the role of digital technologies in improving energy efficiency across production, transmission, and consumption systems while evaluating their implications for energy policies. A comprehensive analysis was conducted through an interdisciplinary lens, supported by a systematic literature review, case studies from developed and emerging economies, and policy evaluations.

The findings of this study emphasize the transformative potential of digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), smart grids, blockchain, and digital twins in enhancing energy systems' efficiency, sustainability, and resilience. Digital innovations significantly contribute increasing energy efficiency, reinforcement the reliability of energy transmission, and helping the establishment of sustainable energy systems.

Digital tools such as IoT-enabled devices and AI-based analytics significantly improve real-time energy monitoring, fault detection, and optimization across energy systems. Predictive maintenance, enabled by AI and digital twins, reduces equipment downtime, minimizes energy losses, and enhances operational efficiency in production systems. Smart grids facilitate demand response, dynamic load balancing, and renewable energy integration, leading to reductions in energy transmission losses and emissions.

Policies such as carbon pricing, renewable energy incentives, and public R&D investments have been instrumental in driving innovation and adoption of clean energy technologies.

The EU's Energy Efficiency Directive and the US Smart Grid Investment Grant demonstrate how integrated policy frameworks and financial incentives can accelerate energy transitions. Emerging economies face challenges related to financial constraints, institutional gaps, and infrastructure limitations, but they also present significant opportunities for adopting renewable-based, decentralized energy systems. Major challenges include high capital costs, cybersecurity risks, lack of standardization, and institutional inefficiencies. Addressing these barriers requires innovative financing mechanisms, robust cybersecurity frameworks, and workforce capacity-building initiatives.

The EU and the US serve as leading examples of effective policy implementation, smart grid deployment, and technological innovation. Emerging economies, despite barriers, have the transform their traditional energy systems by resorting to localized solutions, international funding, and clean energy technologies. However, the risks and vulnerabilities regarding the digitalization in the energy systems should not be overlooked and must be thoroughly discussed and addressed.

In summary, this research highlights that digitalization is a critical enabler of energy efficiency and decarbonization goals. By aligning technological advancements with policy frameworks and addressing adoption barriers, digital technologies can support sustainable energy transitions globally.

7.2 Implications for Policy and Practice

The study provides several actionable insights for policymakers, industry stakeholders, and researchers seeking to accelerate the adoption of digital technologies in energy systems. The following recommendations are offered to address barriers, promote innovation, and maximize the benefits of digitalization:

1. Financial Incentives and Investment Strategies

Subsidies and Tax Incentives: Governments should introduce targeted subsidies and tax credits to reduce the financial burden of adopting smart grids, IoT devices, and

energy management systems. This is particularly critical for industries and small-to-medium enterprises (SMEs) in emerging economies.

Green Bonds and Public-Private Partnerships (PPPs): Financial tools such as green bonds and concessional loans should be utilized to mobilize resources for large-scale digital energy projects. PPPs can play a key role in sharing investment risks and accelerating technology deployment.

Performance-Based Financing: Incentives tied to measurable energy savings encourage private-sector innovation and ensure cost-effective outcomes.

2. Regulatory Reforms and Standardization

Policy Harmonization: Governments must modernize regulatory frameworks to address the complexities of digital energy systems. This includes creating clear guidelines for renewable energy integration, decentralized trading, and cybersecurity.

Standardized Protocols: Developing universal standards for IoT systems, blockchain platforms, and digital twins will ensure interoperability, scalability, and smooth integration into existing energy systems.

Cybersecurity Governance: Establishing mandatory security protocols, encryption measures, and continuous monitoring mechanisms is critical to safeguarding energy infrastructure from cyber threats.

Use of digitalization for policies: The vast data gathered through adopted smart infrastructure and consolidated via digital technologies offer opportunities for the policymakers to make much more advanced, tailored and to-the-point policy decisions to be utilized.

3. Supporting Decentralized Energy Systems

Peer-to-Peer Energy Markets: Blockchain-based platforms should be supported to facilitate transparent, decentralized energy trading. These systems democratize energy markets and encourage renewable energy adoption.

Microgrid Development: Governments should invest in microgrids and off-grid energy systems to improve energy access in remote, underserved and low-income areas, particularly in emerging economies.

4. Capacity Building and Workforce Development

Technical Training Programs: Specialized education and training programs are essential to equip the workforce with skills for managing and implementing digital energy technologies (e.g., smart grids, IoT, AI, and blockchain).

Public Awareness Campaigns: Promoting digital literacy among consumers fosters acceptance of smart meters, automated demand response, and other digital solutions.

5. Facilitating International Collaboration

Developed countries and international financial institutions must support emerging economies through funding, knowledge-sharing, and technology transfer to bridge the digital divide.

Collaborative research initiatives can accelerate innovation and enable the development of localized, cost-effective solutions tailored to regional challenges.

Following table shows the research background of each recommendation:

Table 7-1 Recommendations

Recommendation	Background
1. Financial Incentives and Investment Strategies	The literature, especially by Eshbayev et al. evidentially concludes that digital technology adoption lead to better results in both energy systems and environmental effect and along discusses the importance of governments' financing initiatives to establish the increasing of such utilization. Sani et al. Has similar deductions. Building upon their recommendations from best policy practices, the study deducts the most effective ways to achieve that objective.

Table 7-1 (Continued)

Recommendation	Background
2. Regulatory Reforms and Standardization	Multiple references including Angelo & Chan, Eshbayev et al. and Sani et al. discuss and/or conclude on the crucial nature of robust regulatory frameworks, which was also confirmed when the EU's vast regulatory structure is studied and compared to the progress achieved. The study deduces from the developed country examples and builds upon those with recommendations on utilization of these technologies and their outcome for more effective policies.
3. Supporting Decentralized Energy Systems	The importance of smart and decentralized grids for better environmental results appear to be a widely recognized trend throughout the literature including policies. The recommendations within the study were constructed on research by Majeed Butt et al., Zhang et al., Difulio et al., Van Summeren et al. etc., Cali et al. IEA reports and policy practices from both developed and developing countries.
4. Capacity Building and Workforce Development	Most recommendations within the literature, on both technology and policies include the essential nature of addressing the digital skills gaps for effective implementation. Accordingly, all of the studied policies incorporate measures to mitigate digital divide. Two sub-recommendations appear to be two widely recognized tools to accomplish this target.
5. Facilitating International Collaboration	Whereas part of the existing research including Wang et al., Huang et al., Van Summeren et al., Aloffaysan et al. attribute importance to collaborative efforts, this initiative was recommended as a scaled-up version of the successful policies by the EU, as in the international cooperation within the EU helped approximating the desired environmental results, therefore international collaboration on a wider scale can improve the global performance.

As there are recurring themes within the existing research, only some studies are used within the table as examples.

7.3 Limitations and Future Research Directions

While this study provides comprehensive insights into the role of digital technologies in improving energy efficiency, several limitations must be acknowledged:

1. Data Availability and Regional Focus

The study relied on secondary data sources, which may not fully capture regional disparities and localized challenges, particularly in emerging economies. Future research should involve primary data collection through interviews, surveys, and case studies for more granular insights.

2. Rapid Technological Advancements

Digital technologies such as AI, blockchain, and IoT are evolving rapidly, leading to continuous changes in their applications and impacts. Longitudinal studies are needed to assess the long-term effects and scalability of these technologies.

3. Policy Implementation Challenges

While the study identifies policy recommendations, the effectiveness of these measures depends on governance, institutional capacity, and stakeholder collaboration. Future research should evaluate the implementation and outcomes of specific policy interventions.

4. Environmental Trade-Offs

The energy consumption of digital tools, such as blockchain and IoT devices, raises concerns about their environmental impact. Research should focus on balancing energy savings with the carbon footprint of digital technologies.

5. Cybersecurity and Data Related Risks

Digitalization presents significant risks to energy security. Future research should also explore international collaborations and opportunities to mitigate relevant threats and vulnerabilities to cyberattacks, as well as explore the role of policy tools and legislative regulations in addressing these issues.

6. Quantitative Analysis on Effects of Policies and Digitalization

The findings of the regression analysis within the study should be interpreted with some caution. The analysis is limited to Europe, a region with relatively similar policies and economic conditions, which should be applied to other parts of the world with fitting merits, taking the varying development approaches into consideration. Future studies could explore this relationship in other regions or examine how additional factors, such as renewable energy integration or level of emissions interact with digitalization. Moreover, by the time of the research, the inclusion of digitalization specific actions in the country policies was rather limited and the timing was premature to be able to conduct any sort impact analysis that would yield numeric results and allow for any sort of country level comparison. Therefore, as such policies become more widespread and numeric results occur, further research can be conducted to comprehend which policy approaches lead to model energy digitalization initiatives with better environmental impact.

On a larger scale, following aspects need initiative for data creation:

- **Impact Assessment of Emerging Technologies:** Future studies should explore the potential of new technologies such as quantum computing, advanced energy storage, and digital twins in optimizing energy systems.
- **Regional Case Studies:** Conducting comparative analyses across diverse regions, including Africa, South Asia, and Latin America, will provide deeper insights into localized challenges and opportunities.
- **Consumer Behavior and Digital Solutions:** Research should examine how digital tools influence consumer behavior and promote energy-saving practices.
- **Environmental Impact of Digitalization:** Evaluating the life-cycle emissions of digital technologies will help identify strategies for minimizing their environmental footprint.

7.4 Conclusion

This dissertation has demonstrated the transformative role of digital technologies in enhancing energy efficiency, supporting sustainable energy transitions, and informing policy frameworks. By addressing economic, technological, and institutional barriers, digital tools such as smart grids, AI, IoT, and blockchain have the potential to revolutionize energy systems globally.

The study highlights the importance of governmental interventions, such as financial incentives, regulatory reforms, public-private partnerships, and capacity building in enabling the adoption of digital energy solutions. While challenges remain—particularly in emerging economies—targeted policies and international cooperation can bridge gaps, promote innovation, and ensure equitable access to sustainable energy systems.

Future research should focus on exploring emerging technologies, assessing long-term impacts, and addressing environmental trade-offs to maximize the benefits of digital energy integration. By continuing to advance digital solutions and supportive policies, stakeholders can achieve energy efficiency, resilience, and sustainability goals, paving the way for a smarter, cleaner energy future.

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APPENDICES

A. Subject Data and Regression Analysis

Gathered Data

Table 7-2 Gathered Data for Regression Analysis

Countries	Region	Stage	GD I Sco re	IM D Sco re	Digitalizati on Score	Change in Electricity consumpti on per capita (2000- 2022)
Argentina	America	Emerging	36,5	44,6	40,55	32,00%
Australia	Other	Developed	67,6	81,2	74,4	-4,00%
Austria	Europe	Developed	57,3	72,9	65,1	10,00%
Bahrain	Gulf	Emerging	44,7	68,8	56,75	26,00%
Belgium	Europe	Developed	60,5	75,6	68,05	-18,00%
Brazil	America	Emerging	44,8	48,9	46,85	44,00%
Bulgaria	Europe	Emerging	46,5	49,2	47,85	51,00%
Canada	America	Developed	61,3	83,2	72,25	-16,00%
Chile	America	Emerging	49,5	61,7	55,6	68,00%
China	Asia	Emerging	69,2	82,6	75,9	516,00%
Colombia	America	Emerging	39,9	48,2	44,05	95,00%
Croatia	Europe	Emerging	46,7	55,4	51,05	58,00%
Czechia	Europe	Emerging	49,1	67,8	58,45	7,00%
Denmark	Europe	Developed	71,8	92	81,9	-9,00%
Estonia	Europe	Developed	54,1	73,1	63,6	27,00%
Finland	Europe	Developed	73	83,6	78,3	-6,00%
France	Europe	Developed	62,2	76,6	69,4	-11,00%
Germany	Europe	Developed	63,4	75,3	69,35	-11,00%
Greece	Europe	Emerging	49,9	53,1	51,5	-2,00%
Hungary	Europe	Emerging	48,9	50,6	49,75	39,00%
India	Asia	Emerging	40,3	51,8	46,05	182,00%
Indonesia	Asia	Emerging	33,1	61,4	47,25	230,00%
Ireland	Europe	Developed	68,1	80,3	74,2	5,00%
Italy	Europe	Developed	50,2	62,1	56,15	-5,00%
Japan	Asia	Developed	58,8	68,1	63,45	-6,00%
Kazakhstan	Asia	Emerging	33,2	66,4	49,8	70,00%

Table 7-2 (Continued)

Countries	Region	Stage	GD I Score	IM D Score	Digitalization Score	Change in Electricity consumption per capita (2000-2022)
Korea	Asia	Developed	60,5	88,6	74,55	92,00%
Kuwait	Gulf	Emerging	43	56,9	49,95	20,00%
Lithuania	Europe	Emerging	48,7	75,6	62,15	67,00%
Luxemburg	Europe	Developed	58	69,5	63,75	-29,00%
Malaysia	Asia	Emerging	49,9	65,5	57,7	84,00%
Mexico	America	Emerging	39,6	46,2	42,9	97,00%
Netherlands	Europe	Developed	69,7	87	78,35	-5,00%
New Zealand	Other	Developed	65,6	67,4	66,5	-16,00%
Norway	Europe	Developed	64,9	84,6	74,75	-6,00%
Peru	America	Emerging	38,7	41,8	40,25	136,00%
Philippines	Asia	Emerging	34,9	45,2	40,05	74,00%
Poland	Europe	Emerging	47,8	63	55,4	30,00%
Portugal	Europe	Developed	54,4	66,1	60,25	32,00%
Romania	Europe	Emerging	49	53,2	51,1	37,00%
Saudi Arabia	Gulf	Emerging	54,4	71,6	63	93,00%
Singapore	Asia	Developed	76,1	100	88,05	34,00%
Slovakia	Europe	Emerging	43,7	50,7	47,2	-9,00%
Slovenia	Europe	Developed	48,1	61,7	54,9	12,00%
South Africa	Africa	Emerging	43,4	50,5	46,95	-21,00%
Spain	Europe	Developed	54,3	70,9	62,6	-1,00%
Sweden	Europe	Developed	74,5	90,4	82,45	-23,00%
Switzerland	Europe	Developed	71,4	93,2	82,3	-9,00%
Thailand	Asia	Emerging	47,2	65,5	56,35	99,00%
Türkiye	Europe	Emerging	41,4	50	45,7	117,00%
United Arab Emirates	Gulf	Emerging	61,4	84,1	72,75	37,00%
United Kingdom	Europe	Developed	66,8	78,2	72,5	-32,00%

Table 7-2 (Continued)

Countries	Region	Stage	GDI Score	IMD Score	Digitalization Score	Change in Electricity consumption per capita (2000-2022)
United States	America	Developed	78,8	91,3	85,05	-7,00%

Utilized Data

Table 7-3 Utilized data for regression analysis

Countries	Region	GDI Score	IMD Score	Digitalization Score	Change in Electricity consumption per capita (2000-2022)
Austria	Europe	57,3	72,9	65,1	10,00%
Belgium	Europe	60,5	75,6	68,05	-18,00%
Bulgaria	Europe	46,5	49,2	47,85	51,00%
Croatia	Europe	46,7	55,4	51,05	58,00%
Czechia	Europe	49,1	67,8	58,45	7,00%
Denmark	Europe	71,8	92	81,9	-9,00%
Estonia	Europe	54,1	73,1	63,6	27,00%
Finland	Europe	73	83,6	78,3	-6,00%
France	Europe	62,2	76,6	69,4	-11,00%
Germany	Europe	63,4	75,3	69,35	-11,00%
Greece	Europe	49,9	53,1	51,5	-2,00%
Hungary	Europe	48,9	50,6	49,75	39,00%
Ireland	Europe	68,1	80,3	74,2	5,00%
Italy	Europe	50,2	62,1	56,15	-5,00%
Lithuania	Europe	48,7	75,6	62,15	67,00%
Luxemburg	Europe	58	69,5	63,75	-29,00%
Netherlands	Europe	69,7	87	78,35	-5,00%
Norway	Europe	64,9	84,6	74,75	-6,00%
Poland	Europe	47,8	63	55,4	30,00%
Portugal	Europe	54,4	66,1	60,25	32,00%
Romania	Europe	49	53,2	51,1	37,00%
Slovakia	Europe	43,7	50,7	47,2	-9,00%
Slovenia	Europe	48,1	61,7	54,9	12,00%
Spain	Europe	54,3	70,9	62,6	-1,00%

Table 7-3 (Continued)

Countries	Region	GDI Score	IMD Score	Digitalization Score	Change in Electricity consumption per capita (2000-2022)
Sweden	Europe	74,5	90,4	82,45	-23,00%
Switzerland	Europe	71,4	93,2	82,3	-9,00%
Türkiye	Europe	41,4	50	45,7	117,00%
United Kingdom	Europe	66,8	78,2	72,5	-32,00%

Fit Test Results

In the process of determining the most appropriate regression model to analyze the relationship, a fit test was conducted across multiple polynomial degrees, ranging from a simple linear model to a cubic and quartic model.

Initially, a simple linear regression was performed, which resulted in an R-squared value of 0.382, indicating that 38.2% of the variation in electricity consumption changes was explained by digitalization scores. The p-value for the Digitalization Score coefficient was 0.000460, showing strong statistical significance. Higher-degree polynomial models were tested to determine if a more complex relationship existed. While these models showed slight improvements in R-squared values, they also introduced issues of multicollinearity and higher p-values, reducing the significance of individual predictors.

The linear model had the lowest p-value, indicating that Digitalization Score was a statistically significant predictor of electricity consumption changes. Polynomial models, particularly cubic and quartic models, exhibited high condition numbers, suggesting strong multicollinearity, which can lead to unreliable coefficient estimates. A more complex model may fit the data better but risks overfitting and reduced generalizability to new observations. Given the balance between fit and statistical significance, the linear regression model provided the most robust and interpretable results.

Table 7-4 Results of the fit test

Polynomial Degree	R-squared	Max p-value (excluding constant)	Condition Number (Multicollinearity Indicator)
1 (Linear)	0.382	0.000460	367
2 (Quadratic)	0.425	0.104	155
3 (Cubic)	0.432	0.583	75,800,000
4 (Quartic)	0.461	0.621	123,000,000

Table 7-5 Residuals

Countries	Digitalization Score	Change in Electricity consumption per capita (2000-2022)	Predicted Change in Electricity Consumption	Residuals
Austria	65,1	10,00%	0,084	0,016
Belgium	68,05	-18,00%	0,032	-0,212
Bulgaria	47,85	51,00%	0,391	0,119
Croatia	51,05	58,00%	0,334	0,246
Czechia	58,45	7,00%	0,203	-0,133
Denmark	81,9	-9,00%	-0,214	0,124
Estonia	63,6	27,00%	0,111	0,159
Finland	78,3	-6,00%	-0,150	0,090
France	69,4	-11,00%	0,008	-0,118
Germany	69,35	-11,00%	0,009	-0,119
Greece	51,5	-2,00%	0,326	-0,346
Hungary	49,75	39,00%	0,357	0,033
Ireland	74,2	5,00%	-0,077	0,127
Italy	56,15	-5,00%	0,243	-0,293
Lithuania	62,15	67,00%	0,137	0,533
Luxemburg	63,75	-29,00%	0,108	-0,398
Netherlands	78,35	-5,00%	-0,151	0,101
Norway	74,75	-6,00%	-0,087	0,027
Poland	55,4	30,00%	0,257	0,043
Portugal	60,25	32,00%	0,171	0,149
Romania	51,1	37,00%	0,333	0,037
Slovakia	47,2	-9,00%	0,402	-0,492
Slovenia	54,9	12,00%	0,266	-0,146

Table 7-5 (Continued)

Countries	Digitalization Score	Change in Electricity consumption per capita (2000-2022)	Predicted Change in Electricity Consumption	Residuals
Spain	62,6	-1,00%	0,129	-0,139
Sweden	82,45	-23,00%	-0,223	-0,007
Switzerland	82,3	-9,00%	-0,221	0,131
Türkiye	45,7	117,00%	0,429	0,741
United Kingdom	72,5	-32,00%	-0,047	-0,273

Regression Analysis Results

Dependent Variable: Change in Electricity Consumption Per Capita (2000-2022)

Independent Variable: Digitalization Score

Summary Statistics:

- R-squared: 0.382 (38.2% of the variation in Change in Electricity Consumption Per Capita is explained by the Digitalization Score.)
- Adjusted R-squared: 0.358 (After adjusting for the number of predictors, the model retains significant explanatory power.)
- F-statistic: 16.05 (p-value = 0.00046) (The overall model is statistically significant.)

Coefficients:

Table 7-6 Coefficients

Variable	Coefficient	Standard Error	t-statistic	p-value	Confidence Interval (95%)
Constant	1.240	0.286	4.339	<0.001	[0.653, 1.827]
Digitalization Score	-0.0178	0.004	-4.006	0.000460	[-0.027, -0.009]

Interpretation:

- The constant (2.478) represents the estimated change in electricity consumption per capita when the Digitalization Score is zero.
- The coefficient for Digitalization Score (-0.0295) indicates that for every one-point increase in Digitalization Score, the Change in Electricity Consumption per Capita decreases by approximately 0.0295 units.
- The p-value (<0.001) confirms the statistical significance of this relationship.

Model Diagnostics

- Durbin-Watson Statistic: 2.436 - Suggests some positive autocorrelation in the residuals, which should be considered in future analyses.
- Omnibus Test (Normality of Residuals): Prob(Omnibus): 0.74 - Indicates that residuals are approximately normally distributed.

Formula Used in the Model

$$\text{Change in Electricity Consumption Per Capita} = 1.24 - 0.0177 \times \text{Digitalization Score}$$