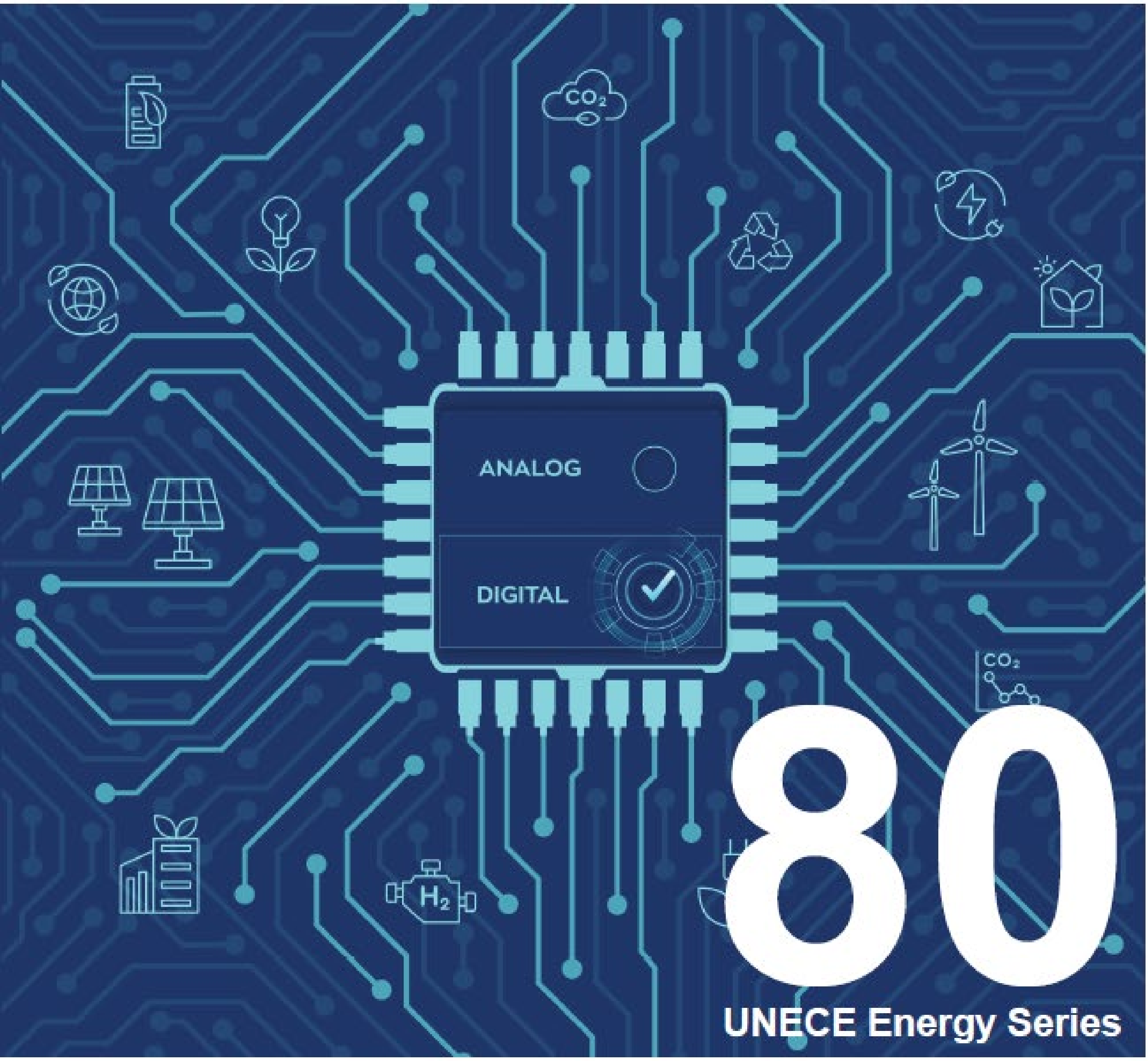
UNECE

Compendium of Case Studies on Digitalization in Energy in the UNECE Region



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COMPENDIUM OF CASE STUDIES ON DIGITALIZATION IN ENERGY IN THE UNECE REGION

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FOREWORD

The increasing complexity of the energy sector due to growing decentralized intermittent generation, the influx of electric vehicles, and other smart assets at the grid edge, requires a combination of digital innovations to manage it.

Digitalization, as a catalyst for expeditious and more effective action for decarbonization and achieving Sustainable Development Goal 7 and other Goals of the 2030 Agenda for Sustainable Development, offers new ways of looking at many energy challenges and finding innovative ways to address them. The digital transformation of the energy sector serves as an enabler to increased systemic efficiency, optimization of energy resource use and costs, and cleaner electricity systems. It is also instrumental for finding a policy balance between energy security, access to affordable, reliable, sustainable and modern energy services, and the environmental sustainability of energy use through the transformation of energy governance

As we stand at the crossroads of technological innovation and environmental responsibility, this compendium of case studies on digitalization in energy within the United Nations Economic Commission for Europe (UNECE) region highlights the critical role of advanced digital technologies in addressing many contemporary challenges that the energy system faces.

This compendium contains selected examples of digital transformation in the energy systems, from grid management and cybersecurity to the adoption of smart meters and artificial intelligence. The range of topics covered illustrates the breadth of opportunities digitalization offers to improve energy efficiency and accessibility. As the result of collaborative efforts by a diverse group of experts, the publication also identifies key barriers that need to be addressed for broader adoption of the available solutions.

These case studies are not merely technical discussions but reflect the broader governance frameworks necessary to effectively manage digital energy transformations, in line with the decisions taken at the seventieth session of the Commission under its high-level theme, “Digital and Green Transformations for Sustainable Development in the Region of the Economic Commission for Europe”. The UNECE Task Force on Digitalization in Energy has played a significant role in guiding this collective effort, and this work serves as a valuable source for policymakers, energy professionals, and stakeholders involved in steering the energy sector towards a more digital, sustainable, and inclusive future.

As we navigate the complexities of the transformation of the energy systems, the insights gathered in this publication are designed to support critical decisions that will shape our collective energy future, ensuring that digitalization contributes meaningfully to resilient and sustainable energy systems in the UNECE member States in line with their developmental aspirations.

T. Molcean

Tatiana MOLCEAN

Executive Secretary
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The present compendium of case studies on digitalization in energy in the United Nations Economic Commission for Europe (UNECE) region, is the outcome of the activities of the Task Force on Digitalization in Energy in 2023–2024 under a dedicated research track that envisaged the development of national case studies. These activities aimed at increasing awareness of the member States on the role that digitalization of the energy system may play in improving system efficiency, of existing sectoral opportunities and of the potential impact of digitalization in energy on the economy and society, through applying UNECE recommendations on digitalization contained in the body of work of the Task Force on Digitalization in Energy since its establishment in 2020.

The following case studies, developed under general oversight by the Chair of the Group of Experts on Energy Efficiency, Stefan M. Buettner (Institute for Energy Efficiency in Production), guidance from the Co-Chairs of the ECE Task Force on Digitalization in Energy, Elizabeth Massey (The Energy Authority) and Andrei Covatariu (Energy Policy Group), and overall supervision and secretariat support by Igor Litvinyuk, UNECE Sustainable Energy Division, are included in the present composite work under the respective Chapters 1-5:

1. *Governance policy of digitalization in energy (2024).*[1] The case study was originally presented at the eleventh session of the Group of Experts on Energy Efficiency (Geneva, 16-17 September 2024). Piyush Verma (United Nations Development Programme (UNDP) Sustainable Energy Hub) is the lead author of the chapter "Governance dynamics in the digital transformation of the energy system", supported by Daria Asmolova (UNDP Chief Digital Office), Dorin Toma and Maria Tarigradean (UNDP Moldova), Maria Knodt and Christelle Odongo-Braun (UNDP Bureau for Policy and Programme Support), and Kestutis Kupsys (European Economic and Social Committee). Alexey Tulikov (Russian Energy Agency) is the lead author of the national case study "Policy approaches for governance of digitization and digital transformation in the fuel and energy complex", supported by Kamil Aminov (Ministry of Energy of the Russian Federation), and Julia Stebakova and Alexander Lukashov (Russian Energy Agency). The established team of ten members of the UNECE Task Force on Digitalization in Energy were invited to review and provide inputs to various chapters of the document at various stages of research; valuable inputs were provided notably by Ana Trbovic (Grid Singularity), Sylvain Clermont (DigiTransfo Expertise), Roberto Monaco (Technical University of Denmark), and Alexander Pombo (Partisia Blockchain Foundation).
2. *Balancing the electricity supply and demand with Artificial Intelligence (2024).*[2] The case study was originally presented at the eleventh session of the Group of Experts on Energy Efficiency (Geneva, 16-17 September 2024). Sylvain Clermont is the lead author of the case study, supported by Serge Fortin (independent expert, electric network planning), Daniel Vézina (Hydro-Québec), Stéphane Dellacherie (Hydro-Québec), and Sean Ratka (United Nations Economic and Social Commission for Western Asia). Valuable inputs at various stages of research were provided by the other members of the UNECE Task Force on Digitalization in Energy.

[1] See: https://unece.org/sed/documents/2024/09/informal-documents/governance-policy-digitalization-energy-sector

[2] See: https://unece.org/sed/documents/2024/08/informal-documents/balancing-electricity-supply-and-demand-artificial

3. *Grid edge management reference architecture and policy recommendations for interoperability and resilience (2023).*[3] The case study was originally presented at the tenth session of the Group of Experts on Energy Efficiency (Geneva, 5-6 October 2023). Ana Trbovich (Grid Singularity) is the lead author of the case study, supported by Brian O Regan (International Energy Research Centre, Tyndall National Institute), Deval Pandya (Vector Institute), and Ioannis Vlachos and Andres Schondube (Energy Web Foundation). Valuable inputs at various stages of research were provided by other members of the UNECE Task Force on Digitalization in Energy.
4. *Cyber resilience of critical energy infrastructure (2023).*[4] The case study was originally presented at the tenth session of the Group of Experts on Energy Efficiency (Geneva, 5-6 October 2023). Andrei Covatariu (Energy Policy Group; Co-Chair of the ECE Task Force on Digitalization in Energy) is the lead author of the case study, supported by Elizabeth Massey (The Energy Authority, Co-Chair of the ECE Task Force on Digitalization in Energy), Sylvain Clermont (DigiTransfo Expertise), Erlijn van Genuchten (Sustainable Decisions), Romanas Savickas (UNEP Copenhagen Climate Centre), and Fabian Heymann (Swiss Federal Office of Energy). Valuable inputs at various stages of research were provided by other members of the UNECE Task Force on Digitalization in Energy.
5. *Behavioural barriers in adoption of smart meters (2024).*[5] The case study was originally presented at the eleventh session of the Group of Experts on Energy Efficiency (Geneva, 16-17 September 2024). Erlijn van Genuchten (Sustainable Solutions) is the lead author of the case study, supported by Alina Mia Udall (University of Warwick), Sudha Setty (Melyoura), and Romanas Savickas (UNEP Copenhagen Climate Centre). Valuable inputs at various stages of research and review were provided by other members of the UNECE Task Force on Digitalization in Energy, including Brian O Regan (International Energy Research Centre, Tyndall National Institute), Sofie Schoenborn (Technical University of Munich), Roberto Monaco (Technical University of Denmark), and Dr Marta Ra (Women in Sustainable Finance).

Accuracy of content of the case studies is the sole responsibility of the authors.

Discussion about the transformative role of digitalization across various energy sectors beyond electricity (Chapter 6) is premised on the informal document The twin transition in non-electricity sector (GEEE-11/2024/INF.6)[6] facilitated by Jose Angel Leiva Vilaplana (Technical University of Denmark) as part of a collaborative effort under general oversight and guidance from Andrei Covatariu (Energy Policy Group), Co-Chair of the ECE Task Force on Digitalization in Energy.

[3] See: https://unece.org/sustainable-energy/publications/digitalization-energy-case-study-grid-edge-management-reference

[4] See: https://unece.org/sustainable-energy/publications/digitalization-energy-case-study-cyber-resilience-critical-energy

[5] See: https://unece.org/sed/documents/2024/08/informal-documents/behavioural-barriers-adoption-smart-meters

[6] See: https://unece.org/sed/documents/2024/08/informal-documents/twin-transition-non-electricity-sector

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ACRONYMS AND ABBREVIATIONS

AEMO	-	Australian Energy Market Operator
AI	-	Artificial Intelligence
AMI	-	Advanced metering infrastructure
AMP	-	Africa Minigrids Program
CENTS	-	Cooperative Energy Trading System
CISA	-	Cybersecurity and Infrastructure Security Agency
CSC	-	Community Self Consumption (energy market management model)
DDoS	-	Distributed denial-of-service
DER	-	Distributed energy resources
DEWA	-	Dubai Energy and Water Authority
DLT	-	Distributed ledger technology
DoS	-	Denial-of-service
EDGE	-	Energy Demand and Generation Exchange (project)
EV	-	Electric vehicle
EVRF	-	Energy Vulnerability Reduction Fund
FBI	-	Federal Bureau of Investigation
FEC	-	Fuel and energy complex
FSP	-	Flexibility service providers
GDP	-	Gross domestic product
HPC	-	High performance computing
HQ	-	Hydro-Québec
HVAC	-	Heating, ventilation, air conditioning
ICC	-	Industrial competence centre
IEC	-	International Electrotechnical Commission
IoT	-	Internet of Things
IT	-	Information technology
ML	-	Machine learning
MSS	-	Microgeneration support scheme
NIST	-	National Institute of Standards and Technology
P2M	-	Peer-to-Market (indirect transactions with peers via select market)
P2P	-	Peer-to-Peer (direct transactions among peers)
PMU	-	Phasor measurement units
PV	-	Photovoltaics
QAMF	-	Quality Assurance and Monitoring Framework
R&D	-	Research and development
RES	-	Renewable energy sources
SCADA	-	Supervisory control and data acquisition
SIS FEC	-	State information system of the fuel and energy complex
SV DT FEC	-	Strategic vector of digital transformation in FEC until 2030
TE	-	Transactive Energy
EU	-	European Union
UAE	-	United Arab Emirates
ECE	-	United Nations Economic Commission for Europe
UNDP	-	United Nations Development Programme
UNEP	-	United Nations Environment Programme
EUR	-	Euro
RUB	-	Russian Ruble
USD	-	United States Dollar

EXECUTIVE SUMMARY

This publication examines the impact of digital technologies on the energy sector, focusing on the dynamics in the United Nations Economic Commission for Europe (UNECE) region and its member States. The publication sheds light on the systemic efficiency potentials that can be unlocked with the use of digital tools; it highlights the opportunities and benefits that such tools provide to empower energy end users and to increase the transparency of operations and transactions, along with challenges to the realization of the potentials energy system optimization enabled by digitalization and the threats that it might bring.

It further discusses how digitalization is being integrated into energy governance frameworks, providing real-world examples of UNECE member States implementing technologies to enhance energy system performance, expand access to energy, and address environmental and economic challenges. Case studies illustrate the range of digital solutions being applied, from load balancing and behavioural changes to creating new business models and increasing stakeholder participation through renewable energy integration and establishment of peer-to-peer trading platforms. The studies also emphasize the importance of building cyber-resilient infrastructures.

A crucial role in managing the complexities of digital transformation in the energy sector, is played by effective governance. The case studies underscore the need for strong regulatory frameworks to ensure secure and inclusive adoption of digital solutions. Strategic approaches to digitalizing the energy sector focus on fostering innovation, enhancing cybersecurity, maintaining regulatory oversight, addressing the digital divide, and harmonizing regulatory standards, also amid the growing role of energy prosumers.

Case studies contained in the publication provide concrete examples of digitalization in action across different national and regional contexts.

INTRODUCTION

United Nations Economic Commission for Europe (UNECE) recognizes that digital solutions not only optimize energy systems but also enhance transparency, efficiency, and resilience, all of which are critical for addressing the contemporary energy challenges and accelerating the transition to more sustainable energy systems. UNECE has been at the forefront of integrating digitalization into energy governance and policy frameworks.

UNECE work on Digitalization in Energy is led and coordinated by the Task Force on Digitalization in Energy, established by the Committee on Sustainable Energy in 2020 under the Group of Experts on Energy Efficiency (ECE/ENERGY/133). Serving as an umbrella for the subsidiary bodies of the Committee on Sustainable Energy to conduct relevant research and assess sectoral opportunities and challenges, the Task Force works closely with policymakers to develop governance and policy frameworks in this domain and their integration in a broader energy landscape.

This publication responds to the request by the Committee on Sustainable Energy contained in the Revised publication plan for 2023 and draft publication plans for 2024 and 2025 (ECE/ENERGY/2023/3) and forms part of the Work Plan of the Group of Experts on Energy Efficiency for 2024-2025 (ECE/ENERGY/2023/10).

The publication contains six thematic chapters that present related case studies and concludes with a set of recommendations.

1. GOVERNANCE POLICIES FOR DIGITALIZATION IN THE ENERGY SECTOR

1.1 Introduction and rationale

The challenge of climate change is prompting diverse approaches to the global energy transition across different regions:

- Europe largely focuses on integrating renewable energy sources (RES) and achieving net-zero emissions;
- North America emphasizes energy independence and innovation in clean technologies;
- Sub-Saharan Africa and many developing regions prioritize sustainable expansion of access to electricity;
- In Asia, the primary goal is to meet the rapidly increasing energy demand sustainably, balancing economic growth with environmental considerations.

Digitalization has the potential to revolutionize energy systems by optimizing energy production, distribution, and consumption through advanced technologies like smart grids, Internet of Things (IoT), blockchain, and Artificial Intelligence (AI) / Machine Learning (ML). These technologies offer real-time data management and analytics, improving energy efficiency and reliability while supporting a more seamless integration of RES, including by enabling new business models in demand response and peer-to-peer local and flexibility trading. From a governance perspective, digitalization can improve transparency and accountability, ensure equitable access to energy including citizen participation in energy markets, engaging a broader range of stakeholders in decision-making processes and addressing the needs and aspirations of all segments of society, including the most vulnerable.

Viewing the digital transformation of the energy system through a governance lens is essential to navigate the emerging opportunities and challenges of an increasingly distributed energy market. By adopting a proactive approach, governance can harness digital technologies to improve monitoring, forecasting, and decision-making processes, ensuring that the energy transition is both efficient and inclusive. This approach also provides the flexibility to adapt to emerging challenges, such as data privacy concerns, the digital divide, low standardization and compatibility across different technologies and regions, the difficulty of balancing rapid innovation with the need for effective regulation, the need for digital and energy literacy and new skills and expertise, environmental concerns related to digital technologies, and the necessity for strong cybersecurity measures. Effective governance must navigate these complexities to harness the full potential of digital technologies while safeguarding the interests of all stakeholders.

Therefore, the digital transformation of energy systems presents a unique intersection of technological advancement and governance innovation. By leveraging digital tools within a robust energy governance framework, stakeholders can achieve a more resilient, secure, sustainable, and inclusive energy future.

1.2 Governance dynamics in the digital transformation of the energy system

In the complex global context, the United Nations Development Programme (UNDP) has developed an energy governance framework that underscores the importance of effective, inclusive, and accountable governance of the energy transition globally.[7] This framework recognizes that digitalization facilitates transparency, enhances stakeholder participation, and ensures that energy policies are more coherent, effective, and responsive to the needs of all people and communities. Therefore, the integration of digital technologies as tools to improve governance outcomes is a key component of the framework. Current trends in energy digitalization

Energy digitalization is transforming the energy landscape, driven by several key trends and technologies:[8]

- Smart grids are being implemented, enhancing grid reliability and efficiency by using digital technology to monitor and manage electricity flows in real time;
- IoT devices, such as smart meters and sensors, enable real-time data collection and analytics, improving energy management and operational efficiency, especially when providing granular, asset-level measurements;
- AI and ML are used to predict energy demand, optimize supply, and enhance fault detection, enabling better data-driven decision-making and cost reductions;
- Blockchain technology is facilitating a more secure, transparent albeit privacy-embedded and efficient energy data management and information exchange among different energy market participants, while also enabling automated, efficient peer-to-peer energy exchange;
- Energy storage systems, such as advanced batteries and thermal storage, are being integrated with digital platforms using cloud computing and big data analytics, as well as increasingly AI and blockchain, to optimize energy storage and distribution, balance supply and demand, and enhance grid stability.

These technological advancements are not only reshaping the energy sector but also influencing the dynamics among stakeholders:

- Stakeholder dynamics are evolving, with traditional stakeholders like utility companies and government agencies rapidly adapting by investing in digital technologies and upskilling their workforce. New entrants, including technology companies and startups specializing in Big Data, AI, IoT, blockchain, renewable energy firms, energy storage innovators, other software developers, and financial institutions focusing on green investments, are bringing innovative solutions to the market. This shift is redefining roles, responsibilities, and interactions within the energy sector, driving a more collaborative and integrated approach to governance.
- A more customer- and citizen-centric energy landscape is emerging as digitalization empowers consumers and prosumers to have greater control over their energy use and a more active energy market participation through digital platforms and smart devices. Citizens can now make more informed choices, promoting energy efficiency and sustainability and increasingly engaging in demand response and local energy trading.

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[7] See: https://www.undp.org/publications/strengthening-energy-governance-systems-energy-governance-framework-just-energy-transition

[8] See: https://unece.org/sites/default/files/2020-12/GEEE-7.2020.INF_.3.pdf

- Importantly, digitalization empowers prosumers – households or communities that both produce and consume energy – by owning or leasing distributed energy generation, such as solar panels and wind turbines, which is managed and optimized via smart technologies. This shift not only promotes decentralized energy trading and enhances market transparency but also contributes to more resilient and democratized energy systems, allowing citizens to actively participate in the energy market and influence how energy is produced and distributed.

Regulatory frameworks are evolving to support the digital transformation of the energy market:

- Policy evolution is increasingly oriented toward a user-centric approach, driven by digital technologies that enable better monitoring, peer-to-peer energy trading, and dynamic pricing models. Regulators are facing the new challenge of developing frameworks that encourage innovation while ensuring grid stability and consumer protection, data privacy, and cybersecurity.
- Regulatory adaptation includes creating incentives for digital investments, addressing challenges like cybersecurity risks, and ensuring the integration of digital technologies aligns with grid reliability and resilience. However, these measures are still not fully implemented, presenting a significant challenge for regulators to ensure a smoother transition towards a digitalized, decentralized, and decarbonized energy system. Establishing clear standards and fostering a more supportive environment will be essential to achieving this goal and bridging the gap between the opportunities provided by new technologies and the current legislative framework.

The changing energy landscape underscores the importance of a robust governance framework to manage these transformations effectively. Digitalization brings both opportunities and challenges, and by adopting a governance lens, stakeholders can navigate the complexities, ensuring that digital advancements contribute to a resilient, sustainable, and equitable energy future. By implementing robust governance frameworks, stakeholders can ensure that digital technologies are deployed responsibly, protecting sensitive data, maintaining security, and fostering inclusivity. This approach not only harnesses the full potential of digitalization but also drives progress while safeguarding public trust and promoting broader societal benefits.

1.3 Digitalizing energy governance: key considerations

In the evolving landscape of energy, digitalization serves a dual purpose: it enhances energy governance mechanisms while also requiring stringent governance over the digital components themselves. Digital tools can significantly improve the efficiency, effectiveness, transparency, and responsiveness of energy systems, as seen with smart grids that leverage real-time data to optimize energy distribution, balance loads, and reduce wastage. However, implementing these tools across regions presents challenges, particularly in areas with limited infrastructure or regulatory support.

As digital technologies become more embedded in energy systems, the need for strong governance frameworks becomes increasingly critical. These frameworks must address crucial issues such as cybersecurity, data privacy, and the ethical use of technology. The collection of sensitive data on consumer behaviour and energy usage by digital tools underscores the importance of maintaining consumer trust and adhering to regulatory standards. Yet, rapid digitalization can outpace governance, potentially leading to gaps in oversight and unintended consequences that could undermine the related benefits.

Furthermore, the governance of digital components is vital to ensuring that these technologies are deployed effectively and responsibly within energy projects. Establishing clear cybersecurity policies and standards is paramount, especially as energy grids become more interconnected, thus vulnerable to cyber threats. Effective governance also involves ensuring data integrity and transparency, enabling stakeholders to rely on the information provided by digital systems. However, governance must be careful not to stifle innovation, as overly stringent regulations could hinder the adoption of new technologies that could otherwise enhance energy systems.

As emerging technologies such as AI and IoT are being integrated into energy systems, governance must ensure that these innovations are effectively aligned with traditional energy infrastructures, enhancing their overall performance and compatibility. A smooth transition to new technologies requires a governance approach that balances risk mitigation with the encouragement of innovation. By fostering an environment where digital advancements integrate seamlessly with existing systems, this forward-thinking strategy will contribute to a more efficient, resilient, and sustainable energy landscape. Effective governance of digital technologies in energy policies and projects requires a balanced strategy that promotes technological progress while protecting against potential risks. This ensures that energy systems remain secure, transparent, and aligned with the highest ethical and regulatory standards.

Following are the key four key components to work upon while ensuring the effective governance of a digitalized energy system:

1. Inclusive and effective institutions. Digitalization plays a pivotal role in transforming energy governance institutions to be more inclusive, effective, and aligned with the goals of a just energy transition. Advanced data analytics optimize decision-making by providing deep insights into energy consumption patterns, forecasting future needs, and ensuring that resources are allocated efficiently and equitably. Digital tools also help institutions bridge the gap between urban and rural, especially remote areas, enabling the extension of energy services to underserved populations and promoting universal access to sustainable energy. By leveraging digital platforms, energy institutions can foster greater public participation, allowing diverse stakeholders to contribute to policy-making processes and ensuring that the transition is not only technologically advanced but also socially equitable. Furthermore, digitalization facilitates continuous learning and adaptation within institutions, enabling them to respond quickly to emerging challenges and integrate innovative solutions. By creating a more transparent, participatory, and adaptive governance framework, digital tools empower institutions to lead a just energy transition that is responsive to the needs of all communities and resilient to future disruptions.
2. Policy and regulatory frameworks. Digital tools are revolutionizing policy-making and regulatory frameworks in the energy sector by enabling more agile, data-driven, and coherent approaches that can swiftly adapt to a fast-evolving landscape. Advanced blockchain-enabled data management combined with AI-enabled data processing capabilities provide national regulatory authorities with increased granularity and accuracy of data from operators, allowing them to monitor individual network components and manage their interaction more effectively. This enhanced visibility reduces information asymmetry between regulators and operators, as well as service providers that are dependent on granular data access, offering a comprehensive overview of network performance and enabling a more competitive and advanced market services. Notably, regulators can innovate their frameworks by developing new incentive schemes that

promote proactive network management and drive efficient operations. Additionally, digital platforms enable real-time updates to regulatory frameworks, ensuring they remain relevant as new technologies and trends emerge and grow, such as renewable integration and decentralized systems. At times they also require a novel market design, transitioning from centralized to bottom-up asset-level energy management. These platforms also democratize the regulatory process by broadening stakeholder engagement, ensuring that policies are socially equitable and inclusive. By enhancing transparency and accountability, digitalization strengthens trust in the governance process, making energy policies more responsive and forward-looking.

3. Civic engagement and empowerment. Digitalization significantly enhances civic engagement in energy governance by enabling broader public participation through tools like social media, online platforms, and virtual forums. These platforms democratize access to information, empowering citizens with the knowledge to make informed decisions and advocate for sustainable energy practices. Moreover, they facilitate real-time feedback, allowing governments and energy companies to tailor policies and services to community needs, fostering a more responsive governance system. Digital tools also enable the creation of local energy cooperatives or communities that take control of their energy use and actively participate in the energy markets, driving grassroots innovations and increasing individual contribution to the energy transition. Additionally, by enhancing transparency and accountability through interoperable and informative data platforms, digitalization ensures that energy governance remains aligned with public interests, paving the way for more equitable and sustainable energy systems. This shift not only empowers communities but also bridges the gap between policy and practice, making energy governance more inclusive and adaptive to future challenges.
4. Appropriate and independent oversight. Integrating digital tools into the oversight mechanisms of the energy sector significantly enhances their effectiveness and independence. Real-time monitoring and advanced reporting systems enable continuous oversight of energy production, distribution, and consumption, allowing for the early detection and resolution of issues. Decentralized blockchain-based energy asset data management results in higher system interoperability and more effective value chain management, with higher transparency and security of data, whilst ensuring privacy. AI and ML further can elevate the auditing process by identifying anomalies and inefficiencies with precision, enabling predictive analytics to anticipate risks. Digital public transparency mechanisms, such as online dashboards and open data initiatives, provide oversight bodies and civic organizations with accessible, actionable information, fostering higher standards of accountability and public trust. Furthermore, institutions such as anti-corruption agencies, human rights organizations, and consumer protection agencies can leverage digital tools to play a more effective oversight role in the energy transition. These institutions can use digital platforms to track and report unethical practices, ensure that energy policies respect human rights, and protect consumer interests by monitoring pricing and service quality. By facilitating independent data verification and creating platforms for open scrutiny, digital tools ensure that oversight institutions, including these critical agencies, remain impartial and robust, upholding the principles of transparency, fairness, and integrity in energy governance.

1.4 Examples of projects integrating digital innovations into energy governance

This section presents examples that highlight the digital transformation of energy systems across different regions and national contexts. These projects provide valuable insights into the challenges faced, strategies employed, and outcomes achieved in integrating digital technologies into energy governance. By examining these real-world examples, one can derive lessons that inform future efforts in enhancing the resilience, efficiency, and inclusiveness of energy systems.

1.4.1 Specialized digital tools and solutions for minigrids (Africa)

1.4.1.1 Background and context

RES-based minigrids, especially solar-battery minigrids, present a significant opportunity to provide electricity to 490 million people globally,[9] with a significant focus on sub-Saharan Africa. This opportunity is driven by declining hardware costs, advances in digital technologies, and innovative private sector business models. However, scaling minigrids faces challenges, particularly in mobilizing private sector investment and navigating the multitude of stakeholders with different interests, who are often lacking coordination. As a result, the minigrid market in Africa remains underdeveloped, with most investments heavily reliant on grants and patient capital. This dependency is largely due to the significant upfront capital expenditures and the low ability and willingness of customers to pay for electricity. Achieving true scalability in this sector would require securing substantial commercial financing, particularly through commercial debt. However, obtaining such financing would depend on improving the economic viability of the business model.

The ongoing Africa Minigrids Program (AMP) is designed to address these challenges by supporting clean energy access and promoting commercial investment in minigrids across 21 African countries.[10] The programme, aligned with the UNDP Digital Transformation framework, involves a broad coalition of stakeholders, and aims to establish a conducive environment for substantial private investment in minigrids and to enhance financial viability and scale up investment by focusing on cost-reduction strategies and innovative business models, which will benefit end-users through lower tariffs and improved service.

1.4.1.2 Digital initiatives

AMP has a distinctive chance to encourage the adoption and utilization of digital tools within the sector and can also curate and promote existing specialized digital tools and solutions tailored to the off-grid and minigrid sectors.[11] AMP includes:

- A digital strategy to improve minigrid scalability using specialized tools and solutions, informed by national digital readiness assessments tailored to the minigrid subsector. This activity involves developing a regional digital strategy aimed at improving the scalability of minigrids through the use of specialized digital tools and solutions. National-level project digital strategies specific to each participating country will then be developed in alignment with the regional digital strategy, and following the conduction of national digital readiness assessments tailored to the minigrid subsector. The importance of this

[9] See: https://openknowledge.worldbank.org/server/api/core/bitstreams/32287154-1ccb-46ce-83af-08facf7a3b49/content
[10] See: https://www.undp.org/energy/our-flagship-initiatives/africa-minigrids-program
[11] See: https://www.undp.org/digital/transformations

output lies in its potential to streamline operations, reduce costs, and facilitate the deployment of minigrids on a larger scale, thereby accelerating access to reliable electricity in underserved areas.

- A framework for data security and consumer protection, along with a standardized Quality Assurance and Monitoring Framework (QAMF) for minigrid pilots Standardization of data and data collection protocols, applied to all AMP minigrid pilots, and disseminated across the minigrid sector. This focuses on developing a framework for data security and consumer protection, which will support data security across the entire minigrid sector. Additionally, this output includes the creation of a standardized QAMF for the minigrid pilots implemented across the programme, ensuring consistent quality and performance monitoring. Here again, a tailored national-level QAMF will be derived from the standardized one in each participating country to take into account national specificities. Ensuring strong data security and consumer protection is crucial for building trust among users and stakeholders, while the QAMF will ensure that minigrid projects maintain high data quality standards, leading to more reliable and sustainable energy solutions.
- A regional digital platform to aggregate data from national projects, facilitating seamless integration and coordination. Data from AMP minigrid pilots will be aggregated digitally at national and regional level, creating value for the sector through insights and regional learning. This involves setting up a regional digital platform designed to aggregate data collected by national digital platforms, thus facilitating seamless data sharing and coordination. The importance of this platform lies in its ability to provide – through the alignment of all national projects with the programme-level QAMF – a unified view of data across multiple projects, enhancing collaboration, improving decision-making, and enabling more effective management and monitoring of minigrid systems.
- The development of a standardized, aggregated dataset to enhance energy access planning and support informed decision-making across the sector. Demonstration of automated data analysis for minigrid development, builds on the standardized, aggregated dataset developed in the previous activity, presenting an important opportunity to enhance informed decision-making and strategic planning for expanding energy access through minigrids. The importance of this standardized dataset is that it enables policymakers, planners, and developers to base their strategies on accurate, up-to-date information, leading to more effective and targeted interventions to improve energy access in remote and underserved regions.
- Digital advocacy and communication tools to enable and facilitate national policy dialogues for AMP national projects. Through its regional-level community of practice and the various inclusive multi-stakeholder platforms and fora established at national level, AMP aims to sensitize key actors of the minigrid sector on the opportunities offered by digitalization. This is further achieved by developing and disseminating suitable knowledge tools as different use cases are implemented, to demonstrate benefits and lessons learnt.

1.4.1.3 Lessons learned to date

The following preliminary observations can be made from this ongoing project, acknowledging that it is still in the early stages of digital tools implementation, with limited lessons learned at this point:

- Effective planning and thorough understanding of the landscape prior to digital tools implementation. It is important to assess the varying levels of awareness and competing interests among stakeholders – such as government, developers, and financiers – regarding data and digitalization in the minigrid sector. This is why sector-specific digital readiness assessments were included at the national level in AMP. Extensive consultations are crucial for aligning expectations, building consensus, and ensuring that digital solutions are adequately integrated and supported across the sector.
- Balancing standardization with customized national solutions. While standardization is essential for ensuring interoperability and scalability, it is equally important to develop tailored digital solutions at the national level that align with these standards. Additionally, a holistic approach is crucial in creating linkages between the various aspects of minigrid deployment supported by digitalization – such as planning, tendering, operations, and monitoring – to maximize synergies and enhance overall system integration.

Recommendations for other regions or countries considering similar initiatives are yet to be documented in future publications, as more time is needed to assess how these approaches work in practice. Additionally, identifying priority investment areas and providing insights into future mini and micro-grid policy support, particularly in rural and high-energy-burden areas, remains an important task.

Further research is also required as to how minigrids could benefit from local energy trading and trading between different minigrids, including identification of obstacles that will likely include insufficient asset-level measurement data required to enable these new business models that can further harness the local energy potential.

1.4.2 Energy vulnerability reduction fund and smart metering (Republic of Moldova)

1.4.2.1 Background and context

Energy landscape in the Republic of Moldova is marked by significant challenges, primarily due to its heavy dependence on energy imports.

In 2022, the Republic of Moldova faced a substantial increase in gas prices due to tightening global energy markets and a newly amended contract with its gas supplier, Gazprom. During the heating period, the Republic of Moldova purchased gas at prices approximately three times higher than in previous periods, a surge which put considerable strain on public finances and on the ability of the most vulnerable households to afford gas throughout the winter. The rising gas prices created a domino effect, driving up the cost of other goods and increasing the risks of not only energy poverty but also food poverty in both rural and urban areas of the Republic of Moldova.

The energy crisis compounded the challenges posed by the COVID-19 pandemic and the associated health crisis, which had significantly impacted the economy of the Republic of Moldova, resulting in a 5 per cent drop in gross domestic product (GDP) in 2022, all while 31.1 per cent of the population was living below the national poverty line.

The war in Ukraine further deepened the energy crisis and has led to a 30 per cent reduction in gas supply and a price increase combined with high inflation rates. The Republic of Moldova was further impacted by the attacks on the electricity generation facilities in Ukraine, which were covering approximately a third of electricity demand of the Republic of Moldova.

As a result, in 2022, more than 71 per cent of the households in the Republic of Moldova were in the most vulnerable energy category and the early income simulation by UNDP suggested that, under the prevailing food and energy inflation levels, approximately 250,000 people were at risk of falling below the poverty line. These circumstances have placed energy vulnerability and poverty at the forefront of policy debates in the Republic of Moldova.

1.4.2.2 Digital initiatives

Energy Vulnerability Reduction Fund

To address the urgent energy crisis in the Republic of Moldova, the Government, with technical support from UNDP, designed and implemented the Energy Vulnerability Reduction Fund (EVRF, Law 241/2022) – an evidence-based, on-bill compensation scheme to minimize the negative impact of energy inflation on households.

The objective of EVRF is to compensate energy-poor and vulnerable households for the increase in centralized heating, natural gas, and electricity tariffs, with the overall aim to create an inclusive solution that minimizes the negative impacts on energy-vulnerable and income-poor households, therefore safeguarding social cohesion. At the same time, in the longer term, EVRF aims to incentivize the transition towards sustainable energy sources and to achieve higher levels of energy efficiency in the residential sector.

A digital platform to register and process requests for on-bill compensation for energy-related expenses was put in place and launched in October 2022.[12] The registration process was implemented using a simple administrative procedure, relying on administrative data, and requiring minimal confirmation from beneficiaries. The system balanced targeting efficiency with a reduced administrative burden, ensuring that even those who did not register received compensation by default under the low energy vulnerability category. This inclusiveness was foundational to the architecture of EVRF, ensuring substantial coverage of the poor and vulnerable.

EVRF offered on-bill compensations for 895,000 households during the 2022/2023 heating season (75 per cent of households in the Republic of Moldova) and for 757,600 households during 2023/2024 (preliminary data).

While most of the funding was provided directly to the Government of the Republic of Moldova by the European Union, nearly USD 30 million was channelled through UNDP interventions funded by Sweden, Switzerland, and Italy. To bridge the digital divide, UNDP established a dedicated Support Unit within the Ministry of Labour and Social Protection to provide in-person, online, and phone consultations to the beneficiaries of EVRF.

Smart metering infrastructure pilot for electricity

An important initiative involves installing smart meters to enhance energy flow monitoring, identify commercial losses, improve distribution quality, and reduce operational costs.

[12] Online application platform for the EVRF energy compensation programme, available at: https://compensatii.gov.md/en#program

The pilot initiative, led by the Ministry of Energy of the Republic of Moldova with support from UNDP Moldova and the Italian Government, aims to install 35,000 smart meters across the country, representing approximately 3 per cent of the total electricity consumers in the Republic of Moldova.

The initiative began with the installation of 3,000 smart meters in Chișinău and its suburbs. These initial installations were carried out by system operators, Premier Energy Distribution in Chișinău and six suburbs, and by RED Nord in the northern region, including Bălți. The initiative has since expanded to cover additional regions, including rural areas.

The households selected for this pilot are chosen based on criteria such as geographical location, population density, energy vulnerability, socio-economic status, and infrastructure availability.

The smart meters measure consumption at short intervals, track energy quality parameters, and transmit data automatically and securely to the energy supplier, eliminating the need for manual readings by distribution company employees. This system ensures billing is based on actual energy consumption rather than estimates and allows distributors to identify and respond to accidents more swiftly. The system's ability to gather real-time remote data facilitates the development of dynamic pricing models aimed at optimizing consumption patterns.

Smart meters also enhance grid security by swiftly detecting irregularities, from minor faults to major outages, allowing for rapid response and minimizing downtime. The detailed consumption data gathered enables more efficient energy resource management, preventing grid overloads and optimizing supply to meet demand.

The smart metering infrastructure employs Power Line Communication technology, which uses power lines and electronic communication operators to transmit data to a central unit for analysis. This centralized data will help monitor consumer behaviour relative to energy prices and aid in policy development.

These meters provide critical technical information that enhances the monitoring of energy flows, identification of commercial losses, and quality of distribution services, while reducing operational costs and impacting electricity distribution tariffs.

In Bălțiul Nou, RED Nord has also replaced overhead power lines with underground networks to improve safety. With smart grids, customers can choose flexible tariffs, and smart appliances can automatically read tariffs from the meter to optimize usage times. Data from this programme will inform new policies for efficient consumption, and the UNDP and the European Union (EU) are exploring technical solutions for nationwide application, including smart meter installation and the "Rabla for household appliances" programme.

1.4.2.3 Lessons learned

Since its operationalization, EVRF successfully reached a broad spectrum of households, significantly alleviating the financial burden of energy costs for vulnerable families in the Republic of Moldova, allowing these households to allocate resources to other essential expenses, thereby improving their overall quality of life.

According to the 2023 UNDP impact assessment of EVRF,[13] the compensations reduced the level of energy poverty by 43 per cent and had the greatest impact on the most vulnerable families. The results of EVRF are confirmed by the recent economic update of the World Bank,[14] which concludes that EVRF reduced the potential poverty impact of energy price shocks by 8 percentage points (limiting the increase in poverty rate from 28 per cent pre-crisis – to 35 per cent, versus 43 per cent without EVRF).

These outcomes were achieved through substantial policy and programmatic support from UNDP, based on a timely assessment of energy poverty conducted in early 2022.[15] The evaluation provided critical insights and recommendations for EVRF, highlighting the need for a more integrated and nuanced approach. It emphasized the importance of establishing robust data governance frameworks and enhancing internal evaluation capacities to ensure data integrity and accuracy.

The journey of the Republic of Moldova towards European Union integration presents both challenges and opportunities in the energy sector, particularly in enhancing energy efficiency and security while improving services for all citizens, especially vulnerable groups. The focus for the continued support shall be on addressing energy security and poverty, promoting comprehensive, co-designed solutions that consider the interconnectivity and feedback loops shaping the future of the energy sector in the Republic of Moldova.

Forward-thinking solutions include the digital transformation of the energy sector, energy efficiency, decarbonization policies, and energy-saving technologies. These initiatives will involve experimenting with new business models, expanding energy sandboxes, promoting renewable energy, supporting community-owned renewable energy cooperatives, fostering public-private partnerships, and securing sustainable finance for renewable energy and climate-resilient infrastructure.

These examples underscore that digital transformation is not just about providing access but also about ensuring that access leads to meaningful improvements in people's lives.

Building on the successes and lessons learned from EVRF, efforts will focus on enhancing its impact by integrating the approach into a broader, digitalized national social protection system. Establishing a robust Data Governance Framework is essential for managing data assets, ensuring consistency, security, and reliability across all levels of governance, and sustaining the momentum of digital transformation to achieve long-term, system-wide improvements. This strategic approach, has the potential of streamlining processes, enhancing service delivery, and improving decision-making through real-time data analytics.

[13] UNDP Moldova, September 2023, The Impact Assessment of the Energy Vulnerability Reduction Fund in the Winter of 2022–2023, available at: https://www.undp.org/moldova/publications/impact-assessment-energy-vulnerability-reduction-fund-winter-2022-2023

[14] World Bank, April 2024, Moldova Economic Update. Special section: Energy affordability, available at: thedocs.worldbank.org/en/doc/d1372d2b12612d7eb259fa07d6270de7-0080012024/original/Moldova-Economic-Update-2024-ENG.pdf

[15] UNDP Moldova, September 2022, Report on Energy Poverty Assessment and Support Mechanisms in the Republic of Moldova, available at: https://www.undp.org/moldova/publications/report-energy-poverty-assessment-and-support-mechanisms-republic-moldova

1.4.3 The prosumer model (Lithuania)

Introduced in 2019, innovative prosumer scheme allows consumers in Lithuania to produce their own electricity, contributing to the country's electricity grid, thereby enhancing energy security, promoting RES, and supporting climate change mitigation efforts. This example offers valuable lessons on integrating principles of energy governance into practical, actionable policies. By focusing on innovation, flexibility, and inclusivity, Lithuania not only advances its own energy security but also contributes to global environmental goals.

1.4.3.1 Key features and systemic innovations

The approach taken in Lithuania includes several pioneering features:

- Nation-wide remote production and (self)consumption: The grid functions as a 'virtual battery,' storing and distributing energy nationwide;
- Digital accessibility: Becoming a prosumer is streamlined through digital platforms, simplifying the process and eliminating paperwork;
- Subsidies while prioritizing private investment: Initial subsidies (approximately 30 per cent for installation costs, capped at certain amount per kilowatt peak) helped kick-start the scheme, which is primarily driven by private investments.

1.4.3.2 Regulatory framework and strategic goals

In 2019, the Government of Lithuania set ambitious targets to reach 510,000 prosumers by 2030 and 750,000 by 2050, which would constitute 30 per cent and 44 per cent of all energy consumers respectively. These targets are supported by an evolving legal framework that progressively broadens the opportunities for both local and remote prosumers, facilitating the adoption of various RES technologies and removing previous capacity restrictions.

As an example, back in 2015, a country-wide quota of 10 MW for cumulative capacity of prosumer solar installations was set. The quota was lifted to 100 MW in 2018, then to 200 MW in 2019, and finally virtually removed altogether later. At the beginning of 2024, cumulative capacity of installed prosumer solar photovoltaics (PV) stood at 1024 MW, with more than 100,000 consumers enjoying prosumer status. Among them, 86 000 were households and 16 000 were legal entities (schools, hospitals, small and medium enterprises and large businesses, etc.).[16]

1.4.3.3 Support mechanisms and community engagement

Support for prosumers and other similar RES support programmes is robust, with EUR 800 million allocated for the fiscal period of 2021-2027.[17] This support extends to various models of prosumer setups, including on-the-spot and virtual power plants, ensuring flexibility and inclusivity. Community campaigns and projects funded by the European Union, further engage consumers in adopting RES technologies. One such project, led by the Lithuanian consumers alliance under the Horizon 2020 programme, was focused on communication and involvement of wider society, including those living in multi-family apartment buildings.

[16] See: https://enmin.lrv.lt/lt/naujienos/gaminanciu-vartotoju-jau-daugiau-kaip-100-tukstanciu/

[17] See: https://enmin.lrv.lt/lt/naujienos/energetiniam-savarankiskumui-ir-efektyvumui-rekordinis-paramos-kiekis/

The project culminated with a collective purchase campaign, as citizens, combining their purchasing and negotiating power together, were able to purchase on-site or remote solar PV installations for a considerably better price.

The fast adoption of prosumer model was made possible thanks to a combination of factors: most families own a computer at home, have internet access, and have appropriate digital skills. Therefore, there was no issue to get people onboard via digital channels. Thus, the whole prosumer scheme was designed and implemented as a fully digitalized from the very beginning.

This example shows how digitalization enables further development in the energy sector, including net-metering system for households and use of the grid as a virtual storage.

1.4.3.4 Challenges and future directions

As the prosumer scheme evolves, it plays an ever-increasing role in national energy security and climate policy. Plenitude of the consumer-produced electricity becomes an issue for the distribution grid, which must cope with disbalances in energy supply, storage, and demand. The ongoing multi-stakeholder interaction necessitates continuous adaptation by the Government of Lithuania of regulations to support technological and market developments in the energy sector.

Despite the visible progress, challenges such as technological integration, infrastructure development, and public acceptance remain. Addressing these will require ongoing policy adaptation, increased public-private partnerships, and sustained educational efforts to raise awareness about the benefits of RES and prosumer models. On a positive side, the latest innovations allow prosumption of not only self-produced solar energy, but also wind energy.[18] With this fresh impetus, the number of prosumers may further grow.

Even if the model of tariff support will move away from net-metering (for solar PV) to net-billing (for wind energy and ultimately for solar PV), the price differential between self-produced energy and grid-sourced energy creates a powerful incentive to become a prosumer. While the Government of Lithuania has rolled back from its target to reach 510,000 prosumers by 2030 to a less ambitious one, 300,000, this systemic innovation model remains promising.

The next leap would be to advance the legislation related to energy communities, moving from self-consumption schemes to peer-to-peer trading and eventually allowing trading between communities to further align local generation and consumption and increase the return and therefore the overall individual investment in renewable and flexible assets.

1.5 Governance of digital transformation in the fuel and energy complex (Russian Federation)

1.5.1 Background and context

The rapid advancement of digital technologies, including AI systems, service platforms, and big data, presents new challenges and opportunities for Russian society. This shift is propelling the Russian Federation into a new phase of development across all sectors, including the energy industry. Unlike previous periods, society now demands faster adaptation to new technologies, along with improved quality, efficiency, and security in the energy sector – the objectives that can only be achieved through comprehensive digitalization.

[18] See: https://www.lrs.lt/sip/portal.show?p_r=35435&p_k=1&p_t=287123

1.5.2 National goals and the programme

The Russian Federation places significant emphasis on supporting digitalization and digital transformation, addressing the challenges faced by the information technology (IT) sector. This includes the development of an electronic component base, the promotion of domestic research and development (R&D), and the enhancement of IT education.

In line with the Government's digitalization policies, it is crucial to highlight the establishment of a hierarchical system of interconnected strategic planning documents in the Russian Federation. This system ensures the continuity of objectives, aligning tasks with available resources. Industry-specific strategic planning documents, including those related to digitalization and digital transformation, are grounded in these overarching national planning frameworks.

Digital transformation has been designated as one of national development objectives of the Russian Federation until 2030 and for the perspective until 2036. This priority is outlined in the Presidential Decrees No. 474 "On National Development Objectives of the Russian Federation for the Period Until 2030", dated 21 July 2020, and No. 309 "On National Development Objectives of the Russian Federation for the Period Until 2030 and the Perspective Until 2036", dated 7 May 2024, both being key documents for strategic planning at the Federal level. Consequently, measures and projects aimed at achieving the national digital transformation goals are integrated into relevant industry-specific strategic plans, Government programmes, and national projects.

One of the key initiatives designed to achieve this national development objective, is the National Programme for the "Digital Economy of the Russian Federation". This programme focuses on enhancing the regulatory legal framework, information infrastructure, human resources for the digital economy, information security, digital technologies, and digital state governance. In 2024, underway towards completion of this National Programme, the President of the Russian Federation issued directives to establish a new national project entitled "Economy of Data and Digital Transformation of the State", which envisages continued implementation of measures aimed at achieving the indicators of the national development objectives related to digital transformation.

In the energy sector, one indicator of progress toward the national development objective in digital transformation is the achievement of "digital maturity" in key sectors of the economy and social sphere, including public health, education, and state governance. This indicator specifically includes the attainment of "digital maturity" for energy infrastructure.

1.5.3 Strategy of digital energy transformation

As part of this indicator and to achieve the set digital transformation goals, the Government of the Russian Federation has approved strategic directions for the digital transformation of key economic sectors, the social sphere, and state governance. This includes the strategic vector for digital transformation in the fuel and energy complex (FEC) until 2030 (hereinafter referred to as SV DT FEC).

The objective of SV DT FEC is to achieve a high level of "digital maturity" among the FEC key players, and to accelerate the transition of the energy sector of the Russian Federation to new managerial and technological levels, thereby promoting technological sovereignty. This transition will create favourable conditions for the development of FEC and will support the long-term sustainable socio-economic development of the Russian Federation. This will be achieved by optimizing and transforming business processes through the use of common information models, "end-to-end" digital technologies, and platform services, all within the context of rapidly changing external and internal factors.

As part of SV DT FEC, the key priorities, tasks, challenges, and strategic vectors for the digital transformation of FEC have been outlined. The main priorities identified include:

- Platformization: Developing unified approaches to structuring the architecture of information systems;
- Implementation of digital transformation: Focusing primarily on utilizing domestic technologies;
- Introduction of unified standards: Establishing standardized information exchange protocols and uniform regulations for interaction between different systems and stakeholders;
- Optimization of service delivery: Optimizing and streamlining the processes of providing services within FEC;
- Active utilization of digital platforms: Notably, leveraging the GOVTECH Unified Digital Platform.[19]

SV DT FEC also includes industry projects aimed at shaping a unified state policy for developing FEC digital platforms. These projects focus on creating conditions that support the replacement of imported software across critical energy information infrastructure within FEC. Additionally, they promote the introduction and development of AI technologies within the sector.

In addition to specific projects, SV DT FEC outlines prospective activities for the digital transformation of FEC of the Russian Federation. These activities consider the strengths, weaknesses, opportunities, and threats specific to the Russian FEC in the context of digital transformation. Key activities include:

- Introduction of digital systems: Implementing systems to balance energy consumption more effectively;
- Data-driven governance: Transitioning the industry to management practices based on high-quality, up-to-date, relevant, accurate, and authentic data;
- Monitoring and maintenance**:** Deploying digital systems to monitor equipment status, shifting from unscheduled and routine repairs to condition-based maintenance;
- Adoption of cloud computing: Encouraging widespread use of cloud computing within FEC organizations;
- Collaboration and knowledge sharing: Enhancing cooperation among Russian FEC organizations to share and replicate developments in "end-to-end" digital technologies;
- Increased investment in R&D: Boosting funding for R&D in "end-to-end" digital technologies, particularly in production control and lifecycle management of energy facilities;

[19] See: https://platform.gov.ru/en/

- Strengthening information security: Introducing and enforcing stringent information security requirements at the legislative level;
- Development of tailored IT solutions: Creating IT solutions for tracking logistics and trade operations within the FEC;
- Standardization of IT requirements: Unifying requirements, including the development of methodological guidelines for describing information and communication technology architectures;
- Integration with science and education: Promoting collaboration between FEC organizations with the science and higher education. This includes research, development, and engineering activities related to FEC projects, as well as updating curricula, state educational standards, hands-on training, and internships to ensure students engage with industry-relevant topics and receive practice-oriented training in partnership with FEC organizations.

SV DT FEC will serve as a guiding document for regional authorities and industry companies in developing their own digital transformation strategies, programmes, and measures.

1.5.4 Advancement of research and development in the corporate sector

To shape a systemic approach for companies with Government participation in implementing digital transformation projects, including import substitution in the energy sector, the Government of the Russian Federation issued Directive No. 3438p-P13 dated 14 April 2021. This directive requires companies with Government participation, including those in the energy sector, to develop and implement digital transformation strategies and programmes. These documents should contribute to achieving the planned indicators of "digital maturity".

Given that the Russian FEC includes large vertically integrated companies with extensive research infrastructure and in-house capabilities for developing digital products, the Government is establishing Industrial Competence Centres (ICC), such as ICC Electroenergetica and Neftegaz (Electric power industry and oil and gas), Neftechimia (Petrochemicals), and Nedropolzovanie (Subsoil use). These centres play a crucial role in replacing imported industrial digital products and solutions with domestic alternatives. The primary task of ICCs is to identify the technological needs of various economic sectors and propose mechanisms for implementing and replicating domestic technologies. ICCs also facilitate coordination and collaboration among companies in developing and implementing digital products, helping to effectively address critical import substitution challenges. The Government may co-finance ICC projects to support implementation of their projects.

As part of their activities, ICC Electroenergetica, Neftegaz, Neftechimia, and Nedropolzovanie have already selected 36 significant projects, some of which are currently being implemented. The IT products developed in the framework of implantation of these projects, are expected to have export potential.

1.5.5 Use of Artificial Intelligence technologies in selected fuel and energy sectors and related information systems

In the Russian Federation, AI technologies are considered "end-to-end" digital technologies, meaning they can be applied across all sectors of the economy, including the energy sector. Since 2019, the foundational National Strategy for AI Development, covering the period until 2030, has been implemented by energy companies, serving as the primary framework for their AI-related action plans.

The AI initiatives mandated by the President of the Russian Federation are integrated into Government schemes and national projects. In this context, the Russian Ministry of Energy, through its ministerial project “Digital Energy Sector” – a key component of the Government programme “Development of the Energy Sector” – has developed action plans. These plans include regular industry workshops to assess the AI technology needs of FEC companies and to implement measures that address these needs, including engaging small technology companies and start-ups.

At the same time, the energy sector is making rapid advancements in the use of AI technologies, with AI recognized as a strategic priority. This focus is reflected in the significant increase in investment in AI-related projects. Additionally, AI action plans are incorporated into the digital transformation strategies and investment programmes of companies with Government participation, as directed by the President of the Russian Federation. This is particularly important for the energy sector, where companies with Government participation hold a significant share in both the electric power and oil and gas industries. By 2024, these FEC companies have already invested over RUB 2.6 billion in AI projects. According to projections, the implementation of AI is expected to contribute, cumulatively, an additional RUB 11.2 trillion to GDP of the Russian Federation by 2030. Given that the FEC generates about one-fifth of national GDP, the impact of AI on the energy sector alone could result in hundreds of billions of rubles being added to the GDP on an accrual basis by 2030.

Among the sectors of the economy, the energy sector holds one of the highest potentials for AI utilization due to the unique characteristics of this technology, particularly its reliance on vast data sets for development. In FEC, the annual volume of data generated amounts to thousands of petabytes, which is several times greater than in industries like retail or social media. Moreover, studies conducted in 2023 show that FEC ranks second among all economic sectors in terms of data availability for AI development and use.

In 2023, 40.6 per cent of organizations within the Russian FEC were already using AI to varying degrees, with 20.2 per cent reporting that the impact of AI on their operations is significant or transformative. Additionally, 18.1 per cent of organizations in the sector plan to adopt AI within the next three years.

1.5.5.1 Oil and gas industry

The implementation of AI in FEC has yielded significant results. For instance, in the Russian oil and gas sector, a project focused on intelligent support for decision-making has optimized the development of oil and gas fields. This project enables the effective arrangement of new wells and the selection of operating modes for existing wells through three-dimensional modelling. According to projections, the benefits of this project at two pilot oil and gas fields are expected to exceed RUB 500 million over five years. In one field, the project is projected to increase oil production by 8 per cent and profits by 11 per cent.

AI models have also been developed to predict downtime in electric centrifugal pump installations based on data analysis, allowing for timely repairs. Over three years, this project has increased the interval between repairs by 20 per cent and reduced oil loss during work shifts by half.

AI is also being used to assess the risks of emergency and pre-emergency situations during well drilling. AI algorithms analyse data from geological and engineering surveys, identifying patterns similar to those preceding emergencies. They classify the drilling process as either normal or at risk of complications. These algorithms can predict emergencies such as drill assembly sticking, drilling mud loss caused by geological formations, drill column failure, drill stem washout, balling-up, and gas, oil, or water shows. In one specific project, the use of this technology reduced the accident rate in wells by 15 per cent, preventing 50-60 incidents of varying severity per year.

1.5.5.2 Electricity industry

In the electricity industry in the Russian Federation, AI technologies are being introduced to enhance consumer service. Voice assistants (AI consultants) equipped with speech recognition and synthesis functions, are starting to be deployed. These systems have reduced the percentage of unserved user calls from 30 per cent to 10 per cent in some cases. For certain projects, up to 60 per cent of incoming calls related to power outages during major grid disruptions can be handled without operator intervention. Additionally, there has been a noticeable decrease in the average time required to process user calls about scheduled and emergency power cuts.

AI technologies are also utilized for precise forecasting of electricity generation at power plants, particularly for those dependent on weather-dependent renewable energy sources.

Furthermore, to prevent offenses in the electricity sector, a project is underway that uses AI to forecast the probability of unaccounted-for electricity consumption at supply points. This project assesses the likelihood of detecting unreported consumption based on computer modelling and the analysis of large datasets, including over 300 logic chains and decision trees. As a result, the efficiency of verifying electricity metering has improved by 4 to 6 times.

1.5.5.3 Coal industry

AI is significantly enhancing various processes in the coal industry, including improving industrial safety. For example, AI solutions utilizing computer vision detect connection joints on conveyor belts and monitor the number of metal rivets at these junctions. This technology has led to a 20 per cent reduction in emergency shutdowns caused by belt cloth ruptures.

Additionally, AI systems are used to monitor the technical condition of hydraulic equipment. The AI system collects data every 30 seconds and identifies deviations from normal operation, alerting mechanics if there is a risk of an emergency. Full-scale implementation of this approach, which supports condition-based maintenance, is a key priority for digital transformation across the coal industry and the broader energy sector.

Moreover, pilot projects are underway in the Russian Federation to use AI for monitoring the use of personal protective equipment by production personnel. Neural networks analyse video footage from production sites to identify instances where safety requirements are not being followed.

1.5.5.4 State information systems

Several federal state information systems have been established and are operational in the Russian Federation to support Government decision-making, digitize services, and manage state, municipal, and regulated organizations.

One key system is the State Information System of the Fuel and Energy Complex (SIS FEC). This federal system provides comprehensive information and forecasts regarding the development of FEC in the Russian Federation. SIS FEC aims to enhance interaction within FEC and create a unified state information space to support management decisions and their implementation, including in related economic sectors. Notably, SIS FEC also includes components focused on energy saving and improving energy efficiency.

The creation, operation, and enhancement of SIS FEC are governed by Federal Law No. 382-FZ "On the State Information System of the Fuel and Energy Complex", dated 3 December 2011. SIS FEC is designed to automate the collection, processing, storage, access, dissemination, and distribution of information related to FEC. It aims to improve the efficiency of information exchange regarding the status and future development of the FEC.

Federal executive authorities, primarily the Ministry of Energy, along with authorized state institutions, regional executive bodies, legal entities, and private entrepreneurs involved in various aspects of energy resources – from extraction and production to distribution and commercial infrastructure – are integral to these processes. The Russian Energy Agency, part of the Ministry of Energy, is the operator of SIS FEC.

Currently, over 2,500 FEC organizations contribute data for integration into the system, which supports the informational and analytical needs of the Russian Ministry of Energy. The obligation to provide this information is established by the "Regulations on the Mandatory Provision of Information for Incorporation into SIS FEC", approved by the Government of the Russian Federation in its Resolution No. 1384, dated 22 December 2012.[1]

To inform and support state policy, a state information system focused on energy efficiency (SIS Energy Efficiency) has been established. This system has been upgraded and currently includes a Register of Greenhouse Gas Emissions. A Register of Carbon Units, which utilizes public-private partnership tools based on a federal concession agreement with a private company, has also been introduced.

In addition to these systems, significant contributions to the digitalization of services and the enhancement of information quality and interaction are made by SIS for housing and communal facilities and for industry. The latter is crucial for managing subsidies to industrial organizations, including those for developing energy-saving products and components. These SIS interact through a system for inter-departmental electronic document exchange.

Russian constituent entities also develop their own regional systems, leveraging both local innovations and scalable solutions proven in other regions. Typically, these regional systems are more integrated with local energy consumption planning and management processes, extending to budgetary institutions and communal enterprises. They include functionalities such as facility passports, integration with the federal system, resource accounting and control tools, and support for action plans, projects, and programmes. A notable example of successful implementation is the system in the Belgorod Region, developed by a local technology institute and implemented by the regional agency for energy efficiency. This system has led to savings of RUB 741 million from the region's budget since 2019 and has stimulated investment in energy efficiency initiatives.

1.5.6 Effects, lessons learned, and long-term plans

A hierarchical system of strategically linked planning documents has been established to ensure continuity in achieving goals, balanced with clear objectives and their necessary resources. This structured approach supports both technical and economic advancements, as well as social benefits.

Key technical and economic effects of this hierarchical system, include:

- Platformization: Development of unified approaches for building the architecture of information systems;
- Optimization of service delivery: Improvement of processes in FEC;
- Digital systems for energy consumption: Implementation of systems to balance energy use efficiently;
- Data-driven management: Transition to asset and operation management based on high-quality, up-to-date, and reliable data;
- Condition-based equipment monitoring: Introduction of digital systems for monitoring energy equipment, shifting from unscheduled repairs to those based on its technical condition;
- Cloud computing: Broad adoption of cloud computing by FEC organizations;
- Enhanced cooperation: Promotion of collaboration among FEC organizations to replicate their advancements in "end-to-end" digital technologies;
- Increased funding for R&D: Investment in R&D of "end-to-end" digital technologies, including those for production management and life cycle management of energy facilities.

Long-term plans envisage:

- Development of electronic component base (expansion of domestic R&D) and enhancement of IT education;
- Achievement of "digital maturity" across key economic and social sectors;
- Achievement of carbon neutrality;
- Meeting the targets set for national digital transformation objectives.

2. BALANCING THE ELECTRICITY SUPPLY AND DEMAND WITH ARTIFICIAL INTELLIGENCE

2.1 Contextual introduction

2.1.1 Balancing generation and demand in electric grid

Balancing the electric grid is a complex and crucial task that ensures a stable and reliable supply of electricity. The primary goal is to ensure that electricity supply meets demand in real-time second by second and in planning, hour-ahead, day-ahead, etc. This process is what is meant by "balancing" the grid.[20]

Demand for electricity fluctuates throughout the day, week, and year based on factors like weather, time of day, economic activity, and societal patterns. Peak demand typically occurs during periods of high energy usage, such as cold winter mornings or hot summer afternoons. Meanwhile, supply can change unpredictably. Maintaining this balance is crucial for the stability and reliability of the power grid. Maintaining a stable frequency (usually 50 or 60 Hz) is critical for the proper functioning of electrical devices and equipment. Fluctuations in supply or demand can impact this stability, leading to blackouts or other grid failures.

The electricity system operator oversees this process of balancing generation and load in real-time and continuously monitor supply and demand and takes actions to balance them in real-time. This may involve adjusting generation output, importing, or exporting power from neighbouring regions. With the increasing integration of renewable energy sources like wind and solar, energy storage systems can play a role in balancing supply and demand. Renewable storage technologies such as large hydro reservoirs, pumped hydro storage, and batteries can store excess energy when generation exceeds demand and release it when needed. Market mechanisms can also contribute by setting timeframes for and controlling the storage and dispatch of electrical energy.

Maintaining a reliable and efficient supply-demand requires coordination among multiple stakeholders, including power generators, grid operators, regulators, and consumers, for different timescale.

Forecasting models can include models for forecasting load, wind, weather, clouds, market changes, and take into consideration the following time-oriented properties:

1. From a short-term perspective (hours to days):
    (a) Real-time monitoring and control mechanisms;
    (b) Forecasting models;
    (c) Congestion analysis and optimization.
2. In the mid-term (weeks to months):
    (a) Adequacy of generation, transmission, and distribution infrastructure to meet expected future demand;

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[20] For a more technical and complete description on balancing, refer to: Cadrage des analyses techniques des scenarios du Bilan prévisionnel, RTE Groupe de travail Fonctionnement du système électrique, section 2.0. Available at: https://www.concerte.fr/system/files/document_travail/2020-04-28-GT8-Fonctionnement-du-systeme-electrique-Document-de-cadrage.pdf (in French)

    (b) Forecasting models;
    (c) Plan for maintenance;
    (d) Capacity markets or longer-term power purchase agreements (PPAs).
3. From a long-term perspective (years to decades):
    (a) Long-term energy plans and investment strategies;
    (b) Integrating more renewable energy into the grid, investing in grid modernization and energy storage infrastructure;
    (c) Multiannual large hydro reservoir management;
    (d) Regulation changes.

From a technology perspective, the supply-demand balance in the electric power system is influenced by various factors related to generation, transmission, distribution, and consumption of electricity. Technology can impact the balancing of generation and load in the following ways:

1. Generation technologies: Advances in generation technologies have a significant impact on the supply side of the equation. The emergence of renewable energy sources such as wind and solar has diversified the generation mix and reduced reliance on fossil fuels. However, the intermittent nature of renewables presents challenges for maintaining supply-demand balance. Innovative solutions such as grid-scale energy storage, AI-based forecasting algorithms, and smart grid technologies help mitigate these challenges by enabling better integration of renewable energy into the grid.
2. Grid infrastructure: Technological advancements in grid infrastructure enhance the efficiency and reliability of electricity transmission and distribution. High-voltage transmission lines, advanced grid monitoring and control systems, and grid automation technologies improve the capacity and flexibility of the grid to accommodate fluctuations in supply and demand. Additionally, grid modernization initiatives, such as the deployment of smart grids and microgrids, enable decentralized energy generation and enhance resilience to disruptions.
3. Demand-side technologies: Technology plays a crucial role in managing electricity demand to match supply. Demand response programs leverage automation, smart meters, and communication technologies to adjust electricity consumption in response to price signals or grid conditions. Smart appliances, building energy management systems, and electric vehicle (EV) charging infrastructure enable consumers to optimize their energy usage and contribute to demand flexibility. These demand-side technologies enhance the resilience and efficiency of the power system by reducing peak demand and improving overall grid stability.
4. Energy storage: Storing electrical energy is largely a process of transforming energy from when and where it is available to when and where it is needed. Energy storage technologies play a critical role in balancing supply and demand in the electric power system and are important to add flexibility and resilience to the electricity system. Key factors for energy storage include timing from instantaneous (for fast frequency regulation) to hours or days

(for energy and capacity applications) and location, which needs the balance of the levelized cost of service (LCOS) and the end-user need for local conditions.[21]

5. Data Analytics and Forecasting: Advanced data analytics and forecasting techniques enable grid operators to predict electricity demand and generation patterns with greater accuracy. ML algorithms, predictive analytics, and real-time monitoring systems provide insights into consumer behaviour, weather patterns, and market dynamics, allowing for more efficient operation and planning of the power system.

Overall, technology plays a transformative role in shaping the supply-demand balance in the electric power system. Continued innovation and deployment of advanced technologies are essential for enhancing grid reliability, resilience, and sustainability in the face of evolving energy challenges and opportunities.

From an economic point of view, the supply-demand balance in the electric power system is crucial for ensuring efficiency, reliability, and affordability in electricity markets. Consistently efficient operations ensures that the economic models used for forecasting cost to serve loads based on hourly annual load profiles provide the data needed for sustainable investment decisions. The economics and operations of the electricity system work to balance the following constraints:

1. Efficiency: A balanced supply-demand equilibrium ensures that electricity is produced and consumed at the lowest possible cost. When supply exceeds demand, electricity prices tend to decrease, incentivizing consumers to increase their usage or invest in energy-intensive activities. Conversely, when demand exceeds supply, prices rise, signalling consumers to reduce consumption or shift usage to off-peak hours.
2. Investment incentives: Maintaining a stable supply-demand balance provides clarity and certainty for investors in the electricity sector. When demand growth outpaces supply capacity, it creates opportunities for investment in new generation capacity, transmission infrastructure, and energy storage technologies. Similarly, when supply exceeds demand, it may signal oversupply conditions, leading to reduced investment in new generation projects or retirement of existing assets.
3. Market competition: A well-functioning electricity market relies on competition among generators and retailers to deliver electricity to consumers at competitive prices. The supply-demand balance plays a central role in determining market prices through mechanisms such as wholesale auctions or bilateral contracts.
4. Resource allocation: The supply-demand balance influences the allocation of resources across different energy sources and technologies. In markets where renewable energy sources like wind and solar are increasingly competitive, a balanced supply-demand dynamic can accelerate the transition towards a cleaner and more sustainable energy system. However, maintaining reliability and grid stability while integrating intermittent renewable energy sources requires careful planning and investment in complementary technologies such as energy storage, demand response, and grid modernization.

As digitalization progresses and as organizations becomes more aware of the value of data generated by their connected assets, and in response transform their processes accordingly, AI can

[21] 'The Energy System: Technology, Economics, Markets and Policy', Bradford, T, 2018. MIT Press, Cambridge, MA. ISBN: 978-0-262-03752-5

help deal with these large volumes of data and unlock value in the entire chain, from data creation to better decision making.

This case study paper explores how Artificial Intelligence (AI) is used to balance supply and demand the context of a rapidly changing grid, changing of customer behaviours and active citizen participation.

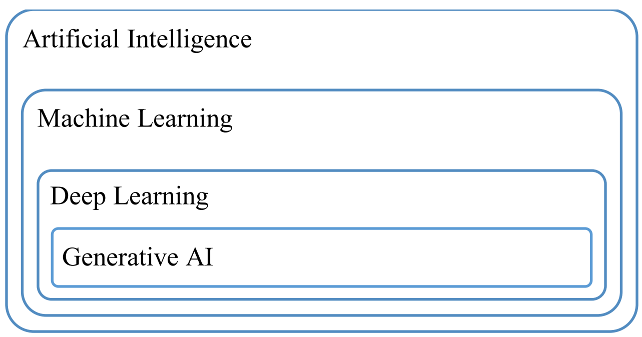
2.1.2 Definition of Artificial Intelligence in the context of electric grid

AI systems can vary in their levels of autonomy and adaptiveness once deployed. One definition for AI, by EU Artificial Intelligence Act, is:

> *"An AI system is a machine-based system that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments"*[22]

As such, Artificial Intelligence is a broad field that includes the areas of Machine Learning, Deep Learning, and more recently, Generative AI. Sometimes these terms are used interchangeably to describe systems with intelligent behaviour. Figure 1 shows the nesting of the categories of AI.[23]

Figure 1
A nested taxonomy forArtificial Intelligence technologies



[22] EU Artificial Intelligence Act, https://artificialintelligenceact.eu/the-act/, final draft (2024).
[23] For a more generalized overview on AI, with detailed descriptions and its technological impact on the electric grid, see: Impact of Artificial Intelligence on the Digital and Data Transformation in the Electricity Sector (ECE/ENERGY/GE.6/2024/3, ECE/ENERGY/GE.5/2024/3), https://unece.org/sed/documents/2024/07/working-documents/impact-artificial-intelligence-digital-and-data

As climate change is one of the greatest challenges facing humanity, ML can be a powerful tool in reducing greenhouse gas emissions and helping society adapt to a changing climate:

> *"Since variable generation and electricity demand both fluctuate, they must be forecast ahead of time to inform real-time electricity scheduling and longer-term system planning. Better short-term forecasts can allow system operators to reduce their reliance on fossil-based standby plants and to proactively manage increasing amounts of variable sources. Better long-term forecasts can help system operators (and investors) determine where and when variable plants should be built. While many system operators today use basic forecasting techniques, forecasts will need to become increasingly accurate, span multiple horizons in time and across registered assets, and better quantify uncertainty to support these use cases. ML can help on all these fronts."*[24]

2.2 Short-term load demand forecasting: use of Artificial Intelligence at Hydro-Québec (Canada)

Hydro-Québec (HQ) is the utility of the province of Québec, Canada. It operates some 60 hydroelectric generating station, making it one of the largest hydroelectricity producers in the world. Close to 100 per cent of its electricity is generated using water thus with very low greenhouse gas emissions and no toxic waste. Transmission system of HQ is the most extensive in North America and includes over 34,000 km of high-voltage lines running from large generating stations in remote areas to the province's more populated areas. It delivers electricity through its distribution lines, which crisscross the province. Its transmission and distribution lines extend for some 260,000 km.

2.2.1 Context

Short-term load demand forecasting (few hours to a few days horizon) is a key activity for HQ that is highly dependent on climatic and economic conditions. It is necessary for purposes as varied as generation management, reliability, maintenance of the power grid and sales positioning on foreign markets. It is therefore an activity that is crucial for the resilience of our activities in the context of climate change and the energy transition.

The traditional legacy models that have been used for decades by HQ to forecast load demand, offer, on average, good performances. These models are built on a base of proven mathematical algorithms whose hundreds of parameters must be adjusted regularly. The objective is to individually model the physical or human phenomena influencing the behaviour of the power grid on a large scale (e.g. heating vs. cooling, weekdays vs. weekend, lighting in cities). These models were patiently developed by specialists over several years based on a detailed knowledge of the behaviour of power grid of HQ based on electrical and climate data.

However, under certain conditions, there is now a trending upward gap between the prediction of these legacy models and the reality, which can result in a risk to the reliability of the power grid and/or loss of sales opportunities for the company.

This gap – which has widened in recent years – can be explained by the rather fast changing behaviour of the power grid induced by societal changes (industry transformation, bitcoin mining

[24] Tackling Climate Change with Machine Learning. ACM Comput. Surv. 55, 2, Article 42 (February 2022), 96 pages. Section 2.1.1 https://doi.org/10.1145/3485128

companies, data centres, urban sprawl, home automation, teleworking, etc.) and by climate change (increase in average temperatures and the frequency of extreme weather events, including heat waves outside the summer period). These changes greatly complicate the maintenance and evolution of these legacy models since it requires rethinking the design parameters on which these models are based and sometimes manually adjusting the algorithmic parameters in the context of real-time operation.

This deterioration is also likely to increase with the advent of the energy transition in response to the climate crisis and the need to reduce greenhouse gas emissions. As cities move towards electrification (EV charging, dynamic pricing, switching heating and industrial processes to electric, etc.) the need for accurate load demand forecasting will increase in a context of energy resources limited by deployment and installation of new centralized and decentralized means of generation.

In this context of complex and rapid transformations, which creates a significant number of unknowns, the requirement for specialists to constantly maintain (i.e., update) these models is infeasible and unsustainable. This is why HQ has been relying for several years on the use of the latest technological advances in AI and big data processing to maintain and improve the accuracy of short-term load demand forecasting.

2.2.2 Innovation

AI based on deep neural networks seems particularly suited to this context of rapid transformation because the AI algorithm is then delegated the responsibility of building the equivalent of the modelling functions database of legacy models built by specialists over several years. This allows for a quick and effective response where old technology struggles to keep up with the breakneck pace imposed by the transformation of electricity consumption and climate change.

Thus, where specialists have taken several decades to build a few models in the context of a relatively stable power grid – models that are also difficult to maintain over time because of their intrinsic technological limitations to old computer programming languages and the loss of skills (via natural attrition or turnover) – the AI algorithm can build many new models and then automate the selection decision to determine the appropriate calculation and post-processing resources.

Also, while legacy models will not automatically take into account new corrective factors (e.g. the COVID-19 pandemic), which can make historical consumption data obsolete, deep neural network-based AI models have the ability to automatically understand, through their training, the existence of particular more or less short periods in historical consumption data such as the pandemic period of COVID-19 as well as longer-term trends such as the gradual increase in average temperatures inherent to global warming.

It is therefore a complete paradigm shift in the activity of forecasting load demand for the modeler and forecaster: humans no longer seek to understand the details of models but seek to guide the multiple AI trainings, to refine the architecture of deep neural networks and to manipulate the massive data intended for training or resulting from it.

In return, the modeler and forecaster can have the ability to anticipate the creation of models adapted to different scenarios simulating the future behaviour of the power grid at a very early stage. And it can create more robust models to meet security objectives in the context of a cyberattack, for example.

For all these reasons, since 2018, HQ has developed a suite of tools dedicated to the creation and operation of AI-based load demand forecasting models. This R&D action was carried out by maintaining a close link between research centre of HQ and the team in charge of operating load demand forecasting models, and then by setting up the associated computing resources within the cloud computing laboratory team.

This constant link between the research laboratory and the business unit has helped to reduce the time to market of AI while constantly ensuring the robustness and security of the new AI tools put into operation in a secure environment under real-time constraints.

It should also be noted that this suite of AI tools makes it possible to create load forecasting models from both a macroscopic (also referred as "top-down") and microscopic (known as "bottom-up") point of view. The difference between these approaches lies in the type of data used. The macroscopic data will use aggregated consumption data from thousands of power meters spread across the province, while the microscopic data will use data from millions of smart meters.

2.2.3 Commissioning

It is in this changing context that a significant event took place at 10:03 on 23 October 2023, at HQ: for the first time, the short-term load demand forecast was officially calculated using deep neural network-based AI models (top-down approach) developed and implemented by a team of researchers and experts from the company. This use of deep neural network-based AI models is believed to be a first in the context of 24/7 + real-time + security zone. The parameters of these AI models were optimized during a test campaign carried out in 2023 by the experts of the team in charge of operations on several hundred processors during which more than 11,000 models were evaluated to select a dozen that were combined to build this new AI load demand forecasting model.

This feat is even more remarkable given that it is the first new load demand forecasting model to be implemented and used in operation since 2004 at HQ.

This event also highlighted the ability of the operations team to adapt, as they had to take control of a completely new technology with High Performance Computing (HPC) in a cloud computing laboratory that did not exist at the beginning of the project (2018) while maintaining operations under real-time constraints. This underlines the importance of establishing long-term links between research and business units with progressive development objectives that are validated step by step.

Further, as research and business units adapt to new requirements from end-users and systems, the need for human capital upskilling becomes increasingly necessary.

2.3 Artificial Intelligence in balancing of generation and demand (United Arab Emirates)

This section highlights application of AI in the United Arab Emirates (UAE) in the context of balancing generation and demand, and relevance to other regions.

2.3.1 Building management

In UAE, significant advancements have been made in applying AI to building management systems, particularly in Dubai and Abu Dhabi. AI is used to monitor and control building environments, optimizing energy use for heating, ventilation, air conditioning (HVAC), and lighting based on occupancy and individual preferences. Smart sensors and AI algorithms analyse user behaviour and environmental data to adjust settings, significantly reducing energy consumption and carbon emissions. This technology aligns with the Green Building Regulations and Specifications of UAE and sets a standard for future developments in sustainable building practices in the Emirates. Many companies offer solutions for smart building management and many policies target the management of load.

2.3.2 Renewable energy and storage

As UAE diversifies its energy sources, AI plays a pivotal role in the development and optimization of renewable energy systems. The country is exploring AI to enhance the efficiency and reliability of solar and wind power installations. For example, AI algorithms are being used to predict solar irradiance and optimize the positioning of solar panels throughout the day, maximizing energy capture and significantly boosting overall system productivity.

Mohammed bin Rashid Al Maktoum Solar Park: The solar park in Dubai utilizes AI-based technology to optimize the performance of solar panels. By analysing data from weather sensors and other sources, the system predicts solar radiation levels and adjusts the angle of the solar panels accordingly, increasing energy production and efficiency.

The country also plans to leverage AI to facilitate real-time energy management in wind farms by predicting wind patterns and adjusting turbine angles to optimize power generation. This not only increases the energy output but also extends the lifespan of the equipment by reducing unnecessary wear and tear.

The integration of AI in the country also extends to energy storage systems, where it manages the charge and discharge cycles of batteries in solar plants, enhancing energy storage efficiency and stability. This is crucial for maintaining a steady supply of energy, especially during peak demand times or in adverse weather conditions. The digital arm of the Dubai Energy and Water Authority (DEWA) is set to use autonomous systems for renewable energy and storage, being one of the first utilities in the region to do so. These AI-driven initiatives in renewable energy are part of the broader strategy of UAE to reduce its carbon footprint and lead in the global energy transition, marking significant steps towards achieving energy sustainability and resilience.

2.3.3 Grid management

The commitment of UAE to AI in renewable energy is also seen in its investments in smart grid technology. Smart grids, enhanced with AI, are essential for managing the complexities of distributing multiple energy sources. They not only improve operational efficiencies but also support the transition towards a more sustainable and decentralized energy model.

AI will be a key tool to optimize grid operations and to enhance the capacity of existing transmission and distribution lines, as well as for extending the lifetime of existing equipment in the UAE. In Dubai, the state-owned utility DEWA has deployed a smart grid system that uses AI to predict electricity demand and manage energy supply. The system analyses data from smart meters and other sources to identify patterns and predict consumption, allowing the utility to optimize the distribution of energy and reduce the risk of blackouts or other disruptions.

AI can also support the grid integration of renewable sources. It helps manage the variability and intermittency of renewable energy, ensuring a stable and reliable power supply. By analysing vast amounts of data from grid operations and weather forecasts, AI systems can predict energy demand and adjust power distribution accordingly.

2.4 Lessons learned

While the integration of AI brings considerable benefits, it also presents challenges and a few lessons learned. From the use on short-term demand forecasting and the other applications, the adaptation (training, development, recruitment) of the workforce to new technologies is identified as one of the top challenges.

HQ has teamed with the research centre and exposed its operational resources to the new technology and participate actively in the development of the model. The UAE is trying to address these challenges by emphasizing education and training, preparing its workforce for the evolving technological landscape. This approach can help mitigate potential disruptions in traditional work processes and fosters a culture receptive to innovation.

In addition to the introduction of AI and models, the introduction of new technology, like HPC in a cloud computing, not widely used in the context of the electric grid and the ability to gain sufficient understanding and confidence in this technology is also a challenge.

An additional lesson learned is to always have in mind the portability of the AI tools between different systems to be able to easily switch from the cloud laboratory to the secure operating area. At HQ, the following elements were part of the "step-by-step" approach and the ongoing research / operational teams link put in place:

1. Building a cloud-based laboratory that is not dependent on "high-level" cloud services in its "core". This approach allowed HQ operational team to easily switch the new AI tools from the laboratory to the operating area because it did not have to implement "high" level services from the cloud provider, services that would have been caused technical issues or non-compliance with the applicable standards. This highlights the strategic importance to remain independent of the cloud provider as much as possible.
2. Cloning production machines in the cloud laboratory - a kind of reverse process from the previous point – to test tools out of the secure zone very upstream of their implementation in the secure zone but in the "real" conditions of the secure zone.

Deployment of new technology and new models while maintaining operations under real-time constraints must also be considered. This underlines the importance of establishing long-term links between research and business units with progressive development objectives that are validated step by step.

As outlined in the UAE National Strategy for Artificial Intelligence 2031, the country is actively exploring further potential of AI in renewable energy technologies and smart grid applications, aiming to lead in the global transition to sustainable energy systems. Signalling the technology's importance within various sectors, UAE also has a specific Minister of State for Artificial Intelligence.

The UAE strategic approach to integrating AI in the energy sector highlights its commitment to enhancing operational efficiencies and environmental sustainability. Through robust investment in technology and human capital, the UAE aims to address immediate operational needs while setting the stage for future advancements in energy management.

3. GRID MANAGEMENT ARCHITECTURE: INTEROPERABILITY AND RESILIENCE

This case study addresses the challenge of distributed energy resources (DERs) integration to support grid resilience, identifying key infrastructure requirements, assessing policy developments and deriving recommendations. The underlying premise of this case study asserts that whilst the energy sector is making advances towards decarbonization, decentralization and digitalization, the increasing share of DERs in the energy mix is still not being sufficiently harnessed for their potential in the energy transition, yet continue to create challenges for grid management.[25]

3.1 Theoretical and Contextual Introduction

Technologies that are driving digitalization of the energy sector include DER in the form of solar PV, batteries (storage), EVs and their charging infrastructure, and the proliferation of Advanced Metering Infrastructure (AMI). However, despite some progress, investment in smart grids needs to more than double annually through 2030 in order to meet the Net-Zero Emissions Scenario by 2050, especially in emerging markets and developing countries.[26]

Three reference infrastructure requirements have been identified for enhanced DER integration:

1. Ease of DER Installation: standardized, transparent and simplified process for DER acquisition and installation to ensure consumer protection and encourage increased DER investment;
2. Submetering Capacity: making available asset-level generation and consumption data to drive interoperability for diverse energy services, and
3. Flexibility Registry: providing DERs with identification and standardized interconnection functionality to ensure fair data access and interoperability of different services including grid integration, while maintaining privacy and security.

Additionally, this case study highlights community and peer-to-peer trading as a key shift towards a more effective energy market design, facilitating economic, environmental and social benefits for local community members, including DER optimization via higher local self-sufficiency, while providing flexibility for the grid to relieve congestion and strengthen system resilience.

3.1.1 Ease of DER Installation

The main driver of exponential DER growth is the government, with policies backed by financial incentives, which have contributed to a significant reduction in DER cost, followed by corporate sustainability action, reinforced by the increased occurrence of extreme weather conditions and energy price volatility,[27] with the latter, combined with heightened environmental awareness, also encouraging greater individual action. However, there are also many obstacles to DER deployment, including administrative hurdles in the form of permitting regulation for large projects

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[25] IEA. *Unlocking the Potential of Distributed Energy Resources*; Power System Opportunities and Best Practices, Paris, 2022, https://iea.blob.core.windows.net/assets/3520710c-c828-4001-911c-ae78b645ce67/UnlockingthePotentialofDERs_Powersystemopportunitiesandbestpractices.pdf

[26] IEA (2022), Smart Grids, IEA, Paris https://www.iea.org/reports/smart-grids, License: CC BY 4.0

[27] Ben Hertz-Shargel, "Distributed energy is poised to take center stage in 2022, but policymakers and regulators must step up," *Utility Dive*, 4 February 2022, https://www.utilitydive.com/news/distributed-energy-is-poised-to-take-center-stage-in-2022-but-policymakers/618331/.

and grid connection as well as individual household use cases. These obstacles are compounded by limited workforce skills, supply chain limitations or disruptions, such as in the case of lithium, underdeveloped recycling and reuse of the raw materials used for DER production, and overall insufficient knowledge and ability to make DER investment decisions by both businesses and individuals. A specific policy challenge also relates to effective support of research and innovation and accelerating the implementation of emerging technologies.[28]

3.1.2 Submetering Capacity

As one of the most prominent energy IoT applications in the energy sector, AMI provides benefits to utilities and grid operators, while also serving as a conduit for emerging user-centric energy services. The number of installed metres is expected to exceed 227 million units in 2026 in EU-27+3 region (from 150 million units in 2020) and yearly shipments of smart electricity metres in North America will grow from 8.8 million units in 2019 to 19.9 million units in 2024.[29]

Connected technologies of synchro phasor measurement units (PMUs), supervisory control and data acquisition (SCADA) systems along with AMI are core enabling technologies for the smart grid. Deployment of these systems means that utilities can harness the power of remote metering for connection and disconnection services, and energy monitoring with a highly granular view of grid operations. Whilst installation of these systems can have relatively low initial costs, there are high maintenance costs, not the least of which are properly skilled and trained personnel.

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[28] NREL, Examining Supply-Side Options to Achieve 100 per cent Clean Electricity by 2035, 2022, https://www.nrel.gov/docs/fy22osti/81644.pdf https://www.energy.gov/eere/articles/nrel-study-identifies-opportunities-and-challenges-achieving-us-transformational-goal

[29] UNECE (2022). Policy discussion – Challenges of big data and analyticsdriven demand-side management (GEEE-9.2022.INF.3). Available at: https://unece.org/sites/default/files/2022-08/GEEE-9.2022.INF_.3-DataAnalytics_rev.pdf, accessed 10 May 2023

Asset-level generation and consumption data is one of key preconditions for efficient DER management but there is scarce data on installed submetering[30] capacity. In terms of policy, in Europe, the Framework Guideline on Demand Response published by ACER in December 2022 provides the first legal guidelines on submetering in Europe, recognizing its importance for energy flexibility services, including data granularity and fair and secure data access:[31]

(para. 19) *"It is important to note that this [Framework Guideline] considers the deployment of smart metres as a key for enabling the full potential of the participation of these resources in all electricity wholesale markets. At least where the deployment of the smart metres is delayed, the new rules shall specify the conditions for the usage of sub-meters, in order for the new rules to become effective. This does not mean that the use of sub-meters should only be restricted to the cases where smart metres have not been installed. Moreover, in order to ensure non-discriminatory access to the markets, the new rules shall specify the different models under which these resources may participate, and clarify the roles and responsibilities under each context. These general requirements, which are considered relevant for ensuring equal access of these resources to all electricity wholesale markets, are included in this Chapter."*

(para. 33) *"If the control of the provision of an [System Operator] service is based on measurement, the granularity of the metre needs to be at least equal to 15 min, which is the harmonised imbalance settlement period. The new rules shall describe the conditions for the use of sub-metering for the measurement of the provision of the service. The new rules shall define sub-meters, shall set up principles for the use of the data in order to avoid manipulation, shall include provisions i) for the respective roles, ii) for the collection of the data, iii) for the verification of the accuracy of the measurements, and iv) for the compliance with relevant standards, ensuring the coherence with the interoperability rules for access to data for demand response."*

In Australia, data rights or contractual arrangements to allow grid operators and third-party service providers access to metre data are also being explored. Australia has also developed a DER Visibility and Monitoring Best Practice Guide[32] for manufacturers and service providers that offer consumers advanced monitoring of their household load and DER devices.[33]

Challenges for submetering include the lack of standardization and consistent regulation around submetering companies and the necessary retrofit measures required for effective installations. In the United States, twenty-two states, three counties and the capital of Washington D.C., have

[30] A utility submeter is a specialised type of electricity metre that measures the amount of electricity used by a specific appliance or group of appliances. Utility submeters are often used in commercial and industrial settings to measure the power usage of specific machines or groups of machines. They can also be used in residential settings to measure the power usage of specific appliances, such as air conditioners or water heaters.

[31] https://www.acer.europa.eu/news-and-events/news/acer-submitted-framework-guideline-demand-response-european-commission-first-step-towards-binding-eu-rules

[32] https://www.dermonitoring.guide/

[33] IEA. *Unlocking the Potential of Distributed Energy Resources*; Power System Opportunities and Best Practices, Paris, 2022, https://iea.blob.core.windows.net/assets/3520710c-c828-4001-911c-ae78b645ce67/UnlockingthePotentialofDERs_Powersystemopportunitiesandbestpractices.pdf

statutes, regulations and rulings on energy submetering.[34] Each state can establish their own procedures and regulations with regards to legality, installation, technology and billing.

3.1.3 Flexibility Registry

Smart grids integrate advanced digital technologies such as sensors, communication networks, and intelligent devices to improve the efficiency, reliability, and sustainability of energy generation, distribution, and consumption. However, the implementation of smart grids also raises significant privacy concerns, some of which include:

- Data privacy: Smart grids generate a vast amount of data, including energy consumption patterns, personal information, and other sensitive data. This data can be intercepted, tampered with, or stolen, compromising the privacy and security of the consumers.[35]
- Cybersecurity threats: Smart grids are vulnerable to cyber-attacks that can result in data breaches, power outages, and other damages. Attackers can exploit vulnerabilities in the communication networks, devices, and software used in smart grids to gain unauthorized access to the system and steal or manipulate data.[36]
- Surveillance: Smart grid technologies such as smart metres and sensors can collect granular information on the energy consumption habits of consumers, raising concerns about potential surveillance and profiling of individuals.
- Lack of transparency and control: Consumers may not have full visibility into how their data is collected, stored, and used by smart grid operators, limiting their ability to control the use of their data.[37]

Deploying AI and ML models on smart grid infrastructure can also raise specific privacy concerns. Some of these concerns include:

- Profiling and discrimination: Smart grids can use AI and ML algorithms to analyse large amounts of data to predict energy consumption patterns, detect anomalies, and optimize the grid's performance. However, this can also lead to the profiling of individual consumers based on their energy consumption habits, which could potentially lead to discrimination. European Data Protection Supervisor, EDPS, highlighted the risk of profiling via smart metre data as part of rollout of smart metering systems in Europe. [38]
- Lack of transparency and accountability: AI and ML algorithms can be opaque and difficult to interpret, which can make it challenging to identify when and how they are making

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[34] National Conference of State Legislatures, January 15, 2016, https://www.ncsl.org/energy/utility-submetering, accessed 15 May 2023

[35] Neeraj Kumar Singh, Vasundhara Mahajan, End-User Privacy Protection Scheme from cyber intrusion in smart grid advanced metering infrastructure, International Journal of Critical Infrastructure Protection,Volume 34,2021,100410,ISSN 1874-5482, https://doi.org/10.1016/j.ijcip.2021.100410.

[36] Kenneth Kimani, Vitalice Oduol, Kibet Langat, Cyber security challenges for IoT-based smart grid networks,International Journal of Critical Infrastructure Protection,Volume 25,2019,Pages 36-49,ISSN 1874-5482, https://doi.org/10.1016/j.ijcip.2019.01.001.

[37] Cavoukian, A., Polonetsky, J. & Wolf, C. Smart Privacy for the Smart Grid: embedding privacy into the design of electricity conservation. IDIS 3, 275–294 (2010). https://doi.org/10.1007/s12394-010-0046-y

[38] See: https://edps.europa.eu/sites/default/files/publication/12-06-08_smart_metering_en.pdf

decisions that affect privacy. This can limit transparency and accountability, making it difficult for consumers to challenge or contest decisions made by the algorithms.[39]

- Biased algorithms: AI and ML algorithms can be trained on biased or incomplete data, which can lead to inaccurate or discriminatory outcomes. For example, if the data used to train an algorithm is biased towards certain demographics or seasonality, the algorithm may perpetuate or amplify these biases.
- Data breaches and misuse: The use of AI and ML on smart grids can generate large amounts of sensitive data, such as energy consumption patterns and personal information, which can be attractive targets for cybercriminals. Additionally, if this data falls into the wrong hands, it can be misused for nefarious purposes.

There are several ways to mitigate the privacy challenges associated with smart grids and the deployment of AI and ML algorithms. Some of the most effective measures include:

- Data anonymization and aggregation: Smart grid operators can anonymize and aggregate consumer data to protect individual privacy while still providing valuable insights for grid optimization. This can involve removing personally identifiable information, PII, from the data, such as names and addresses, and aggregating the data at a larger geographic or demographic level.[40]
- Encryption and access controls: Smart grid operators can use encryption and access controls to protect consumer data from unauthorized access and theft. This involves encrypting data in transit and at rest, as well as implementing strong access controls to limit who has access to sensitive data.[41]
- Transparent and explainable algorithms: Smart grid operators should ensure that their AI and ML algorithms are transparent, explainable, and free from bias. This involves providing clear explanations of how the algorithms work, what data they use, and how they make decisions. It also involves testing the algorithms for bias and taking steps to eliminate any biases that are detected.[42]
- Consent and control mechanisms: Smart grid operators should provide consumers with clear consent and control mechanisms that enable them to decide how their data is used. This involves providing clear and easy-to-understand privacy notices, obtaining explicit consent for data collection and use, and providing opt-out mechanisms for consumers who wish to revoke their consent.[43]

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[39] Anna Volkova, Amit Dilip Patil, Seyyed Ahmad Javadi, and Hermann de Meer. 2022. Accountability challenges of AI in smart grid services. In Proceedings of the Thirteenth ACM International Conference on Future Energy Systems (e-Energy '22). Association for Computing Machinery, New York, NY, USA, 597–600. https://doi.org/10.1145/3538637.3539636

[40] C. Efthymiou and G. Kalogridis, "Smart Grid Privacy via Anonymization of Smart Metering Data," *2010 First IEEE International Conference on Smart Grid Communications*, Gaithersburg, MD, USA, 2010, pp. 238-243, doi: 10.1109/SMARTGRID.2010.5622050.

[41] Fursan Thabit, Ozgu Can, Asia Othman Aljahdali, Ghaleb H. Al-Gaphari, Hoda A. Alkhzaimi,Cryptography Algorithms for Enhancing IoT Security, Internet of Things, Volume 22, 2023, 100759, ISSN 2542-6605, https://doi.org/10.1016/j.iot.2023.100759.

[42] Williams, R., Cloete, R., Cobbe, J., Cottrill, C., Edwards, P., Markovic, M., . . . Pang, W. (2022). From transparency to accountability of intelligent systems: Moving beyond aspirations. Data & Policy, 4, E7. doi:10.1017/dap.2021.37

[43] See: https://energycentral.com/c/iu/how-does-gdpr-affect-smart-grids

To address privacy and security concerns and enable a higher level of grid visibility and system interoperability, the policy makers, as well as researchers and grid operators from Europe to Australia are considering energy asset identification tools and the development of flexibility registries.[44] This is also one of the critical policy recommendations by the International Energy Agency with the objective of unlocking the DER potential.[45]

According to a European business association smartEn:

> *"Flexibility registers should be bi-directional tools for service providers and system operators, with data access management rights. They should include not only information on the flexible assets but also data on flexibility needs by system operators and detailed information on congestion."*[46]

One such implementation in Australia is presented below, followed by an overview of peer-to-peer trading regulatory developments and an analysis of its implementation in Ireland.

3.2 Decentralized data exchange platform for energy assets (Australia)

By 2050, 40 per cent of the total installed energy system capacity in Australia will come from DERs.[47] The Australian Energy Market Operator (AEMO) engaged in project on Energy Demand and Generation Exchange (EDGE),[48] with the Energy Web Foundation,[49] aiming to showcase how a decentralized data exchange can contribute to maximising DER utilization and increasing grid resilience.[50]

This increasing deployment of DER, creates challenges for AEMO and distribution network operators in balancing and protecting the grid, but also creates new opportunities for consumers and other market participants to create value via supporting the energy transition with their DER. Enabling widespread and beneficial DER participation requires, among others, electricity network operators, market operators, flexibility service providers (FSPs), and consumers / prosumers to be able to exchange large volumes of data under common data models, commands, and communication protocols. Key challenges and innovations to enable DER integration and data exchange were identified across three core elements outlined in Table 1.

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[44] TSO-DSO Report, "An Integrated Approach to Active System Management", 2019, https://docstore.entsoe.eu/Documents/Publications/Position per cent20papers per cent20and per cent20reports/TSO-DSO_ASM_2019_190416.pdf. Florence School of Regulation, Roadmap on the Evolution of the Regulatory Framework for
Distributed Flexibility, https://fsr.eui.eu/distributed-resources-and-flexibility/; smartEn, A Network Code for Demand-Side Flexibility, 2021, https://smarten.eu/position-paper-a-network-code-for-demand-side-flexibility/.

[45] IEA. *Unlocking the Potential of Distributed Energy Resource*s; Power System Opportunities and Best Practices, Paris, 2022, https://iea.blob.core.windows.net/assets/3520710c-c828-4001-911c-ae78b645ce67/UnlockingthePotentialofDERs_Powersystemopportunitiesandbestpractices.pdf

[46] smartEn, Spotlight Report on Data Sharing by System Operators, February 2023, https://smarten.eu/wp-content/uploads/2023/03/Spotlight-Data-sharing-from-system-operators_GA-approved.pdf

[47] DER Integration to provide flexibility services is remarked in Energy Security Board's Post-2025 reforms.

[48] The project partners included AEMO, AusNet Services, and Mondo, and the project is financially supported by the Australian Renewable Energy Agency (ARENA).

[49] See: https://www.energyweb.org/

[50] Policy shifts in many countries are being taken to enable access for DERs to wholesale and local markets, examples include FERC Order 2222 in the US, Ofgem's Call for Input on the Feature of Distributed Flexibility in the UK or CEER's Position Paper on the future of TSO and DSO Relationship in the EU.

Table 1
Key challenges and innovations to enable interoperable DER data exchange

	Key challenge	*Data exchange innovations*
Identities and permissions	DERs remain largely invisible and unidentifiable for Network Operators. Identifying and authenticating, is a precondition to exchanging data between parties. Only if an identity is asserted will parties communicate based on roles and responsibilities.	Self-Sovereign Identity technology Enabling participants to perform authentication and authorization processes for multiple markets and use cases with a single portable, self-sovereign digital identity.
Integration	DER data exchange requires integrating siloed legacy IT systems that support the current operations of network and market operators, retailers, FSPs, or DER owners.	Decentralized Data Hub A standardized integration mechanism allowing participants to exchange multiple data types and formats via a single integration.
Information integrity	The increasingly large volume of DER data requires market participants to access and work with accurate and consistent data. DER data exchange needs validation processes to ensure data quality and integrity between systems are flawless.	Decentralized Logic Execution (DLE) By combining a shared messaging transport layer with identity-based message authentication, DLE's novel distributed consensus technology ensures consistency and security in the exchange of information among stakeholders.

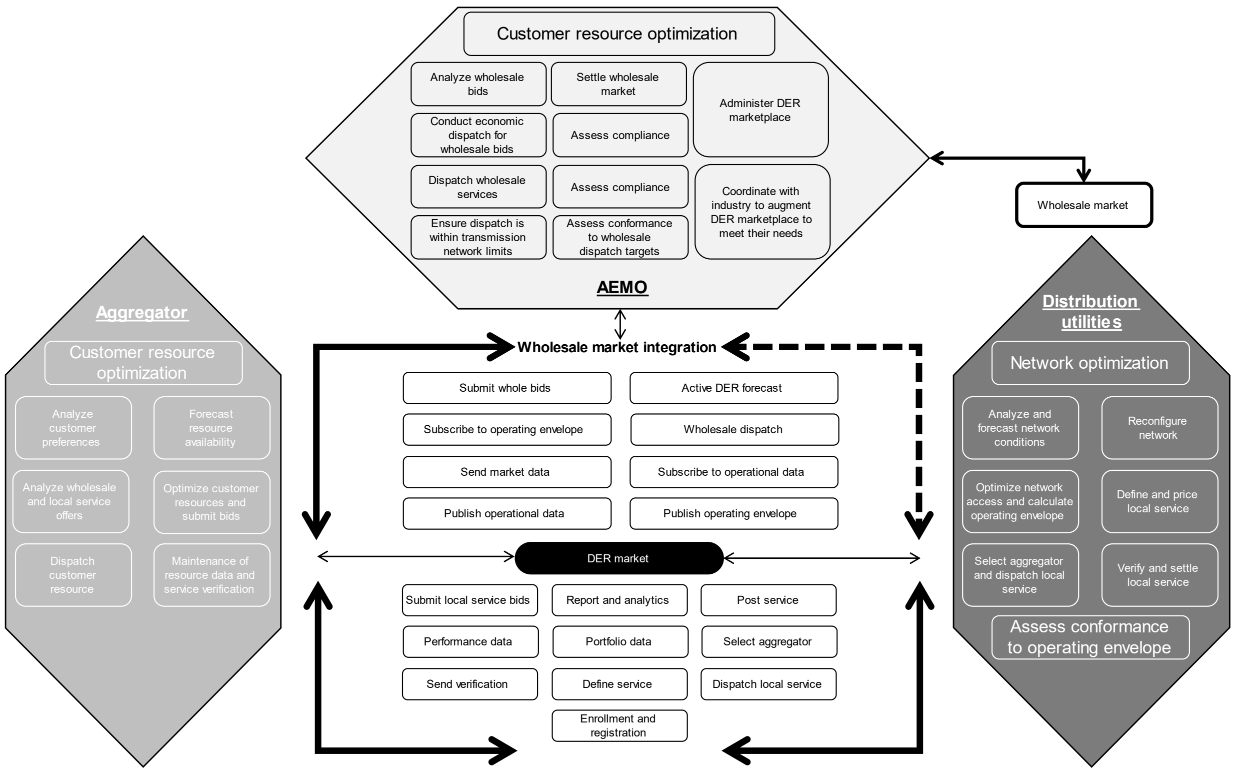
These core elements form the backbone of the digital infrastructure needed to enable DER coordination at a system-wide level. The innovations listed above seek to fill the gap precluding flexibility market integration and preventing DERs from delivering valuable grid services. Decentralized data exchange of EDGE delivers the following functionalities:

- Scalable Data Exchange: DER data comes in large volumes and in a variety of types and formats. A single integration Data Hub (as opposed to bespoke IT integrations) for market actors enables scalable multiparty data exchange.
- DER Registry: Authentication and authorization frameworks are needed to establish trusted relationships between systems, assets, and organizations. EDGE showcases a digital "passport" and "visa" solution for DER to be fully engaged in market transactions and services.
- Data Processing for Wholesale and Local services: Data from market actors (e.g., distribution utilities, FSPs, or market operators) is ingested and processed to deliver several use cases at the wholesale level (e.g., dispatch DER fleets as a forecasted resource) and local level (e.g., enrol DER in demand and response schemes).[51]
- Governance and system integrity: Organizations can encode business logic and enforce rules based on requirements and responsibilities needed for specific use cases. By having a decentral logic execution predefined and embedded into the solution verifiability is ensured without relying on a single broker.

[51] Tests under EDGE at the wholesale level included activating DER capacity aggregated by FSPs on a 5-minute periodicity following simplified dispatch rules (e.g., market signals, limits to DER imports and exports). While at the local network level, a Local Service Exchange was facilitated as a communication channel between the Distribution System Operator and FSPs to procure local network flexibility services on a bilateral basis. See: DER Data Hub Lessons Learnt Report.

Having a DER data exchange built leveraging the functionalities listed above can host a diverse set of business functions and use cases with data flowing between market actors and devices (Figure 2).

Figure 2
Project EDGE data exchange functions and data flows



Source: Adapted from: Project EDGE: DER Data Hub Lessons Learnt Report (June 2023), p.6. Available at: https://aemo.com.au/-/media/files/initiatives/der/2023/project-edge-der-data-hub-lessons-learnt-final-june-2023.pdf?la=en

Project EDGE showcases that a decentralized data exchange, in comparison with point-to-point or centralized data exchange solutions, is the most suitable approach because:

(a) It has no single point of failure by design;

(b) The architecture is modular and highly interoperable providing greater flexibility, there is no single entity under control but a shared governance, and can support any agreed upon *data model and communication protocol.*[52]

3.3 Peer-to-peer energy marketplace development (Ireland)

Transactive Energy (TE) in the form of Peer-to-Peer (P2P) or Community Trading and Community Self-Consumption (CSC) are three emerging models in bottom-up energy market management that typically leverage distributed energy resources. These decentralized systems generate electricity close to where it is consumed, turning consumers into "prosumers" – a term for consumers who

[52] Ibid.

are also energy producers. While each approach has certain similarities, it also presents its own unique characteristics and challenges presented in the Table 2 below.

P2P method enables direct energy trading between consumers / prosumers, with any additional market needs supplied by other energy suppliers, namely utilities. P2P benefits can be significantly enhanced in terms of market access fairness and transparency, as well as automation of clearance and settlement by deploying emerging distributed ledger technology (DLT or blockchain). P2P systems can distribute energy more efficiently, promote energy savings, and reduce costs for consumers, while supporting grid resilience. The benefits can be further enhanced if a market-based pricing mechanism is enabled,[53] including dynamic grid tariff implementation by grid operators to source and manage system flexibility. The method requires a more advanced metering infrastructure with submetering capacity and investment in DER.

A more limited form of TE is Peer-to-Market (P2M) community trading whereby consumers / prosumers trade energy against a single community-level price that is usually established by a regulator and not based on market conditions in a certain timeslot. This also requires submetering capacity but can be managed with less sophisticated energy trading digital applications, although even in this case DLT would provide additional functionality. This more conservative approach is currently pursued by several EU member states, including a project in Ireland discussed below.

CSC, on the other hand, is a model in which groups, organized as energy communities, cooperatives and alike, within a specific geographical area produce and consume energy together, primarily from local renewable resources such as solar power and wind turbines, sometimes investing in shared storage (battery).

All the described local energy actions can facilitate community cooperation, encourage the use of local renewable energy, and reduce energy costs for participants. Initial costs can be high, both in terms of investment in DER and digital technology, and ongoing government support may be required, including in education and organizing a community (Table 2).

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[53] Exemplified by the technology approach by open-source developer Grid Singularity, https://gridsingularity.com/.

Table 2
Comparison of bottom-up energy market management models

	P2P / TE	*P2M / Community Trading / Limited TE*	*CSC*
Short Description	Decentralized or centralized exchange operating a marketplace where prosumers/ producers/ consumers trade energy directly	Decentralized or centralized exchange operating a marketplace where prosumers / producers / consumers trade energy with the community at a single community price (usually set by regulator)	Community generates and consumes energy together, typically from shared DER such as a community PV or battery but other than sharing common resources there is no trading
Ownership	Individual and possibly also community-owned DER; marketplace operated by software in line with local regulation and community usually registered as a legal entity	Individual and possibly also community-owned DER; marketplace operated by software in line with local regulation and community usually registered as a legal entity	Community-owned DER
Benefits	Most efficient energy distribution / DER use, cost reduction, especially if trading between communities is also enabled (bottom-up energy market design)	More efficient energy distribution / DER use, cost reduction, energy conservation incentives, such as demand response or other flexibility services	Use of renewable energy, cost reduction, community building
Challenges for Greater Adoption / Scale	Requires digital infrastructure (submetering) and sophisticated marketplace operation technology, investment in DER; limited user-friendly applications available	Requires digital infrastructure (submetering) and simple marketplace operation technology, investment in DER; limited user-friendly applications available	Investment in DER required; administrative hurdles for shared resources and governance of these resources
Policy and regulation considerations	Needs a regulatory framework that supports P2P trading based on market conditions, ideally using DLT for marketplace operation and support for community management and uptake of digital solutions with higher user interaction and more user choices	Needs a regulatory framework that supports P2M (community) trading, support to community registration and uptake of digital solutions	Policies that support renewable energy and community energy initiatives are beneficial. Regulatory barriers might include zoning restrictions and utility regulations. Other barriers include permitting related to DER acquisition and knowledge gap.

	P2P / TE	*P2M / Community Trading / Limited TE*	*CSC*
Environmental Impact	Positive impact as it encourages the use of renewable energy and conservation, while any carbon footprint of digital solutions should be mitigated by a choice of sustainable tools	Positive impact as it encourages the use of renewable energy and conservation, while any carbon footprint of digital solutions should be mitigated by a choice of sustainable tools	Positive impact as it encourages the use of renewable energy and conservation, while any carbon footprint of digital solutions should be mitigated by a choice of sustainable tools
Social impact	Prosumers/producers/consumers empowerment but may also increase the digital divide, although studies have shown that households with less resources also benefit from reduced prices	Prosumers/producers/consumers and community empowerment but may also increase the digital divide, although studies have shown that households with less resources also benefit from reduced prices	Community collaboration improves and potential reduction of costs for community members.
DLT integration benefits	Enables a range of new choices for the individual energy user, transparency of market operation (equitable market access), optimized clearance and settlement	Enables enhanced market transparency and optimized clearance and settlement albeit with a reduced impact due to limitation posed by single price	Not applicable
AI/ML integration / benefits	Enable dynamic pricing and smart trading strategies, provide intelligent condition monitoring and enhanced security for threat detection	Enable dynamic pricing, provide intelligent condition monitoring and enhanced security for threat detection	Enable improved asset management

EU has a range of directives and initiatives aimed at promoting renewable energy and making EU carbon-neutral by 2050, such as the European Green Deal introduced in 2019[54] and its Renewable Energy Directive (REDI)[55], fostering clean technologies and novel frameworks such as energy communities. As an EU member state, Ireland had set a target to produce 16 per cent of all its energy from renewable sources by 2020, revising it to 14 per cent by 2030[56] and launching several national strategies and programmes, including the microgeneration support scheme (MSS)[57]. MSS scheme is designed to provide a way for homeowners, farmers, businesses, and communities to generate their own renewable electricity, and to be paid for the excess power they export back to the grid. MSS operates on a self-consumption first principle, so producers, using micro-generation technologies such as solar PV panels, micro-wind turbines, micro-hydro generators, and micro-combined heat and power units, who export excess energy back into the grid are only paid for 30 per cent of the energy exported in an attempt to encourage micro-generators to use energy when its being generated to reduce demands on the grid at times of low or no renewable generation.

Cooperative Energy Trading System (CENTS), project funded by the Irish Government under its Disruptive Technology Innovation Fund, DTIF),[58] enables both individual consumers/producers and their broader communities generating their own electricity to use a blockchain-based platform to trade electricity based on a cooperative model. CENTS aims to co-exist with the current market by providing additional services to current consumers to generate income from exported excess energy and participation in other grid related services such as demand response and flexibility services. The project identified several challenges with the introduction of P2P energy trading, but were able to provide solutions (software and hardware) to help address these, as a result of these solutions it also opened up opportunities for other flexibility services and demand response by providing localised management of DER assets and real time data gathering and analysis. CENTS is now part of other projects, such as trading energy from battery storage, which further increases the maximising of renewable energy when it is being generated, if there is little demand then it can be stored until it is needed by using storage elsewhere on the grid. Other project findings and studies have also demonstrated benefits in terms of reduced cost (and increased revenue for prosumers) and increased self-sufficiency, importantly not only for resource-rich communities but also for communities with no DER investment who engage in local trading with neighbouring DER-intensive communities.[59]

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[54] See: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[55] See: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
[56] See: https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/renewables/
[57] See: https://www.gov.ie/en/publication/b1fbe-micro-generation/
[58] See: https://enterprise.gov.ie/en/news-and-events/department-news/2018/december/10122018a.html
[59] See for instance, studies of P2P trading in Germany and in Columbia: https://gridsingularity.medium.com/modelling-study-to-assess-the-potential-benefits-of-trading-in-and-between-local-energy-d721395ddd4b;https://smartcities.ieee.org/newsletter/january-2022/advancing-from-community-to-peer-to-peer-energy-trading-in-the-medellin-colombia-local-energy-market-trial

4. CYBER RESILIENCE OF CRITICAL ENERGY INFRASTRUCTURE

Digitalization is gaining more and more attention as a way to support and complement the energy transition process. Digitalization entails the use of digital technologies for existing processes, as it helps address existing challenges in new ways.

While using an integrated energy system with intelligent connected devices has many advantages, it also causes challenges. One of these challenges is the increased surface of attack and thus the related cybersecurity risk.

In general, the aim of cyberattacks is to take control of the system, of the data and/or harm/damage/incapacitate the physical equipment. Thus, in the case of the smart integrated energy systems, the goal is to take control of the energy system so that energy cannot be produced, transmitted, distributed, and/or used as intended.

As energy systems are considered critical infrastructure, dealing with cyberattacks is critical for reliable sustainable development. This can be done by preventing, mitigating, and – eventually – recovering from cyberattacks:

- Prevention means that measures are put into practice that prevent cyberattacks on the energy system from taking place and being successful.
- Mitigation means that the consequences of cyberattacks on the energy system are limited as much as possible.
- Recovery means that the energy system is brought back to normal functioning as soon as possible after a successful attack.

To be able to prevent, mitigate, and recover from cyberattacks effectively, measures can be implemented both top-down and bottom-up:

- Top-down means that policies and regulations inform the workforce what to do to increase security.
- Bottom-up means that identified security issues on a technical level are reported to the management so that policies and regulations can be improved accordingly.

If these top-down and bottom-up strategies are implemented thoroughly and consistently, the number of different attack points for attackers reduces, leading to a higher overall security level of the energy system. As a consequence, this contributes to different sustainability aspects of the energy system:

- On the economic level, a secure energy system reduces the loss of profits and reputational damage;
- On the social level, a secure energy system ensures many critical services including healthcare and communication;
- On the environmental level, a secure energy system prevents energy waste and environmental damage.

In the following case study, an example of a successful cyberattack on the energy system and the consequences are explored in more detail.

4.1 Cybersecurity attacks on energy system components and their example consequences

As the energy system is identified as critical infrastructure and energy is the backbone of society, consequences of cyberattacks can be far-reaching, including economic, social, and environmental consequences. Recent examples of ransomware-based cyberattacks on critical infrastructure, resulting in temporary shutdowns and data loss, show a growing trend: ransomware attacks nearly doubled in 2022, and the last 6 months of 2023 witnessed a 35 per cent increase of ransomware attacks and a 53 per cent increase of malware and viperware that impacted industrial infrastructures.[60]

This trend is not surprising considering that preventing cyberattacks and mitigating the consequences is not a simple task; moreover, cybersecurity is often neglected for integral processes, from design to operations, despite the extensive attack surface of modern energy systems.

The integrated and intelligent devices, servers, computers, and systems by virtue of their connectedness can all be potentially attacked in a myriad of ways as exemplified below:

1. Servers: by using services that should not be available to the outside world, by exploiting outdated software that has known vulnerabilities, by exploiting insecure configuration settings such as default passwords, and by gaining unauthorized access to sensitive data;
2. Networks: by bypassing authentication, by overloading the network so that normal functioning is impaired, by exploiting insecure configuration settings such as weak encryption, and by gaining unauthorized access to communication data of other users;
3. Websites: by using functionalities that should not be accessible, by exploiting known vulnerabilities, by exploiting insecure configuration settings such as default passwords, by gaining unauthorized access to sensitive data such as the underlying database or unencrypted communication, by gaining unauthorized access to the underlying server, by attacking other users, and by uploading malware;
4. Mobile applications: by using functionalities that should not be accessible, by exploiting known vulnerabilities, by exploiting insecure configuration settings such as default passwords, by gaining unauthorized access to sensitive data such as the underlying database or unencrypted communication, and by gaining unauthorized access to the underlying mobile devices;
5. Software and firmware: by bypassing authentication, by exploiting known vulnerabilities, by exploiting insecure configuration settings such incorrect/insufficient access rights management, and by gaining unauthorized access to sensitive data such as source code;
6. Webservices: by exploiting known vulnerabilities, by exploiting insecure configuration settings such as authentication without password, by gaining unauthorized access to sensitive data such as data from other users, and by gaining unauthorized access to the underlying server;
7. Cloud-based platforms: by obtaining unauthorized access to data from other users such as files, by gaining unauthorized access to the underlying server, by exploiting insecure configuration settings such as authentication by guessing a weak password, by gaining unauthorized access to sensitive data such as passwords or access keys, and by exploiting known vulnerabilities;
8. Sensors, motors, relays, etc.: by exploiting known software vulnerabilities, by exploiting insecure configuration settings, by tampering with data sent by a sensor/motor/relay/etc, by manipulating functionality of sensors, motors, relays, etc., by making the sensor unavailable, and obtaining unauthorized access to data;
9. Hardware: by manipulating the hardware design, by adding malicious hardware in the network, by attacking interfaces that are made available for finding problems, and by manipulating transferred data;
10. Users: by malicious emails such as phishing emails that invite readers to provide sensitive data or attachments with malware, by inciting fear in people so that they are triggered to

[60] Fortinet, Global Threat Landscape Report. A Semiannual Report by FortiGuard Labs (February 2023).

perform an action that harms them and may go unnoticed, by disinformation activities that provokes them into sharing sensitive information.

Many other types of attacks are potentially possible. These can be categorized into four types:

1. Physical attacks (on the physical components of the system), including:
   (a) Physical damage: attacking a component causing physical damage, or activating inappropriate or non-operational behaviors;
   (b) Social engineering: deceiving and manipulating individuals into sharing sensitive information that can be used for further attacks;
   (c) Node tampering or malicious node injection: a node in the smart integrated energy system is a part that connects a physical device to the Internet and is responsible for collecting, processing, and/or controlling data. Tampering sensitive data means not only reading but also changing it. This can be achieved by attacking an existing node, but also by adding a new node.
2. Software attacks (on computer programmes that are executed by physical devices in the energy system), including:
   (a) Malicious scripts: adding to existing software so that the latter contains additional, harmful functions, e.g., to steal login data;
   (b) Malware: installing software, which can support all kinds of harmful activities, e.g., spyware to steal data, viruses to damage or change files and/or data, viperware to wipe data and software, and ransomware to encrypt data;
   (c) Denial-of-service: a denial-of-service (DoS) attack makes the software or device unavailable, e.g., by overloading the software or shutting it down. If such an attack is performed from many computers at the same time, it is called a distributed denial-of-service (DDoS) attack.
3. Network attacks (gaining unauthorized access to, and perform unauthorized actions in the network), including:
   (a) Traffic analysis: gaining knowledge from characteristics of a data flow that can be observed, even when the content of the data flow remains hidden;
   (b) Routing information: intercepting, changing, and/or redirecting data sent through the network to a different destination, e.g. to monitor or steal data, or disrupt the energy system service delivery;
   (c) Sinkhole: a harmful node in the grid sends bogus messages to other nodes and tricks these nodes into sending information to the harmful node;
   (d) Unauthorized access: getting access to the network without having permission.
4. Encryption attacks (circumventing the security by adding encryption, which requires a key to turn the code back into readable information or data), including:
   (a) Cryptanalysis: aiming at finding out what information or data is encrypted, without knowing the key;
   (b) Side-channel: using information that is unintentionally provided by a computer system when doing cryptographic operations to gain access to encrypted information;
   (c) Man-in-the-middle: positioning between two communicating components, so that encrypted messages can be eavesdropped and even changed.

Oftentimes, different types of cyberattacks can be observed at once, therefore overlapping challenges and disruptions to potential victims. Additionally, cyberattacks can also complement other types of physical attacks.

4.2 Pipeline cyberattack (United States of America)

4.2.1 Contextual introduction

The Colonial Pipeline is a North American oil pipeline system originating in Houston, Texas, and transports refined oil products (gasoline, diesel, jet fuel) to the Eastern areas of the United States. It carries more than half of all fuel consumed on the East Coast.

The sequence of events has been established as follows:

- 6 May 2021: Malicious actors launch an attack, stealing data, locking computers, and requesting a ransom.
- 7 May 2021: Colonial Pipeline pays the ransom.
- 8 May 2021: Colonial Pipeline publicly announces attack, then shuts off servers and some pipelines.
- 9 May 2021: Colonial Pipeline makes a second public announcement, discussing its system restart plans.
- 10 May 2021: The Federal Bureau of Investigation (FBI) confirms DarkSide ransomware caused the attack, and Colonial Pipeline releases two more statements around its restoration process.
- 11 May 2021: Federal agencies release an advisory describing DarkSide ransomware and mitigation strategies while Colonial Pipelines releases a statement around fuel shipping.
- 12 May 2021: Colonial Pipeline restores operations and announces fuel delivery timelines, amidst people "panic buying" gasoline.

The attack shut down Colonial Pipeline's operations for approximately five days, causing localized shortages of gasoline, diesel fuel, and jet fuel. Panic-buying by consumers depleted gasoline supplies at some service stations on the East Coast while also driving up retail gasoline prices.[61]

Alternatives to the pipeline, in the form of transporting fuel through trucks and tanker cars for trains, were slow to organize.[62]

Colonial Pipeline shut down its operational technology systems out of caution to halt further infection, but eventually paid the hackers over $4 million in cryptocurrency to restore its operating systems. Even after receiving the decryption key, it took days of work to restart the pipeline.

Cybersecurity experts also note that Colonial Pipeline would never have had to shut down its pipeline if it had more confidence in the separation between its business network and pipeline operations. Cybersecurity best practices indicate there should always be separation between data management and the actual operational technology. That a pipeline carrying almost 50 per cent of gas to the East Coast, had not implemented this as a basic practice raised questions for regulators and governments and its agencies.

The cybersecurity incident occurred at a time when there were increasing concern about the vulnerability of critical infrastructure to cyber threats. This heightened concern followed a series of prominent cyber incidents (e.g. SolarWinds breach), which targeted numerous federal government agencies, including the Departments of Defense, Treasury, State, and Homeland Security.

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[61] See: https://www.washingtonpost.com/business/2021/05/12/faq-gas-shortages/
[62] See: https://www.nytimes.com/2021/05/14/us/politics/pipeline-hack.html

Cyberthreats are becoming increasingly prevalent across all economic sectors, and they pose cascading national security risks for the energy industry. The Colonial Pipeline attack could have gone further. For instance, the infamous Russian NotPetya (Ransomware) attack brought down most of Ukraine's operating systems by infiltrating computers via a common accounting software mechanism and wiping information.[63] The NotPetya attack caused approximately $10 billion in damages spread across multiple international industries[64] and crippled the country's infrastructure.

4.2.2 The intervention and the changing factor

From an AAG-IT 2023 report, *Ransomware* is a malware designed to deny a user or organization access to files on their operational systems (computers). By encrypting these files and demanding a ransom payment for the decryption key, cyberattackers place organizations in a position where paying the ransom is the easiest and cheapest way to regain access to their files. Some variants have added functionality – such as data theft – to provide further incentives for ransomware victims to pay the ransom.[65]Over 93 per cent of ransomware attacks are on Windows-based executables and organizations in the US account for 47 per cent of attacks. It is not all bad news however, approximately 90 per cent of ransomware attacks fail or have the result in zero-losses for the organization attacked.

On 6 May 2021, the Colonial Pipeline suffered a ransomware attack. It started when a hacker group identified as DarkSide accessed the Colonial Pipeline network, culminating in a multiple staged and multilayered attack. Attackers stole 100 gigabytes of data within the first few hours of the attack. The second wave of the attack was the infection of the IT network with ransomware that infected many computer systems (billing and accounting included).

The most common entry point for ransomware is phishing. Attackers were able to penetrate the Colonial Pipeline network through an exposed VPN password account. From that moment onward, the DarkSide group used its ransomware-as-a-service (RaaS) model to hold the pipeline network hostage until the ransom was paid.

The initial response of the Colonial Pipeline was to shut down its systems to prevent the ransomware attack from spreading, pay the ransom, decrypt the locked systems and begin the damage control needed to quell the growing panic of Americans for whom petroleum-based gasoline is a daily necessity. Subsequently, authorities were notified to begin an official investigation. The Biden Administration issued an executive order for U.S. Government agencies, directing them to take a series of proactive cybersecurity steps. As this attack crossed state boundaries, and affected major geographical and economic regions, federal authorities such as FBI, U.S. Department of Energy (DoE), Department of Homeland Security (DHS), and Cybersecurity and Infrastructure Security Agency (CISA) were now involved. The effects of the Colonial Pipeline attack were both immediate and lasting. In the immediate term, once news reached the public channels about the attack, panic-buying due to fears of an impending gas shortage led to long lines at gas stations across Florida, Georgia, Alabama, Virginia and the Carolinas. Seizing the competitive opportunity, station owners raised prices to USD $3/gallon (expensive at the time). Longer lasting effects included a product safety alert being issued to those who were filling plastic bags with gasoline, while the Product Safety Commission considered issuing new regulations to enforce proper dispensing of flammable liquids.

The Biden administration issued an order that advocates a Software Bill of Materials (SBOM). This has the effect to allow developers of software components to ensure those components are up to date

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[63] See: https://www.washingtonpost.com/world/national-security/russian-military-was-behind-notpetya-cyberattack-in-ukraine-cia-concludes/2018/01/12/048d8506-f7ca-11e7-b34a-b85626af34ef_story.html
[64] See: https://www.wired.com/story/notpetya-cyberattack-ukraine-russia-code-crashed-the-world/
[65] See: https://aag-it.com/the-latest-ransomware-statistics.

and to respond quickly to new vulnerabilities. Buyers are protected as well by the SBOM by using it to perform vulnerability or license analyses, both of which can be used to evaluate risk in a product.[66]

By 7 June 2021, and with the collaborative efforts of multiple agencies, 63.7 bitcoin (approximately USD $2.3 million at the time) were recovered from the attackers.[67] The Biden administration is seeking USD $26 billion is cyber funding for the 2024 fiscal year.

4.2.3 The effects and lessons learned

Numerous major effects have derived from the cyberattack and the forces shutdown.

The perspective of gas shortage led to individual customers filling their personal stocks, leading to long lines at gas stations. This caused a spike in the prices of gas and, in some cases, real shortages.

The airline industry was also significantly disrupted, as jet fuel shortages were recorded by many carriers, including American Airlines, leading to limited disturbance to major airports.[68]

After the attack, the DarkSide group asked for a ransom of 75 bitcoins (approximately $4.4 million on the day of the attack).

As the Colonial Pipeline CEO later testified during Congressional hearings, at the time of the ransom demand it was unclear how large the intrusion was or how long would the restoration of exposed systems would take, therefore how long the disruption would last.

Consequentially, the Colonial Pipeline paid the hacking group the amount claimed, for the decryption key needed to restore the management of the systems. The Colonial Pipeline restarted pipeline operations on 12 May 2021.

Since that attack two years ago this past May, which is known as ‘a watershed moment in the short but eventful history of cybersecurity’[69], CISA has focused on implementing and deploying systems and protocols to improve the resilience of critical infrastructure across the US. One of the areas of greatest need for companies and industries vulnerable to cyberattacks is access to actionable and timely information on best practices for system cyber- and cyberphysical security. To address this need CISA established Stop Ransomware, the Government-sponsored website as a central repository of information for businesses to learn about and report ransomware related attacks.[70]

To ensure that efforts can scale to meet both today’s and tomorrow's cyberthreats, the Joint Ransomware Task Force, JRTF,[71] has been established as a collaboration with FBI partners and a Joint Cyber Defense Collaborative, JCDC,[72] a cross-sectoral initiative which brings together experts in cybersecurity from public and private sectors and industries to share insights and information in real-time and as a feedback/feed-forward loop into the central information repository for, among other things, publicly accessible services.

Although a variety of efforts have brought successful outcomes (e.g., avoided potential future threats, heretofore unseen collaborations amongst government entities, open communication across sectors and amongst competitive agencies) much is still to be done. In light of complex threats and increasing geopolitical tensions, diligence across major economic systems (e.g., transportation, communications, food supply, etc.) and attack surfaces is evermore necessary. Policy support is strongly needed to upgrade technologies that underpin critical infrastructures with a focus on security

[66] See: https://www.cisa.gov/sbom
[67] See: https://www.techtarget.com/whatis/feature/Colonial-Pipeline-hack-explained-Everything-you-need-to-know
[68] See: https://www.techtarget.com/whatis/feature/Colonial-Pipeline-hack-explained-Everything-you-need-to-know
[69] See: https://www.cisa.gov/news-events/news/attack-colonial-pipeline-what-weve-learned-what-weve-done-over-past-two-years
[70] See: https://www.cisa.gov/stopransomware
[71] See: https://www.cisa.gov/news-events/news/readout-second-joint-ransomware-task-force-meeting
[72] See: https://www.cisa.gov/topics/partnerships-and-collaboration/joint-cyber-defense-collaborative

rather than commercialization, with cybersecurity being part of the earliest requirements and design processes.

Further, cybersecurity needs to be prioritized at the highest levels of industry with proactive collaboration amongst government and industry, regardless of commercial or competitive interests and with a core focus on the effect to society at large and those who are most vulnerable to attack.

4.3 Considerations and solutions to ensure cyber resiliency in the smart integrated energy systems

Digitalization, as the application of digital technologies and business models for existing processes, is gaining more attention as a way to support and complement the energy transition. However, integration of different energy sources and interconnection of various energy system components which constitute smart integrated energy systems, involve exchange of large amounts of data that increases the exposure to cybersecurity risks.

With the increasing integration of intermittent renewable energy sources, energy surplus and shortage events occur more often. In response to such a reliability challenge, a concept of 'smart energy systems' that integrate various energy sources and energy storage and provide opportunities for an active role of the prosumer, evolve.[73]

Apart from integrating different energy sources, these smart systems contain various connected components, which enable gathering detailed and real-time data about energy production, transmission, distribution, and consumption, as well as analysis of this data with such tools as AI providing new insights that drive better forecasts and decision-making support in planning, operations and maintenance. Because of this multi-way inter-connection, a more digital and intelligent system is available, therefore called "Smart Grid". Such systems can be either single directional (where data is collected without a feedback loop), or bidirectional (where the collected data is analyzed and used to control, operate, and/or manage specific equipment or devices). Also, smart integrated energy systems can coordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders. Thus, enabling the operation of the system at maximum efficiency, reliability, resilience, flexibility, and stability, while minimizing costs and environmental impacts while maximizing system.

With a higher level of digitalization and intelligence, different solutions can be provided, including demand side management, peaks shaving (prioritizing energy consumption during low demand periods), and energy storage of surplus energy. Also, digitalization allows predicting energy flow and provides an opportunity to change the energy supplier, consumer, and prosumer behavior via taxation, pricing signals, or policies.

While using a smart integrated energy system has many advantages, it also causes challenges. One of these challenges is the increased exposure to risk of cybersecurity attacks. This is an inherent consequence of going from separated physical devices to intelligent devices and integrated equipment connected over networks.

In general, the goal of cyberattacks is to take control of the system and/or of the data, and/or damage physical equipment, thus causing reputational damage to, or diminishing trust in an entity. This means that in the context of the smart integrated energy systems, the goal is to take control of the energy system in a way that would impede its ability to deliver energy.

The increase in the number of devices makes cybersecurity attacks more likely. This is because sensors, relays, machine controls, controls, etc., all have different attack surfaces. The attack surface is the sum of all entry points that hackers can use to control the system, including the network used to connect its components. In the case of a smart integrated energy system, the attack surface includes

[73] GEEE-7/2020/INF.3 (https://unece.org/sites/default/files/2020-12/GEEE-7.2020.INF_.3.pdf).

at least components related to energy production, transportation, energy transmission and distribution network, energy storage devices, energy consuming devices, and a digital communication network.

4.3.1 Cybersecurity attacks on smart integrated energy system components and their example consequences

As the energy system is identified as a critical infrastructure and energy is the backbone of the society, consequences of cyberattacks can be far-reaching, including economic, social, and environmental consequences. A few recent examples of ransomware cyberattacks on critical infrastructure, resulting in temporary shutdowns and data loss, show a growing trend: while, ransomware attacks nearly doubled in 2022, only last 6 months of this year witnessed a 35 per cent increase of ransomware groups that impacted industrial infrastructures and a 53 per cent increase of malware and viperware.[74]

This trend is not surprising considering that preventing cyberattacks and mitigating the consequences is not a simple task; moreover, cybersecurity is often neglected from design to operations whereas smart integrated energy system has a huge attack surface. The exposed components of the smart integrated energy system used for energy generation, transmission, distribution, are presented in Table 3.

Table 3
Some components of the smart integrated energy system used for energy generation, transmission, distribution, and use

Generation	*Transmission*	*Distribution, distributed energy resources, and customers*
Equipment monitoring	Optical transformers	Advanced metering infrastructures (smart meters)
Control Systems	Equipment monitoring	Automation (automatic reclosure, feeders, etc.)
Protection devices (relays, etc.)	Protection devices (relays, etc.)	Protection devices
Recorders	Phase measurement units	Mobility devices
Interfaces to energy management system, to supervisory control and data acquisition system, to maintenance console, etc.	Control systems	Monitoring and control of: • *Solar panels* • *Batteries (storage)* • *EV and charging* • *Smart buildings* • *Microgrid*
	Recorders	Load management
	Interfaces to energy management system, to supervisory control and data acquisition system, to maintenance console, etc.	Customer interaction
	Substation automation	
	Remote terminal units	

These connected and intelligent devices, servers, computers, and systems used in the smart integrated energy system contain different parts that can all be potentially attacked in ways exemplified below:

(a) Servers: by using services that should not be available to the outside world, by exploiting outdated software that has known vulnerabilities, by exploiting insecure configuration settings such as default passwords, and by gaining unauthorized access to sensitive data;

(b) Networks: by bypassing authentication, by overloading the network so that normal functioning is impaired, by exploiting insecure configuration settings such as weak encryption, and by gaining unauthorized access to communication data of other users;

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[74] Fortinet, *Global Threat Landscape Report. A Semiannual Report by FortiGuard Labs* (February 2023).

(c) Websites: by using functionalities that should not be accessible, by exploiting known vulnerabilities, by exploiting insecure configuration settings such as default passwords, by gaining unauthorized access to sensitive data such as the underlying database or unencrypted communication, by gaining unauthorized access to the underlying server, by attacking other users, and by uploading malware;

(d) Mobile applications: by using functionalities that should not be accessible, by exploiting known vulnerabilities, by exploiting insecure configuration settings such as default passwords, by gaining unauthorized access to sensitive data such as the underlying database or unencrypted communication, and by gaining unauthorized access to the underlying mobile device;

(e) Software and firmware: by bypassing authentication, by exploiting known vulnerabilities, by exploiting insecure configuration settings such incorrect right management, and by gaining unauthorized access to sensitive data such as source code;

(f) Webservices: by exploiting known vulnerabilities, by exploiting insecure configuration settings such as authentication without password, by gaining unauthorized access to sensitive data such as data from other users, and by gaining unauthorized access to the underlying server;

(g) Clouds: by obtaining unauthorized access to data from other users such as files, by gaining unauthorized access to the underlying server, by exploiting insecure configuration settings such as authentication by guessing a password, by gaining unauthorized access to sensitive data such as passwords or access keys, and by exploiting known vulnerabilities;

(h) Sensors, motors, relays, etc.: by exploiting known software vulnerabilities, by exploiting insecure configuration settings, by tampering with data sent by a sensor/motor/relay/etc, by manipulating a sensor's/motor's/relay's etc functionality, by making the sensor unavailable, and obtaining unauthorized access to data;

(i) Hardware: by manipulating the hardware, by adding malicious hardware in the network, by attacking interfaces that are made available for finding problems, and by manipulating transferred data;

(j) Users: by malicious emails such as phishing emails that invite readers to provide sensitive data or attachments with malware, by scaring people so that they are triggered to perform an action that harms them unnoticed, by disinformation activities to provoke them to sharing sensitive information.

Many other types of attacks are potentially possible. These can be categorized into four types:

(a) Physical attacks (on the physical components of the system),including:

- Physical damage: attacking a component causing physical damage, or its inappropriate or non operation;
- Social engineering: deceiving and manipulating individuals into sharing sensitive information that can be used for further attacks;
- Node tampering or malicious node injection: a node in the smart integrated energy system is a part that connects a physical device to the Internet and is responsible for collecting, processing, and/or controlling data. Tampering sensitive data means not only reading but also changing it. This can be achieved by attacking an existing node, but also by adding a new node.

(b) Software attacks (on computer programmes that are executed by physical devices in the smart integrated energy system), including:

- Malicious scripts: adding to existing software so that the latter contains additional, harmful functions, e.g., to steal login data;
- Malware: installing software, which can support all kinds of harmful activities, e.g., spyware to steal data, viruses to damage or change files and/or data, viperware to wipe data and software, and ransomware to encrypt data;
- Denial-of-service: a DoS attack makes the software or device unavailable, e.g., by overloading the software or shutting it down. If such an attack is performed from many computers at the same time, it is called a DDoS attack.

(c) Network attacks (gaining unauthorized access to, and perform unauthorized actions in the network), including:

- Traffic analysis: gaining knowledge from characteristics of a data flow that can be observed, even when the content of the data flow remains hidden;
- Routing information: intercepting, changing, and/or redirecting data sent through the network to a different destination, e.g. to monitor or steal data, or disrupt the energy system service delivery;
- Sinkhole: a harmful node in the grid sends bogus messages to other nodes and tricks these nodes into sending information to the harmful node;
- Unauthorized access: getting access to the network without having permission.

(d) Encryption attacks (circumventing the security by adding encryption, which requires a key to turn the code back into readable information or data), including:

- Cryptanalysis: aiming at finding out what information or data is encrypted, without knowing the key;
- Side-channel: using information that is unintentionally provided by a computer system when doing cryptographic operations to gain access to encrypted information;
- Man-in-the-middle: positioning between two communicating components, so that encrypted messages can be eavesdropped and even changed.

Oftentimes, different types of cyberattacks can be observed at once, therefore overlapping challenges and disruptions to potential victims. Additionally, cyberattacks can also complement other types of physical attacks.

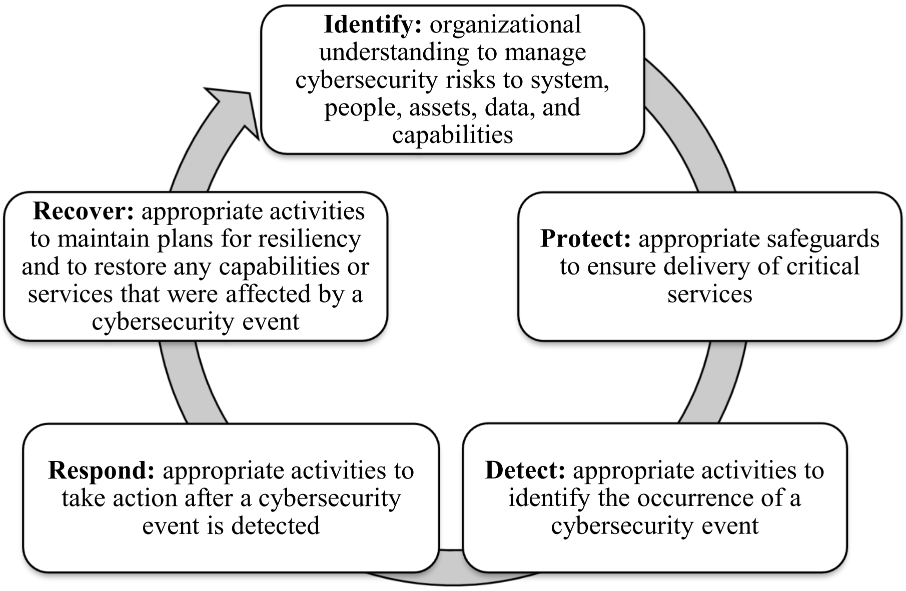
4.3.2 Measures for preventing cybersecurity attacks on smart integrated energy system components

As the smart integrated energy system is part of the critical infrastructure, preventing cyberattacks is essential. And when attacks nevertheless take place, the consequences should be mitigated. To do so, multiple solutions should be implemented to form an overall, unified strategy, sometimes referred to as "defense in depth".

Many frameworks and standards, such as National Institute of Standards and Technology (NIST) Framework for Improving Critical Infrastructure and International Electrotechnical Commission (IEC) 62443 Series[75], provide good starting points for development and implementation of efficient cybersecurity programmes.

For example, the NIST Framework details a list of activities categorized around five core development and implementation functions (Figure 3). It would also cover resources (human, material, and financial), oversight (governance), processes, and technology.

Figure 3
National Institute of Standards and Technology framework



Source: adapted from NIST, "NIST Releases Version 1.1 of its Popular Cybersecurity Framework" 16 April 2018. Available at : https://www.nist.gov/news-events/news/2018/04/nist-releases-version-11-its-popular-cybersecurity-framework.

Also, prevention, mitigation, and recovery should be done on a management level and on a technical level (Table 4).

[75] ISA/IEC 62443 series of standard, Automation and Control Systems Cybersecurity Standards.

Table 4
Some prevention, mitigation, and recovery activities for cybersecurity programmes

Level	*Prevention*	*Mitigation*	*Recovery*
Management (top-down): policies and regulations inform the workforce	(i) Risk management: involves identifying digital assets, whereas a digital asset is anything digital that is valuable, such as files with photos, videos, audio files, and text. (ii) Asset management: reviewing existing security measures and implementing additional measures. (iii) Update or patch management: as outdated software increases the attack surface of software, update management regulations should inform administrators about installation and deployment of updates. (iv) Cybersecurity systems: firewalls can be used to control incoming network traffic based on predefined security rules, thus ensuring only authorized access to the network or network segment. Network Access Control, NAC, ensures that only users who are authenticated and devices that are authorized and compliant with security policies can enter the network. (v) Network segregation: i.e., separating networks, especially a critical network from the Internet and other less critical networks such as administrative networks, thus making it is less likely that unauthorized access to a critical network is obtained. (vi) Access management (including authentication and key management): usernames and passwords, as well as other authentication means such as keys, shall be stored and managed (involves generating, distributing, storing, and updating). To make sure that different parts of the smart integrated energy system work together, the authentication methods have to match. Which method is most suitable depends on different factors such as scalability and security. (vii) Code attestation and code analysis: code attestation means checking the integrity of the software and ensuring that it has not been tampered with. Code analysis means checking the quality of code and making sure the code does not contain security issues that can potentially be used by attackers. A zero-trust approach is another possible solution to secure a system. (viii) Device and software security: the security of components of a smart integrated energy system needs to be tested, for example by performing a penetration test. (ix) Cryptography: to make sure that data can be exchanged securely and remains hidden from unauthorized access. To transform data into unrecognizable codes, different algorithms and methods can be used depending on the security criteria and context. Also, the strength of the algorithm is important in this context. (x) Awareness: e.g., live hacks in which it is shown how hackers attack different components, might be an important part of cybersecurity culture or hygiene. They can not only be used to teach technical staff but also non-technical staff what they can do to improve cybersecurity. (xi) Cybersecurity programme and culture: providing organizations the confidence that all aspects of cybersecurity are covered taking account of any the economic, societal, and environmental risks. (xii) Use zero-trust strategy based on the idea of "never trust, always verify," which means that users and devices should not be trusted by default, even if they are connected to a permissioned network.	(i) Intrusion detection system: to continuously observe a system and look for anomalies. Anomalies can take many different forms, for example an unusual number of login attempts for an account, an unusual amount of network traffic from a computer, an additional device in the network, etc. If an anomaly is detected, it is isolated. Or when an unusually high amount of traffic is sent by a computer, this computer is blocked. Often, network administrator is informed about the anomaly, so that further appropriate measures can be taken. As false alarms are possible, machine learning and artificial intelligence can be used to improve detection. (ii) Data loss prevention techniques: these are used when a virus tries to use or send confidential information. The goal of these techniques is to prevent information loss and prevent obtaining data that is affected by a virus. This can be done by isolating an infected device or blocking access from unauthorized devices.	Can be specified in regulations based on these standards, include recovery planning which includes processes and procedures to be executed to ensure restoration of systems or assets affected by a cybersecurity incident. These shall be used as part of business continuity management to revert to normal operations as soon as possible.

Level	*Prevention*	*Mitigation*	*Recovery*
Technical (bottom-up): identified issues are reported to the management, providing feedback so that improving policies and regulations	(a) Code analysis (when possible as it may not be possible for all operational devices): code analysis means analyzing the source code of an application for vulnerabilities. This analysis can be static or dynamic. Static code analysis means that the security analyst has full access to the source code and looks for vulnerabilities in the lines of code. In dynamic code analysis, the analyst does not have access to the source code and instead executes the computer program. During execution, the program can be scanned for vulnerabilities. (b) Vulnerability scanning: vulnerability scanning involves automatically assessing security issues on systems and the software that is executed on these systems. These scans are helpful to identify possible entry points that attackers can use to enter a system and potentially use as a stepping stone for further attacks. (c) Penetration test: a penetration test is an authorized cyber attack on a network, system, device, or software with the goal of testing the security level of the tested object. The goal of these tests is to find a wide range of security issues. (d) Red teaming: red teaming is like a penetration test, an authorized cyber attack. The main differences are that the scope of the test is usually wider, such as a company, as the goal is to find an exemplary way of the far-reaching consequences of a cyber attack as opposed to identifying a wide range of security issues.	Security operation centre: A team of security professionals that monitors an organization's entire information systems infrastructure, to detect cybersecurity events in real time and address them as quickly and effectively as possible. It selects, operates, and maintains the organization's cybersecurity technologies, improves threat detection, security posture, response, and prevention capabilities by coordinating all cybersecurity technologies and operations. To perform its functions, it analyses data from various sources including intelligence shared by authorities and industry, including a Security Information and Event Management (SIEM) system, which analyses behavioural anomalies with artificial intelligence to automatically detect and respond to cyberattacks.	(a) Digital forensics: involves gathering evidence, by identifying, collecting, and analysing data and devices that potentially provide information about cyberattack. It also provides valuable insights on the ways to avoid future cyberattacks. (b) Elimination: Eliminating the source of the incident and rebuilding the attacked system(s) is essential to be able to return them to normal operations (utilizing backups, recovery plans, and business continuity plans).

Note: The types of prevention and mitigation strategies should be specified. These prevention and mitigation strategies should preferably be documented in regulations. For example, such regulation can be implemented in the context of the IEC 62443 Series and the ISO/IEC 27032:2012 Information technology – Security techniques – Guidelines for cybersecurity standard (https://www.iso.org/standard/44375.html). The first addresses cybersecurity for operational technology in automation and control systems, and the latter focuses on protecting sensitive data, systems, and online operations and activities from being hacked, sabotaged, or modified. When taking security at a higher level, to the information level, the ISO/IEC 27001:2022 Information security management systems standard (https://www.iso.org/standard/27001), which helps organizations manage their information security by addressing people, processes, and technology, could be implemented.

4.4 Lessons learned and considerations for other geographies

Considering the above-described events a few considerations ought to be formulated both for developed energy systems and economies, as well as for developing energy networks and emerging economies. Moreover, a series of recommendations for both operators (be they private or state-operated) and public authorities are proposed.

- Setting up cross-national and national cybersecurity strategies that extensively describe how to prevent and manage cyberattacks of critical infrastructure and smart integrated energy systems.
- In doing so, collaborating with peer countries on potential threat actors and how to effectively overcome potential cybersecurity risks is paramount.
- To this end, the strategy development processes must identify roles and responsibilities of different stakeholders, including government agencies, central and local authorities, businesses and their employees, and individuals.
- Implementing business continuity management plans describing how to manage cybersecurity events is very important, especially where the threat of energy system outages is higher.
- From a regulatory point of view, an important element is to enforce (and reinforce) the implementation of applicable standards and guidelines which address matters of improving cybersecurity for operational technology in automation, control systems, and cybersecurity for critical infrastructure;
- In this context, developing regulations to make reporting of data protection and cybersecurity standards to official bodies to stimulate bottom-up strategies is essential.
- Financially, tax incentives for the adoption/implementation of relevant cybersecurity standards ought to become a common practice across all geographies.
- Equally important, awareness-raising actions – both among employees involved in the energy sector, as well as among customers – is highly recommended, as the pace of digitalization adoption intensifies.

5. BEHAVIOURAL BARRIERS

5.1 Theoretical and contextual introduction

The transition from fossil fuels to renewable energy such as solar and wind, aimed at mitigating environmental issues, is taking place globally and takes time. Achieving deployment at scale, requires system integration and a level of funding which usually needs to be facilitated by government institutions. Newly built energy systems need to be prepared to integrate energy from renewable energy sources into the electricity grid or district heating/cooling network, such that the grid's capacities are suitable for intermittent renewable sources utilization. This can provide the grid opportunities to control and manage equipment and software to avoid grid overload during peak times of the day when energy demand is high.

5.1.1 Behavioural aspects of energy transition

There are various reasons why the clean energy transition takes time; these involve technical, economic, organizational, regulatory, and human factors. In particular, consumers need time to transit to renewable energy sources in order to get used to new solutions. While some are eager to adopt new technology, others need to overcome psychological barriers first. The identified barriers include (but are not limited to):[76]

1. The experienced cost of change: Changing a habit requires effort, and humans tend to only change their habits when the cost of keeping a habit outweighs the cost/effort of changing their behaviour.
2. Fear of failure: When people are concerned that they may fail or do something wrong, they feel anxious. Their anxiety causes them to continue doing things the way they are used to and makes them less likely to adopt a new behaviour.
3. A focus on either alleviating pains or creating gains: People focus their decision making on either moving away from personal pain or moving towards personal pleasure.
4. Missing intrinsic motivation: When people are intrinsically motivated, their behaviour change is usually deeper and lasts longer, because they want to make the change, instead of feeling that they have to (through extrinsic motivation).
5. Disempowering beliefs: Humans have beliefs about themselves, which can be, but do not have to be true (Stern et al., 1999). These beliefs can both help and hinder humans to achieve milestones and also to make decisions.
6. Actions can have adverse results: When a one-off decision is made for a specific purpose, this can have the unintended consequence for a non-standard or non-generalizable result. This means that the one-time action can change based on future situations such that the intended behaviour change is not put into practice after all.
7. Negatively formulated goals: Humans have the tendency to focus intensely on where they do not want to go, and the consequence is that they are way more likely to end up just there. Therefore, it is much better to formulate goals in a positive way.

5.1.2 Smart energy networks and regulation of energy consumption

Smart grids are energy networks that can monitor energy flows and automatically adjust to changes in energy supply and demand. Smart grids are the backbone of the digitalization of the energy system.

[76] See: Addressing Behavioural Barriers to Energy Digitalization (ECE/ENERGY/GE.6/2022/5)

For example, the deployment of smart grids is one of the 3 priority thematic areas of the Trans-European Networks for Energy, TEN-E,[77] which aims to integrate renewable energy, complete the European energy market design, and allow consumers to better regulate their energy consumption. Hence, investment in the grid infrastructure is important to a successful transition.

Smart meters are one of the technologies important for the energy transition. Smart meters:

- Measure the energy that flows into and consumed from the grid and can provide near real-time information on energy-usage to consumer and suppliers;
- Can enable consumers to actively participate in energy communities, energy savings programs and energy generation (prosumer-model) activities;
- Enable two-way communication between the point of generation and the point of usage and provide actual and historical energy information (e.g., consumption, time, generation, returned, heating temperature, network events and local grid asset health information;
- Support the integration of renewable energy technologies by sending measured data to a display or smart device (e.g., phone or tablet) display in a format that customers can understand. This information lets users see their energy consumption (or generation) and learn how to use energy more efficiently. For customers who have also deployed in-residence batteries, the state-of-charge of the battery can be made available to the customer and the energy provider for demand response and energy arbitrage programmes.

To promote the digital transition, the European Union first mandated its member states to roll out smart meters back in 2009. Minimum technical requirements for the meter functionality were given (e.g., consumption levels, varying price tariff responses, data protection and security measures), with the intent that member states were to equip 80 per cent of their end users with smart metering technology by 2020 unless a cost-benefit analysis result was negative (implying that smart meters could be installed 'voluntarily'). By 2019, and with the adoption of the New Green Deal, the European Parliament and Council passed a revised directive that made a full deployment of smart metering systems in the EU Member States mandatory[78].

5.1.3 Rationale for the case study

Previous studies on Distribution System Operator (DSO) suggest that there is generally a positive trend with respect to smart meter installations in European Countries overall.[79] Nearly 50 per cent of DSOs surveyed have started to rollout smart meters. However, not every country has readily adopted this technology. As of 2022, Germany reported 14 per cent smart meter penetration, although this number will likely nevertheless increase as Germany adopted a law in 2023 which makes using a smart meter mandatory from 2025.

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[77] TEN-E, 2022, https://energy.ec.europa.eu/topics/infrastructure/trans-european-networks-energy_en, last accessed July 5, 2024.

[78] https://www.ecologic.eu/sites/default/files/publication/2023/33007-Case-Study_4-German-delayed-smartmeter-rollout.pdf

[79] Meletiou, A. Vasiljevska, J., Prettico G., Vitiello, S., *Distribution System Operator Observatory 2022*, Publication Office of the European Union, Luxembourg, 2023 doi:10.2760/778963, JRC132379.

A national case study report on smart meter rollout in Germany,[80] identifies a core issue to the delay of the country-wide rollout as a lack of regulatory intervention which created uncertainties among market players. And, while this report acknowledges social acceptance as a necessary reason for successful transformative policy within the context of smart meter deployment, this topic is addresses at a rather high level.

Hence, it is important to look at what is inspiring and holding back the population in Germany from voluntarily adopting smart meters, so that lessons can be learned to help other countries speed up the adoption of smart meters even without regulatory requirements being put in place.

In this document, factors that inspire users in Germany to adopt a smart meter and what determines consumers' behavioural change are discussed. The case study further suggests the ways how the relevant experience can be used in other geographies.

5.2 Implementation of smart meters (Germany)

Germany has an advanced energy system with a large part of electricity being generated from renewable energy sources, including local generation from rooftop solar PV. The share of electricity generation from renewable energy increased from 48 per cent in 2020 to 56 per cent in 2023. Wind power provides the largest amount of electricity, accounting for 32 per cent of the electricity for the public grid, followed by PV systems that generate renewable energy both for self-consumption and the public grid. Other renewable energy sources are biomass and hydropower. Hence, for such a decentralized energy system smart metering is essential.

Germany, nestled in Central Europe, boasts a robust industrial base and high population density, positioning it as one of the major economies globally. This economic strength brings significant environmental challenges, particularly in reducing emissions and transitioning to renewable energy. The nation's commitment to environmental sustainability is underscored by its ambitious energy transition policy ("*Energiewende*"), aimed at reducing reliance on fossil fuels and nuclear energy.

Before intensifying its focus on smart meters and renewable energy integration, energy mix in Germany relied heavily on coal, nuclear power, and imported gas. This reliance brought about several challenges: high emissions from coal plants, nuclear waste issues, dependence on the fossil fuel imports, and vulnerability to energy supply fluctuations. Despite these issues, opportunities were present in the engineering sector, widespread public support for green initiatives, and policies favouring investments in renewable energy. These factors collectively laid the groundwork for innovative energy solutions and opened new markets for German technologies, both domestically and internationally.

Decarbonization strategy in Germany is aiming for net-zero greenhouse gas emissions by 2045. This involves drastically increasing renewable energy to 65 per cent by 2030, phasing out coal by 2038, and enhancing energy efficiency across all economic sectors. Sector coupling is also critical, linking electricity with heating and mobility to optimize renewable energy use.

5.2.1 Challenges in tackling energy efficiency, integration of renewables, and affordability

The integration of renewables like solar and wind presents complex challenges due to their intermittent nature, requiring advanced grid management and significant infrastructure investment. Although the transition intends to reduce energy costs long-term, the initial

[80] NCS Report #4: Electricity smart meter rollout in Germany, https://www.ecologic.eu/sites/default/files/publication/2023/33007-Case-Study_4-German-delayed-smartmeter-rollout.pdf

financial outlay could burden consumers and the Government. Moreover, the rollout of smart meters – mandatory for new PV systems – faces practical hurdles, such as a shortage of installers and delays in installation. While these dual-direction meters are essential for using flexible tariffs and eventually enabling Vehicle2Grid technologies, the higher cost for smart functionality, which reports meter readings directly to suppliers, remains a significant barrier.

While hurdles such as shortage of installers needs to be overcome, social support is also essential for the success of energy policy. Ensuring public acceptance through transparent planning processes and addressing equity concerns are vital, as is balancing the costs of the energy transition to avoid disproportionately affecting low-income households. Enhancing public understanding through educational initiatives is crucial to foster broad support for the transformation. These strategies ensure that the country not only meets its environmental targets but also serves as a benchmark for pursuing a sustainable energy future in other geographies.

5.2.2 The intervention and the changing factor

To investigate the acceptance of smart meters of users in Germany,[81] researchers asked 346 potential users between the ages of 18 and 69 whether they intended to adopt a smart meter based on different benefits, such as whether people feel a smart meter: is helpful to them; makes daily life easier; is entertaining technology-wise; and makes their homes more secure.

The first factor that inspires users to adopt smart meter technology is hedonic motivation, the pleasure that a user experiences when using a technology. This motivation is probably triggered by the interaction users can have with this technology. For example, it is possible to see how much electricity is generated by solar panels on the roof in real time; or a graph shows how much electricity is used throughout the day. Other smart devices, such as smart thermostats that only offer automation without providing feedback, do not trigger hedonic motivation. The interaction triggers pleasure because it allows users to control, monitor, and analyse energy use.

The second factor is social influence, in a sense that other people and media can trigger interest in this technology. This means that the social environment is very important for influencing whether this technology is spread and adopted more often. This influence can be applied directly and indirectly. A direct influence means that other people or media inspire new users to start using a smart meter. An indirect influence means that people are inspired to, for example, install solar panels, which in turn requires the installation of a smart meter. For example, advertisements for smart meters use various techniques, such as persuasive language, emotional appeals, and social proof, to influence consumer behaviour and encourage smart meter adoption. Also, social influence of people, deciding to start using a smart meter, can inspire others to do the same.

The third factor is the local environmentalism. Although hedonic and social influences are stronger, environmentalism means the concern about the environment and actions to protect it. This influences the willingness to install a smart meter to reduce energy consumption based on the device's feedback: for example, switching off devices completely as opposed to stand-by.

Important to note about this study is that it is limited in a sense that a stated motivation does not mean a practical implementation (i.e., buying a smart meter). In many jurisdictions, including Germany, the rollout of smart meters is typically orchestrated by DSOs, not

[81] Große-Kreul, F. (2022). What will drive household adoption of smart energy? Insights from a consumer acceptance study in Germany. Utilities Policy, 75, 101333, https://epub.wupperinst.org/frontdoor/deliver/index/docId/7902/file/7902_Grosse-Kreul.pdf.

purchased individually by consumers. DSOs incorporate the deployment of smart meters into their infrastructure development plans, which must be approved by national regulators. In Germany, this is overseen by the Federal Network Agency (*Bundesnetzagentur*), which ensures that the deployment aligns with national energy policies and regulations.

The process for connecting smart meters in Germany involves several key steps, as follows:[82]

1. Regulatory framework and mandates: The German regulatory framework mandates the rollout of smart meters based on specific timelines and criteria set by the Federal Network Agency. These criteria often include energy consumption thresholds; for instance, households consuming more than a certain amount of electricity per year may be required to have a smart meter installed.
2. DSO planning and deployment: Once the regulatory requirements are established, DSOs integrate smart meter installation into their operational plans. These plans detail the logistics of the rollout, including the procurement of smart meters, scheduling of installations, and communication with customers.
3. Installation and activation: The actual installation is conducted by technicians authorized by DSOs. After installation, smart meter must be activated and integrated into the grid's operational network, allowing it to communicate usage data back to DSO and, potentially, to the consumer.
4. Consumer interface and data management: Consumers typically access their consumption data through an online platform, or a digital interface provided by DSO. This data can be used by consumers to manage their energy usage more efficiently.
5. Ongoing maintenance and upgrades: DSOs are responsible for the maintenance and any necessary upgrades to smart meters to ensure they continue to function correctly and benefit from advancements in technology.

In sum, consumers psychological barriers may fall into three main categories:[83]

1. Motivation: Involves whether the behaviour is desired by an individual and whether they are intrinsically motivated (as opposed to extrinsically motivated), experience little cost of change, and installing a smart meter alleviates a pain or creates a gain.
2. Ability: Involves whether an individual can comply with the behaviour requirements. This involves not only being able to buy a smart meter but also being able to overcome the fear of failure and they have empowering beliefs about their ability.
3. Environmentalism: Involves whether individual's behaviour is facilitated or prompted by the state of environment. This means that their goals related to smart meters should be positively formulated and that their decision should be consistent over time.

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[82] For detailed, authoritative information on the implementation of smart meters in Germany, the Bundesnetzagentur's official (websitehttps://www.bundesnetzagentur.de/DE/Home/home_node.html) and their annual reports provide comprehensive insights. These documents outline the regulatory policies, progress reports, and future plans concerning smart meter technology in Germany. By understanding these aspects, one can appreciate the organized and regulated nature of smart meter rollout in Germany, which is quite distinct from consumer-purchased models prevalent in some other markets.

[83] Gerald Schweiger, Lisa V. Eckerstorfer, Irene Hafner, Andreas Fleischhacker, Johannes Radl, Barbara Glock, Matthias Wastian, Matthias Rößler, Georg Lettner, Niki Popper, Katja Corcoran, Active consumer participation in smart energy systems, Energy and Buildings, Volume 227, 2020, 110359, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2020.110359.

5.2.3 The effects and lessons learned of the case study

5.2.3.1 Considerations of the action performed

The initiative of the Government of Germany to integrate smart meter gateways into the national electricity grid was a visionary component of the energy system transformation towards renewable energy. The ambitious programme was intended to retrofit the energy infrastructure with advanced technology, fostering the integration of renewables while promoting energy conservation and efficiency among consumers. The modernized grid was anticipated to be more responsive and capable of handling the fluctuating nature of renewable energy sources, such as wind and solar power, which were becoming a larger part of the country's energy mix. The importance of this initiative escalated as energy imports have recently been affected by supply uncertainty. Electricity prices increased dramatically and the country had to temporarily open decommissioned coal plants.[84]

Yet, despite its promising objectives, the smart meter implementation encountered a series of barriers that highlighted the gap between policy formulation and its execution. Technological hurdles emerged in the form of integrating new devices into existing infrastructures,[85] while regulatory frameworks were not sufficiently agile to accommodate the fast pace of technological innovation.[86] Societal acceptance posed another significant hurdle, as public apprehension towards new technology and data security concerns became apparent.[87,88,89]

5.2.3.2 Positive direct and indirect effects of the policy (technical, economic, social perspectives)

The technical benefits of the smart meter policy were poised to be substantial. The grid operators would gain the ability to manage energy demands in real-time, optimizing the flow of electricity and enhancing the overall stability and efficiency of the power system.[90] This was also essential for the accommodation of renewable energy sources, whose intermittent nature required more sophisticated control and distribution methods. This also fostered consumer behaviour change in using household appliances in non-peak hours.[91]

Economically, the ripple effects of the policy were expected to be significant. Operational efficiencies were predicted to lead to cost reductions for both energy providers and consumers. Grid operators would benefit from cost reductions in billing and metering operations such as modifications of contracted power, change of tariff plan and connection/disconnection actions. The implementation of smart meters would facilitate dynamic pricing models, giving consumers the opportunity to adjust their usage in response to real-time pricing data, potentially lowering their energy costs and incentivizing energy efficiency.

The social impact of the smart meter initiative was multifaceted. The policy was anticipated to drive a societal shift towards empowered, energy-efficient consumers, and align individual consumption habits with broader net-zero goals. This shift was expected to promote a culture

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84 https://www.smart-energy.com/regional-news/europe-uk/germany-to-make-smart-meters-mandatory/.
85 https://www.smart-energy.com/industry-sectors/smart-meters/re-energizing-the-future-the-next-german-smart-meter-rollout/#:~:text=According per cent20to per cent20statistics per cent2C per cent20smart per cent20meter,(End per cent202022).
86 Ibid.
87 https://www.power-technology.com/features/eu-smart-meter-optimism-dampened-by-slow-uptake/?cf-view
88 https://iot-analytics.com/smart-meter-adoption/.
89 https://www.cleanenergywire.org/news/electricity-smart-meters-become-standard-german-homes-2032
90 https://energy.ec.europa.eu/publications/study-cost-benefit-analysis-smart-metering-systems-eu-member-states_en
91 https://publications.jrc.ec.europa.eu/repository/handle/111111111/27878

of responsibility, where consumers could actively engage in managing their personal energy use and their carbon footprint.

5.2.3.3 Potential negative effects

Initially conceived as the Metering System 2020, MS2020, the smart metering approach in Germany involved the adoption of a gateway technology that connected various elements of the energy supply chain. The smart meter gateway was the interface between the energy provider and the consumer, which had the ability to communicate with digital meters in the house such as the digital electricity meter, and digital meter connected to the solar system. With a unique approach, and the country was charting new territory without the guidance or reference of other established international frameworks. The path forward was marked by complex negotiations and often conflicting interests among stakeholders, including device manufacturers, utility providers, regulatory bodies, and consumer protection agencies. Standards were set by the Federal Office for Information Security for smart meter gateways and because of the disagreements, the standards had to be revised more than once. Yet, these requirements introduced many complexities including logistical challenges that drastically slowed deployment and provoked public concern.[83]

Added to this, media reports frequently discussed other potential challenges, such as the susceptibility of smart meters to hacking and the possibility of them losing smart functionality, leaving consumers with expensive, non-functioning meters. Such media scrutiny and public concern came at a time when the smart metering system benefits were yet to be fully realized and understood by an average consumer. The reports of potential security breaches and loss of functionality created a climate of mistrust and doubt. The complexity of the implementation, compounded by these fears, led to a delay in adoption rates and a hesitant engagement from the public. These societal factors highlight the need for transparent communication and robust education campaigns to dispel myths and showcase the technology's advantages.

This backdrop of technological challenges, regulatory wrangling, and media scrutiny resulted in a hesitant adoption among consumers. All this has led to Germany being almost a decade behind in implementing smart meters than many other countries.

5.2.3.4 Adjusted long-term plans for decarbonization

The country's ambition to become net-zero by 2045 necessitated a recalibration of strategies following the early challenges faced by the smart meter rollout. With the recognition that the initial goals were overly optimistic, the Government revised its approach, outlining a more practical and staggered strategy that extended the full deployment timeline to 2032.

This adjusted strategy sought to address the complexities of the initial rollout through incremental installation targets and a new pricing structure. The proposed 'agile rollout' would enable the swift deployment of certified smart meters in homes and businesses, ensuring that the adoption would effectively contribute to decarbonization efforts of Germany. The plan of the Government included capping the metering fees and requiring energy suppliers to offer dynamic contract offerings by energy suppliers, reinforcing the country's commitment to a holistic and sustainable energy system. By mandating a progressive rollout – 20 per cent by 2025, 50 per cent by 2028, and 95 per cent by 2030 for residential and small business consumers up to 100,000 kWh (and optional for those below 6,000 kWh) and generators up to 25 kW (and optionally 1-7 kW). For large users over 100,000 kWh and generators over 100 kW, these targets are extended respectively to 2028, 2030 and 2032. The strategy aimed to facilitate a smooth transition with stringent requirements for data protection and cybersecurity, reflecting a commitment to consumer rights in an increasingly digitalized energy landscape.

The legal framework also recognized the importance of flexibility and choice for consumers, encouraging the energy market to adapt and offer diverse contract options. The stipulation for all energy providers to offer dynamic tariffs from 2025 was indicative of a broader shift towards a more consumer-centric and environmentally responsible energy landscape.

These changes were designed to not only address the immediate challenges of rollout but also to anchor the long-term vision of a decarbonized energy system.

5.2.3.5 Outcomes, findings, and advantages derived from the mass deployment of smart meters

Despite the slow start, the mass deployment of smart meters holds the promise of significantly reshaping energy consumption patterns in Germany. By providing real-time data to consumers, these devices enable more informed decision-making, allowing for an optimization of energy usage that contributes to efficiency of the national grid. The implementation of dynamic tariffs presents an opportunity for consumers to benefit financially from off-peak energy consumption, leading to a reduction in the necessity for high-cost peak power production.

In the context of energy transition goals in Germany, smart meters are expected to be indispensable. They are considered key to creating a grid that is both flexible and resilient, capable of integrating the variable generation patterns of renewable energy sources. The broader deployment of smart meters is anticipated to streamline the process of balancing energy supply and demand, facilitating a more responsive and sustainable energy system.

The experiences gleaned from smart meter initiative in Germany, offer a wealth of information and insight. As the country continues to refine its approach to energy policy, the understanding gained from the successes and setbacks of the smart meter rollout will shape future energy strategies. These lessons are not confined to the German context; they hold valuable insight for other countries navigating similar transitions, providing a framework for effective policymaking and technology adoption.

The example of Germany in establishment of a comprehensive smart metering system is reflective of the broader global movement towards digitalization and sustainable energy. It is a narrative not only of technological innovation but also of the adaptive, responsive policymaking that is required to steer such a significant transformation with a commitment to an intelligent, resilient, and environmentally conscious energy infrastructure. Although other countries, including Italy, Sweden, Denmark, are at the forefront of smart meter roll-out with percentages exceeding 90 per cent, Germany represents an example of resilience and policy adaptability that has been able to overcome the initial barriers.

As Germany forges ahead with its ambitious energy policies, the lessons learned from the smart meter rollout are likely to influence not just future deployments within the country but also serve as case studies for other nations embarking on similar transformative energy projects.

5.3 Lessons learned and considerations for other geographies

The case study of adoption of smart meters in Germany, including overcoming psychological barriers, provides a comprehensive insight into the factors that can facilitate or impede the integration of renewable energy technologies into a national grid. Drawing conclusions from this intervention and considering the implications for other geographies, it is evident that policy recommendations must be context-specific yet guided by broader principles that have universal applicability.

5.3.1 Conclusions from the intervention

The proactive approach exercised in the case of Germany towards the adoption of smart meters, highlights the importance of combining technology with targeted policy measures to accelerate the transition to renewable energy. Key conclusions from the case study include:

- Legal and regulatory environment: The key component which opens the window for the wide scale deployment of smart meters requires that the legal and regulatory environment should be in place. In Germany, the situation typically revolves around several regulatory and legal aspects. To foster a conducive environment for the deployment of smart meters, it is essential that the legal and regulatory frameworks are robust, transparent, and aligned with the interests of all stakeholders involved. Enhancements in legislation regarding tariffs, opt-out policies, and the mandatory nature of installations are critical components that need thorough review and possible revision to ensure smooth deployment and operation.
- Technological readiness: The successful integration of smart meters is contingent upon the existing technological infrastructure and the readiness for a wide scale deployment of the technology. To avoid unnecessary costs and to increase social acceptance, the technological evolution of smart meters must guarantee smooth and cost-effective upgradeability. Meters also need to provide data granularity, i.e. consumption and generation at asset level and not just net metering.
- Consumer engagement: Active engagement with the community through educational programmes and real-time data access empowers consumers, making them active participants in energy management. This happens only if the tariff structure or other means are implemented.
- Behavioural insights: Understanding the psychological barriers to adopting new technologies is crucial. In Germany, addressing these barriers through motivational and social influence strategies was essential to increase adoption rates.

5.3.2 Recommendations for implementation in other geographies

Based on the experience from Germany, other regions considering similar technological deployments could benefit from the following strategies:

- Tailored communication strategies: Develop communication plans that resonate with local values and norms. Use local influencers and community leaders to promote technology adoption, ensuring the message aligns with regional environmental and economic priorities.
- Regulatory frameworks: Implement supportive regulatory frameworks that mandate the adoption of smart technologies while ensuring that these mandates are feasible given the local economic and technological landscape. Such regulatory frameworks must reduce the uncertainty of stakeholders, enabling an innovation-looking environment.
- Infrastructure investments: Invest in upgrading the energy infrastructure to support the seamless integration of renewable technologies. This involves enhancing grid capacity and stability to handle increased renewable inputs.

5.3.3 Potential limits for "importing" the best practice

While the case of Germany offers valuable lessons, there are inherent challenges in applying these practices universally:

- Diverse starting points: Countries vary significantly in their current energy infrastructure, technological advancement, and renewable energy adoption rates. Policies must be designed to accommodate these starting points, possibly requiring phased, piloted, or tiered implementation strategies.
- Socio-economic variability: Economic disparities can influence the feasibility of adopting new technologies. In regions with limited financial resources, large-scale investments in technology might not be immediately practical without substantial external support or innovative financing models. Communities can be engaged through workshops, demonstrations, and open fora where benefits and operations of smart meters are discussed with a panel of brokers or qualified consultants.
- Cultural and social barriers: Cultural perceptions and the social fabric of a region can affect the acceptance of new technologies. Tailored strategies that consider local beliefs and practices are essential for successful adoption.
- Long-term sustainability plans: The alignment of technology adoption with long-term sustainability and climate goals may vary. Some regions might prioritize immediate economic benefits over long-term environmental sustainability, necessitating a balance between short-term gains and long-term goals. As smart meters are rolling out across various regions, renewable energy projects should be considered in with a ‘success by design’ methodology. In other words, a series of actionable measures for the purpose of renewable integration, potentially bespoke to the region, need to be developed and then be included as part of both the roll-out of the smart meters as well as the installation of RES.

6. TWIN TRANSITION IN NON-ELECTRICITY SECTOR

6.1 Background and introduction

The energy sector is undergoing a significant transformation, driven by the move towards sustainable energy. The pursuit of lowering emissions from the energy sector requires technological innovation to ensure operational efficiency for sustaining industrial competitiveness. Within this framework, digitalization emerges as an enabler, facilitating both innovation and enhanced productivity.

Digital transformation process plays a paramount role in ensuring the technical and environmental efficiency of conventional energy sectors, while also facilitating a seamless transition to cleaner alternative solutions.

While electrification plays a major role in reducing emissions footprint from the energy use in the transport, industry, and residential sectors, the broader success of these efforts hinges on comprehensive modernization across the established sectors, such as oil and gas, alongside emerging areas like hydrogen. These sectors stand to gain substantially from the efficiencies, novel products and services, and innovative business models facilitated by digitalization. Additionally, on the demand side, digitalization enables energy-efficient behaviours, enabling better planning and more inclusive decision-making while accelerating the electricity system transformation.

Acknowledging the transformative role of digitalization across various energy sectors beyond electricity, the initial research into theoretical application of digital technologies in sectors other than electricity, focusing on the oil and gas sectors, as well as on hydrogen, heating and cooling, cooking, and transport, is presented in this chapter. The objective of this prospective research track is to provide a comprehensive overview of the synergies and the current state of digitalization across the energy system.

6.2 Energy supply side and other energy vectors

6.2.1 Oil sector

The oil sector represents a major area within the global energy landscape, accounting for approximately 30 per cent of the world's primary energy supply in 2023.[92] Despite its predominant supplier role across multiple industrial sectors, the oil sector is facing increasing environmental challenges and stricter requirements for fossil fuel investments. Such challenges highlight the need for technological innovation and digitalization across the entire oil value chain, which encompasses upstream (prospecting, exploration, and production), midstream (transportation), and downstream activities (refining), as well as distribution and consumption.

Historically, the oil sector has recognized relatively low levels of digitalization, with applications primarily restricted to upstream activities such as seismic data collection, reservoir modelling software, and pipeline transportation.[93] Although the sector's capital-intensive nature has contributed to this slow adoption, recent advancements in automation have enabled operations in previously inaccessible environments, such as deepwater and challenging land conditions. These innovations underscore the significant potential of digitalization in the oil

[92] IEA (2023), World Energy Outlook 2023, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2023, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)
[93] Al-Rbeawi, S. (2023). A Review of Modern Approaches of Digitalization in Oil and Gas Industry. Upstream Oil and Gas Technology, 11 (November 2021), 100098. https://doi.org/10.1016/j.upstre.2023.100098

sector, offering opportunities to reduce operational and maintenance costs by 10-20 per cent and to increase technically recoverable oil resources by up to 5 per cent.[94]

The opportunities presented by digitalization, combined with market competition, economic pressures to reduce costs across the oil supply chain, stringent environmental regulations, and declining investment in fossil fuels, are driving the sector's innovation and digital transformation. This shift is further accelerated by advancements in computational power, increased data collection, and the substantial expansion of digital technologies such as IoT, Big Data, AI, robotics and automation, 3D printing, digital twins, and cloud computing.

These technologies are applied across various segments of the oil value chain, enhancing operations in distinct areas:

1. In exploration and production:
    - (a) IoT facilitates real-time monitoring and management of oil wells and critical equipment;
    - (b) Big Data analytics enable accurate forecasting of reservoir behaviour during exploitation;
    - (c) AI optimizes drilling processes and enhances decision-making for reservoir selection;
    - (d) Robotics and automation improve precision in drilling while reducing human exposure to hazardous conditions;
    - (e) Additionally, 3D printing is employed for prototyping offshore platforms, and digital twins are used for predictive maintenance of essential equipment in the oil rig.
2. In distribution and supply chain:
    - (a) Technologies such as asset tracking and management, supply chain optimization, and inventory management enhance operational efficiency and reliability in distribution and logistics;
    - (b) Cloud computing supports comprehensive data management and analysis, enabling more effective oversight and optimization of the supply chain.
3. In health, safety, and environment, innovations in risk assessment and mitigation, environmental monitoring, and incident response and management bolster safety and compliance:
    - (a) Virtual reality is utilized to prepare the workforce for hazardous conditions, improving training and safety protocols;
    - (b) AI and Big Data analytics can be applied to detect methane emissions early and mitigate their global warming potential.

Despite the advantages of digitalization, the oil sector faces barriers to its adoption, categorized into technical, organizational, and sector specific. Technically, insufficient IT infrastructure and a shortage of skilled personnel impede the effective use of digital technologies – much like the digitalization challenges in the electricity sector. High initial costs, cybersecurity risks, and complexities in data integration and regulatory compliance further complicate implementation.

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[94] IEA (2017), Digitalisation and Energy, IEA, Paris https://www.iea.org/reports/digitalisation-and-energy, Licence: CC BY 4.0

Organizationally, conservative management culture and risk-averse decision-making result in delays and hinder the timely integration of innovative technologies. Sector-specific challenges include the industry's fragmented structure, which disrupts the coordination of digital initiatives, and the slow pace of large-scale capital projects relative to rapid technological advancements, compounded by outdated infrastructure that inadequately supports innovations.

6.2.2 Natural gas sector

The natural gas industry has played a vital role in the global energy sector, offering a more environmentally sound option compared to coal and oil. Nevertheless, the industry encounters obstacles that span from market conditions to heightened regulatory scrutiny aimed at mitigating carbon emissions, while also being subject to geopolitical dynamic. In order to maintain competitiveness and to address the increasing environmental requirements, the natural gas industry is increasingly exploring the implementation of digitalization.

Over the years, the natural gas sector has witnessed advancements in digital technologies. Early digital tools primarily focused on process automation and basic data management. However, the sector has experienced additional transformation due to the emergence of advanced technologies such as IoT, AI, and Big Data analytics. Key milestones include the adoption of digital twins for real-time system simulation, predictive analytics for maintenance, and AI-driven optimization in both exploration, production, and downstream operations.

IoT devices offer real-time monitoring of natural gas critical infrastructure, providing early detection of leaks or technical anomalies. AI and machine learning are used to optimize drilling operations and reservoir management, while big data analytics unlock more informed decision-making processes. As for preventive maintenance, digital twins simulate entire systems to optimize operations. Other automation tools are also playing a significant role in reducing downtime and enhancing operational efficiency.

Digitalization is positively impacting the various stages of value chain. In exploration and production, AI-driven seismic data and reservoir modelling are improving the accuracy of resource identification and extraction. Liquefied Natural Gas operations are also benefiting from process optimization and predictive maintenance, reducing downtime and energy consumption.

Digitalization in the gas sector also faces significant challenges, such as:

- High initial investment costs for upgrading infrastructure and integrating advanced technologies can deter companies to adopt these solutions;
- Skill gaps and the need for workforce training, as employees may lack the digital expertise required for modern technologies;
- Data integration and management are also complex due to the vast amounts of information generated from various sources, and poor data governance can limit the benefits unlocked by digital tools and platforms.

6.2.3 Hydrogen

Hydrogen can contribute to fast-pacing the energy transition process, especially in hard-to-abate sectors.

Key among the drivers advancing digital transformation in the sector are the competitive pressures and economic constraints that industries face, prompting the need for even more cost-efficient operations. Environmental regulations are also a significant driver, as hydrogen operators aim to meet sustainability targets.

Advances in AI, IoT, and Big Data have contributed to operational efficiency and cost reduction, through real-time data analytics and process automation. Additionally, safety and risk management are crucial, as hydrogen production and distribution require precise control and monitoring.

Digital technologies play a critical role in optimizing hydrogen production. For instance, electrolysis, the most common method for green hydrogen production, benefits significantly from process monitoring, control systems, and predictive maintenance tools. These technologies help in maximizing uptime and ensuring that the electrolysis process is as energy efficient as possible, which is crucial because energy costs make up a large part of the total production cost of hydrogen. Moreover, as policy objectives are supporting clean hydrogen solutions, such as green hydrogen that uses renewable generation, digitalization supports the integration of renewable into the hydrogen production processes, increasing predictability.

Digitalization also supports the storage and transportation of hydrogen by providing complex solutions for pipeline and tanker management, helping to effectively manage safety risks. Automated systems monitor the integrity of storage facilities and transportation infrastructure, minimizing the risk of accidents and enabling quick responses to any potential hazards.

As safety is a priority in hydrogen operations, digital tools are supporting continuous risk assessments and ensure proper incident response and mitigation strategies, while also facilitating continuous monitoring of safety parameters.

Despite its potential, the hydrogen sector faces challenges in digitalization, with high initial investment costs being the primary concern.

6.3 Energy demand side

Digitalization plays a crucial role in optimizing energy demand across various sectors by improving efficiency, reducing costs, and promoting sustainability. Overall, digital technologies contribute to significant cost savings, enhanced energy security, and reduced carbon emissions, making them essential for meeting the growing global energy demand sustainably.

Non-electricity energy demand refers to such key sectors as heating and cooling, cooking, and transport, all of which face unique challenges and limitations. In heating, the reliance on fossil fuels such as natural gas and oil remains high. Similarly, in cooking, many households and industries depend on non-electric energy sources, although such fuels as liquefied petroleum gas, natural gas, biogas, solar, alcohol, and biomass (classified as Tier 4 or 5 for PM2.5 emissions and Tier 5 for CO emissions) that power stoves, constitute clean fuels and technologies).[95] In the transport sector, the challenge is even higher, as it continues to be heavily dependent on oil-based fuels despite significant and growing efforts to shift toward alternative, cleaner mobility solutions.

6.3.1 Heating and cooling

The heating and cooling is increasingly being shaped by digitalization, which enhances energy efficiency, reduces operational costs, and integrates renewable energy sources.

Digitalization is argued to have the potential to reduce global residential and commercial buildings' energy use by around 10 per cent by 2040.[96] A sizeable portion of global energy

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[95] https://www.who.int/tools/clean-household-energy-solutions-toolkit/module-7-defining-clean

[96] Asif, M., Naeem, G., & Khalid, M. (2024). Digitalization for sustainable buildings: Technologies, applications, potential, and challenges. Journal of Cleaner Production, 450, 141814. https://doi.org/10.1016/j.jclepro.2024.141814

consumption occurs in buildings, digital technologies in HVAC systems may offer numerous benefits in driving sustainability and improving indoor climate management. Among the benefits brought by digital solutions, cost efficiencies arising from more informed energy consumption or informed decision-making on the maintenance and service operations of heating and cooling assets.

The integration of IoT with HVAC systems is another important aspect. IoT devices enable real-time monitoring and control of HVAC components, facilitating seamless communication between different system parts. This connectivity allows for better data collection and increased energy management efficiency.

The information sourced through digital tools can be used manually by end users or their utility companies for modifying consumption patterns and favouring energy efficiency initiatives, or autonomously via smart thermostats and automated control systems based on AI and model-based control. For instance, smart thermostats are a key digital tool, which uses advanced algorithms and machine learning to optimize temperature settings based on occupancy, weather forecasts, market conditions, or user behaviour.

Data analytics and predictive maintenance further enhance the efficiency and reliability of this infrastructure. By continuously collecting and analysing operational data, these technologies can identify inefficiencies, forecast potential equipment failures, and schedule maintenance proactively. This approach reduces downtime, extends equipment life, and lowers maintenance costs.

Digitalization also supports the use of renewable energy sources for HVAC systems. To this end, dual-energy systems – which combine two energy sources – are gaining importance in the pursuit of energy resilience and sustainability.[97] These systems often pair traditional energy sources, like natural gas, with renewables such as solar or wind power, providing flexibility and reliability in energy supply. Digital solutions enable seamless transitions between these energy sources based on real-time demand and availability, ensuring continuous operations while optimizing energy costs and reducing environmental impact.

In the context of district heating and cooling, digital technologies enable more efficient and flexible energy distribution. By utilizing real-time data, advanced controls, and predictive analytics, district heating and cooling systems can optimize the generation and distribution of heat and cold across urban areas, balancing supply and demand more effectively. This leads to reduced energy waste, lower greenhouse gas emissions, and enhanced reliability of heating and cooling services.

6.3.2 Cooking

Digitalization is transforming energy consumption in cooking by introducing smart technologies that optimize energy usage, through smart cooking appliances equipped with automation and remote control. Moreover, as digitalization continues to advance, it is playing a critical role in creating more energy-efficient and sustainable cooking environments.

Smart cooking appliances can adjust cooking settings based on real-time data, reducing unnecessary energy use and lowering utility bills. Additionally, digital solutions such as IoT-enabled kitchens allow for advanced integration of appliances, further enhancing energy management. IoT-enabled kitchens can automate tasks such as cooking, inventory management, and energy consumption tracking, making kitchens more efficient and reducing

[97] https://www.hydroquebec.com/residential/customer-space/rates/rate-dt.html

manual effort. For instance, smart refrigerators can monitor their contents and suggest recipes, while connected ovens can adjust settings based on the cooking progress.

This connectivity enhances user experience by providing greater control and reducing energy, as well as food, waste, making kitchens smarter and more responsive to user needs. By using these tools, homeowners can track and optimize energy consumption, while also understanding their environmental impact and adopting certain energy behaviours.

6.3.3 Transport

Given the extent of the transport sector, as well as the negative externalities generated by it, digitalization is crucial for enhancing efficiency, reliability, and environmental protection.

By implementing advanced digital tools such as real-time monitoring systems, predictive maintenance, and automated control mechanisms, the conventional transport sector can optimize the flow of energy across vast networks, reduce operational costs, and minimize environmental impact. These advancements help meet the growing demand for energy while supporting global efforts to reduce carbon emissions and transition to cleaner energy solutions. Several innovative solutions have been tested and are now considered for scale utilization.

Telematics systems have become a cornerstone of modern fleet management, blending telecommunications and informatics to enhance vehicle tracking and operational efficiency. These systems provide real-time data on vehicle location, driver behaviour, and engine diagnostics, enabling better decision-making and proactive management. Key benefits of telematics include route optimization, which minimizes fuel consumption by selecting the most efficient paths, and predictive maintenance that helps schedule vehicle servicing, reducing downtime. This data-driven approach allows fleet managers to improve fuel efficiency and vehicle longevity while maintaining compliance with regulations. Moreover, the findings can also lead to the development of new business models for insurance providers or car manufacturers, among others.

Vehicle-to-Everything (V2X) communication is another emerging technology that connects vehicles to their surroundings: other vehicles (V2V), infrastructure (V2I), pedestrians (V2P), and the grid (V2G). The tool plays a crucial role in enhancing transportation efficiency and safety by facilitating real-time data exchange. It can support traffic management by providing vehicles with information about traffic lights and congestion, thus enabling better routing.

Smart infrastructure is key to supporting efficient and modern mobility across various transport modes. Digital infrastructure such as smart traffic lights and dynamic routing systems help manage traffic congestion and improve fuel efficiency by adjusting signals based on real-time traffic data. Real-time data analytics provided by these systems support urban mobility by enhancing route planning, reducing travel time, and minimizing environmental impact.

CONCLUSIONS AND RECOMMENDATIONS

The theoretical background provided in the publication and the analysis of case studies, lead to the following conclusions.

On governance policies for digitalization in energy

Digitalization is characterized by the transformative impact on energy systems and governance. Digital tools are essential for enhancing efficiency, transparency, and stakeholder engagement, making them key drivers of a successful energy transition, as well as the move towards carbon neutrality. However, the integration of these technologies also introduces challenges, particularly related to data privacy and cybersecurity. Addressing these complexities requires robust governance frameworks that not only maximize the benefits of digital transformation but also ensure that digital technologies are implemented responsibly, ethically, and inclusively.

Effective governance is central to the successful digitalization of energy systems. It safeguards data privacy and security while promoting transparency and inclusivity, enabling active participation from all stakeholders in the energy transition. Additionally, ensuring economic viability through targeted incentives is crucial for encouraging investments in digital technologies. To support this process, the following policy recommendations are proposed:

By adopting these recommendations, governments and policymakers can navigate governance challenges and fully leverage the opportunities presented by digitalizing energy systems, leading to a more resilient, efficient, and inclusive energy future.

1. Develop comprehensive regulatory frameworks: Governments should establish clear policies and standards that promotes the adoption of digital technologies and practices while also addressing the emerging challenges, including cybersecurity, data privacy, and ethical technology use. Regulatory testbeds should be encouraged and the process for innovators to transition from testing and demonstrations to mainstream regulation should be rendered more transparent and efficient.
2. Promote inclusive stakeholder engagement: Encourage active participation from all stakeholders – local communities, industry players, and civil society – to ensure that the digital transformation efforts of energy transition are inclusive and meet diverse needs.
3. Invest in capacity-building: Strengthen the capabilities of public institutions and stakeholders to manage digital energy systems effectively through targeted training and education programmes focused on digital skills, taking into account that local digital developments can demonstrate significant efficiency compared to imported ones.
4. Facilitate economic incentives for digitalization: Establish regulatory frameworks that encourage investment in digital technologies that increase system transparency and interoperability and enable new business models based on improved access and higher granularity of energy data. This strategy is essential for recognizing the value of digital investments and ensuring long-term accountability and sustainability.
5. Foster international collaboration: Encourage countries to share knowledge and collaborate on digitalizing energy systems. Joint economic and policy studies and other types of partnerships can highlight successful funding policy mechanisms and investment strategies, fostering innovation and best practices.

6. Ensure continuous monitoring and evaluation: Implement mechanisms for ongoing assessment of digital initiatives to promptly address challenges and adapt strategies, improving governance practices over time.

On the use of Artificial Intelligence for balancing electric load and demand

The digitalization of the electric grid unlocks multiple opportunities, including enhanced system operation and planning with advanced measurement and monitoring systems, holistic forecasts and predictive maintenance, demand-side opportunities, and optimized cyber security systems. With the availability of rich and reliable data, AI can help deal with these large volumes of data and unlock value in the entire chain, from data creation to better decision making.

From the lessons learned identified in the previous section, governmental authorities and regulators could support the adoption of AI to favour better decision making that would help managing the increasing complexity of the electric grid, the integration of RES and DER and a cleaner electricity system with policies and regulations:

- To support digitalization of the grid;
- To support the adaptation (training, development, recruitment) of the workforce to new technologies and to the use of AI;
- That favour innovation, development of new technologies, use of AI and its deployment.

Policy can help accelerate the use of AI technologies through actions such as:

- Develop a (national) strategy for AI that would include guidelines and safeguards on data use, privacy and ethic;
- Provide robust investment in technology and human capital, to address immediate operational needs and future developments;
- Better end market definitions for how renewables and storage can be incorporated and monetized. Setting reasonable expectations around timing, location and creating monetary products and economic opportunities around ancillary services and grid resilience that are applicable closer to the consumers (i.e., behind-the-meter) can help to better parameterize the forecasting models.

On interoperability and resilience

The conducted analysis and review of the case studies allows making the following recommendations, which are aligned with UNECE policy discussions on accelerating the electricity system transformation through digitalization:[98]

1. To further ease DER installation and enhance submetering capacity:
   (a) DER acquisition and installation, including submetering, and necessary retrofit installations to be provided as turnkey or packages, with permitting simplified.
   (b) Legal and standardization frameworks are needed to ensure clear discernment among different submetering options for end customers and options to apply different forms of submetering, be they actual smart metres or home management

[98] UNECE (2022). Digitalization: Accelerating the Electricity System Transformation. Joint Paper by the Task Force on Digitalization in Energy of the Group of Experts on Energy Efficiency and the Group of Experts on Cleaner Electricity Systems. Available at: https://unece.org/sites/default/files/2022-07/ECE_ENERGY_GE.6_2022_4_ECE_ENERGY_GE.5_2022_4_Final.pdf

system with the relevant functionality (one such example is the Australian DER monitoring guide).[99]

(c) Standards for submetering systems should be consistent in their requirements for areas such as location of commodity (i.e., electricity, water and gas) entry into the building (or unit - be it interior or exterior), property size, building structure, system lifespan, ease of maintenance, and how the sub-meter will be read. Billing systems are an understandably bespoke setup based on the needs of the premise owner and yet consumer help and call centres need to ensure that homeowner questions or complaints can be addressed in a timely and consistent manner. Allowing customers self-help options should be part of the standard offering.

2. To advance DER flexibility management with increased interoperability, privacy and security:

(a) Smart grid operators and service providers should ensure that they are compliant with relevant privacy and data protection regulations, such as the General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA). This involves conducting regular privacy impact assessments, maintaining records of data processing activities, and appointing a data protection officer (DPO) to oversee privacy compliance and ensure that consumer privacy rights are respected and protected. Anonymising data and using decentralized databases additionally improve data security. Techniques like differential privacy and federated learning can also be applied to ensure secure and private analytics.

(b) Implementing a data exchange hub/flexibility registry, should be a priority across jurisdictions. Such action can simplify, reduce cost and increase the security of data exchange between industry participants.[100]

(c) A data exchange hub should be based upon well-designed interconnection standards, rules and regulations[101], outlining procedural and technical requirements for connecting DERs to the grid or otherwise accessing DER data to provide a range of energy services.

(d) A decentralized data exchange can potentially offer greater scalability, resilience, and security benefits than centralized systems.[102]

3. To enable peer-to-peer energy trading for a more optimal DER use and grid resilience:

(a) Findings from regulatory testbeds and pilot projects[103] should be reviewed and objectives set for any further testing, supporting development and accelerating application of emerging technology to enable local energy trading methods that bring most benefits to individuals while supporting grid resilience, especially based

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[99] https://www.dermonitoring.guide/

[100] For more details see Project EDGE's *DER Data Hub Lessons Learnt Report* produced by the Energy Web foundation and published by AEMO.

[101] Radina Valova and Gwen Brown, Distributed energy resource interconnection: An overview of challenges and opportunities in the United States, Solar Compass, Volume 2, 2022, 100021, ISSN 2772-9400, https://www.sciencedirect.com/science/article/pii/S2772940022000157

[102] Phase examples include deploying under a controlled environment, testing with a limited number of use cases and/or assets, and operating in parallel or separately from existing systems.

[103] Europe has called for further support for energy sector regulatory testbeds in the *EU action plan on digitalising the energy system*, adopted in October 2022, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6228.

on peer-to-peer trading, and encompassing not just intra but also inter-community trading.

(b) Review for applicability national policy from other countries that are specifically made to remove barriers for DERs to compete fairly in the regional organized capacity, energy and ancillary services markets.[104]

(c) Explore dynamic tariff model research and implementation to benefit from local flexibility.

For successful implementation of improved and new grid edge business models, diverse stakeholders should be engaged and educated, particularly empowering communities and community members to take on a more active role in the energy market and use the emerging technology to enjoy a wider set of choices. This effort should be complemented with workforce education and upskilling to bridge the identified skills gap in production and installation of DERs, as well as in development and accelerated uptake of advanced AI/ML and DLT/blockchain technologies.

On cybersecurity and cyber resilience of energy infrastructure

In view of the foregoing discussion on cybersecurity of smart integrated energy systems, the following conclusions, actions, and policy recommendations are proposed for consideration:

1. Regulatory: enforcing implementation of applicable standards and guidelines which address matters of improving cybersecurity for operational technology in automation, control systems, and cybersecurity for critical infrastructure;
2. Financial: offering tax incentives for companies that have implemented relevant cybersecurity standards, and allocating funding for cybersecurity initiatives such as cybersecurity-related R&D and education;
3. Structural:
   (a) Setting up national cybersecurity strategies that: describe how to prevent and manage cyberattacks on smart integrated energy system and; identify roles and responsibilities of different stakeholders, including government agencies, businesses, and individuals;
   (b) Collaborating with other countries to benchmark their standards and share information on potential threat actors to be able to manage cybersecurity risks more effectively;
   (c) Implementing business continuity management plans describing how to manage cybersecurity events, including e.g., those leading to power outages;
   (d) Ensuring proper allocation of responsibilities of cybersecurity in the energy sector (governance) across stakeholders on national and supranational levels;
   (e) Reporting: requiring data protection and cybersecurity reporting to official bodies to stimulate bottom-up strategies;
4. Awareness-raising: identifying industry leaders to lead by example, and providing education and training to support companies and governmental bodies to implement cybersecurity measures on both management and technical levels.

[104] FERC Order No. 2222: A New Day for Distributed Energy Resources, FERC Order No. 2222: Fact Sheet, https://www.ferc.gov/media/ferc-order-no-2222-fact-sheet, September 17, 2020.

On behavioural aspects in the context of adoption of digital technologies

Many technologies have been developed recently to reduce greenhouse gas emissions through digitalization. Although many of these technologies are readily available, the pace of energy system transformation is slow. One of the crucial factors, and the missing link in understanding the lagging implementation of these technologies, is human psychology. Individual psychological and behavioural barriers to adopting digitalization must be overcome to realize the full potential of technologies.

Understanding these behavioural barriers and overcoming them has many advantages for human energy behaviour. Leveraging behavioural changes contributes to speeding up the energy transition. To achieve this, the following key conclusions and policy recommendations are put forward:

1. Realizing that psychology is key driver to change in energy use: Awareness of human psychology enables the formulation and implementation of effective behavioural change instruments that are more likely to succeed in changing energy use habits. This knowledge should be used as a facilitating factor in decision-making and communication, as well as when taking action.
2. Using digitalization as a facilitator for psychological and behavioural change: Digitalization is not only useful in facilitating transformation of energy systems but can also be used as a tool to address psychological aspects as well. Well-designed digital technologies can address both the systemic and behavioural transformation of systems and make it easier for individuals to contribute.
3. Making the use of digitalization technologies easy: When digitalization is implemented, it is important that these digital solutions are as simple as possible to use. This means that the final product for the consumer should be easily understandable by the general public (i.e., non-energy experts). Also, it is important that solutions are highly accessible and affordable, and that users are informed about the multiple benefits at the individual as well as the system level.
4. Making change easy: Whenever individuals are required to change, the experienced hurdles of such a change should be made as low as possible. This is because humans prefer to keep their habits, and most people are only willing to change when the experienced cost is lower than the experienced hardship of continuing this habit.
5. Addressing people's 'pains and gains': Apart from making sure that the cost of change is as low as possible, it is important to communicate and consider people's pains when they do not change, and their gains when they do decide to change. This is because moving away from pain or towards gain are the two main forces in decision-making. When digital solutions are employed, it should be clear to a user how these solutions contribute to relieving pain and creating gain in their life.
6. Triggering intrinsic motivation: To make sure that users are willing and likely to keep their new behaviour, and continue using digital solutions, it is important that they are motivated from within. This ensures that users want to keep up their behaviour. When they would instead feel that they are forced to make a change, the perceived cost of that change is increased, making it less likely to continue or even inspire others do the same.
7. Reducing people's mental load: Adding new tasks and decisions to the routine may not be possible as it may require too much capacity. That is why digitalization should be used to encourage automated task performance and decision-making as much as possible and ethically viable.

8. Leveraging empowering beliefs: Everyone has beliefs, either consciously or unconsciously, that guide their behaviour. When such beliefs include a perceived limit to a person's ability to contribute to the transformation of energy systems (e.g., the belief that individual contribution is so small that it does not make a difference) they should be addressed and overcome. Instead, empowering beliefs should be cultivated.
9. Supporting consistency over time: Apart from inspiring people to take action once, it is important to create consistency over time. This ensures that all small changes add up to make a difference. At scale, this can make a significant contribution to transforming the energy system. Digital solutions can be used to automate processes and create consistency.
10. Formulating positive goals: To implement a sustainable energy development strategy, it is important to communicate positive goals and generally foster positive goal setting in legislation and regulations.

On digital transformation in the energy sectors other than electricity

The interlinkages and synergies between digitalization of energy sectors and end uses, , raise the following questions to be addressed in the future research:

1. General digitalization process challenges
   (a) What are the most significant barriers to digitalization in non-electricity sectors, and how can they be addressed through policy? What is the role of business operators in ensuring that the right public policy framework is being developed?
   (b) What are the cybersecurity risks associated with increased digitalization in non-electricity sectors, and how can these be mitigated?
   (c) What role does regulation play in advancing digitalization efforts in non-electricity sectors? What are the incentives needed for a higher-pace adoption of digital tools?
2. Sector specific challenges
   (a) What new digital innovations can further reduce the environmental impact of oil and gas operations?
   (b) How can digital technologies support the green hydrogen production process, and what is needed to make it more cost-effective and scalable?
   (c) How can digitalization in district heating and cooling systems be scaled, and what are the case studies to learn from?
   (d) What are the potential environmental, social, and economic benefits of highly digitalized cooking systems, and how can they be made accessible to both developed and developing regions?
   (e) How can digital infrastructure support the decarbonization of conventional transport sectors, while also ensuring a smooth transition to alternative mobility options, including through location efficiency?
   (f) How can digital applications facilitate decarbonization, cost-effectiveness, and resilience of the industrial sector?
   (g) How can digital solutions help increasing the systemic efficiency of the energy system transformation across energy carriers (to expedite an efficient integration of renewable energy sources)?

3. Advanced digital integration solutions
    (a) What cross-sectoral synergies can be unlocked through digitalization?
    (b) How can digitalization support the integration of renewable energy across non-electricity sectors?
    (c) What emerging digital technologies hold the most promise for transforming non-electricity sectors? How will advancements in AI, blockchain, and IoT shape the future of fuel and energy sectors in the context of the energy transition?

Compendium of Case Studies on Digitalization in Energy in the UNECE Region

This compendium serves as a testament to the transformative power of digitalization in the energy sector, revealing the tangible impact of integrating cutting-edge technologies into real-world energy systems.

These case studies help bridge the gap between theory and practice, showcasing how the theoretical recommendations of the UNECE Task Force on Digitalization in Energy have been put to the test across diverse geographies. These examples collectively illustrate the importance of adaptability in policy, infrastructure, and technology as regions with varying energy needs and digital maturity levels navigate their own paths toward modernization and resilience of the energy systems.

The compendium presents an examination of governance structures essential for guiding digitalization in the energy sector and balancing innovation with security, and provides a set of examples of effective governance policies for responsible digital transformation.

This publication offers an exploration into examples of the transformative power of digital technologies within the energy sector. Aiming to cover the whole energy value chain, it showcases how digitalization is reshaping the energy landscape worldwide, driving efficiency and sustainability of the energy systems. From smart grids and energy management systems to predictive analytics and blockchain applications, the case studies discuss benefits and challenges of integrating digital technologies into energy systems and highlight lessons learned from such transformations.

With contributions from leading experts in the area, this publication synthesizes insights from a range of contexts. It is designed to facilitate informed decision-making for policymakers, industry leaders, and to serve as a knowledge hub for stakeholders who seek to navigate the complexities of digital transformation in the energy sector in the UNECE region and beyond.

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