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Unlocking the Potential of AI and Generative AI in European Smart Grids

A Strategic Position Paper and Guide for Action

ETIP SNET

European Technology and Innovation Platform

Smart Networks for Energy Transition

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This paper is truly a testament to the collaborative spirit fostered by the ETIP SNET platform. It reflects the collective intelligence and commitment of the European smart energy community working together towards a shared vision. We thank everyone involved for their invaluable contributions.

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FOREWORD

Europe's energy system is undergoing a profound transformation, driven by the imperatives of decarbonisation, digitalisation, and the essential revamping of European industry. In this dynamic landscape, smart grids are not merely an option but a necessity, enabling the flexibility, efficiency, and resilience required for a sustainable energy future. The emergence of artificial intelligence (AI) and generative AI (GenAI) presents both unprecedented opportunities and complex challenges within this transition.

The European Technology and Innovation Platform for Smart Networks for Energy Transition (ETIP SNET) has established itself as a central forum for collaboration. It provides a unique European platform where diverse stakeholders share insights, identify innovation priorities, and determine the drivers needed to accelerate the organised, rapid deployment of advanced energy system solutions.

This strategic position paper on AI and GenAI in smart grids represents another significant, independent contribution from ETIP SNET towards navigating the energy transition and bolstering European industry, particularly in the realm of smart energy networks. Its publication is timely, coinciding with the ongoing revision of the European R&D Roadmap on Smart Grids for the next decade. The continued confidence vested in ETIP SNET by the European Commission and various European associations to provide relevant insights for the sector is a testament to the platform's value and serves as encouragement for our ongoing work.

The genesis of this paper lies in both a challenge set forth by the European Commission, notably DG ENER, and a proactive initiative from within the platform itself, recognising the critical need to address the transformative potential and implications of AI. The ambition for this work was set exceptionally high. Developed in a remarkably condensed timeframe, it has drawn upon the expertise not only of established ETIP SNET members but also external contributors – a novel and enriching approach for our community, demonstrating a new level of collaborative practice.

It is our sincere hope that the analysis and recommendations presented herein will support in demonstrating the relevance and capability of ETIP SNET. Furthermore, we trust this paper will serve as a catalyst, encouraging more stakeholders – researchers, industry players, policymakers, and citizens – to join this movement. Contributing collectively to a European energy system that is more secure, cost-efficient, intelligent, and oriented towards the energy transition and the strengthening of Europe's industrial competitiveness is a shared goal.

The path forward requires concerted effort and open cooperation. We count on the active involvement of all stakeholders to harness the potential of AI responsibly and effectively, shaping a brighter energy future for Europe.

Luís Vale Cunha
Chair of ETIP SNET/AI Task Force Lead ETIP SNET

EXECUTIVE SUMMARY

Europe's energy system is undergoing a profound transformation, driven by the urgent need to combat climate change and secure a sustainable energy future. This transition towards a decarbonised, decentralised, and digitalised system, spearheaded by initiatives like the European Green Deal, presents immense opportunities but also significant complexities. Smart grids, modernised electricity infrastructure integrating digital technologies, are fundamental to managing this transition effectively.

This strategic position paper explores the transformative potential of artificial intelligence (AI) and generative AI (GenAI) within the context of European smart grids. These technologies offer powerful capabilities to enhance grid efficiency, reliability, flexibility, and resilience. AI can optimise grid operations, improve forecasting for variable renewable energy sources (RES) like solar and wind, enable predictive maintenance, facilitate active consumer participation through demand response, and bolster cybersecurity. GenAI adds further value by enabling synthetic data generation to overcome data scarcity, assisting complex decision-making, and enhancing human-AI collaboration.

However, realising this potential requires navigating a complex landscape. Key challenges include ensuring data availability, quality, and governance (especially concerning privacy under GDPR); harmonising regulations across Member States, particularly regarding the implementation of the EU AI Act; addressing the shortage of personnel skilled in both AI and energy systems; upgrading digital infrastructure (including HPC and edge computing); closing standardisation gaps for interoperability; and building trust and acceptance among operators, consumers, and regulators regarding AI's reliability and fairness.

This paper synthesises findings from extensive analysis and stakeholder engagement. It outlines the policy context (Chapter 2), explores the technical foundations (Chapter 3), analyses the benefits and challenges (Chapter 4), proposes a phased roadmap for implementation (Chapter 5), and offers strategic conclusions and recommendations (Chapter 6). The roadmap progresses from building foundational readiness (regulatory clarity, data access, pilots, skills) in the short term (0-2 years), through scaling proven concepts and harmonising standards (2-5 years), to achieving full, optimised integration and establishing European leadership (5+ years).

Success demands a concerted, collaborative effort. Policymakers must provide regulatory clarity and targeted funding. Grid operators need to invest strategically in technology and skills, prioritising trust and ethical deployment. Technology developers must align solutions with EU needs and standards, focusing on security and efficiency. Academia plays a vital role in targeted research and talent development. A cohesive strategy, underpinned by shared European values of trustworthiness, security, and sustainability, is essential.

By addressing the identified gaps and implementing the proposed recommendations, Europe can unlock the full potential of AI and GenAI, positioning itself as a global leader in developing and deploying responsible, human-centric AI for a smarter, cleaner, more secure, and competitive energy future, fully contributing to the Green Deal, Clean Industrial Deal, and Digital Decade objectives.

1 INTRODUCTION

This chapter establishes the context of Europe's energy transition, highlights the critical role of smart grids, and introduces the transformative potential of AI and GenAI in this domain. It concludes by outlining the paper's objectives and presenting its logically structured framework.

1.1 Context of the Energy Transition in Europe

Europe stands at the forefront of a profound energy transformation, driven by the urgent need to confront climate change and ensure a resilient, sustainable energy future. This multifaceted transformation involves shifting from fossil fuels to renewable energy sources, electrifying various sectors (transport, heating, industry), and creating more efficient and resilient energy systems. The European Green Deal, a landmark policy initiative, sets an ambitious target of climate neutrality by 2050. Achieving this goal necessitates an overhaul of the energy system, presenting both challenges and opportunities. This transition is not just an environmental imperative but also crucial for Europe's economic competitiveness and energy security. Digital technologies, particularly AI, are deemed essential for managing the increasing complexities of this evolving energy landscape. Ensuring a just and equitable transition, where benefits are shared widely, is also paramount. Policy initiatives like the Digitalisation of Energy Action Plan demonstrate the EU's commitment to leveraging digital solutions, including AI, for grid management and renewable energy integration. Integrating variable renewable energy (VRE) sources like solar and wind power, while critical for decarbonisation, introduces challenges related to grid stability and reliability due to their intermittent nature. The REPowerEU plan (European Commission, 2022), launched in response to geopolitical events, further accelerates the transition by reducing reliance on fossil fuels and boosting renewable energy adoption.

1.2 The Importance of Smart Grids for the Energy Transition

Smart grids, modernised electricity infrastructures integrating digital technologies, are indispensable for enabling the energy transition. They enhance the efficiency, reliability, and sustainability of energy systems by leveraging real-time data and advanced communication networks. Key functionalities of smart grids include near real-time monitoring, providing detailed insights into grid conditions; dynamic demand response, enabling flexible energy consumption patterns; and seamless integration of decentralised renewable energy resources (DERs), such as rooftop solar panels, wind turbines, and home batteries. Smart grids are also crucial for supporting the widespread adoption of electric vehicles (EVs) by efficiently managing their charging needs (IEA, 2023) and for orchestrating the complex interactions of DERs within the distribution network. These capabilities facilitate a more interactive and responsive energy system, optimising the balance between energy supply and demand.

1.3 The Role of AI and Generative AI in Transforming Smart Grids

AI and GenAI are poised to revolutionise smart grid operation and management due to their ability to process vast datasets, optimise complex systems, and unlock new functionalities:

- **AI for Data Analysis and Optimisation:** AI algorithms analyse data from diverse sources (smart meters, sensors, weather data) to optimise energy distribution, predict equipment failures, manage demand, and enhance overall grid management.

- **GenAI for Enhanced Decision-Making:** GenAI synthesises data and generates scenarios for strategic decision-making in grid planning and operation, enabling proactive adaptation to changing conditions and future uncertainties.

- **AI for Renewable Energy Integration:** AI is vital for managing the variability of VRE sources (solar, wind) and optimising their integration, including tasks like BESS optimisation, RES generation forecasting, and grid stability control.

- **AI and Cybersecurity:** AI plays a crucial role in detecting and mitigating cyber threats to safeguard critical smart grid infrastructure through techniques like intrusion detection, anomaly detection, and vulnerability assessment.

- **AI for Active Consumer Participation:** AI empowers consumers to actively participate in the energy system through smart home energy management systems, personalised energy consumption insights, and demand response programmes, fostering demand-side flexibility.

- **AI for Automated Processes:** AI automates tasks like software development for grid optimisation, fault detection and isolation, grid restoration, and voltage control, enhancing operational efficiency.

- **GenAI for Grid Design and Optimisation:** Research suggests GenAI's potential in designing and optimising complex grid architectures for improved resilience and efficiency (Choi et al., 2024).

- **AI for Real-Time Grid Control:** AI is being explored for real-time grid control and automated decision-making to manage dynamic grid conditions, ensuring stability and reliability (U.S. Department of Energy, 2024).

1.4 Objectives and Structure of this Paper

This paper aims to provide a comprehensive analysis of the transformative potential of AI and GenAI in smart grids, offering valuable insights for policymakers, regulators, network operators, technology developers, and researchers.

1.4.1 Main Objectives:

- Analyse the benefits of AI and GenAI in grid optimisation, energy efficiency, consumer participation, renewable energy integration, and cybersecurity.

- Identify key implementation challenges, including data availability, integration complexities, regulatory hurdles, and ethical concerns.

- Formulate actionable recommendations to address these challenges and unlock the full potential of AI and GenAI.

- Promote responsible and ethical AI development and deployment in the energy sector.

- Contribute to the EU's objectives for a sustainable, secure, and competitive energy system through digitalisation.

Structure of the Paper: This paper guides the reader through a structured journey: starting with the broader context and policy landscape, moving into technical foundations, examining benefits and challenges, and finally presenting implementation strategies, key findings, and ethical considerations. Each chapter builds on the previous, offering a coherent, layered analysis that moves from understanding the ‘why’ to exploring the ‘how’ and addressing the ‘what next’ of AI in smart grids:

- **Chapter 2: European Policy and Regulatory Landscape:** This chapter analyses the European policies and regulations influencing AI's development and use in smart grids: the European Green Deal, the AI Act, the Digitalisation of Energy Action Plan, and cybersecurity frameworks. It assesses how these policies support or hinder AI adoption, identifying areas for improvement.

- **Chapter 3: Technical Foundations of AI and Generative AI in Smart Grids:** This chapter delves into the specific AI and GenAI techniques for smart grids, exploring algorithms, models, and architectures for forecasting, optimisation, control, and anomaly detection. It covers machine learning, deep learning, natural language processing, computer vision, evolutionary algorithms, and discusses computational infrastructure and data requirements.

- **Chapter 4: AI and Generative AI in Smart Grids: Benefits and Challenges:** This chapter analyses the benefits and challenges of implementing AI and GenAI in smart grids, exploring their potential to enhance efficiency, reliability, resilience, and sustainability, while addressing technical, economic, social, and ethical challenges like data privacy, algorithmic bias, cybersecurity risks, and workforce development. It examines AI's impact on stakeholders in the energy ecosystem.

- **Chapter 5: Roadmap for Concrete Implementation of Solutions:** This chapter proposes a roadmap for implementing AI and GenAI solutions in smart grids, offering actionable recommendations for policymakers, regulators, energy providers, technology developers, and researchers to foster responsible and effective adoption. It encompasses strategies for data management, algorithm development, infrastructure upgrades, workforce training, stakeholder engagement, standardisation, interoperability, and scaleability.

- **Chapter 6: Conclusions and Recommendations**: This chapter summarises the key findings of the previous chapters and offers clear actionable recommendations for stakeholders. It further provides an outlook on the future trajectory of AI in the energy sector and its potential to help bring about energy transition.

2 EUROPEAN POLICY AND REGULATORY LANDSCAPE

This chapter analyses the European policy and regulatory landscape relevant to smart grids, Artificial Intelligence (AI), and Generative AI (GenAI). It examines the approaches to implementation in EU Member States, highlighting the challenges and opportunities in regulatory harmonisation, and discusses the specific implications of key legislation like the EU AI Act for the energy sector.

2.1 Overview of Relevant European Policies for Smart Grids and AI

The European Union (EU) has recently introduced two transformative policy initiatives to accelerate the green and digital transitions while ensuring energy affordability and industrial competitiveness. The Clean Industrial Deal (European Commission, 2025a) is a €100 billion strategy designed to mobilise investments in industrial decarbonisation, streamline regulatory reforms, and strengthen Europe's position as a global leader in clean technologies. This initiative focuses on six strategic pillars, including affordable energy access, financing the transition, and workforce development, all aimed at reducing energy costs and enhancing industrial resilience. The deal emphasises the critical role of AI and digitalisation in optimising energy systems, accelerating grid modernisation, and supporting the integration of renewable energy sources.

Complementing the Clean Industrial Deal, the Affordable Energy Action Plan (European Commission, 2025b) outlines concrete measures to lower energy costs for citizens, businesses, and industries across the EU. The plan targets annual savings of €45 billion by 2025, rising to €130 billion by 2030 and €260 billion by 2040, through measures such as reducing energy taxes, expanding grid infrastructure, and promoting corporate Power Purchase Agreements (PPAs). A key focus of the plan is enhancing grid flexibility and digitalisation, leveraging AI-driven solutions to optimise energy distribution, improve demand response, and empower consumers. Together, these policies create a favourable environment for the integration of AI and generative AI (GenAI) in smart grids, supporting the EU's broader goals of decarbonisation, energy security, and affordability.

The EU has established a comprehensive set of interconnected policies and regulations designed to drive the energy transition, promote the adoption of AI, and support the development of a sustainable, efficient, secure, and affordable energy system, as outlined within the framework of the Energy Union (European Commission, n.d.-f). Achieving affordable energy for all Europeans is a cornerstone objective, addressed through various initiatives and action plans (European Commission, n.d.-g), including the recent Electricity Market Design reforms and the REPowerEU plan, which specifically tackled the energy price crisis (European Commission, 2022b; European Commission, 2023c). These policies are interconnected and designed to support the development of a sustainable, efficient, and secure energy system. However, as highlighted in EU competitiveness analyses (e.g., European Commission, 2023d) and emphasised by both Letta and Draghi reports, Europe faces challenges in translating ideas into marketable technologies and boosting productivity growth, which requires urgent action (Euractiv, 2024). Key policies include:

- **The European Green Deal:** This overarching framework aiming for climate neutrality by 2050 significantly impacts smart grid development through ambitious targets for renewable energy integration and energy efficiency. It emphasises the need for a smarter, more interactive energy system crucial for decarbonisation and highlights AI's role in the green transition (European Commission, n.d.-b). The strong policy focus appears to be stimulating innovation, as reflected in the significant growth of patenting activity in clean energy technologies across Europe, even outpacing overall patent growth (European Patent Office [EPO], 2024). Crucially, the transition must be managed to ensure energy security and affordability for citizens and businesses, a goal reinforced by initiatives like REPowerEU (European Commission, 2022b). The need to reduce energy costs and price volatility drives the requirement for more efficient, flexible, and intelligently managed grids, where AI can play a vital role in optimising operations and integrating lower-cost renewables, contributing to the affordability goals. Innovation in technologies that enhance grid flexibility, stability, and utilisation – crucial for integrating variable renewables and managing new loads – is accelerating globally, evidenced by strong growth in patent filings in these areas over the last two decades (International Energy Agency [IEA], 2023).

- **The New European Industrial Strategy & Green Deal Industrial Plan:** Focused on boosting industrial competitiveness via innovation, digitalisation, and sustainability, this strategy recognises AI as a key economic driver (European Commission, 2020). It operates within the framework of the **Green Deal Industrial Plan**

(European Commission, 2023b), which aims to enhance the competitiveness of Europe's net-zero industry while supporting the broader energy transition goals, including security and affordability. This plan includes key legislative pillars like the Net-Zero Industry Act and the Critical Raw Materials Act, designed to scale up clean tech manufacturing and secure supply chains necessary for technologies like smart grids, renewables, advanced power electronics, energy storage, and enhanced grid control systems identified as key innovation areas in patent data (IEA, 2023; European Commission, n.d.-e). The plan's focus on scaling up clean tech manufacturing is crucial, as patent data shows European companies hold strong positions in several key clean energy technologies (CET) areas, although global competition, particularly from China and the U.S., is intense (EPO, 2024). Continued innovation, reflected in patent filings, is essential for maintaining and enhancing this competitiveness.

- **The European Digital Strategy:** Aims to make Europe 'fit for the digital age,' focusing on data, digital infrastructure, and digital skills (European Commission, n.d.-c). It promotes AI development and deployment while addressing risks, advocating for a secure, open digital single market respecting user rights and fair competition. The convergence of digital and energy sectors is evident in innovation trends. Analysis of global patent data specifically for smart grids and enhanced electricity grids confirms a surge in innovation over the past two decades, particularly driven by the need for digitalisation to manage complex energy systems with higher shares of renewables and electric vehicles (IEA, 2024; IEA, 2023). Patents related to sensors, smart metering, control systems, cybersecurity, and AI/machine learning applications form a significant and growing part of this innovation landscape (IEA, 2023). Smart grid technologies, including advanced metering, automation, and communication systems, represent a significant share of clean energy patenting (EPO, 2024; IEA, 2024), indicating active development of the digital backbone for the energy transition. Digitalisation, including the deployment of smart meters and grids, is a key enabler for achieving energy efficiency and empowering consumers, both critical components of the EU's strategy for affordable energy (European Commission, n.d.-g). Digitalisation is also seen as essential for lifting Europe's productivity growth (European Commission, 2023d).
- **The Artificial Intelligence Act (AI Act):** Adopted by the European Parliament in March 2024 (final version adopted by the EU on 13 June 2024), this landmark regulation establishes a harmonised framework for AI systems in the EU (European Parliament, 2024a) (European Parliament and Council, 2024). It follows a risk-based approach:
    - *Prohibited AI:* Practices deemed an 'unacceptable risk' (e.g., social scoring, manipulative techniques) are banned. Operators in the electricity sector must ensure their systems avoid these practices.
    - *High-Risk AI:* Systems listed in Annex III (including those for managing critical infrastructure like electricity grids) or those acting as safety components of products are subject to strict requirements (risk management, data governance, technical documentation, transparency, human oversight, accuracy, robustness, cybersecurity).
        - *Safety Components & Critical Infrastructure:* An AI system intended as a safety component for critical infrastructure management is high-risk if its failure poses a risk to life/health "at large scale" (AI Act, Art. 6(2)). The term 'safety component' is defined relatively narrowly (see AI Act, Recital 55), focusing on direct protection of physical integrity, excluding purely cybersecurity components (European Parliament, 2024a). Clarity is needed on which specific grid AI systems meet this definition. A potential interpretation, suggested by some stakeholders, links the assessment of 'large scale' impact under the AI Act to the thresholds defined in the CER Directive (Art. 7), aligning AI risk with critical entity resilience assessments (European Union, 2022).
        - Grid operators (DSOs/TSOs) using high-risk systems must comply with deployer obligations and potentially provider obligations if they develop the systems themselves.
    - *Limited Risk AI:* Systems with specific transparency obligations (e.g., chatbots, GenAI for synthetic content, emotion recognition). Users must be informed they are interacting with AI or that content is AI-generated.
    - *Minimal Risk AI:* Systems like spam filters or recommender systems face no additional obligations under

the Act.

- *General-Purpose AI (GPAI) Models:* Specific rules apply, including transparency (training data summaries), technical documentation, and compliance with EU copyright law. Providers of GPAI models with 'systemic risk' face additional obligations (model evaluation, risk assessment, incident reporting, cybersecurity). Providers integrating GPAI models into AI systems must comply with *both* GPAI rules *and* AI system rules (if applicable, e.g., high-risk) (European Parliament, 2024a).

- *Governance & Implementation:* Establishes an AI Office, regulatory sandboxes, and phased implementation (prohibitions ~6 months post-entry into force, GPAI rules ~12 months, general obligations ~24 months, high-risk systems ~36 months) (European Parliament, 2024b).

- *Limitations:* While significant, the AI Act may not cover many AI uses in the energy sector if they do not qualify as high-risk. Important risks related to fairness, access, market function, security, and sustainability might remain unaddressed by the Act itself, potentially requiring sectoral approaches or voluntary codes (Assessing potential future..., 2023). Existing laws (GDPR, cybersecurity, market regulations) apply but may not fully capture AI-specific challenges. The Act currently lacks explicit sustainability requirements for AI systems (Espinosa Apráez & Noorman, 2024).

- **Digitalisation of Energy Action Plan:** Specifically addresses the energy sector's digital transformation, promoting digital tech for grid optimisation, RES integration, and consumer empowerment, emphasising data sharing and interoperability (European Commission, 2022a). It notes the need to increase the adoption of digital technologies, including AI, among EU businesses (European Commission, 2022a). It also includes actions focused on establishing a data exchange framework (Action Area 1) and promotes investments in smart grids (Action Area 2). Furthermore, this position paper aims to provide timely input for the ongoing revision of this crucial Action Plan.

- **Critical Entities Resilience (CER) Directive:** Aims to strengthen the resilience of critical infrastructure (including energy) against threats like cyberattacks and disruptions (European Union, 2022). As mentioned, its thresholds (Art. 7) could potentially inform the AI Act's high-risk assessment for safety components in critical infrastructure.

- **Data and Cybersecurity Initiatives:** Includes the General Data Protection Regulation (GDPR), Data Governance Act (DGA), and the Data Act, aiming for a trusted data ecosystem while promoting data-driven innovation (European Commission, n.d.-d). Directive (EU) 2019/944 (part of the Clean Energy Package, precursor to RED IV) also mandates MS to require TSOs/DSOs to provide access to metering and consumption data (relevant context for RED IV data sharing, see Policy Table pg 30). Cybersecurity efforts emphasise coordinated incident response and cloud strategies.

- **Net-Zero Industry Act:** Aims to scale up clean tech manufacturing in the EU, supporting investments in areas like renewables and energy storage crucial for smart grids (European Commission, n.d.-e).

- **Grid Action Plan:** Outlines initiatives for grid modernisation and expansion, addressing infrastructure upgrades for RES capacity and stability (European Commission, 2023a). The plan directly addresses the need to deploy technologies that enhance flexibility, stability, and capacity utilisation – areas where the IEA (2023) identifies substantial global innovation activity through patent trends. Bridging the gap between innovation (patents) and widespread deployment is a key challenge the Action Plan seeks to address. It includes actions like digitalising permitting procedures (Action Plan /A11), launching online support tools (potentially using GenAI) for permitting questions (Action Plan /A11), updating the smart grid 'technopedia' (Action Plan /A7), and requiring network users to provide data for DSO planning (Action Plan /A3).

- **Electricity Market Design (EMD) Reform:** Recent reforms aim to make electricity bills less dependent on volatile fossil fuel prices, accelerate renewables deployment, improve consumer protection, and enhance market stability (European Commission, 2023c). These reforms are central to the EU's efforts to ensure more affordable and stable energy prices in the long term. They rely heavily on increased grid flexibility, enabled by technologies for demand response, storage, and advanced grid control, precisely the areas showing significant patent growth according to the IEA (2023). Smart grids and AI are crucial for enabling the enhanced flexibility, demand response, and efficient market participation envisioned in the reformed market design.

2.2 Regulation and Implementation in Member States

While the EU provides a common framework (like the AI Act aiming for harmonisation), Member States exhibit varying approaches to regulating and implementing smart grids and AI. This reflects diverse national priorities, energy mixes, legacy infrastructure, and digital maturity. Europe's competitiveness hinges on aligning EU and national policies with common objectives.

2.2.1 Comparative Analysis of Different Approaches

- **National AI Strategies:** Many Member States have national AI strategies promoting AI development and deployment, often with specific measures for the energy sector. However, priorities differ – some focus on RES integration, others on cybersecurity or efficiency. Examples range from Austria and Belgium focusing on ethical AI in public services to France and Germany leading research and experimentation, Nordic nations leveraging data protection laws, and Eastern European countries prioritising digital transformation.

- **Smart Grid Regulations & Deployment:** Regulations, standards, and deployment pace for smart grids vary significantly. Some countries have advanced infrastructure and frameworks (e.g., pioneers in AMI rollout like Denmark, Estonia, Finland, Italy, Spain, Sweden), while others are progressing and others have recently ended (e.g., Austria, France, Netherlands, Portugal) (JRC, 2022; JRC, 2023). AMI data use cases also vary between DSOs (grid management, control, planning) and consumers (efficiency, flexibility programmes) (JRC, 2023).

- **Regulatory Sandboxes:** Used by several Member States to test innovative AI/smart grid solutions in controlled environments, but their design and scope differ, potentially creating cross-border challenges.

- **Data Governance:** Differing interpretations of data privacy (GDPR) and sharing rules affect AI development, impacting data availability for training models.

2.2.2 General view on the situation at Member State level

Europe exhibits a tension between the push for EU-level harmonisation (e.g., via the AI Act for ethical governance) and the persistence of national diversity reflecting local contexts and historical investments. Smart grid rules remain fragmented despite efforts like the Clean Energy Package, particularly concerning technical standards and market incentives. This underscores Europe's dual challenge: fostering innovation while respecting regional autonomy in a competitive global arena.

2.2.3 Challenges and Opportunities in Regulatory Harmonisation

2.2.3.1 Challenges:

- *Fragmented Regulations*: Creates barriers for cross-border operations and deployment.

- *Varying Implementation*: National specificities lead to divergence even when adopting EU policies.

- *Balancing Innovation & Regulation*: Finding the right balance to foster innovation responsibly without stifling it or creating unacceptable risks.

- *Conflicting Priorities*: Divergent national energy policy goals (e.g., RES vs. security vs. affordability).

- *National Interests*: Reluctance to relinquish control over national regulations.

2.2.3.2 Opportunities:

- *Harmonised Standards*: EU promotion of common standards (e.g., through CEN/CENELEC, ETSI, or initiatives like IEEE 2030.5 (IEEE, n.d.)) simplifies compliance and deployment (World Standards Cooperation, n.d.).

- *Cross-Border Collaboration*: Sharing best practices and experiences, especially on complex issues like RES integration and cybersecurity. Initiatives like developing common tech specifications (ENTSO-E/EU DSO Entity) improve visibility.

- *Mutual Recognition*: Mechanisms for recognising national certifications can reduce administrative burden.

- *EU Funding*: Programmes incentivise harmonisation and common solutions.

- *The AI Act as a Unifying Force*: Provides a horizontal baseline, promoting alignment, particularly for AI regulation.

2.2.3.3 Global AI Landscape: A Strategic Overview

The global AI landscape continues its rapid and transformative evolution, increasingly dominated by advancements in large-scale foundation models and GenAI. This dynamic environment is characterised by intense geopolitical competition, substantial but uneven investment flows, diverging regulatory approaches, and a growing awareness of the resource demands and societal implications of powerful AI systems. Understanding this complex global picture is essential for Europe to navigate its own path in AI adoption, particularly within critical sectors like energy and smart grids, and to maintain competitiveness (European Commission, 2023d).

- **Leading AI Nations & Blocs:**
  - *United States:* Remains the dominant global leader, particularly in the development and funding of cutting-edge foundation models, driven largely by major technology corporations and significant private investment (the dominance of the United States is already being challenged by many today, considering the rapid emergence of several top-tier models coming from China). The U.S. approach to governance relies heavily on the framework set by Presidential Executive Orders, promoting voluntary commitments, risk management frameworks (like the NIST AI RMF), and sector-specific guidance, prioritising innovation leadership alongside safety considerations. The U.S. also shows strong patenting activity across many clean energy technology (CET) and grid technology areas (EPO, 2024; IEA, 2023; IEA, 2024).
  - *China:* Continues its push to become a world leader in AI, backed by strong state support and a vast domestic market. While facing challenges, such as U.S. export controls on advanced semiconductors, China possesses a vibrant AI ecosystem, excels in specific applications and AI patent volumes (including for grid technologies), and is rapidly developing its own large models. Its regulatory landscape is distinct, featuring rules focused on algorithmic transparency, content moderation, and specific AI service types (e.g., generative AI). State Grid notably leads globally in energy management GenAI patents. (EPO, 2024; IEA, 2023; IEA, 2024).
  - *European Union:* Establishes itself as a leader in *AI regulation* with the final adoption of the comprehensive, risk-based AI Act (European Parliament, 2024a). The EU aims to foster a trustworthy AI ecosystem aligned with European values. While lagging behind the U.S. and China in large-scale private AI investment and foundation model development, the EU is investing in sovereign capabilities, including supercomputing infrastructure (e.g., EuroHPC JU) and research programmes. Europe maintains significant innovative capacity, particularly from companies in Germany and France, holding strengths in specific CET fields and contributing substantially to grid technology patenting (EPO, 2024; IEA, 2023; IEA, 2024). There is also considerable interest in supporting open-source AI initiatives within the bloc.
  - *United Kingdom:* Carves out a distinct path, positioning itself as a global hub for AI safety research and dialogue (e.g., hosting AI Safety Summits). Its regulatory approach is described as "pro-innovation" and context-based, relying on existing regulators to develop AI guidance within their sectors, rather than horizontal legislation like the EU AI Act. The UK remains a top-tier AI nation for talent and startups, and contributes significantly to European CET patenting (EPO, 2024).
  - *Other Major Players:* Nations like South Korea and Japan remain critical innovation hubs, particularly

strong in hardware (semiconductors), robotics, specific AI applications, and relevant patenting activity in CET and grid technologies (EPO, 2024; IEA, 2023; IEA, 2024). Canada is noted for its strong AI research community.

- **Emerging AI Hubs**: Countries like Singapore, India (with high AI skill penetration), Israel, Switzerland, and the UAE continue to develop significant AI capabilities, often specialising in particular niches or leveraging specific national advantages.

- **Key Trends & Dynamics:**

Understanding the following key trends and dynamics is crucial for navigating the competitive and rapidly changing global AI environment:

  - *Foundation Model Dominance:* The development, training, and deployment of large-scale foundation models (especially LLMs) remain the central focus of cutting-edge AI, driving both excitement and concern. Competition among leading model providers (primarily U.S.-based) is fierce.
  - *Policy Solidification and Divergence:* Major powers are solidifying their distinct regulatory philosophies – the EU's comprehensive risk-based regulation, the U.S.'s framework-and-voluntary approach, China's state-influenced specific rules, and the UK's context-based model. International dialogues (e.g., G7 Hiroshima Process, OECD AI Principles, AI Safety Summits) continue, aiming for interoperability and shared understanding on risks, but a globally harmonised regulatory regime remains distant.
  - *Compute as a Bottleneck:* The availability of immense computing power (particularly high-end GPUs) and associated data centre infrastructure has become a critical bottleneck and a key determinant of leadership in training large models, concentrating power among nations and companies with access to these resources.
  - *Open Source vs. Closed Source Models:* A dynamic interplay exists between highly capable proprietary models (e.g., from OpenAI, Anthropic, Google) and increasingly powerful open-source alternatives (e.g., Meta's Llama series, Mistral AI, DeepSeek). This debate involves trade-offs concerning innovation diffusion, access, safety, and control.
  - *National Security & Geopolitics:* AI is increasingly viewed through a national security lens, influencing international collaborations, talent mobility, and technology controls (e.g., semiconductor export restrictions). Strategic competition is a major driver of national AI strategies.
  - *Investment Concentration:* While overall AI investment is broad, funding for the extremely expensive development of leading foundation models remains highly concentrated, primarily within a few large U.S. technology companies and their partners, widening the gap with other regions.
  - *Talent Mobility and Concentration:* Attracting and retaining top AI talent remains crucial and highly competitive, with established hubs continuing to hold an advantage.
  - *Responsible AI, Safety & Ethics:* Alongside rapid capability gains, ever greater focus is being put on AI safety, alignment with human values, bias mitigation, transparency, and managing societal risks. However, approaches and standards for achieving "responsible AI" are still evolving and vary globally.
  - *Cost and Sustainability:* The significant financial and environmental costs associated with training and running large-scale AI models are receiving greater scrutiny.
  - *Grid Technology Innovation:* Patent data confirms that AI and data analytics are increasingly central components within the innovation landscape for both smart grids and broader grid enhancement technologies (IEA, 2024; IEA, 2023).

- **Implications for Smart Grids:** The rapid advancements require caution, particularly in foundation models, signal transformative potential, but direct application in critical infrastructure like smart grids. While global GenAI developments capture attention, the energy sector often needs *specialised, robust, and validated AI models* tailored for specific tasks like grid optimisation, predictive maintenance, and security. European DSOs, TSOs, and technology providers must navigate this landscape by:

- leveraging validated AI tools where appropriate, while being mindful of risks and regulatory requirements (especially the AI Act),
- understanding the capabilities and limitations of both proprietary and open-source models,
- contributing to the development of domain-specific models (like GridFMs) suited for the energy sector's unique needs,
- navigating the different global regulatory environments when deploying or sourcing AI technologies,
- engaging in standardisation efforts to ensure interoperability and trustworthiness,
- staying abreast of global innovation trends, indicated by research, investment, and patent activity, to inform strategic decisions.

2.3 AI Act Implications for DSOs and TSOs: A Strategic Perspective

The AI Act introduces a comprehensive framework with significant implications for DSOs and TSOs. Their distinct roles necessitate tailored compliance strategies.

2.3.1 Key Impacts of the AI Act

- **Risk-Based Approach:** Requires DSOs/TSOs to conduct risk assessments, implement mitigation, and classify AI systems (minimal, limited, high, unacceptable). Many grid management systems, especially those qualifying as high-risk 'safety components' under the act's criteria (potentially informed by CER thresholds), will face stringent obligations.
- **Compliance Requirements for High-Risk Systems:**
  - *Transparency & Documentation:* Systems must be understandable, especially those impacting prices, reliability, or emergency response. Clear information on decisions is needed for stakeholders. Customer-facing AI must be identifiable. Extensive documentation on data, algorithms, and processes is required.
  - *Data Governance & Privacy:* This ensures data quality and integrity, robust governance frameworks, compliance with GDPR.
  - *Human Oversight:* Effective human oversight mechanisms are mandatory to prevent/mitigate risks from automation failures. Roles, responsibilities, and training are key.
  - *Accuracy, Robustness, Cybersecurity:* Systems must meet high standards. Given increased connectivity, robust cybersecurity is paramount.
  - *Conformity Assessment & CE Marking:* This is required before placing high-risk systems on the market or putting them into service.
- **Ethical Considerations:** Systems must be fair, unbiased, and non-discriminatory. This requires monitoring, impact assessments, and potentially ethics committees.
- **Liability and Accountability:** New liability rules mean operators could be held liable for damages caused by non-compliant AI systems. Accountability frameworks must be established.
- **Incident Reporting:** Serious incidents involving AI systems must be reported to relevant authorities. Monitoring systems and log-keeping (min. 6 months) are required.

- **Phased Implementation:** This requires careful planning to meet staggered deadlines over 12-36 months post-entry into force.

2.3.2 DSOs: Specific Implications

DSOs manage regional/local grids and interact directly with customers. Key AI focus areas and implications include:

- *Impact Areas:* Consumer interaction, demand management, local grid stability, DER integration, cybersecurity.
- *Customer-Facing AI:* Smart metering, demand-side management, personalised recommendations require transparency and robust data privacy (GDPR alignment).
- *Compliance Complexity:* Managing diverse AI systems across localised networks can be challenging.
- *High-Risk Systems Examples:* Managing distribution networks (critical infrastructure), safety-critical components, worker management, decisions on essential service access.

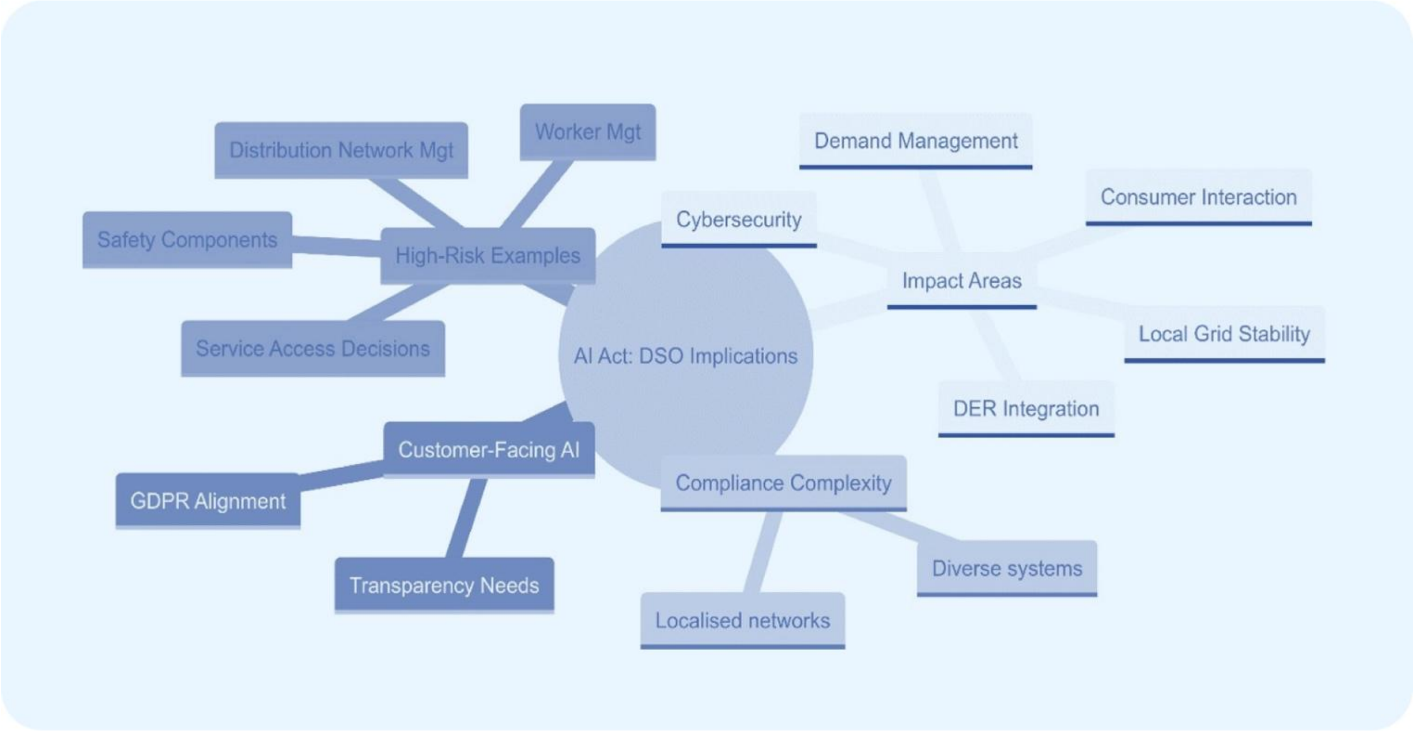

Figure 1- AI ACT: DSO Implications

2.3.3 TSOs: Specific Implications

TSOs manage national/international transmission grids. Key AI focus areas and implications include:

- *Impact Areas:* Large-area grid stability, cybersecurity, cross-border energy trading.
- *Large-Scale Operations:* High-stakes systems with cross-border implications require collaboration with other TSOs/regulators and standardisation.
- *High-Risk Systems Examples:* Similar to DSOs but often at a larger scale, managing transmission networks, critical safety components.

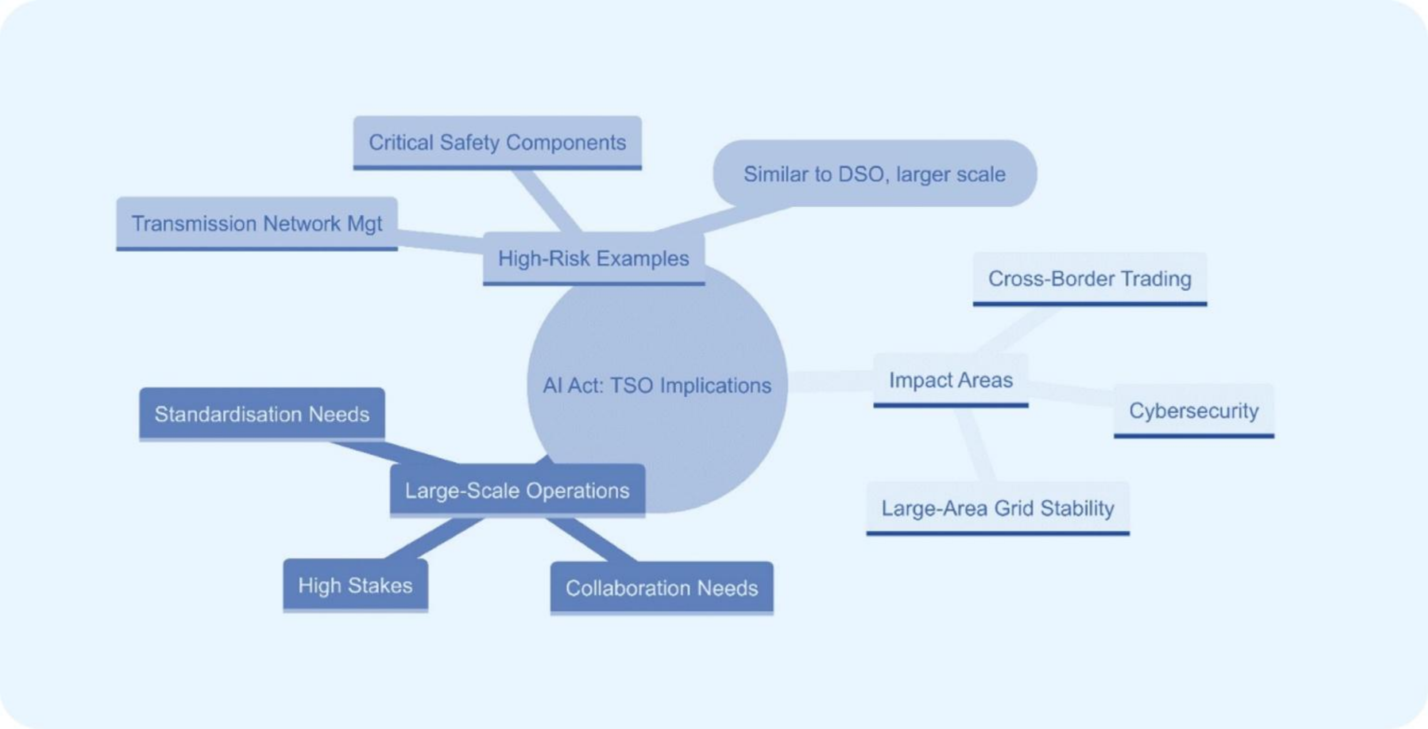

Figure 2 - AI ACT: TSO Implications

2.3.4 Strategic Considerations Arising from the AI Act

DSOs and TSOs should consider the following:

- *Tailored Strategies:* Develop bespoke compliance plans based on specific roles and operational contexts.
- *Proactive Planning:* Initiate gap analysis and compliance planning well before deadlines.
- *Resource Allocation:* Budget for legal, technical, operational adjustments, potentially including new technology, training, and personnel.
- *Risk Management Frameworks:* Develop comprehensive frameworks addressing AI-specific risks (see Section 2.5).
- *Standardisation:* Advocate for and adopt harmonised standards to ensure interoperability.
- *Collaboration & Knowledge Sharing:* Engage with peers, tech providers, regulators, associations (e.g., ENTSO-E, EU DSO Entity).
- *Innovation & Sandboxes:* Utilise regulatory sandboxes for testing; collaborate with AI providers.
- *Governance Structures:* Establish clear responsibility for AI risk management and ethical deployment.
- *Training & Development:* Ensure staff understand AI Act requirements; create cross-functional compliance teams.
- *Financial Implications:* Assess costs of compliance (infrastructure, training, potential penalties).
- *Ethical Practices:* Emphasise ethical, transparent deployment.
- *Continuous Improvement:* Establish ongoing monitoring, auditing, and adaptation processes.
- *Focus on Innovation:* While ensuring compliance, leverage the AI Act's framework (e.g., sandboxes) to foster responsible innovation.

2.4 AI Act Implications for Other Stakeholders

The AI Act's impact extends beyond grid operators:

- **Policymakers:** Need to create adaptive regulations, balance innovation with safety, lead by example in public sector AI use, engage in international collaboration (harmonisation), and consider ethical implications deeply. They must also define CER thresholds relevant to AI risk.
- **Technology Developers:** Must ensure transparency (especially for high-risk), prioritise human-centric design, address ethical concerns (bias, misinformation), adapt to regulations, ensure compliance, and engage with other stakeholders.
- **Consumers:** Require clear communication about AI use and how it impacts their energy management and costs. They should be involved in development processes in order to build trust and satisfaction. Consumers must be protected from high-risk systems via conformity assessments and transparency. Empowering consumers with data and tools (often AI-enabled via smart meters/apps) allows them to participate more actively in the market (e.g., demand response), potentially reducing their energy bills and contributing to the overall affordability and efficiency goals outlined by the EU (European Commission, n.d.-g).
- **ETIP SNET and Stakeholders (Industry Associations, Research Institutions, Financial Institutions):** Play roles in driving AI integration, establishing guidelines/standards, collaborating on roadmaps, amplifying DSO/TSO concerns, facilitating knowledge sharing, supporting R&D, developing risk strategies, advancing ethical deployment, and addressing financial aspects.

A collaborative approach involving all stakeholders is essential for balancing innovation with ethics, transparency, and safety in the energy sector's AI adoption.

2.5 AI Risk Management in Critical Energy Infrastructure

Deploying AI, especially industrial AI, in energy systems requires a robust approach to risk management that considers both traditional power system risks and new AI-specific vulnerabilities. A systems perspective ("power system with AI inside") is needed which evaluates AI function, system interaction, and stakeholder impact. The increasing integration of AI into core grid functions like stability control, flexibility management, and predictive maintenance, as evidenced by patent trends (IEA, 2023), increases the importance of addressing potential AI-specific risks through rigorous testing, validation, and adherence to frameworks like the EU AI Act. Key potential AI risks include (adapted from U.S. Department of Energy [DOE], 2024; Assessing potential future..., 2023; RAND Europe, 2023):

1. **Unintentional AI Failure:** Well-intentioned AI failing or being misused accidentally, causing negative events.
2. **Adversarial Attacks:** Malicious actors targeting AI systems (e.g., data poisoning, evasion attacks) to disrupt operations.
3. **Hostile AI Applications:** Adversaries using AI to plan or execute cyber/physical attacks on energy infrastructure.
4. **Supply Chain Compromise:** AI software supply chains targeted by standard cybersecurity threats, using AI as an infiltration vector.
5. **Safety Race & Concentration:** Competitive pressures leading to insufficient safety focus; over-reliance on few specialised AI vendors increasing influence and risk.
6. **Exacerbated Inequality:** AI applications potentially increasing costs or reducing service quality for vulnerable groups (e.g., decisions based on housing energy efficiency).
7. **Manipulation & Misinformation:** AI used for fraud or spreading disinformation impacting energy markets or system stability.
8. **Jurisdictional/Sovereignty Risks:** Challenges arising from deploying AI across different legal regimes, including

liability issues.

9. **Unexplainable/Unexpected Actions:** AI making decisions difficult to understand or predict, hindering diagnostics and trust.

Managing these risks requires specific technical measures, robust governance, continuous monitoring, and clear incident response plans.

2.6 The Need for Domain-Specific AI Models for the Grid

While general-purpose AI (GPAI) like large language models (LLMs) show promise, their direct application to complex, safety-critical domains like electricity grid management faces significant hurdles.

- **Limitations of General Models:** Current LLMs, without significant domain-specific adaptation, often lack the domain-specific knowledge and reasoning capabilities required for grid operations. They can struggle with correctness, reliability, and transparency ("hallucinations"), making them unsuitable for critical tasks (Evaluating trust and safety, 2023). As demonstrated by Hamann & Brunschwiler, models like ChatGPT can fail basic power system calculations (IBM Research, 2023).

- **Trust and Safety Concerns:** Issues around data governance (lack of clarity on training data), potential biases, and the difficulty of verifying outputs hinder trust, especially in critical infrastructure contexts (Evaluating trust and safety, 2023; Bringing transparency, 2022).

- **Grid Foundation Models (GridFMs) / Grid GPAI:** There is a growing recognition of the need for foundational models or GPAI specifically trained on diverse grid data (time series, topology, etc.). These models aim to:

    - learn rich representations of power system dynamics,

    - perform downstream tasks like power flow, contingency analysis, forecasting, and outage prediction,

    - be fine-tuned by stakeholders using proprietary data economically.

    Examples include the open-source GridFM framework (LF Energy, n.d.) and research like eGridGPT (NREL) exploring LLMs for control room decision support (NREL, 2023).

- **Data Infrastructure:** The effectiveness of GridFMs relies on robust data infrastructure, potentially leveraging concepts like dataspaces – unified frameworks for managing heterogeneous energy data, allowing flexible integration and potentially natural language querying via LLMs.

- **Innovation Trends:** The increasing prevalence of AI and data analytics within patents for enhanced grid technologies globally (IEA, 2023; IEA, 2024) further emphasises the practical drive towards deploying these advanced digital solutions, reinforcing the need for reliable, domain-specific models and appropriate regulatory oversight (like the AI Act) for their application in critical infrastructure.

Developing and deploying trustworthy, grid-specific foundational models is crucial for unlocking the full potential of AI/GenAI in enhancing grid operations safely and effectively.

2.7 Enhancing Smart Grid Performance and Resilience with AI

AI offers significant potential for improving key aspects of smart grid performance, resilience, and sustainability:

- **Improving Key Performance Indicators (KPIs):** AI can directly enhance standard smart grid KPIs:

    - *Reliability (SAIDI/SAIFI):* Predictive maintenance reduces failures.

    - *Efficiency:* Optimised dispatch, voltage control, and loss reduction. Demand forecasting enables better load balancing. Improved efficiency directly contributes to lower operational costs and potentially more affordable energy.

  - *RES Integration:* Improved forecasting and control facilitate higher and more cost-effective integration of RES, helping to reduce reliance on more expensive fossil fuels.
  - *Flexibility & Demand Response:* AI optimises DR programmes and grid adjustments, allowing better management of peak loads and potentially reducing system costs.
  - *Resilience:* Faster anomaly detection, fault location, and restoration strategies enhance robustness against disruptions and climate events.
  - *Cybersecurity:* AI-based threat detection and response.
  - *Affordability Contribution:* Overall, AI contributes significantly to the EU's objective of ensuring affordable energy by enhancing efficiency, optimising RES integration, enabling flexibility, and potentially reducing infrastructure investment needs through better utilisation..
- **Supporting Resilience:** AI contributes by enabling forecasting, real-time optimisation, creation of accurate digital twins for simulation, anomaly detection, cyber defence, and optimised demand-side flexibility, thus enhancing the grid's ability to withstand and recover from disruptions.

2.8 Achieving Harmonisation for AI in Smart Grids

Realising the benefits of AI across the EU energy sector requires overcoming fragmentation through "reasonable harmonisation":

Challenges: Diverse regulations, technical standards, implementation strategies, data governance approaches, and conflicting national priorities hinder seamless AI deployment.

Strategies:

- *Development and Alignment of International Standards:* Collaborative efforts through bodies like IEC, ISO, ITU (via WSC) and IEEE to create unified technical standards for interoperability and compatibility (World Standards Cooperation, n.d.; IEEE, n.d.).
- *Policy Coordination and Regulatory Alignment:* Aligning national regulations with EU frameworks (like the AI Act) and international standards through dialogue and partnerships.
- *Establishment of Data Governance Frameworks:* Implementing standardised data governance policies (building on DGA, Data Act) to ensure consistent privacy, security, and facilitate trusted data sharing crucial for AI.

3 TECHNICAL FOUNDATIONS OF AI AND GENERATIVE AI IN SMART GRIDS

This chapter first describes current and emerging smart grid technologies and how they can enhance (or supply) data for AI-driven applications. Then, it explores the specific AI and GenAI techniques that can be applied in smart grids using that data, with examples from international cooperation, pilot projects, and real-world operational deployment with AI technology.

3.1 Emerging Smart Grid Technologies and AI

The transformative potential of AI in the energy sector relies on the availability of robust, high-quality data. This data forms the foundation for AI-driven applications, providing insights, predictions, and solutions that revolutionise how energy systems are managed and optimised. The current and emerging smart grid technologies not only enhance the availability of this data but also enable new paradigms for its use through advanced hardware, software, and computational techniques.

At the heart of data availability in modern grids lie smart meters. These devices have evolved beyond their initial purpose of enabling accurate and automated billing. Today, they play a crucial role in recording granular data on energy consumption and transferring it to grid operators in near real time. This wealth of information enables DSOs to analyse consumption patterns, optimise grid performance, and design effective demand-side management strategies. However, in some Member States, there are regulatory constraints related to GDPR that prevent DSOs from using smart metering data for operation and planning tasks, which undermines the benefit that can be extracted from this data. For residential consumers, the data from smart meters, if accessible via a DSO App or directly from a home area network (HAN) access port, shows usage patterns, helping identify periods of peak demand. This insight can be leveraged to reduce energy-intensive processes during high-demand periods, alleviating stress on the grid. Furthermore, this data supports internal energy management practices in industrial and commercial settings, contributing to overall system efficiency.

Beyond smart meters, the deployment of internet of things (IoT) devices and advanced sensors is expanding the data collection capabilities of smart grids. IoT-enabled sensors monitor various parameters, including voltage, current, temperature, and weather conditions. These devices provide high-frequency data streams that capture the dynamic behaviour of the grid, allowing for real-time monitoring and diagnostics.

Phasor measurement units (PMUs), which provide synchro phasor data, are increasingly used to monitor grid stability and detect anomalies. These data is critical for AI-driven dynamic security assessment, where machine learning models predict potential stability issues and recommend preventive measures. In fact, wide area monitoring systems (WAMS) significantly enhance power grid monitoring by providing real-time, high-precision data collection and analysis across extensive geographical areas through PMUs and GPS synchronisation. This integrated approach enables meticulous event sequencing and deep insights into state estimation, fault detection, stability assessment, and power flow optimisation. Additionally, WAMS supports AI-driven dynamic security assessments, facilitating predictive maintenance and improving renewable energy integration. Initiatives are emerging, such as the South Korean power grid (KEPCO) using WAMS to solve fault classification problems and an energy management system to reduce the stability analysis and topology processing time (Lee et al., 2024). However, challenges such as managing large data volumes, ensuring data accuracy, and maintaining cybersecurity must be addressed through robust data management strategies and security protocols.

Combining these sensors with advanced communication protocols ensures that data is transmitted reliably and securely to central or edge computing platforms. The integration of 5G technology further enhances this capability by enabling ultra-low latency and high bandwidth, supporting the massive data flows required for AI applications.

Digital twins (DT) are among the most promising developments in the software and digital domain. These virtual replicas of physical grid components use data from IoT devices and sensors to simulate real-time operations and predict future states. A DT is generally defined as a co-existing virtual representation of a physical asset and its bidirectional communication ('two-way data flow'). In this context, one should also take into consideration the concept of digital twin systems consisting of horizontally and vertically interconnected digital twin systems on all system levels such as component, unit, plant, and grid (system) level, for example, capable of mirroring the EMT system behaviour. Incorporating DTs into power grids offers several opportunities, including enhanced asset management, predictive maintenance, and improved operational efficiency. For instance, DTs enable real-time monitoring and control of grid components, facilitating proactive maintenance strategies that can reduce downtime and extend asset lifespans.

Open-source software frameworks are also vital in making AI capabilities more accessible (Parisot et al., 2025). These frameworks allow researchers and practitioners to develop, test, and deploy AI models tailored to specific grid challenges. For instance, transformer models can analyse time-series data from the grid, identifying trends and anomalies. In contrast, diffusion models offer potential applications in generative tasks, such as creating realistic load profiles or simulating rare grid events.

The increasing complexity and scale of energy systems demand high-performance computing (HPC) resources to process and analyse data efficiently. Cloud computing platforms provide scaleable and cost-effective solutions for training large AI models and storing massive datasets. Cloud-based services enable energy companies to access state-of-the-art computational resources without significant capital investment. Edge computing is another emerging paradigm that complements cloud solutions by processing data locally at the collection point. This reduces latency and bandwidth requirements, making it suitable for real-time applications such as fault detection and distributed energy resource (DER) management. For instance, an edge device installed at a substation can analyse incoming data to detect faults and coordinate corrective actions without relying on centralised processing. Although still in its infancy for energy applications, HPC combined with quantum computing holds promise for solving optimisation problems at unprecedented speeds. These technologies could revolutionise grid operations, enabling real-time optimisation of power flows, renewable integration, and market dynamics.

The availability of data for AI applications is also expected to grow thanks to the development of Common European Data Spaces, particularly in the energy sector. The European Commission has supported a set of projects that have developed the key technology, while an implementation project is expected to start in 2025 within the Digital Europe programme. A reference architecture for data spaces has been proposed in a blueprint document available online (Dognini et al., 2024). Data spaces make possible data sharing while keeping data sovereignty under control. This feature should, in the near future, facilitate an ecosystem of data sharing and a real data economy, which could be considered vital support for all kinds of AI applications.

To conclude, the convergence of smart grid technologies, advanced hardware, and innovative software solutions create conditions to develop and deploy advanced AI-based systems, and GenAI in particular.

3.2 Applications and Implementation of AI in Smart Grids in Production

AI has already proven capable of creating new market opportunities, with key energy stakeholders benefiting from these market-ready (in production) AI applications. This section will focus on AI implementations that have already been deployed in real systems and embedded into energy stakeholders' workflow. Market-ready applications of AI algorithms primarily include the use of various types now considered classical models (e.g., linear regression, tree-based models, and neural networks) for the estimation (short term) and forecast (long term) of a variety of variables and parameters intrinsic to energy systems. Applications of AI-based forecasting algorithms include the prediction of market prices and/or bidding strategies, electrical energy production (including renewables), power demand, and lines' loading (Sweeney et al., 2020). A significant number of scientific studies have been devoted to this issue (Fan et al., 2023; Pinheiro et al., 2023; Rahimi et al., 2023a, 2023b; Suganthi & Samuel, 2012), with even recent competitions established to encourage the development of new models (Browell et al., 2023).

The deployment of AI-based forecasting models has greatly improved decision-making for market participants and operators, playing an essential role in the current operational scenario characterised by high shares of renewable energy generation. AI-based forecasting models have generally enabled more effective bidding strategies under uncertainty, reduced operational risks, and boosted profitability through more accurate forecasts. From the network operation perspective, operators use AI-based forecast models to estimate expected PV solar generation and electric vehicle charging demand. The forecasted data is used to determine the volume of energy flexibility that will need to be acquired (e.g., via balancing markets or direct contracts) to avoid grid congestion events. These developments have facilitated the deployment of demand response initiatives and the increase of integration of renewable energy sources.

Classical ML algorithms have been proven sufficient for energy systems forecasting applications, with mature implementations available in open-source projects such as the Linux Foundation Open STEF (Short-Term Energy Forecasting) project (Linux Foundation Energy, n.d.), led by the Dutch operator Alliander. The successful implementation and usage of the Open STEF project come from the standardised ML pipelines (e.g., scikit-learn) that combine several sources of data, including weather and measurement data, to provide forecasts via a customisable and extensible API. Standardisation of such development and implementation of ML pipelines facilitates its adoption by other operators.

The expectation for AI-based forecasting algorithms is to be enhanced by new generative AI models, enabling advanced algorithms to extract useful information from heterogeneous sources of information, including satellite images and sky camera frames. Examples of successful market implementation of generative AI forecasting tools include the ones by the Dutch startups Pythia Energy (https://pythia-energy.nl/) and Dexter Energy (https://dexterenergy.ai/). Heterogeneous data handling enables AI-based forecasting algorithms to extract information beyond time series data (Visser et al., 2022), for instance, by exploiting space and spatial data (E.ON Space Economic, n.d.). Based on this, a new generation of forecasting models with improved accuracy and lower computational time (due to the fast inference provided by new generative AI algorithms) should be available in the future. Handling such heterogeneity of data is not possible with classical AI algorithms.

Advancements in AI are also triggering a paradigm shift in power system protection. Under the Kopernikus ENSURE project, the newly developed Protection Toolchain (Pro-TOC) represents a significant leap forward by automating the design and assessment of protective relays. This integrated toolchain is an open, modular architecture and comprises a sequence of interoperable modules—from typical matching and algorithm selection to setting calculation, protection security assessment, and optimisation—that collectively streamline and digitise complex configuration processes. Moreover, incorporating a hybrid binary particle swarm optimisation algorithm enhances the precision of setting values while offering a comprehensive evaluation of grid reliability and security.

Other areas with already some maturity regarding the use of AI are predictive maintenance, fault detection and location, linear assets (lines, cables) and generation assets, and outage management (Kezunovic et al., 2024).

3.3 Potential of GenAI in Transforming Smart Grids

The defining characteristic of GenAI, in contrast to conventional AI/ML approaches for classification, regression, and clustering, is its ability to contextualise and consolidate available information into new, synthetic data. This feature makes GenAI particularly promising for decision support in smart grid operations, offering improved situation awareness, bridging critical data gaps, and simplifying complex decision-making processes. Furthermore, GenAI focuses on creating new data—text, images, or code—by learning underlying patterns, whereas LLMs specialise in text-based tasks like answering questions, summarising, and translating. While LLMs are a subset of GenAI, the broader GenAI field also includes models for image synthesis, music composition, and design automation.

In the context of electric power systems, situation awareness is defined as "the cognition of those elements that enable an effective reaction by the operators during routine operations and electrical disturbances" (Panteli & Kirschen, 2015). The foundation for such operator situation awareness lies in processing large amounts of power system data, especially in forecasting, state estimation, and security analysis applications. In energy forecasting, GenAI can be employed to generate temporal and spatiotemporal trajectories (or short-term forecast scenarios) of forecast uncertainty. These trajectories provide valuable information for robust optimisation (Soares et al., 2018) and stochastic optimisation (Garcia-Torres et al., 2021), aiding in managing power grids and market offers. For example, diffusion models have been used to generate wind power forecast scenarios (Dong et al., 2023) and to estimate the epistemic and aleatoric uncertainty of load forecasts (Wang et al., 2024). Additionally, NREL's eGridGPT showcases GenAI's capabilities in grid forecasting and state estimation by synthesising and analysing structured numerical data and descriptive metadata from grid operations (NREL, 2025). Similarly, Pacific Northwest National Laboratory's ChatGrid™ tool uses GenAI to enhance operators' understanding of complex grid data through advanced visualisation and real-time contextual insights (PNNL, 2024).

In the realm of security analysis, the proliferation of uncertainties has created the need for advanced simulation tools that can predict system behaviour at a low computational cost and with high accuracy. A U.S.-EU working group (Hamann et al., 2024) highlighted the potential of foundation models (FM) as proxies for tasks such as power flow and optimal power flow calculations. These proxies facilitate real-time application for critical tasks such as contingency analysis by running calculations at inference time. Traditional ML solutions, like graph neural solvers for AC power flow (Donon et al., 2020) or physics-guided graph convolution neural networks (Gao et al., 2024), have addressed similar tasks. FM's potential advantage lies in its attention-based mechanisms, enabling high transferability and generalisability across related applications and even to previously unseen network topologies. Among the so-called traditional ML solutions, graph neural networks can also generalise over variable grid topologies (Donon et al., 2024).

Another important challenge for security analysis relates to extreme weather events. Although these are becoming more frequent, access to realistic data is limited. Here, GenAI proves invaluable by generating high-impact, low-probability scenario data. Modified generative adversarial networks (GANs), incorporating extreme value theory, have been employed to create spatiotemporal precipitation scenarios for flood risk simulations impacting electrical infrastructure (Bhatia et al., 2021). Similarly, pre-trained conditional diffusion models generate renewable energy scenarios tailored to extreme weather events (Zhu et al., 2023). The use of GAN has also been reported for data abnormality detection, as indicated by KEPCO in Korea, due to its ability to distinguish between genuine and generated data (Lee et al., 2024).

The restricted access to training data from TSOs and DSOs is a general challenge for developing new approaches. Combining open and synthetic data offers an alternative approach for developing power system proxies, which can be later fine-tuned with proprietary data. GANs and variational autoencoders (VAEs) have been used to generate synthetic data, including building electrical load profiles (Wang & Hong, 2020), electric vehicle charging profiles (Yang et al., 2021), and renewable energy time series (Chen et al., 2018). Conditional diffusion models have also been applied to create synthetic datasets, such as energy meter data using building metadata (Fu et al., 2024) and temporally correlated EV charging scenarios (Li et al., 2024). Moreover, the NetGAN model introduced generative approaches for network data that effectively capture essential topological properties (Bojchevski et al., 2018). Building on these principles, GANs have been used to generate synthetic three-phase unbalanced distribution grids (Yan et al., 2022). Physics-informed approaches are critical to ensuring realistic and meaningful network data generation. For instance, the PowerGraph library employs cascading failure models to produce high-quality data for AI training (Varbella et al., 2023).

Integrating GenAI technologies and LLMs into power grid management has unlocked significant new possibilities for enhancing system reliability and security. One key application is in formal verification, a crucial method for assessing the robustness of AI-driven grid operations. As outlined in ISO/IEC 24029-2, formal verification plays a vital role in systematically evaluating AI systems, ensuring their reliability, and identifying potential adversarial vulnerabilities (Nellikkath et al., 2024). A comprehensive robustness evaluation in power grids should consider multiple critical factors, including load distribution, generator operational costs, and network topology (Popli et al., 2024). These elements influence the overall stability and efficiency of the grid and must be rigorously analysed to prevent disruptions. GenAI technologies can contribute significantly by automating robustness assessments and generating adversarial test cases—simulated scenarios designed to expose weaknesses in grid operations. By leveraging AI-generated adversarial examples, researchers and operators can systematically identify vulnerabilities, test grid resilience under extreme conditions, and refine mitigation strategies (Li et al., 2024). This integration of AI-driven methodologies enhances the security and adaptability of modern power grids, ensuring they can withstand cyber-physical threats and unexpected disturbances.

Digital twins of electricty networks, enabled by GenAI, represent a transformative approach to smart grid management. These twins simulate and test new technologies in virtual environments, enhancing planning, efficiency, and resilience. For instance, the HILLTOP+ microgrid simulation platform allows utilities to experiment with innovations like utility-scale battery storage in a "safe space" (Generative AI for Smart Grid Modelling | MIT News, n.d.). As the demand for sustainable energy systems grows, integrating GenAI into grid management constitutes a critical step towards achieving global energy goals.

3.4 Pilot Projects and Demonstration Initiatives in Europe

Across Europe, pilot projects are demonstrating the potential of classical AI and generative AI in energy systems, focusing on grid optimisation, asset management, forecasting, and operational efficiency. These initiatives address real-world challenges through innovative AI solutions while emphasising collaboration, scaleability, and adaptability. A more detailed description of some initiatives can be found in Annex 1.

GridFM, an open-source initiative, aims to develop foundation models for power grids, enabling scalable solutions for tasks such as AC power flow and optimal power flow calculation (Hamann et al., 2024). The project uses transformer architecture pre-trained on synthetic grid data, addressing data-sharing challenges. Pre-trained models are fine-tuned with minimal labelled data, providing significant simulation acceleration and overcoming confidentiality barriers. The adaptability of these models has been highlighted in similar contexts, such as weather modelling (Chen et al., 2023) and remote sensing (Hong et al., 2024). The project is now an activity within the Linux Foundation Energy.

The LF Open Synth Project is an open initiative that aims to develop GenAI models to generate synthetic smart meter data that can later be used to support other smart grid planning and operation tasks. The focus of the Open Synth project, led by the Centre for Net Zero (UK), Alliander (NL) and TU Delft (NL), is to not only make synthetic smart meter data available but also the models used to obtain such data. The expectations are for smart meter data owners to also make use of such models to create synthetic databases that can later be released.

The Kopernikus ENSURE project applies advanced artificial intelligence to modernise electricity grids while enhancing their sustainability and reliability. In a collaborative framework involving industry partners, grid operators, academia, and civil society, the initiative harnesses digital twin technologies and AI-driven simulations to optimise grid operations and pave the way for the seamless integration of renewable energy sources. Additionally, ENSURE integrates machine learning-driven alarm management that clusters, classifies, and prioritises alerts, thereby reducing operator fatigue and enhancing situational awareness. Together, these innovations enable renewable energy installations to reliably supply regulation and reactive power, functions traditionally fulfilled by conventional power plants.

E-REDES and Elia have tested AI-based smart alarm management systems to handle the increasing volume of alarm data in grid operations. In the E-REDES project, machine learning was used to group alarms, detect patterns, and provide contextual insights, improving operational efficiency (Andrade et al., 2022; Campos et al., 2024). Elia tested tools like interactive alarm lists, heat maps, and flood visualisations, addressing the unique challenges of power systems (Mitrentsis et al., 2022). Success requires collaboration between vendors and operators, clear communication, and user-centric design (Marot et al., 2024).

Real-time congestion management has been explored through reinforcement learning. Projects like the Paris Region AI Challenge, supported by RTE, used RL agents and the Grid2Op simulator to propose topology actions, mitigating congestion caused by fluctuating renewable energy (Lehna et al., 2023; Donnot, 2020). AI mirrored human operator behaviour, showing the value of early operator engagement, gradual deployment, and measurable outcomes (Sintes & Dang, 2024).

Condition-based monitoring of circuit breakers, implemented by grid operators, leverages supervised learning and predictive analytics to optimise maintenance. AI-based solutions process operational data, predict failure probabilities, and generate actionable insights, reducing downtime and costs. Similarly, the DSO Netze BW's predictive maintenance tool for distribution networks integrates geospatial, telemetry, and operational data to identify critical assets. This scaleable framework has significantly improved asset management and compliance with ISO 55001. The PQsmart project by Netz Niederösterreich uses voltage measurements from smart meters and computer vision to enhance power quality management and predictive maintenance. By processing billions of data points, the initiative detects component errors, rectifies voltage violations, and optimises local grids in line with European standard EN 50160.

AI-based forecasting models for low voltage networks developed at Netze BW in Germany use data from sensor-equipped substations, weather inputs, and master data to generate load profiles. Similar load forecasting models are developed by Stedin in the Netherlands for medium-voltage grids. These models fill data gaps, providing real-time insights essential for planning and operations. High-quality training data and adaptability to customer usage patterns are critical to the project's success. Furthermore, at Netze BW, virtual inspections of grid assets use drones equipped with high-resolution cameras supported by AI for anomaly detection and classification. Projects in Sweden and other European regions automate LiDAR data analysis, reducing manual effort and improving inspection accuracy. Scaleability and access to training data are key to these projects, with a focus on enhancing anomaly detection capabilities.

The Nele App, developed at Netze BW using GenAI, supports field technicians by integrating a vector database and large language models. The app delivers context-aware answers and facilitates knowledge-sharing among users. It has proven essential for improving efficiency and safety, with success relying on maintaining an extensive, up-to-date knowledge base.

In PV production forecasting, the H2020 MATRYCS initiative, applied in Coopérnico's solar parks, employs transfer learning to address data scarcity. Pre-trained models fine-tuned on limited local data have significantly improved accuracy. GenAI could further enhance this approach by creating synthetic training data, addressing gaps for underrepresented plants. The scaleability of transfer learning enables implementation across diverse regions, supporting smart city initiatives and energy communities (Sarmas et al., 2022a). Moreover, incremental learning has been successfully applied in energy demand forecasting for microgrids. The H2020 BD4NRG project in Terni, Italy, uses adaptive training strategies to address concept drift, maintaining accuracy in dynamic environments (Sarmas et al., 2022b). This lightweight framework reduces computational resource requirements, making it suitable for smaller energy systems. Scaleability and real-time adaptability are crucial factors in its success.

Utilities across Europe, such as Enedis, E.ON, Stedin and i-DE, are exploring AI for various applications. Enedis developed DeepCourboGen, a GenAI system for synthetic smart meter data, enabling broader applications while ensuring privacy. Drone-based inspections, implemented in Sweden (E.ON) and Poland (Enea Operator), use AI-powered image analysis with aerial vehicle flights to automate the detection of asset defects and the identification of grid objects. For instance, the results in Poland confirmed the system's ability to adapt object lists to GIS standards, automate the generation of output data, and produce standardised, "online" passporting reports. E-REDES developed Analytics4Vegetation to automate vegetation management, reducing manual effort by 80%. The DORA platform by Enedis analyses drone-captured images for anomaly detection, streamlining maintenance processes. Scottish Power Energy Networks (SPEN) used an AI-powered 3D digital model to simulate the impact of Storm Arwen, which caused widespread outages due to 160 kph winds. The AI-based simulation replicated environmental conditions, such as wind speed, direction, and floods, to identify weak points in the network requiring upgrades for improved resilience. By integrating data like asset health indicators, severe weather areas, and protection zones with structural analyses and weather simulations, SPEN assessed risks and optimised CAPEX spending. This approach enables targeted investments, reducing costs while enhancing network reliability and resilience against extreme weather events. Stedin deploys AI tools to specify available capacity for EV charging at numerous charging poles in southern Netherlands. In addition, a pilot project of Stedin uses AI models to determine the optimal location for MV stations in residential areas under development, leading to efficient usage of scarce space and engineering time. Stedin is running another pilot related to GenAI, particularly virtual assistants for knowledge discovery and augmenting content creation. This involves interactive data search within the databases, making minutes of meetings, and assistance for writing documents.

These projects highlight the transformative potential of AI in energy systems. Open-source initiatives like GridFM and proprietary tools by utilities emphasise collaboration between AI experts, operators, and stakeholders. Success relies on early engagement, scaleable infrastructure, high-quality training data, and user-centric designs. GenAI adds value by creating synthetic data and enhancing model performance, enabling solutions to address data scarcity and operational challenges effectively.

Regarding power grid cybersecurity, Darktrace is considering GenAI and uses AI-generated cybersecurity simulations for energy sector clients. Also, Siemens & NREL are developing AI-driven cyberattack scenario generators for utilities.

Regarding Generative AI for energy market strategy and trading, Norwegian power company Statkraft is experimenting with AI-driven market simulation tools. Also, Next Kraftwerke uses AI-generated scenarios for its virtual power plant energy trading, and Tesla's Autobidder already uses AI for real-time VPP energy trading.

In grid outage prediction and restoration, GenAI is being used by GE Digital Grid Solutions in testing AI-driven outage prediction models, and National Grid ESO uses AI for power restoration planning.

In the field of power system training and workforce support, Siemens Energy & ABB are developing AI-powered engineering support chatbots and ELES (TSO Slovenia) is testing AI-generated training simulations for control room operators.

3.5 Breakdown of AI/GenAI Applications in Smart Grids based on Maturity Level

This section presents Table 1, which summarises the AI/GenAI applications by maturity level, i.e., technology readiness level (TRL), and key technologies used. The TRL scale used follows the Horizon Europe programme, as outlined in Annex 2. However, ongoing studies (Eljasik-Swoboda et al., 2019; Lavin et al., 2022) are exploring tailored TRL scales and definitions specifically for AI technologies. This remains an area of potential refinement within the EU, reflecting the need for more precise assessment frameworks suited to AI-driven innovations.

Table 1 - Breakdown of AI/GenAI applications in smart grids based on maturity level

Maturity Level	Technolog Readiness Level (TRL)	Description	Key Technologies Used	Example Application	Challenges & Future Prospects
Research (Prospective Applications)	TRL 2-3	Theoretical AI concept for fully autonomous grid operation.	AI agents, Operator-in-the-loop systems	AI-driven autonomous grid operation.	High complexity, operational risks, and regulatory constraints.
Research (Prospective Applications)	TRL 2-4	AI-powered policy modelling and simulation.	Generative AI, Transformer models	AI-driven policy modelling and scenario simulation.	Regulatory challenges and model transparency concerns.
Research (Prospective Applications)	TRL 2-3	Decentralised energy trading and AI decision-making.	Blockchain, Smart Contracts, Federated AI	Fully decentralised energy trading and market optimisation.	Significant regulatory, market, and cybersecurity barriers.
Research (Prospective Applications)	TRL 2-4	Self-learning that adapts grid dynamics.	Self-supervised Learning; Reinforcement Learning	'AI-building AI' and AI-driven security design.	Lack of explainability and risk of uncontrolled adaptation.
Research (Prospective Applications)	TRL 3-4	Generative AI for extreme weather scenario simulation.	Diffusion Models, Generative Adversarial Networks (GANs)	Simulating high-impact weather events to stress-test grids.	Accuracy and computational requirements remain challenges.
Research (Prospective Applications)	TRL 1-3	Quantum AI for grid optimisation.	Quantum Machine Learning (QML)	Solvingcomplex power flow problems using quantum computing.	Still in its infancy; it requires hardware advancements.
Proof of Concept (Research-Grade Applications)	TRL 5-6	Generative AI models for synthetic data generation.	GANs, Variational Autoencoders (VAEs)	AI-generated grid data for resilience testing.	Ensuring realistic data quality and avoiding biases.
Proof of Concept (Research-Grade Applications)	TRL 5-6	AI for improving load flow calculations.	Graph Neural Networks (GNN), Bayesian Networks	AI-enhanced real-time power flow simulations.	Scaleability and integration with existing grid models.
Proof of Concept (Research-Grade Applications)	TRL 5-6	Transformer- based forecasting for renewable energy.	Transformer architectures, Probabilistic AI	Improving solar and wind power forecasting accuracy.	High data dependencies and long training times.
Proof of Concept (Research-Grade Applications)	TRL 5-6	Bayesian Networks for risk assessment and decision-making.	Probabilistic AI, Bayesian Inference	Improving decision-making under uncertainty.	Complexity in real-time deployment and explainability issues.
Pilot Test (Pilot-Tested Real-Life Applications)	TRL 7-8	AI-enhanced predictive maintenance.	Autoencoder- based anomaly detection, Smart Sensors	Detecting operational faults and reducing downtime.	Deployment at scale and integration with legacy grid infrastructure.

Pilot Test (Pilot-Tested Real-Life Applications)	TRL 7-8	AI-driven cybersecurity threat detection.	Unsupervised Learning, GANs	Using AI to detect cyberattacks and anomalies.	Adversarial AI risks and evolving cyber threats.
Proof of Concept (Research-Grade Applications)	TRL 5-6	Digital twins for real-time grid simulations.	Physics-Informed Neural Networks, Reinforcement Learning	Simulating energy networks to optimise performance.	Computational demands and validation of digital twin outputs.
Operational Deployment (Mature Applications)	TRL 9	Supervised learning models for load forecasting.	LSTM Networks, XGBoost	Accurate short- term and long-term demand prediction.	Ensuring adaptability to sudden demand fluctuations.
Operational Deployment (Mature Applications)	TRL 9	Supervised ML models for renewable energy forecasting.	CNNs, Probabilistic Forecasting	Improving wind and solar energy integration into grids.	Dependence on high-quality meteorological data.
Proof of Concept (Research-Grade Applications)	TRL 5-6	Edge AI for real-time grid processing.	TinyML, Federated Learning	Reducing latency and enabling real- time grid adjustments.	Trade-off between model accuracy and computational efficiency.
Operational Deployment (Mature Applications)	TRL 7-8	AI-driven cybersecurity for grid monitoring.	Intrusion Detection Systems, AI-enhanced encryption	Mitigating threats to smart grid infrastructure.	Ensuring robustness against adversarial AI attacks.
Operational Deployment (Mature Applications)	TRL 5-6	Federated learning for privacy-preserving grid analytics.	Federated AI, Edge Computing	Balancing computational efficiency and data privacy.	Security of distributed models and communication protocols.

3.6 Lessons Learnt and Best Practices

Several lessons and best practices have emerged from the implementation of AI and GenAI in smart grids:

- Effective implementation of AI and GenAI in smart grids requires partnerships among grid operators, vendors, digital service providers, and regulators. These collaborations ensure that solutions are practical, scaleable, and aligned with regulatory requirements.
- It is important to ensure that operators also have access to the national and EU HPC infrastructure. Advanced applications require large computational power that local and national operators may not have, which limits their ability to develop and deploy large GenAI models. Partnerships with research and universities can facilitate this.
- The success of AI and GenAI solutions depends on access to high-quality, real-world data. Accurate analysis and reliable predictions hinge on robust data validation and preprocessing pipelines. Regulations should be clear so that data owners are willing to make public anonymised or synthetic data. The lack of access to data is currently hindering many innovation projects in the smart grid area.
- Integrating AI and GenAI tools demands expertise in AI and domain knowledge. Training programmes are essential to reskill and upskill personnel on the use of these technologies effectively, fostering interdisciplinary understanding.
- Solutions must adapt to diverse regional contexts and ensure compatibility across national grids, as well as with existing standards, promoting a broader adoption. Scaleability is also difficult to reach in large-scale grids, and it

should be a primary requirement from the very beginning.

- Policymakers must recognise that technical development is only part of AI implementation. Awareness of new task allocations, roles, and compliance measures is crucial for successful deployment.
- Policymakers must recognise that development and innovation are hindered by the lack of GenAI models, such as LLMs, developed at the EU level. Companies are limited to using models made available by third parties, which brings concerns related to EU data privacy and security. The lack of high-performing EU LLMs is putting EU GenAI sovereignty at risk.
- Protecting AI-enhanced grid technologies from cyber threats is vital. Robust cybersecurity measures must address potential vulnerabilities introduced by AI systems.
- AI applications must be transparent and accountable and address biases and security concerns. Clear guidelines and ethical practices are essential to build trust.
- It is essential to have clear documentation outlining the specific problems that AI is designed to solve. Without this, there is a risk of unrealistic expectations, misuse, or misinterpretation of AI capabilities. Well-defined documentation ensures transparency, helps stakeholders understand AI's role, and allows for better evaluation of its effectiveness in addressing real-world challenges.
- Extensive digital and hardware infrastructure is necessary to support the intensive data and computational requirements nature of AI and GenAI applications in smart grids.
- While operational and maintenance enhancements are vital, planning and designing AI solutions for long-term sustainability is equally important (i.e., solutions with low return on investment).
- Many utilities and TSOs still rely on legacy systems, making AI integration costly and complex.
- Real-time grid operations require low-latency AI, which is challenging with large-scale AI models.

3.7 Concluding Overview of AI & Generative AI Techniques in Smart Grids

To conclude this chapter, a comprehensive overview is presented, detailing the current state, challenges, and future directions across various subtopics in this rapidly evolving domain.

At the core of this AI transformation lie various AI techniques, spanning traditional ML approaches, deep learning (DL) models, probabilistic frameworks, and the emerging field of GenAI.

ML plays a pivotal role in several grid applications. Supervised learning methods such as long short-term memory (LSTM) recurrent neural networks and XGBoost are widely deployed for load forecasting, achieving high technology readiness levels (TRL 8-9) and surpassing conventional statistical methods. Unsupervised learning, particularly autoencoder-based anomaly detection is now mature (TRL 7-8), proving its effectiveness in detecting operational irregularities, including faults and cybersecurity threats. RL is gaining traction in dynamic pricing mechanisms and in the dispatch of DERs, though still at an experimental stage (TRL 6-7).

Deep learning techniques, such as convolutional neural networks (CNNs), have succeeded in grid asset inspections, particularly through drone-based imagery analysis (TRL 6-7). Meanwhile, transformer architecture is increasingly used for solar and wind power forecasting, demonstrating improvements in renewable energy integration (TRL 5-6). GNNs, though still in earlier phases (TRL 4-5), hold promise for modelling grid topologies more accurately, assisting in grid optimisation and fault localisation. Probabilistic approaches, such as Bayesian networks (TRL 5-6), are also valuable for risk assessment and decision-making under uncertainty.

In addition to conventional AI models, GenAI is opening new frontiers in grid management. GANs are being employed to synthesise grid data for resilience testing and adversarial cybersecurity defence (TRL 5-6). VAEsVAEs emerge as tools for compressing latent grid states, facilitating more efficient grid simulations (TRL 4-5). Diffusion models are beginning to be explored for extreme weather scenario simulation (TRL 3-4), helping grid operators prepare for high-impact events.

Transformer-based generative models are also being tested to create synthetic load profiles to enhance forecasting models (TRL 5).

These advancements are driving key applications in smart grids. Load and renewable energy forecasting, one of the most mature AI-driven applications (TRL 8-9), continues to improve thanks to AI's ability to capture nonlinear dependencies in energy consumption patterns. Predictive maintenance has also seen substantial progress, with autoencoder-based fault detection significantly reducing downtime and operational costs (TRL 7-8). Demand response optimisation is increasingly leveraging RL-based strategies to balance energy supply and demand dynamically (TRL 6). In cybersecurity and resilience, AI-driven methods, including GANs for cyberattack detection, are being actively explored (TRL 5-6). The coordination of microgrids, facilitated by federated learning techniques, remains an area of ongoing research (TRL 4-5).

Despite these advancements, several technical challenges remain. Ensuring the quality of synthetic data generated by AI models is crucial, as inaccurate data can compromise decision-making (TRL 4). Real-time processing is another key challenge, with edge AI solutions such as TinyML emerging to facilitate fast, localised computations (TRL 6). Model interpretability remains an obstacle, necessitating the development of explainable AI techniques like SHAP and LIME to enhance transparency and trust (TRL 5-6). Scaleability is also a concern, as processing the vast datasets generated by smart grids requires distributed machine learning approaches (TRL 5). Furthermore, cybersecurity threats persist, with adversarial attacks against AI models posing significant risks to grid operations (TRL 4-5).

The successful deployment of AI in smart grids also depends on its seamless integration with existing grid infrastructure. The widespread adoption of IoT and edge devices, particularly smart meters (TRL 8-9), forms the foundation for data acquisition. Communication protocols, such as IEC 61850 and DNP3 (TRL 9), ensure interoperability among grid components. Digital twins, leveraging physics-informed neural networks, are being explored to enhance real-time grid simulation capabilities (TRL 6). In computing architecture, federated learning is increasingly tested as a means of balancing computational efficiency with data privacy (TRL 7).

Several emerging frontiers in AI research are poised to redefine smart grid management. Quantum machine learning, though in its infancy (TRL 2-3), holds the potential for solving complex power flow optimisation problems. Neuro-symbolic AI is an area of active investigation, aiming to integrate traditional grid rules into AI models for enhanced decision-making (TRL 3). GenAI is being explored for scenario planning, particularly in simulating rare but high-impact-low-probability events (TRL 3-4). Physics-informed AI, which embeds power flow equations directly into learning models, is emerging to improve the accuracy of AI-driven grid simulations (TRL 4). Additionally, autonomous grid agents powered by LLMs are being tested for real-time decision support, though their application remains experimental (TRL 2-3).

While AI and generative AI are rapidly advancing smart grid capabilities, several critical research gaps remain. Robust models for handling renewable energy variability are still needed, especially under extreme weather conditions. There is a pressing need for enhanced interoperability solutions that facilitate the seamless integration of diverse energy resources. AI-driven grid stability mechanisms must be further developed to ensure the reliable management of distributed energy systems. Privacy-preserving AI techniques like federated learning require scaling to function effectively in decentralised grid environments. Another key focus area is reducing energy consumption associated with AI model training and deployment. Long-term grid planning, particularly in the context of evolving climate policies, remains underexplored in AI applications. Research is also needed to develop resilience mechanisms for AI failures, ensuring grid stability in the case of erroneous AI-driven predictions. Additionally, improving human-AI collaboration through user-friendly interfaces and regulatory compliance frameworks will be crucial in achieving widespread adoption of AI in energy systems.

In conclusion, AI and generative AI are poised to play a transformative role in the future of smart grids. However, overcoming technical limitations, addressing emerging cybersecurity threats, and closing existing research gaps will be essential to fully realise the potential of AI in driving a more efficient, resilient, and sustainable energy infrastructure.

4 AI AND GENERATIVE AI IN SMART GRIDS: BENEFITS AND CHALLENGES

This chapter analyses the benefits and challenges of implementing AI and GenAI in smart grids. It explores their potential to enhance efficiency, reliability, resilience, and sustainability, while addressing technical, economic, social, and ethical challenges like data availability, integration complexities, privacy concerns, cybersecurity risks, and workforce development. It also examines the impact of these technologies across various aspects of the energy ecosystem.

4.1 Benefits of Applying AI and Generative AI

AI and GenAI offer significant advantages for modernising energy systems, improving efficiency, and enabling a more sustainable and resilient energy future. These technologies vary in their level of maturity; some have been applied for many years, whereas others are being tested for the first time. Their deployment requires careful consideration, often complementing rather than replacing established methods, particularly in critical operations.

4.1.1 Grid Optimisation and Energy Efficiency

AI and GenAI can be used to optimise grid configurations (Bernier et al., 2025), reduce congestion, improve load distribution, minimise energy losses, and facilitate the integration of renewable energy sources. Advanced control algorithms are pivotal in transmission/distribution networks, economic dispatch, and demand-side management processes. Predictive algorithms manage energy storage and balance supply and demand, minimising fossil fuel reliance and improving grid efficiency. Vehicle-to-grid (V2G) technology, managed by AI, allows electric vehicles (EVs) to store excess energy and feed it back into the grid, supporting stability and maximising renewable energy use. AI-controlled EV charging schedules prevent grid overloads, contributing to peak shaving and enhancing efficiency. Nevertheless, challenges, such as dispatching hundreds of EVs simultaneously while meeting operational network constraints, still need to be addressed. AI-powered algorithms can address such scaleability challenges, providing charging schedules in near real time (Orfanoudakis et al., 2025).

Furthermore, AI enables predictive maintenance, preventing equipment failures and ensuring grid stability (Fassi et al., 2024). Similarly, AI can identify or calibrate phase labels and grid models based on smart meter and other grid measurements (Knezovic et al., 2022; Subasic et al., 2022) and estimate the state of power grids (e.g., voltage, current, transformer temperatures). Distribution grids, in particular, tend to have low observability, which AI can help mitigate (Habib et al., 2024).

In power grids, AI's potential for self-awareness and adaptability enables more autonomous operations. AI allows the analysis of vast datasets to optimise grid management, learn from past operational decisions, and incorporate forecasts into decision-making. Automatic energy management systems in homes and workplaces, powered by AI, adjust consumption based on real-time data, optimising demand response and forecasting conditions. Advanced control algorithms (e.g., reinforcement learning, model predictive control) are essential for maintaining grid requirements, such as voltage control and frequency regulation, providing real-time solutions for challenges posed by decentralised and renewable-integrated grids (Chen et al., 2022).

Customers with AI-driven smart homes can become flexible and price-sensitive; their energy consumption (power, heat, gas, etc.) can be shifted in response to dynamic price or penalty signals derived from data-driven demand response models, such as flexibility functions (Madsen et al., 2024a, 2024b) (see also Section 4.1.2). AI can also relieve customers from the burden of managing complex contracts and making rapid decisions. While implementing AI in smart grids involves challenges – including data quality requirements, algorithmic guarantees (e.g., robustness), and investment needs – its potential benefits make it a crucial technology for achieving net-zero goals. AI's evolving role in grid optimisation and energy efficiency can drive the transition towards a sustainable energy future, but accuracy must be carefully validated against conventional techniques, especially in critical applications where trade-offs between speed and proven reliability exist.

List of recommendations (Grid Optimisation & Energy Efficiency):

1. **Infrastructure:** Promote the national rollout of essential infrastructure like smart meters and automated energy management systems (EMSs).

2. **Data Sharing:** Facilitate data sharing (subject to GDPR/anonymisation/aggregation) and support organisations enabling real-time data streams (e.g., Energy Data Spaces).

   Test Facilities (TEFs):

   - Short-term: Continue funding energy-related TEFs with viable business models.
   - Mid-/long-term: Promote TEF usage by companies and support TEF business model development.
   - Prioritise funding for test facilities connected to a TEF.

3. **Fundamental AI Research:**

   Fund studies on:

   - Convergence guarantees for iterative AI solutions.
   - Robustness of AI solutions against realistic challenges.
   - Data informativity requirements for effective AI solutions.
   - Specialisation of general-purpose AI for energy-specific problems.
   - Scaleability and technical requirements for AI solutions, especially in demand-side flexibility.

4. **Regulatory Framework:** Develop a clear framework for determining liability in complex AI solutions involving multiple stakeholders.

4.1.2 Active Consumer Participation and Grid Flexibility

In smart grids, consumers play a crucial role by participating in demand response (DR) and utilising distributed energy resources (DERs), such as EVs and buildings with flexible loads (e.g., HVAC systems, smart appliances, storage). Smart meters and EMSs enable consumers to manage energy consumption via dynamic tariffs, stabilising the grid and reducing costs. Consumers shift from passive recipients to active participants ('prosumers'), managing their energy use and potentially generating renewable energy. They can adjust consumption in response to real-time grid needs, facilitated by smart meters and EMS applications. While these technologies improve sustainability and efficiency, they can also introduce complexity for consumers navigating sophisticated systems. Clear standards for fair participation, interoperability, and data privacy are essential.

AI enhances EMS functionality by analysing data, predicting trends, and optimising energy schedules in response to price signals to balance the grid. It helps manage energy production and demand fluctuations, optimises market bidding strategies (economic dispatch), and automates energy management tasks, enhancing overall grid flexibility. AI also enables local consumer participation and community energy schemes by managing microgrids and facilitating peer-to-peer (P2P) energy trading.

AI-powered dynamic pricing models encourage demand response by optimising flexibility potential in assets like EVs and buildings with smart heating, cooling, and storage systems, reducing peak loads and enhancing grid stability. However, users might feel overwhelmed by technical complexity. AI can mitigate this by providing tailored recommendations and simplifying data, reducing cognitive load while ensuring consumers retain control over their decisions, thereby fostering empowerment rather than a sense of being controlled.

A key contribution of AI, particularly GenAI, is its ability to assess flexibility baselines for DERs with different flexibility modes (e.g., peak shaving, load shifting). By leveraging historical data, user habits, and comfort preferences, AI can determine baseline nominations, essential for consumer participation in local flexibility markets and aggregator programmes. Additionally, GenAI-powered energy advisors can guide consumers with intuitive, natural language-based recommendations, helping them optimise energy usage and behaviour. This interactive, user-friendly approach can make energy management more accessible and engaging.

Despite challenges such as data quality and regulatory requirements, AI is essential for enabling active consumer participation in demand-side flexibility. It supports the energy transition, facilitates DER integration, and ensures grid stability in the face of rapidly growing energy demands.

Table 2- Recommendations Table (Active Consumer Participation & Grid Flexibility).

Timeline	Stakeholder	Recommendation
Short-term (1-2 **years)**	Regulatory & Policy (EC, NRAs)	• Standardise flexibility baseline calculations for fair consumer participation. • Establish clear interoperability standards (smart meters, EMS, DERs) • Strengthen data privacy/cybersecurity regulations for AI-driven energy management. • Encourage proven AI use (e.g., predictive maintenance) via regulation.
	Grid Operators & Aggregators	• Deploy AI-powered demand response for grid balancing/consumer participation. • Develop local flexibility markets to integrate DERs and enhance grid stability.
	Technology Providers	• Launch AI-driven energy advisors (using natural language processing). • Improve AI explainability in EMS for trust and adoption.
Mid-term (3-5 **years)**	Regulatory & Policy (EC, NRAs)	• Implement a unified EU framework for AI-driven demand-side flexibility. • Establish data-sharing frameworks (consumers, DSOs, aggregators), ensuring TSO access.
	Grid Operators & Aggregators	• Expand AI-powered local flexibility/energy trading platforms. • Optimise market bidding strategies for DERs using AI.
	Technology Providers	• Advance AI models for flexibility forecasting, load shifting, and scheduling. • Enhance cybersecurity for AI-driven EMS and market platforms.
Long-term (5-10 **years)**	Regulatory & Policy (EC, NRAs)	• Fully integrate AI-based energy management into grid regulations. • Support decentralised AI-driven energy markets for autonomous trading/flexibility.
	Grid Operators & Aggregators	• Implement fully autonomous AI-based grid balancing and market operations.
	Technology Providers	• Deploy self-learning AI systems for real time, grid-wide optimisation.

4.1.3 Integration of Renewable Energy and Decarbonisation

AI and GenAI are pivotal in integrating RES into smart grids, addressing challenges posed by their intermittent nature. AI can support power system operators and RES owners in planning, operation, and maintenance. In planning, AI can predict congestion probabilities, enabling higher RES connection rates compared to deterministic methods. In operation, EMSs benefit from AI-driven forecasting and control algorithms. AI also optimises fault detection and clearing. In maintenance, AI enhances failure detection and prediction, improving system reliability and reducing downtime.

AI improves forecasting accuracy for RES generation and consumption patterns, essential for integrating intermittent sources and helping shift demand towards low-emission periods (Abisoye et al., 2024; Boza & Evgeniou, 2021; Yousef et al., 2023). By incorporating probabilistic models, AI provides comprehensive probability distributions accounting for uncertainties, crucial for robust decision-making in electricity markets and grid operation (Haupt et al., 2020). AI-powered forecasting can leverage diverse data sources (e.g., GIS, satellite data) beyond traditional methods (Buster, 2020; Dellosa & Palconit, 2021; Shoaei et al., 2024).

In optimal power flow (OPF) management, AI techniques can enhance optimisation processes for complex distribution grids, potentially reducing computational needs compared to traditional tools and accelerating operator decisions (Li et al., 2024; Mittal et al., 2024; Wang et al., 2022). AI optimises generator bidding and energy storage cycles, balancing supply and demand to mitigate RES intermittency (P. & Vijaya Chandrakala, 2020). AI also optimises demand response, managing consumer demand in real time to balance loads and reduce reliance on fossil-fuel peaking plants (Rashid, Biswas, Biswas, et al., 2024).

Additionally, AI provides real-time inertia estimations, vital for maintaining grid stability with high RES integration (Baltas, 2021; Liu et al., 2023; Muhammed et al., 2024; You et al., 2020). It enhances grid stability by analysing vast datasets to detect anomalies and implement corrective actions (Rajora et al., 2022). AI-driven predictive maintenance analyses grid infrastructure data to predict equipment failures, reducing downtime and extending equipment lifespan.

GenAI shows promise for generating synthetic data for network planning, scenario testing, risk-based planning, and minimising investment needs (Rashid, Biswas, Al Masum, et al., 2024). GenAI models can facilitate optimal infrastructure planning by creating multiple design scenarios for higher RES penetration (Martínez et al., 2024; Ziegler et al., 2023, 2024).

While challenging due to data quality and regulatory requirements, AI integration offers significant benefits for decarbonisation. Traditional approaches remain essential, with AI primarily adding value in handling high-complexity problems and enabling faster, data-driven decision-making where traditional methods face limitations.

List of recommendations (RES Integration & Decarbonisation):

- **All Stakeholders → Use AI as a Complementary Tool:** Leverage AI for high-complexity problems and faster decisions but retain essential conventional methods for reliability. AI should enhance, not replace, traditional approaches.

- **Aggregators, Asset Managers, Communities, TSOs, DSOs → Enhance RES Forecasting:** Implement AI-driven forecasting (including probabilistic models) and exploit diverse data sources (GIS, satellite) to improve accuracy beyond traditional methods.

- **Grid Planners, TSOs, DSOs, Policymakers → Optimise Grid Planning for RES:** Use AI to predict contingencies for higher RES connection rates. Leverage GenAI for synthetic data for scenario testing and risk-based planning.

- **Aggregators, Asset Managers, Communities → Improve Grid Operation Efficiency:** Deploy AI-powered EMS for real time forecasting, control, and state estimation. Apply AI-driven optimisation for energy storage.

- **Aggregators, Asset Managers, Communities → Optimise Demand Response:** Develop AI-driven DR systems. Use AI analytics to shift demand to low-emission periods and detect anomalies.

- **Aggregators, Asset Managers, Communities → Enhance Fault Detection & Predictive Maintenance:** Utilise AI for fault detection/clearing and predictive maintenance to improve resilience and reduce RES downtime.

4.1.4 Improved Cybersecurity and Resilience

Integrating AI enhances efficiency but also introduces vulnerabilities to sophisticated cyber threats. Simultaneously, AI can improve cybersecurity through real-time threat detection, adaptive defences, and resilience. AI-based intrusion detection systems (IDS) analyse network traffic to identify and mitigate anomalies. Techniques like adversarial training and ensemble learning enhance AI model robustness against data manipulation attacks aimed at deceiving them. AI-driven differential game models can optimise control strategies by modelling attacker-defender interactions, using adaptive reinforcement learning. AI-powered digital twins simulate operations under attack scenarios, providing predictive cybersecurity insights and enhancing IoT device security. AI also enhances communication protocol security via automated threat modelling, anomaly detection, and adaptive encryption. Overall, AI is critical for maintaining a secure and resilient smart grid, addressing evolving threats while ensuring stability and reliability. This includes augmenting simulation capabilities for analysing vast 'what-if' scenarios and generating synthetic datasets for testing.

List of recommendations (Cybersecurity & Resilience):

- **Data for Cybersecurity AI:** Address the scarcity of real-world cyberattack data. Develop open-source benchmark datasets (in collaboration with grid operators) and create anonymised databases for sharing incident information.

- **Grid Monitoring:** Invest in technologies to enhance grid monitoring, especially at the distribution level where data availability is often limited.

- **Cyber Defence:** Invest in proactive cyber defence solutions, develop cost-benefit analysis models, and favour solutions integrating diverse information sources (physical, network, context-aware).

4.1.5 Process Automation and Efficiency

AI and GenAI offer significant potential to improve and automate both critical and non-critical processes in smart grids. Distinguishing between them is essential, as critical processes (e.g., real-time grid control) directly affect safety and continuity, and require extra safeguards (human oversight, stringent testing, transparency). Non-critical processes can be optimised more freely. Frameworks like Heymann et al. (2024) suggest classifying processes based on data input, AI model type, task, output, and economic context.

- **Non-Critical Processes:** AI can automate tasks supporting DSO/TSO workers, such as validating meter readings, enhancing data quality, and predictive maintenance. Computer vision can aid asset inspection and excavation damage prediction. GenAI applications include chatbots (customer or internal support), knowledge management (preserving expertise from experienced workers, bridging generational gaps), and automated reporting/documentation management. These support productivity without directly impacting grid operations. For instance, AI for administrative tasks can save time and improve deliverable quality (e.g., Lorbada Rodríguez et al., 2024, reported a 16% quality increase at Repsol).

- **Critical Processes:** Automating critical processes (e.g., day-ahead congestion management, real-time stability updates) requires stringent measures. AI systems must prioritise security, ensure human oversight, and maintain resilience. Data integrity and model transparency are crucial. Integrating AI into legacy systems and employing human-in-the-loop approaches help balance innovation and safety.

List of recommendations (Process Automation & Efficiency):

- **Process Classification:** Recognise that not every AI use case in critical infrastructure affects a critical process. Enable AI/GenAI for non-critical process automation.

- **GenAI Support:** Leverage GenAI for common support tasks like knowledge management and simplifying work, facilitating workforce transitions. Balance GenAI use cases with risks.

- **Critical Processes & Human Oversight:** For AI affecting critical processes (e.g., real-time grid management), mandate human-in-the-loop approaches to ensure safe implementation and operation.

4.2 Challenges in Implementing AI and Generative AI

Despite the benefits, implementing AI and GenAI in smart grids presents challenges requiring careful consideration and strategic solutions. Key areas include data management, legacy system integration, ethical and privacy issues, investment needs, regulatory adaptation, sustainability concerns, and cross-sector collaboration. A thorough cost-benefit analysis is also crucial before deployment, considering the resources required.

4.2.1 Data Availability, Quality, and Governance

Robust data management – encompassing availability, quality, and governance – is fundamental for AI in smart grids. Smart grids generate vast data from smart meters, sensors, weather forecasts, etc. Ensuring data availability and integrity is crucial. Smart meter data availability, for instance, often depends on customer consent. Currently, consent management processes vary across stakeholders, highlighting the need for standardised, interoperable solutions, perhaps based on semantics and standards, usable across Europe to facilitate secure cross-border data sharing.

Implementing a "Ssngle source of truth" (SSoT) concept at the stakeholder level can be highly supportive. An SSoT stores the official, accurate data version centrally, ensuring consistency even if data resides in multiple systems. This improves data model accuracy, enhances grid reliability, and enables faster adoption of AI, as high-quality data is essential for training reliable models. Data cleansing, a necessary SSoT side effect, reduces redundancy which can otherwise lead to inconsistencies. Consistent data formatting is vital for machine learning compatibility and avoids analysis distortions. While SSoT is one approach, linking multiple authoritative sources via standardised interfaces is another possibility, such as with data mesh architectures.

High-quality data is essential, although training AI on diverse and noisy data can improve resilience to real-world complexities. Managing data presents challenges: cyber-physical systems face communication delays, data overload, and sensor degradation. Incompatible formats and timestamps cause interoperability issues, demanding standardised protocols. Data pipelines automating flow from collection to cleaning, processing, and analysis can address these.

Data quality is ensured via cleaning (error correction), redundancy reduction (addressing duplication), and augmentation (increasing data volume/diversity). Techniques like annotation, valuation, and selection refine data quality. An SSoT helps ensure stakeholders use the same reliable data. However, processes like large-scale data cleaning remain challenging. Data quantity also matters, especially for modelling seasonal patterns, necessitating long-term data collection, potentially encouraged at the DER level.

Data governance involves policies for data usage, privacy, and security, ensuring regulatory compliance (e.g., GDPR) and protecting sensitive information. Data encryption and integrity mechanisms are vital against cyber threats. Initiatives like European Energy Data Spaces establish frameworks for secure, efficient data sharing adhering to regulations and promoting interoperability. The use of GenAI to create synthetic data is a potential solution to data scarcity but faces regulatory uncertainty regarding its efficacy and usage permissions.

List of recommendations (Data Availability, Quality, Governance):

- **DSOs, TSOs, Policymakers → Synthetic Data:** Promote synthetic data modelling, generation, and sharing. Clarify regulations regarding the efficacy and use of synthetic data.
- **Aggregators, Energy Communities, Policymakers → DER Data:** Encourage data recording and sharing at the DER level across Europe to improve data availability for AI.
- **Policymakers → Standardisation & SSoT:** Consolidate information among standards (e.g., IEC 61850, CIM) across versions, promoting semantic interoperability and exploring SSoT principles or equivalent data harmonisation approaches. Promote standardised consent management tools.

4.2.2 Integration with Legacy Systems and Interoperability

Integrating AI with legacy smart grid systems is challenging due to the heterogeneity of nodes, devices, and systems. Legacy systems often use outdated technologies incompatible with modern AI, complicating real-time data exchange. The long lifecycles of grid assets (decades) further hinder rapid upgrades. Diverse protocols and standards (e.g., IEC CIM, IEC 61850, SAREF extensions like SAREF4GRID, metering standards like IEC 62056, demand response standards like OpenADR/IEC 62746) impede interoperability, as many legacy systems lack necessary interfaces for AI communication. This can lead to vendor lock-in if not managed carefully.

Initiatives like the EU's "BRIDGE" initiative foster information sharing between European energy/digitalisation projects, focusing on data management, communication, and handling. However, a unified data modelling approach remains elusive. Models like SGAM and IEC CIM provide basic frameworks, but comprehensive semantic integration, like that explored in projects H2020-SmartNet (Madina et al., 2019) and H2020-SYNERGY, are needed. The decentralised nature of energy systems requires advanced harmonisation with cross-sectoral standards (e.g., for buildings, mobility).

The European Energy Data Space project (INSIEME) aims to provide access to validate historical and near-real-time data via a decentralised, open-source platform using minimal interoperability mechanisms (MIMs). The proposed flexibility function (MIM 2) is a key data model for connecting markets with grid physics, acting as a fundamental AI tool. Projects like EDDIE also aim to build pan-European energy data spaces using standards like IEC CIM to enhance interoperability.

List of recommendations (Legacy Systems & Interoperability):

- **Standards Assessment:** Draft a document analysing existing interoperability standards (pros/cons) and their position across the energy value chain (appliances, buildings, industries, districts, DSOs, TSOs, etc.).
- **Interoperability Frameworks:** Fund projects studying frameworks for interoperability between different energy vectors.
- **MIM Evaluation:** Study the current MIM standards (e.g., from INSIEME), evaluating their general applicability for data spaces and AI in the short, mid, and long-term.

4.2.3 Ethical, Privacy, and Security Issues

Deploying AI in smart grids requires addressing significant ethical, privacy, and security challenges. Ethical considerations include fairness, accountability, transparency, and privacy, alongside safety and reliability. Fairness is crucial, especially in consumer interactions; for example, RES curtailment decisions must avoid arbitrary disadvantages (Noorman et al., 2023). Energy justice principles (distributional, recognition, procedural) are essential for equitable benefit/burden distribution and inclusive decision-making. Ethical, Legal, and Societal Aspects (ELSA) must align with human agency, technical robustness, safety, and data protection laws (GDPR).

Transparency and explainability (XAI) are critical for making AI decisions comprehensible, fostering trust and accountability. Especially for safety-critical applications (e.g., grid control), operators must trust AI outputs, necessitating robust validation and potentially favouring inherently more interpretable models like physics-informed neural networks. Consumer applications require digital literacy, ensuring no people are left behind. Views on ethical AI vary; an ETIP SNET poll showed mixed opinions on whether ethics hinders competitiveness versus building long-term trust (43% saw trust/advantage, 27% saw slower innovation, 27% stressed balancing with R&D, 3% saw ethics as irrelevant).

Privacy and data security are vital due to sensitive energy data. Robust protection is needed. Privacy-enhancing technologies like homomorphic encryption exist but face scaleability challenges and potential delays (latency) in real-time applications. AI models are vulnerable to adversarial attacks (e.g., data poisoning, evasion attacks) that can impact grid operations. Mitigations include adversarial training, moving target defence (MTD), and hybrid approaches combining data-driven AI with physics-aware constraints. Comprehensive security protocols (end-to-end encryption, zero-trust architecture, PKI) and secure authentication are necessary. Edge AI and federated learning offer scaleable solutions enhancing privacy and reducing latency.

List of recommendations (Ethics, Privacy, Security):

- **Cross-Industry Collaboration:** Promote cross-industry working groups on AI-specific security frameworks for smart grids.
- **Knowledge Sharing & Tools:** Promote knowledge sharing, testing, and validation/qualification tools for the technical robustness and trustworthiness of AI-based applications.

4.2.4 Need for Investment and Skills Development

Deploying AI requires substantial financial investment and human capital development. Key investments include upgrading national/EU infrastructure, enhancing data collection (smart meters, IoT sensors), and implementing robust cybersecurity. Advanced computing resources (including cloud infrastructure) are needed for large data volumes. Continuous funding is essential for developing and maintaining AI solutions. Careful cost-benefit analysis is needed to justify these investments.

Human capital requires skills development in data science, data engineering, software development, cybersecurity, and deep understanding of grid operations/energy systems. AI specialists need proficiency with energy sensor data. Training programmes must cater to both technical AI developers and operational personnel using AI tools (including prompt engineering for GenAI). Bridging the knowledge gap between AI specialists and grid experts is crucial. The energy sector competes with other industries for AI talent, necessitating competitive compensation and career opportunities.

Technologically, deploying AI requires integrating IoT sensors and smart meters capable of high-frequency data collection. Standard smart meters often lack the granularity for specific applications, requiring additional sensors (high/medium/low voltage), which pose challenges (cost, accuracy, space, cybersecurity). Strategic investments are needed to ensure collected data is accurate, secure, and effective. Increased collaboration between research centres/universities (with AI development expertise and HPC access) and industry (with domain knowledge and commercialisation routes) is also vital.

List of recommendations (Investments & Skills):

- **Secure Strategic Funding:** Establish targeted EU/national funding programs for AI infrastructure (HPC/edge/sensors) and ongoing R&D.
- **Develop Human Capital:** Launch coordinated upskilling/reskilling programmes and adapt engineering/CS curricula for AI energy needs.
- **Foster Collaboration:** Promote joint industry-academia projects for relevant R&D, talent development, and accessing shared resources (e.g., HPC).

4.2.5 Adaptable Regulatory Frameworks and Responsible Innovation

AI deployment presents regulatory challenges and opportunities. Smart grids need real-time monitoring and dynamic demand response, but AI in critical infrastructure requires careful regulation. Data privacy (GDPR compliance) is crucial due to sensitive high-resolution data, manageable via privacy-enhancing techniques. Robust cybersecurity (e.g., adhering to NIS2 directive) is essential. Reliability, safety, and robustness are paramount; AI models need rigorous testing to prevent blackouts, supported by multilayered safeguards (redundancy, human-in-the-loop). Explainable AI can foster trust and meet regulatory needs for high-risk systems (as defined by the EU AI Act). The EU AI Act classifies critical infrastructure AI as high-risk, mandating robust risk management, documentation, and human oversight. Liability is complex with multiple stakeholders; thorough documentation, contracts, and specialised insurance can help. Interoperability requires evolving standards (IEC 61850, CIM). Regulatory sandboxes allow safe testing, informing standard refinements. Policymakers should use a risk-based approach, harmonise regulations, promote sandboxes, encourage public-private partnerships, and use iterative standard-setting/certification to ensure AI grids are safe, trustworthy, and innovative without stifling progress.

List of recommendations (Regulation):

- **Provide Regulatory Clarity:** Issue timely, sector-specific guidance on AI Act and GDPR application in energy; clarify liability.
- **Enable Safe Innovation:** Utilise and potentially expand regulatory sandboxes for testing AI solutions.
- **Drive Harmonisation:** Promote alignment of national regulations and support iterative development of EU-wide standards and certifications.

4.2.6 Sustainability and Power Challenges in AI and Data Centres

Integrating AI offers benefits but has significant environmental costs. Data centres, crucial for AI, are major energy consumers (up to 4% of global energy, projected to rise). The IEA estimated a 30% increase in EU data centre electricity demand by 2026, with AI demand growing tenfold. However, efficiency gains in hardware/IT (difficult to track due to transparency issues, Masanet et al., 2020) and smaller, efficient LLMs might mitigate this.

Electricity is a major operational cost for IT companies, stimulating efficiency. However, using non-renewable energy for data centres has detrimental environmental impacts. Hyperscale operators often build centres in high-RES regions (e.g., Northern Europe), but this concentrates demand (e.g., data centres consume nearly a third of Ireland's electricity), requiring close collaboration between data centre and grid operators for reliability. Data centres also offer sector-coupling opportunities (e.g., waste heat for district heating networks).

Improving data centre efficiency is vital. AI optimises advanced cooling techniques and server workload distribution. New AI-driven solutions are needed for grid interactions: deferrable computation tasks can be shifted in space/time to balance the grid; AI model training can be paused or distributed to manage peak demand. This requires automation via AI and increased grid awareness in the data centre industry.

Policy action is essential. Regulatory frameworks should include sustainability assessments, standardised energy reporting (as addressed by recent EU delegated regulations), and RES targets for transparency and accountability. Developing European open-source, energy-efficient LLMs is technically feasible and could mitigate environmental impact and privacy concerns while meeting GDPR requirements.

List of recommendations (Sustainability & Data Centres):

- **Regulatory Frameworks:** Include comprehensive sustainability assessments, standardised energy reporting, and renewable energy targets in regulations for AI developers to understand model impacts.
- **Waste Heat Utilisation:** Address the lack of financial incentives and technical knowledge hindering effective waste heat reuse by smaller/medium data centres (despite EED requirements for larger ones).
- **Hybrid Cooling:** Optimise data centre energy efficiency by implementing hybrid cooling strategies (e.g., free-air/mechanical or air/liquid combinations) based on predefined criteria.
- **Strategic Siting:** Encourage siting new data centres in regions with low-year-round temperatures to reduce cooling energy usage (where feasible).
- **Best Practices:** Promote research and sharing of best practices in small/mid-size data centre management to bridge the gap with hyperscale providers.
- **Grid Integration:** Facilitate data centre integration into grid infrastructure. Develop grid-aware IT management platforms to provide ancillary services.
- **Efficient European LLM:** Develop a European open-source and energy-efficient LLM to minimise AI's impact while meeting GDPR requirements.

4.2.7 Cross-Sector Collaborations

Achieving net-zero targets requires traditionally centralised power grids to open to diverse actors (DERs, demand-side flexibility aggregators like bidirectional EV charging) and coordinate with interdependent infrastructure (gas, transport, etc.). Jointly optimising design and operations across sectors can significantly improve overall system efficiency. Managing modern power grids thus demands coordination between entities with varying technological readiness. Cross-sectoral collaboration and interoperability, including semantic translation and defined interfaces between systems built on different standards, are therefore key challenges for successful AI deployment in smart grids. Sharing best practices and developing common evaluation metrics across sectors can also accelerate progress.

List of recommendations (Cross-Sector Collaboration):

- **Establish Common Ground:** Develop cross-sectoral data standards, interfaces, and semantic translation frameworks.
- **Stimulate Joint Projects:** Fund pilot projects demonstrating cross-sector AI applications and benefits.

- **Facilitate Knowledge Exchange:** Create platforms for sharing best practices and evaluation metrics across energy, transport, buildings, etc.

5 ACTION LIST AND ROADMAP

This chapter proposes a phased roadmap for implementing AI and GenAI solutions in European smart grids. It offers actionable recommendations structured across short-term (0-2 years), medium-term (2-5 years), and long-term (5+ years) phases, focusing on key areas like governance & regulation, data & infrastructure, technology & R&D, collaboration & skills, and standards & interoperability. The roadmap aims to guide stakeholders in fostering responsible and effective AI adoption.

Unlocking the Potential of AI and GenAI in Smart Grids: A Guide for Action

AAI and GenAI are emerging as powerful tools in the transformation of Europe's electricity system. These technologies [see Chapters 3 and 4] offer significant potential to improve forecasting, grid optimisation, asset management, cybersecurity, and system flexibility—supporting the transition to a decarbonised, decentralised, and digitalised energy landscape. GenAI contributes new capabilities by enabling synthetic data generation, assisting complex decision-making, and enhancing human-AI collaboration—opening pathways to greater system intelligence, adaptability, and innovation.

Across Europe, there is growing momentum to adopt AI and GenAI in smart grids. While some Member States have taken early steps towards deployment, and others are in earlier stages of exploration, a common theme has emerged. Access to high-quality data, clear regulatory guidance, and robust digital infrastructure remain essential for progress. Supporting the development and deployment of AI is therefore not only a matter of innovation but also of coordination, investment, and alignment with key European policies and evolving regulations, notably the AI Act [See Chapter 2].

To support practical action, this roadmap presents a flexible "shopping list" of short-, medium-, and long-term action points. Developed through dialogue among grid operators, industry experts, researchers, and policymakers, it reflects the shared priorities and practical insights of Europe's smart grid community. The listed actions are designed to be adaptable across a variety of national contexts and system needs, helping stakeholders take meaningful steps towards responsible, effective AI integration. By focusing on opportunity-driven, high-impact measures, the guide contributes to Europe's broader ambition: to lead in ethical, secure, and forward-looking AI adoption in the energy sector.

Stakeholders may select action points they feel responsible for and in the position to make it a reality.

5.1 Phase 1: Short-Term (0-2 Years) – Build the Foundation

Focus: Rapidly establish the essential groundwork – regulatory clarity, initial data access, pilot projects, foundational skills, and trust mechanisms.

Short-term actions are actions for which significant support has been found. Furthermore, following discussions with the writing teams and workshops with stakeholders, these actions were deemed acceptable, feasible and needed. These actions could possibly be completed within two years, as they do not require extensive negotiation or discussion efforts.

5.1.1 Governance & Regulation:

1. **Establish EU-wide Smart Grid AI Task Force:**

    - **Elaboration:** Create a formal, recognised body bringing together regulators, TSOs, DSOs, AI vendors, researchers, and consumer groups to provide strategic direction, coordinate fragmented efforts, identify emerging issues, and ensure alignment between EU goals and national implementation.
    - **Why:** Avoids duplication of effort, fosters essential collaboration across silos, provides a central point for guidance and monitoring progress in a rapidly evolving field.
    - **Who:** EU Institutions (e.g., EC DG ENER/CNECT - Lead), involving Member States, National Regulators, TSOs/DSOs, Industry (AI Vendors, Utilities), Academia, Consumer Groups.
    - **Activities:** Draft and agree on charter/mandate; secure high-level membership from key stakeholder groups;

establish focused working groups (e.g., on data, standards, ethics); publish initial strategy and work plan; organise regular coordination meetings.

2. **Clarify AI Act & GDPR Interpretation (incl. AI Risk & Liability):**

- Elaboration: Issue practical, sector-specific guidance on interpreting the AI Act's risk categories (especially 'high-risk') for common smart grid applications (e.g., forecasting, demand response, grid control), clarifying liability principles in case of AI failure, defining proportionate compliance pathways for SMEs, and advising on effective GDPR-compliant anonymisation techniques suitable for smart meter and grid operational data. Develop interim guidance mapping the AI Act's risk framework to energy-specific use cases through multi-stakeholder workshops.

- Why: Reduces critical legal uncertainty currently hindering investment, innovation and deployment of AI solutions in the energy sector. Provides a clearer path forward for developers and operators, leading to lower regulatory uncertainty and safer pilot deployment of high-risk AI systems.

- Who: EU Institutions (EC, EDPB – lead for guidance), national regulators, national data protection authorities (DPAs). Input required from TSOs/DSOs, industry, legal experts, standards bodies.

- Activities: Conduct multi-stakeholder workshops to gather input on specific use cases and challenges; draft and publish official guidance documents; establish Q&A mechanisms or helpdesks; monitor interpretation issues arising in practice.

3. **Launch & Enhance Regulatory Sandboxes (incl. AI-Specific Sandboxes):**

- **Elaboration:** Create well-defined, supervised environments where innovative AI solutions (e.g., AI for predictive maintenance, optimising EV charging, local flexibility markets) can be tested in real-world grid conditions with temporary, specific waivers from certain regulations. Ensure simplified access for SMEs and focus on testing integration with legacy systems. Results and learnings must be systematically collected and shared publicly. Create test environments for AI services like demand-response or predictive maintenance, with temporary regulatory waivers.

- **Why:** Allows controlled testing of novel AI applications without the immediate full regulatory burden, accelerates innovation cycles by providing real-world feedback, informs future evidence-based regulation, leading to better-informed regulation.

- **Who:** National regulators (lead for implementation and supervision), EU Institutions (coordination, potential funding frameworks), TSOs/DSOs, AI vendors, SMEs, research institutions (participants).

- **Activities:** Define clear sandbox scope, eligibility criteria, application process, safety protocols, and reporting requirements; issue public calls for participation; select and monitor projects closely; publish aggregated results and policy recommendations documenting learnings on AI risk, ethics, and performance.

4. **Develop Foundational Data Governance (incl. Initial Frameworks & GDPR Alignment):**

- **Elaboration:** Establish initial, clear rules and potentially pilot frameworks regarding data ownership (especially consumer data vs. system data), access rights for different actors (e.g., AI developers, researchers, grid operators) under specific conditions, and accountability protocols for data handling, all explicitly aligned with GDPR and existing energy regulations. Explore practical implementation through pilots of secure data-sharing platforms or "data trust" models. Issue sector-specific operational guidelines on data handling, privacy-by-design, and consumer consent.

- **Why:** Creates the necessary trust, legal clarity, and technical framework for data sharing, which is fundamental for developing, training, and operating effective AI systems in the energy sector. Accelerates pilot deployment, reduces legal friction, increases legal certainty and public trust in AI applications.

- **Who:** EU institutions (Framework setting), national regulators (implementation/oversight), TSOs/DSOs (operationalisation), involving industry, consumer groups, data infrastructure providers. DSOs, TSOs and energy actors gain shared data governance models.

- **Activities:** Conduct stakeholder consultations on data access needs and concerns; draft initial framework documents outlining principles and rules; launch pilot projects for data-sharing platforms or trusts; issue operational guidelines on secure data handling and anonymisation.

5. **Establish Interim Certification & Conformity Assessment:**

- **Elaboration:** Develop preliminary, voluntary "trust labels" or certification schemes specifically for grid-relevant AI solutions, based on existing cybersecurity (e.g., ENISA guidelines) and emerging AI risk management standards (e.g., CEN/CENELEC work, ETSI). This provides an initial signal of quality, security, and potentially ethical alignment before full AI Act standards are finalised.

- **Why:** Builds confidence for grid operators procuring AI solutions in the interim, encourages vendors to adopt good practices early on, provides a stepping-stone towards future mandatory compliance. Boosts trust and competitiveness through compliance transparency.

- **Who:** Standards bodies (e.g., ENISA, CEN/CENELEC, ETSI – lead for developing criteria/schemes), supported by EU institutions, national regulators, industry/vendors (seekers of certification), grid operators (users of certified tools).

- **Activities:** Establish relevant criteria and assessment procedures through expert groups; partner with existing certification bodies or establish new ones; pilot the labelling/certification process with volunteer vendors/products; promote awareness of the scheme. Output includes a pre-deployment certification scheme for grid-relevant AI solutions.

6. **Evaluate Innovation Barriers in Regulation:**

- **Elaboration:** Systematically review existing energy regulations, grid codes, technical standards, and AI-relevant rules (including the proposed AI Act) to identify specific clauses, gaps, or overlaps that create barriers or uncertainty for the development or deployment of AI solutions in smart grids. Conduct structured reviews of AI-relevant rules to identify gaps in risk/performance/compliance requirements.

- **Why:** Proactively identifies specific regulatory roadblocks that need modification or clarification to enable responsible AI innovation, preventing unintended negative consequences of existing rules. Leads to clearer alignment between innovation cycles and evolving regulations (AI Act, CER, etc.).

- **Who:** EU institutions, national regulators (lead), involving TSOs/DSOs, industry, including vendors, Aacademia, legal experts.

- **Activities:** Conduct structured desk reviews of relevant legislation and standards; solicit input from stakeholders on perceived barriers; analyse findings; publish a consolidated report (working list of unclear or conflicting regulatory provisions) identifying key barriers and potential conflicts (e.g., between AI Act and CER).

7. **Mandate Critical Safeguards (Human-in-the-Loop - HITL):**

- **Elaboration:** For AI systems making decisions with potentially significant immediate consequences on grid stability, safety, or security (e.g., automated network reconfiguration, critical load shedding decisions), explicitly require mechanisms for human oversight and intervention ('human-in-the-loop' for direct approval or 'human- on-the-loop' for ability to override).

- **Why:** Ensures safety, maintains human accountability, and builds public/operator trust during the early stages of deploying powerful AI in critical infrastructure functions.

- **Who:** EU institutions (guidance via AI Act interpretation/standards), national regulators (enforcement/incorporation into licences).

- **Activities:** Clearly define the scope of "critical" grid applications requiring HITL/HOTL; incorporate these requirements into interim certifications, regulatory guidance, or licence conditions for grid operators.

5.1.2 Data & Infrastructure:

1. **Develop Common EU Energy Data Spaces:**

- **Elaboration:** Fund and technically support the creation of federated platforms enabling secure, GDPR-compliant access to and sharing of anonymised or aggregated energy data from diverse sources (TSOs, DSOs, market participants, potentially consumers with explicit consent), without requiring data centralisation. Emphasise interoperability standards and robust security protocols.

- **Why:** Breaks down harmful data silos, provides the necessary "fuel" for training and validating AI models, facilitates cross-border analysis and learning, fosters a competitive market for AI services. Improves AI development and scaling by reducing data access barriers.

- **Who:** EU institutions (Funding/Coordination - e.g., via Digital Europe Programme), multi-stakeholder consortia (e.g., involving TSOs, DSOs, industry, research – implementation lead), data infrastructure providers.

- **Activities:** Establish common technical architecture and semantic interoperability standards (e.g., building on IEC CIM); issue funding calls for platform development and pilot implementations; develop clear governance rules for data space participation and usage; actively encourage utility and stakeholder participation. Provides broader access to clean, validated grid datasets across stakeholders.

2. **Generate Synthetic Energy Data:**

- **Elaboration:** Develop and provide access to validate GenAI tools specifically trained to produce realistic, statistically representative, yet artificial, smart grid datasets (e.g., load profiles, generation patterns, network topology variations, fault scenarios). These datasets must preserve the privacy of the original data sources. Develop domain specific GenAI tools while protecting privacy.

- **Why:** Addresses the critical bottleneck of limited access to real-world grid data (due to privacy, security, or commercial sensitivities), enabling broader AI model training, testing, and benchmarking, especially benefiting SMEs and researchers. Accelerates AI innovation by addressing data scarcity.

- **Who:** Research institutions/academia, AI vendors specialising in GenAI (development lead), supported by EU/national funding bodies. SMEs, researchers, DSOs, TSOs, industry (users).

- **Activities:** Fund R&D for energy specific GenAI models; establish frameworks for validating the quality and representativeness of synthetic data; create platforms or mechanisms for accessing these tools or datasets; develop guidelines for responsible use. Provides access to high-quality synthetic grid data without breaching confidentiality.

3. **Invest in Foundational Infrastructure (AI Testbeds & IoT/Edge):**

- **Elaboration:** Provide targeted public funding for: (a) Creating new, or expanding/upgrading existing, physical, and digital laboratories (Testing and Experimentation Facilities – TEFs) that accurately simulate complex, realistic grid conditions for testing AI algorithms (e.g., hardware-in-the-loop simulation), building on existing lab/research infrastructure. (b) Supporting pilot deployments of advanced sensors (especially in medium/low voltage grids) and the associated edge computing hardware/software needed for local data processing and real-time AI execution.

- **Why:** (a) Enables safe, rigorous, and realistic validation of AI algorithms before deployment on the live grid, accelerating solution validation and trusted adoption. (b) Provides the essential high-granularity, real-time data and low-latency processing capabilities required for many advanced AI applications (e.g., local voltage control,

- rapid fault detection), leading to better situational awareness and more robust AI analytics.

- **Who:** Funding bodies (EU/national – lead for funding calls), research institutions, universities (TEF implementation/operation), TSOs/DSOs (IoT/edge pilot implementation, TEF users like EnerTEF), industry vendors (Supplying technology).

- **Activities:** Launch competitive funding calls specifically for energy AI TEFs and sensor/edge deployment pilots; define clear objectives and evaluation criteria for funded projects; promote knowledge sharing between projects; facilitate access to TEFs for third parties (esp. SMEs). Provides safe, high-fidelity simulation environments for AI pilots with stakeholder collaboration and high-granularity data from the field.

5.1.3 Technology & R&D:

1. Develop Open-Source EU AI Model (LLM):

- **Elaboration:** Launch and fund an ambitious EU-backed consortium (involving leading European industry players and research institutions) to build a large language model (and potentially smaller, more efficient variants) specifically trained on high-quality, trustworthy, multilingual European data sources relevant to the energy sector and potentially wider industrial applications. Ensure the model and its training methodologies are openly available under appropriate licences. Set up an EU consortium to develop a multilingual, high-performing, open-source LLM trained on trustworthy and legally obtained data.

- **Why:** Promotes EU technological sovereignty in a critical AI domain, provides a reliable and potentially more context-aware foundation model for various energy applications (e.g., documentation analysis, operator decision support, synthetic data generation), enables SME innovation without dependence on potentially less transparent non-EU models. Supports EU sovereignty and enables innovation across startups and SMEs.

- **Who:** EU-backed consortium (industry, academia – implementation lead), strongly supported and potentially co-funded by EU institutions (e.g., via Horizon Europe, Digital Europe).

- **Activities:** Form the consortium and establish governance; secure significant funding and compute resources; identify and legally secure high-quality, diverse training data; design, train, and rigorously evaluate the model; establish mechanisms for release, maintenance, and community contribution. Delivers an accessible, trustworthy European LLM in multiple parameter sizes.

2. Fund Priority AI Applications & Infrastructure:

- **Elaboration:** Direct initial public R&D funding (e.g., through specific calls within Horizon Europe, Digital Europe, or national programmes) towards developing and piloting high-impact, near-term AI use cases with clear operational benefits or addressing urgent needs. Examples include real-time grid stability monitoring/prediction, predictive maintenance for critical assets (transformers, cables), AI-powered cybersecurity intrusion detection systems (AI-IDS), and the necessary supporting edge computing infrastructure for these applications.

- **Why:** Kick-starts development in areas with demonstrable value, addresses pressing challenges like cybersecurity and asset management, builds momentum and shows the potential of AI in the energy sector.

- **Who:** Funding bodies (EU – Horizon Europe, Digital Europe; national R&D agencies – Lead for calls), research institutions, industry (utilities, vendors – project implementers).

- **Activities:** Establish priority areas through stakeholder consultation; launch targeted funding calls with clear objectives; select and fund high-potential R&D and pilot projects; monitor progress and facilitate dissemination of results.

3. Pilot Explainable AI (XAI):

- **Elaboration:** Specifically fund and actively encourage pilot projects that not only deploy AI for grid applications but also implement and rigorously test explainable AI (XAI) techniques. For example, an AI predicting a fault or recommending a control action should provide operators with understandable insights into the key factors driving its conclusion.

- **Why:** Crucial for building essential trust and acceptance among grid operators, enabling effective debugging and validation of AI models, meeting potential future regulatory requirements for transparency, and facilitating safer human-AI collaboration.

- **Who:** Funding bodies (lead for targeted funding/incentives), research institutions (developing XAI techniques), AI vendors, TSOs/DSOs (implementing and evaluating XAI in pilots).

- **Activities:** Include XAI requirements or evaluation criteria in relevant funding calls; fund specific research on effective XAI methods for grid applications; support pilot projects demonstrating practical XAI implementation; develop and share best practices for using XAI in energy operations.

4. Initiate Foundational Cybersecurity Measures (Zero Trust):

- **Elaboration:** Begin the strategic process of designing and adopting eero trust architecture (ZTA) principles for operational technology (OT) and IT networks within the energy sector, particularly where AI systems will be deployed or integrated. ZTA shifts from perimeter-based security to a model where trust is never assumed, and verification is required from everyone, and everything by trying to connect or access resources.

- **Why:** Essential for significantly enhancing the security posture of increasingly interconnected and AI-dependent energy grids against sophisticated cyber threats, including those potentially targeting AI systems themselves.

- **Who:** TSOs/DSOs (implementation lead within their networks), supported by national cybersecurity agencies (e.g., ENISA providing guidance/frameworks), industry vendors (providing ZTA-compatible technology).

- **Activities:** Develop energy-sector specific zero trust strategy and roadmaps; conduct security assessments based on ZTA principles; initiate pilot implementations in limited network segments; train staff on ZTA concepts and practices.

5.1.4 Collaboration & Skills:

1. Form Initial Consortia & Networks (incl. Open-Source AI Collaboration):

- **Elaboration:** Provide seed funding, matchmaking platforms, and logistical support to encourage the formation of new collaborative partnerships, especially cross-sector ones (e.g., DSOs + telecoms + AI startups for developing 5G-enabled edge AI solutions). Also, support the creation or strengthening of networks dedicated to open- source AI tool development, data sharing, and best practice dissemination for the energy sector. Fund networks and platforms for sharing code, data, and practices, building on existing initiatives.

- **Why:** Pools diverse expertise needed for complex AI solutions, shares development costs and risks, accelerates innovation through shared learning and avoids redundant efforts, fosters a more vibrant ecosystem. Increases collaboration and startup participation in AI tool development.

- **Who:** EU/national funding bodies (providing funding/facilitation), industry associations (matchmaking), industry (utilities, vendors, telecoms), TSOs/DSOs, academia (participants/leaders of specific consortia/networks).

- **Activities:** Launch funding calls specifically requiring multi-stakeholder collaboration; host workshops and networking events; provide platforms for open-source communities; support standardisation efforts within networks. Makes lower-cost, reusable tools and models available across the EU energy sector.

2. **Launch Visible Open Innovation Programmes:**

- **Elaboration:** Organise high-profile, well-publicised EU-level or national events like "AI for Energy" hackathons, challenges with substantial prizes for innovative solutions, and targeted calls for pilot projects explicitly open to diverse participants (startups, researchers, individual innovators, utilities). Use branded EU-level hackathons, prizes, and project calls to attract early-stage multi-stakeholder pilots.

- **Why:** Attracts new talent, fresh perspectives, and innovative ideas to the energy sector's AI challenges; provides high visibility for AI applications in energy; allows for rapid exploration and validation of novel concepts. Strengthens project pipelines and early validation of scalable solutions.

- **Who:** EU institutions, national innovation agencies (organisers/funders), supported by industry sponsors. Startups, researchers, TSOs/DSOs, students, developers (participants).

- **Activities:** Plan and execute hackathons/challenges with relevant problem statements; secure sponsorship/prizes; manage submission and judging processes; provide support/mentorship during events; facilitate follow-up on promising ideas (e.g., pilot funding). Leads to higher participation and visibility of AI use cases.

3. **Initiate AI Upskilling & Literacy (incl. Micro-Credentials):**

- **Elaboration:** Develop and start rolling out foundational AI training modules (covering AI concepts, data basics, ethical considerations), alongside essential cybersecurity awareness and data analytics skills, specifically tailored for the needs and context of the existing energy sector workforce (operators, engineers, technicians, managers). Launch initial micro-credential programmes for specific, in-demand skills. Establish partnerships with universities to pilot revised engineering and IT curricula incorporating AI. Fund initial "Centres of Excellence" dedicated to pooling AI training resources and expertise for the energy sector. Fund short AI bootcamps and modular learning programmes tailored to energy sector needs.

- **Why:** Addresses the critical skills gap, enabling the current workforce to effectively operate, manage, trust, and collaborate with new AI systems, which is essential for successful adoption. Enables faster adoption and more effective use of AI tools across the grid workforce.

- **Who:** Education ministries/agencies, universities, vocational training providers, industry associations, TSOs/DSOs (lead partners for content development and delivery), supported by EU/national funding. Energy sector workforce (target audience/participants).

- **Activities:** Conduct skills needs analysis; develop tailored curricula and training materials; deliver pilot training sessions (online/offline); establish micro-credential frameworks; fund initial CoE pilots; initiate university curriculum reviews. Equips the workforce with baseline AI, cybersecurity, and data analytics skills.

4. **Support SMEs & Startups:**

- **Elaboration:** Implement targeted programmes offering direct financial support (grants, subsidies) or vouchers to SMEs and startups developing or adopting AI solutions specifically for energy applications. This support could include subsidising access to essential but potentially costly resources like HPC time, high-quality datasets (potentially curated synthetic data), specialised AI software tools, or expert consultancy.

- **Why:** Fosters a diverse and dynamic innovation ecosystem, lowers entry barriers for smaller players, prevents market domination by large incumbents, potentially leading to more specialised and novel AI solutions.

- **Who:** EU/national funding bodies, economic development agencies, innovation hubs (programme design and administration Lead). SMEs/startups in the AI/energy space (beneficiaries).

- **Activities:** Design and launch specific grant/subsidy/voucher schemes with clear eligibility criteria and simple application processes; establish partnerships to provide subsidised access to resources; promote awareness of these support programmes.

5.1.5 Standards

1. **Develop AI Maturity Framework:**

- **Elaboration:** Create a structured classification system, analogous to TRLs, but tailored for assessing the maturity of AI applications within the energy sector. This framework should evaluate dimensions beyond just technical feasibility, including data readiness, model robustness/validation, regulatory compliance status, organisational preparedness for deployment, and potentially societal acceptance or ethical review status. Develop a TRL-like maturity classification system that also considers legal, societal, and organisational readiness.

- **Why:** Provides a common language and standardised methodology for assessing the progress and deployment readiness of AI applications, helps target funding, procurement, and regulatory efforts more effectively based on demonstrated maturity, facilitates benchmarking. Allows better targeting of funding, procurement, and regulatory focus.

- **Who:** Standards bodies (e.g., CEN/CENELEC, potentially IEEE/IEC task forces), industry associations (e.g., Eurelectric, E.DSO, ENTSO-E, DSO Entity), research institutions (development lead through expert consultation), EU institutions (promotion and potential adoption).

- **Activities:** Form expert working group; define maturity levels and specific criteria for each dimension; conduct pilot assessments using the framework; consult stakeholders for feedback; publish and promote the framework. Provides guidelines for assessing GenAI maturity across different energy applications.

5.1.6 Short-Term Conclusion:

In essence, the short-term agenda is about **building the runway** for AI in electricity systems. Key technologies like open-source AI models, synthetic data generation, and initial pilot projects drive **implementation readiness**. Simultaneously, establishing data spaces, governance frameworks, standards compliance, and training programmes ensures the electricity sector is **prepared** legally, technically, and organisationally – to integrate these innovations. Stakeholders should collaborate closely on these items, sharing early successes (and lessons from failures) to maintain momentum. By the end of this phase, Europe should have multiple proven AI prototypes in smart grid operations, a more data-sharing-friendly culture, and initial regulatory clarity, all of which lay the foundation for scaling up in the medium term.

5.2 Phase 2: Medium-Term (2-5 Years) – Scale & Harmonise

Focus: Move from pilots to broader deployment, harmonise standards and regulations across the EU, strengthen infrastructure and collaboration.

Medium-term actions are potential high impact initiatives that cannot be done without carefully consulting industry and policy stakeholders. Actions are defined as the medium term if we found consensus on a result that should be achieved but no shared view among stakeholders on how to deliver the desired outcome. Medium-term actions are planned to deliver results in 2-5 years from now. Medium-term actions require action in the form of exploration, discussion or consultations on the short-term. With this list we invite stakeholders to proactively start such explorations.

5.2.1 Governance & Regulation:

1. **Implement EU-wide AI Certification & Compliance Labelling:**

- **Elaboration:** Finalise and roll out harmonised technical standards (building on work by CEN/CENELEC, ETSI etc.) and mandatory conformity assessment procedures across all Member States for high-risk AI applications used in the energy sector, as foreseen by the AI Act. Establish a clear "AI compliance label" indicating adherence. Ensure these procedures incorporate security, ethical requirements, and potentially energy efficiency aspects.

- **Why:** Creates a predictable single market for trusted AI solutions in energy, ensures consistent levels of safety and ethical practice across the EU, simplifies compliance for vendors selling across borders, builds operator and public confidence.

- **Who:** EU institutions (EC – lead for implementing acts/standards references, coordination), standards bodies (finalising harmonised standards), notified bodies/accredited certification authorities (performing assessments), national market surveillance authorities (enforcement), industry (vendors ensuring compliance), TSOs/DSOs (procuring certified systems).

- **Activities:** Finalise and officially adopt relevant harmonised standards in the Official Journal; designate and oversee notified bodies; establish clear procedures for conformity assessment, technical documentation, and labelling; set up robust market surveillance mechanisms; ensure alignment with finalised AI Act provisions and implementing acts.

2. **Establish Clear Liability Frameworks:**

- **Elaboration:** Establish legally binding rules, potentially through revisions of existing liability directives or new legislation, clarifying how liability is allocated among AI developers, data providers, grid operators, and potentially consumers in the event of damages or failures caused by AI systems in the grid. Outline principles for shared responsibility across the AI value chain.

- **Why:** Provides essential legal certainty, reducing a major barrier for the deployment of higher-risk or more autonomous AI applications by clarifying who is responsible when things go wrong. Facilitates insurance coverage.

- **Who:** EU institutions (legislative lead – EC proposing, Parliament/Council adopting), Member States (implementation/transposition), judiciary (interpretation through case law), industry (vendors, operators), insurers (adapting products).

- **Activities:** Conduct impact assessments and stakeholder consultations; draft and negotiate legislative proposals (e.g., AI Liability Directive revisions); adopt and transpose legislation; develop supporting guidance; monitor court decisions.

3. **Refine Data Governance & Consent (incl. Common Consent Tools):**

- **Elaboration:** Based on pilot outcomes and evolving needs, potentially introduce targeted mandates for sharing specific categories of anonymised/aggregated grid data via standardised APIs (formalising the "EU Grid Data Space" concept). Implement and promote the use of robust, user-friendly, standardised common consent management tools for accessing consumer energy data where required, ensuring GDPR compliance and effective consumer control. Launch GDPR-aligned frameworks to manage user consent for energy data use. Establish or empower regulated "data trusts" or intermediaries if pilots prove successful.

- **Why:** Ensures sufficient data liquidity needed for developing and operating advanced AI applications, enhances consumer control and trust through clear consent mechanisms, potentially creates regulated pathways for secure data sharing. Creates greater public trust and legal clarity for data-driven AI services.

- **Who:** EU institutions/national regulators (lead for potential mandates/revisions, promoting tools), TSOs/DSOs/aggregators/market participants (implementing APIs/using consent tools), technology providers (developing tools), consumer groups (advocacy/input), data intermediaries/trusts (potential operators).

- **Activities:** Evaluate results from data space/trust pilots; potentially propose legislative updates regarding data access/sharing; fund/promote development and adoption of standardised consent management tools; establish clear rules and oversight for data intermediaries if used. Results in standardised consumer data access mechanisms used EU-wide.

4. **Update Grid Codes & Procedures:**

- **Elaboration:** Formally review and begin incorporating AI-driven operations into relevant national and European network codes, operational guidelines, and standard market procedures. This includes defining roles, responsibilities, data exchange requirements, and performance expectations for AI systems involved in functions like forecasting, ancillary service provision, congestion management, or automated demand response participation.

- **Why:** Embeds AI functionality into the formal operational and market framework of the energy system, moving it from pilot stage to standard practice, ensuring system integrity and fair market participation.

- **Who:** Grid code committees (national/European - e.g., ENTSO-E, DSO Entity – Lead for drafting revisions), national regulators (approval/implementation), TSOs/DSOs, market operators (implementing updated procedures), AI solution providers (providing input).

- **Activities:** Identify grid codes/procedures impacted by AI deployment; establish working groups within relevant committees (e.g., ENTSO-E, DSO Entity); draft, consult on, and finalise revisions; implement updated procedures and IT systems.

5.2.2 Data & Infrastructure

1. **Establish Unified EU Digital Marketplaces & Data Spaces:**

- **Elaboration:** Scale up successful initial data space pilots into robust, interconnected, potentially EU-wide digital platforms or marketplaces. These platforms should provide standardised, secure access to a wider range of energy data (real time, historical, geographical, cross-border) for AI development, operational use, and potentially new service creation, building on common standards and governance. Support development of secure cross-border platforms for standardised energy data.

- **Why:** Creates a vibrant, accessible data ecosystem facilitating advanced AI development, pan-European grid optimisation, enhanced situational awareness, and potentially new data-driven business models, accelerating innovation and democratisation of data access. Leads to accelerated development, interoperability, and democratised data access.

- **Who:** EU institutions (funding/coordination/potential governance framework), multi-stakeholder consortia or designated entities (implementation/operation lead), TSOs, DSOs, market operators, data providers, industry/research (users).

- **Activities:** Secure long-term funding and sustainable business models; define and implement robust interoperability standards and APIs; establish strong governance structures and access rules; onboard more data providers and users; ensure scaleability and cybersecurity. Results in digital infrastructure facilitating real-time and historical data exchange.

2. **Scale Data Infrastructure & Federated Learning:**

- **Elaboration:** Significantly invest in pan-European data sharing infrastructure (building on Data Spaces). Deploy robust, scalable, and user-friendly federated learning frameworks and platforms, enabling AI models to be trained across multiple distributed datasets (e.g., held by different utilities) without centralising sensitive raw data.

- **Why:** Enables the development of powerful, accurate AI models trained on diverse European datasets while preserving data privacy and security, overcoming major barriers to accessing sensitive operational or customer data.

- **Who:** EU/national funding bodies (investment lead), technology providers (cloud services, AI platforms), research institutions (developing FL techniques), TSOs/DSOs/industry (data holders/participants in FL).

- **Activities:** Major infrastructure investment programmes; fund development and deployment of production-ready federated learning platforms; create standardised protocols for FL; incentivise participation by data holders; address challenges like communication overhead and statistical heterogeneity.

3. **Expand HPC & Edge Computing:**

- **Elaboration:** Provide broader and easier access to High-Performance Computing (HPC) resources (e.g., via EuroHPC) for energy sector stakeholders needing to train complex AI models (like large foundation models). Simultaneously, significantly expand the deployment of edge computing infrastructure (potentially leveraging 5G/6G networks) across distribution grids to support real-time AI applications requiring low latency. Implement hybrid architectures balancing central and edge processing.

- **Why:** Provides the necessary computational power at the right location – massive power in HPC centres for training complex models, and distributed, low-latency power at the edge for real-time control and analytics – enabling a wider range of sophisticated AI applications.

- **Who:** EU/national funding bodies/infrastructure providers (HPC access, edge funding), TSOs/DSOs (edge deployment lead), telecom operators (network infrastructure), industry vendors (edge hardware/software), research community/AI developers (users).

- **Activities:** Facilitate easier access schemes to HPC for energy sector; fund large-scale edge computing deployment programmes linked to grid modernisation; develop standardised edge platforms; research optimal hybrid computing architectures.

5.2.3 Technology & R&D:

1. **Deploy Interoperable AI Systems:**

- **Elaboration:** Move successful, validated AI pilot projects (e.g., in predictive maintenance, demand response optimisation, renewables forecasting and integration, voltage control) into full-scale operational deployment within TSO and DSO control centres and processes. Critically, ensure these deployed systems adhere to agreed interoperability standards (like IEC CIM for data exchange) and open interfaces where appropriate.

- **Why:** Realises the tangible operational benefits (efficiency, reliability, cost savings) of proven AI applications across the wider energy system, moving beyond isolated trials. Interoperability ensures integration and avoids vendor lock-in.

- **Who:** TSOs/DSOs (deployment lead, operational integration), AI Vendors/System Integrators (Supplying and customising solutions), Standards Bodies (Providing standards), Regulators (Potentially encouraging/mandating interoperability).

- **Activities:** Develop scaling and rollout plans for successful pilots; procure and integrate AI systems into operational workflows; ensure staff training; enforce use of interoperability standards in procurement; monitor performance and benefits.

2. **Operationalise AI Agents with Human-in-the-Loop:**

- **Elaboration:** Deploy AI-powered agents or assistants designed to work collaboratively with human grid operators in control centres. Scale pilot AI agents with operator supervision for grid control decision-making. These agents could monitor complex situations, identify potential issues, suggest optimal control actions, or automate routine tasks, always ensuring clear interfaces and maintaining appropriate levels of human oversight and final decision-making authority (Human-in-the-Loop or Human- on-the-Loop).

- **Why:** Enhances operator capabilities, improves situational awareness in increasingly complex grids, speeds up response times, reduces operator workload, while maintaining safety and accountability through human oversight. Leads to enhanced situational awareness, operational speed, and trust in AI-supported control.

- **Who:** TSOs/DSOs (deployment/operation lead), AI vendors (developing agent systems), research institutions (human-AI interaction design, cognitive systems engineering).

- **Activities:** Develop and refine AI agent functionalities based on operational needs; design intuitive human-AI interfaces; rigorously test agent performance and reliability; train operators on how to interact effectively with agents; establish clear protocols for interaction and oversight. Output includes live AI support systems improving grid operations while preserving human authority.

3. **Develop AI-Driven Tools:**

- **Elaboration:** Scale the development and deployment of a wider range of specialised AI tools addressing key challenges of the energy transition. Examples include sophisticated aggregation platforms for diverse flexibility resources (demand response, batteries, EVs), advanced algorithms for minimising renewable energy curtailment, optimised management systems for large-scale EV charging infrastructure, and AI for enhanced short-term forecasting.

- **Why:** Provides essential tools needed to manage the increasing complexity, variability, and decentralisation of the future energy system with high shares of renewables and flexible loads.

- **Who:** AI vendors, research institutions (development lead), funding bodies (support r&d and commercialisation), TSOs/DSOs/aggregators/charging point operators (users, providing requirements).

- **Activities:** Continued R&D funding focused on specific energy transition challenges; support for commercialisation and market uptake; development of benchmarks for tool performance; integration with market platforms and grid operations.

4. **Develop Sector-Specific LLMs:**

- **Elaboration:** Collaboratively build and deploy Large Language Models (LLMs) or other foundation models specifically trained on high-quality, curated, shared energy sector data (e.g., technical documentation, standards, operational logs, research papers, market reports). These models could power applications like advanced scenario planning tools, intelligent search for technical information, automated reporting, or sophisticated chatbot support for operators or even customers.

- **Why:** Provides powerful, contextually aware AI tools tailored to the specific language, knowledge, and challenges of the energy sector, potentially offering higher accuracy and reliability than generic models for specialised tasks.

- **Who:** Collaborative consortia (involving DSOs, TSOs, vendors, research institutions – lead), supported by eu/national funding, potentially building on the foundational EU LLM (action 3.1 phase 1).

- **Activities:** Establish data pooling initiatives with clear governance; secure high-quality, diverse energy-specific data; collaboratively fine-tune or train models; develop specific applications leveraging these models; establish validation protocols.

5. **Promote Energy-Efficient AI:**

- **Elaboration:** Implement policies, standards, and incentives actively promoting the development and deployment of AI algorithms and hardware solutions with lower computational and energy footprints ("Green AI"). Introduce stricter energy efficiency requirements or best practices for data centres supporting grid operations and AI workloads.

- **Why:** Mitigates the potential negative environmental impact of widespread AI deployment in the energy sector itself, aligning AI adoption with overall sustainability goals (EU Green Deal), potentially reducing operational costs.

- **Who:** EU institutions/national regulators (policy/standards lead), standards bodies, AI developers/hardware manufacturers (implementing efficient designs), research institutions (developing efficient techniques), data centre operators.

- **Activities:** Define metrics and methodologies for measuring AI energy consumption; introduce energy efficiency standards or labels for AI systems/services; provide R&D funding or incentives for Green AI research; promote best practices in model optimisation and hardware selection.

6. **Foster Sovereign Capabilities:**

- **Elaboration:** Strategically invest public funds (e.g., through IPCEI - Important Projects of Common European Interest, or other dedicated programmes) in developing key EU- based AI platforms, critical components (e.g., specialised chipsets optimised for grid AI), or foundational models (like a hypothetical "GridFM" – a grid foundation model) to reduce over-reliance on non-EU technology in this critical infrastructure sector, while integrating global best practices.

- **Why:** Enhances Europe's strategic autonomy, economic competitiveness, and security of supply in critical AI technologies needed for the future energy system.

- **Who:** EU institutions/member states (strategic funding/policy lead), consortia of EU AI companies, hardware manufacturers, research institutions (development/implementation).

- **Activities:** Identify critical AI technology areas for energy sovereignty; launch targeted strategic funding initiatives (e.g., IPCEI); support the growth of European AI champions in the energy sector; foster partnerships while ensuring EU control over key elements.

5.2.4 Collaboration & Skills:

1. **Scale Collaborative Ecosystems (incl. Cross-Sector Clusters):**

- **Elaboration:** Establish a dedicated, well-funded EU "AI in Energy" funding umbrella or programme to streamline support and create critical mass. Scale up funding for successful collaborative R&D hubs and Centres of Excellence, making them permanent fixtures in the European innovation landscape. Formally establish and incentivise AI Innovation Clusters linking Energy with related sectors like Mobility and Buildings (combining DSOs, automotive, ICT, building automation stakeholders), promoting cross-sector data sharing (e.g., Energy Data Spaces) and solution development.

- **Why:** Creates a sustainable, large scale, interconnected European ecosystem dedicated to AI in energy innovation, fostering collaboration, pooling resources, accelerating knowledge transfer, and enhancing competitiveness. Enables broader systemic innovation through cross-sector synergies.

- **Who:** EU institutions (funding umbrella/coordination lead), national agencies, industry associations, universities, research centres, TSOs/DSOs, SMEs, related sector players (participants/hub/cluster leaders).

- **Activities:** Establish the single funding umbrella structure; provide long-term core funding for successful hubs/CoEs/clusters; develop governance models for clusters; implement incentives for cross-sector data sharing within data spaces; actively promote networking and joint projects. Develop use-case specific AI solutions tested across connected infrastructures.

2. **Establish Co-Funded AI Deployment Programmes:**

- **Elaboration:** Create specific funding programmes that blend public funds (e.g., from EU programmes like InvestEU, CEF, Horizon Europe or national sources) with private investment (venture capital, corporate funds, loans) to help scale up successful, validated AI pilot projects into wider commercial deployment across the energy sector. These programmes aim to share the financial risk associated with first large-scale deployments.

- **Why:** Bridges the critical "valley of death" between successful R&D/piloting and full market adoption by de-risking investment in scaling up innovative AI solutions, accelerating their market entry and impact. Leads to shared risk and expanded implementation across member states.

- **Who:** EU/national public funding bodies (e.g., EIB, national promotional banks), private investors (VCs, corporate VCs, banks) (funding partners), ai companies/utilities/TSOs/DSOs (project implementers seeking co-funding).

- **Activities:** Design effective co-funding mechanisms and eligibility criteria; actively engage with private investors to attract co-investment; manage the application and funding allocation process; monitor the success of deployed solutions. Creates robust innovation pipelines and procurement structures for trusted AI tools.

3. **Formalise Public-Private Research Partnerships:**

- **Elaboration:** Establish more structured and systematic frameworks for embedding academic researchers and PhD students within industry-led AI demonstration projects and operational environments. Embed academic research in demonstration projects with industry funding support. This should be supported by joint funding mechanisms and clear agreements on IP, publication rights, and research objectives.

- **Why:** Strengthens the crucial link between cutting-edge academic research and real-world industry application, ensures research remains relevant to operational needs, accelerates the validation and transfer of innovative AI techniques into practice. Leads to faster validation and market maturity for AI innovations.

- **Who:** Universities/research institutions, industry (utilities, TSOs, DSOs, vendors) (implementing partners), funding bodies (providing joint funding mechanisms).

- **Activities:** Create template agreements for joint research projects; establish dedicated funding schemes for industry-academia collaboration; facilitate researcher mobility between sectors; promote joint publications and dissemination. Delivers research insights applied to real-world use cases and scaled deployments.

4. **Expand Workforce Development (Structured Programmes):**

- **Elaboration:** Introduce mandatory AI training modules or certifications for specific grid operator roles where AI interaction is significant. Establish joint Master's degree programmes ("AI in Energy") co-designed and co-delivered by universities and industry partners. Partner with universities and technical institutes to design cross-disciplinary degrees. Fully integrate relevant AI concepts, data science, and cybersecurity skills into traditional electrical engineering, power systems, and computer science curricula at bachelor's and master's levels. Launch structured university/industry certification tracks for specialised AI skills.

- **Why:** Builds a pipeline of skilled professionals and upskills the existing workforce at scale, ensuring Europe has the human capital needed to develop, deploy, manage, and innovate with AI across the entire energy sector. Creates a skilled, mobile workforce with energy-AI specialisation.

- **Who:** Universities, vocational training providers, education ministries (curriculum/programme lead), TSOs/DSOs/industry (providing input, co-design, internships, demand signals), certification bodies, technical institutes.

- **Activities:** Conduct detailed workforce needs analysis for future AI roles; develop and update curricula/modules; launch joint degree programmes (aligned with IEC/IEEE standards) and certification tracks; invest in teacher/trainer training; promote lifelong learning opportunities. Delivers AI-for-energy MSc and certificate programmes.

5. **Build Consumer Trust & Engagement (incl. Regional Campaigns):**

- **Elaboration:** Launch broad, sustained public awareness and communication campaigns explaining the role, benefits, and safeguards associated with AI in the energy transition. Implement transparent communication protocols for utilities regarding their use of AI affecting customers. Run regional consumer education workshops focusing on AI literacy, data privacy, fairness, and equity implications. Promote understanding and equity in AI access through government-supported outreach. Potentially pilot and evaluate "consumer trust rating" dashboards or labels for AI-driven energy services.

- **Why:** Essential for gaining and maintaining public acceptance and trust for potentially disruptive AI-driven changes in the energy system, empowers consumers to participate actively and make informed choices, addresses concerns about privacy and fairness proactively. Increases participation and reduces the digital divide.

- **Who:** TSOs/DSOs (lead for direct communication), consumer associations, regulators, public communication agencies, educational bodies (campaign/education partners).

- **Activities:** Develop clear communication materials; run multi-channel campaigns; organise workshops and public dialogues; establish transparent reporting on AI use; pilot and evaluate trust rating mechanisms; create accessible channels for consumer feedback and redress. Leads to higher awareness of AI-based services, especially in underserved regions.

5.2.5 Standards & Interoperability:

1. Deploy Minimal Interoperability (MIM) Standards:

- **Elaboration:** Implement and promote the adoption of agreed-upon baseline interoperability standards and architectural principles (Minimal Interoperability Mechanisms - MIM) for key AI applications and data exchanges within the energy system. Implement and refine MIM test protocols and adoption plans. This ensures basic "plug-and-play" capability between different systems and vendors.

- **Why:** Facilitates a more competitive market for AI solutions, simplifies integration efforts for utilities, reduces the risk of vendor lock-in, enables easier data sharing and system-wide optimisation. Streamlines integration and leads to less vendor lock-in.

- **Who:** Standards bodies (finalisation/maintenance), TSOs/DSOs/vendors (adoption/implementation), industry associations (promotion), regulators (potential encouragement or mandating in procurement).

- **Activities:** Finalise and publish MIM standards/profiles; develop conformance testing tools and processes; actively promote adoption through industry channels; potentially reference MIM in public procurement requirements. Provides a functional plug-and-play architecture for energy system AI applications.

2. Strengthen Cybersecurity (incl. Grid-Specific NIS2/AI Act Implementation):

- **Elaboration:** Widely deploy mature Zero Trust Architectures across relevant OT and IT network segments in the energy sector. Implement advanced security techniques like adversarial training (making AI models robust against malicious inputs designed to fool them) as a standard practice for critical AI systems. Actively manage and mitigate cybersecurity risks originating from the AI supply chain (e.g., vulnerabilities in third-party AI libraries, data poisoning risks). Adopt and localise the AI Act and NIS2 directive in energy system use cases with clear compliance models.

- **Why:** Significantly hardens AI systems and the surrounding grid infrastructure against increasingly sophisticated and potentially AI-driven cyber threats, ensuring the resilience and reliability of critical energy services. Lowers compliance cost and provides greater clarity for innovators and regulators.

- **Who:** TSOs/DSOs (implementation lead), cybersecurity agencies (guidance/standards/threat intelligence), AI vendors (developing secure/robust models), research institutions (developing defence techniques), regulators.

- **Activities:** Implement comprehensive ZTA across networks; mandate adversarial testing and robustness evaluations for critical AI; develop and enforce supply chain security requirements for AI components; conduct regular security audits and penetration testing. Leads to harmonised EU-wide regulations tailored for grid operations.

5.3 Phase 3: Long-Term (5+ Years) – Achieve Full Integration & Optimisation

Focus: Realise the full potential of AI for a highly optimised, resilient, and sustainable energy system, establish EU leadership, and ensure continuous adaptation.

Long-term action points require developments such as the result of medium-term actions or technological progress. Actions are defined as long-term actions if we find the current state of organisation, ICT infrastructure or AI technology is not at the level that is required for this action and we are not aware of planned developments to that state in next years. Long-term actions are expected to take place in 5-10 years from now. With the long-term action list the authors of this document intend to inspire stakeholders to take into account these actions in their long-term strategy and vision development and actively monitor the relevant developments.

5.3.1 Governance & Regulation:

1. Mature Governance Frameworks (incl. Periodic Legislative Reviews):

- **Elaboration:** Transition from initial regulatory sandboxes and interim measures to permanent, yet adaptive and future-proof, governance frameworks specifically designed for AI in the energy sector. Implement mechanisms for periodic legislative reviews (e.g., every 3-5 years) to ensure regulations keep pace with rapid technological advancements, operational experience, and evolving ethical considerations. Mandate formal updates of the AI Act and energy regulations every 3-5 years.

- **Why:** Ensures long-term regulatory stability while retaining the flexibility needed to adapt to unforeseen challenges and opportunities presented by advanced AI, avoiding outdated rules that stifle innovation or fail to address new risks. Provides long-term adaptability, innovation alignment, and minimised legal uncertainty.

- **Who:** EU institutions (ec, parliament, council), national legislators/regulators (lead for review, adaptation, implementation).

- **Activities:** Establish permanent governance structures replacing temporary ones; implement regular, systematic review cycles for AI-related energy legislation; continuously monitor technological and market developments; adapt regulations based on evidence and foresight analysis. Creates dynamic regulatory frameworks that evolve with AI capabilities.

2. Institutionalise Data Governance:

- **Elaboration:** Create permanent, independent, and expert EU-level or national bodies specifically tasked with overseeing energy data sharing practices and the ethical use of AI in the sector. These bodies would have mandates for ensuring compliance, conducting audits, resolving disputes, and potentially managing critical data infrastructure or standards. Establish permanent, independent governance bodies for energy data and AI oversight.

- **Why:** Provides sustained, specialised, and impartial oversight for the increasingly complex and sensitive area of energy data and AI, ensuring long-term trust, fairness, and compliance beyond initial implementation phases. Ensures sustained trust, accountability, and responsible data use in AI-enabled energy systems.

- **Who:** EU institutions / Member States (establishing bodies and defining mandates), independent governance bodies (operational execution).

- **Activities:** Legislate to establish independent bodies; define their powers, responsibilities, and funding; appoint expert members; establish operational procedures for monitoring, auditing, and dispute resolution. Creates structured EU- wide oversight with transparent audits and ethical frameworks.

3. **Implement Full Accountability:**

   - **Elaboration:** Deploy comprehensive legal and technical frameworks that ensure clear and effective accountability for actions and decisions taken by AI systems, especially highly autonomous ones operating in critical grid functions. This includes robust audit trails, mechanisms for redress when harm occurs, and potentially establishing industry-wide accountability structures or insurance pools.

   - **Why:** Essential for maintaining trust, ensuring safety, and enabling the deployment of highly autonomous AI systems by providing clarity on responsibility and recourse when failures or unintended consequences arise.

   - **Who:** EU institutions/national legislators (lead for refining legal frameworks), judiciary (setting precedents), industry (implementing technical measures, potential self-regulation), insurers (developing relevant products).

   - **Activities:** Develop advanced legal frameworks addressing autonomous AI liability; mandate implementation of robust technical logging and explainability features; establish clear redress mechanisms for affected parties; explore industry-led accountability initiatives.

4. **Manage Autonomy:**

   - **Elaboration:** Develop specific policies, operational protocols, and advanced oversight mechanisms for managing grid segments or functions that operate with a high degree of AI-driven autonomy. This involves defining safe operating envelopes, ensuring alignment with overall system security and economic goals, and designing effective human supervision strategies for these autonomous components.

   - **Why:** Provides necessary guardrails and control mechanisms to safely and effectively manage the increasing levels of automation and autonomy introduced by advanced AI in critical infrastructure.

   - **Who:** Regulators, TSOs/DSOs (lead for developing policies and operational procedures), research institutions (developing advanced oversight techniques).

   - **Activities:** Define acceptable levels and types of autonomy for different grid functions; develop policies governing autonomous operation; design and implement advanced monitoring and supervisory control systems; conduct extensive simulation and testing.

5. **Protect Consumer Rights in Autonomous Systems:**

   - **Elaboration:** Mandate and enforce robust consumer protection measures specifically for autonomous energy systems driven by AI. This includes rights to transparency (clear explanations of AI decisions affecting them), fairness guarantees (audits for bias), effective appeal mechanisms against automated decisions (e.g., related to pricing, curtailment, connection), and requirements for independent ethical review of systems with significant consumer impact. Mandate transparency, appeal mechanisms, and ethical review for AI systems affecting end users.

   - **Why:** Safeguards consumer rights and ensures fair treatment in an energy landscape increasingly managed by complex and potentially opaque AI algorithms, maintaining public trust and preventing discrimination. Ensures high consumer trust and ethical compliance in future grid operations.

   - **Who:** EU institutions/national legislators (regulation lead), consumer protection agencies, energy ombudsmen, regulators (enforcement).

   - **Activities:** Implement specific consumer protection regulations tailored to AI in energy; establish accessible and effective redress/appeal mechanisms; mandate transparency and fairness audits for relevant AI systems; empower consumer advocacy groups. Delivers AI-driven services with built-in fairness, privacy, and explainability.

5.3.2 Technology & Infrastructure:

1. Achieve Deep Integration & Autonomous Grids (incl. (Semi-)Autonomous Systems):

- **Elaboration:** Implement AI pervasively across the entire energy value chain, enabling fully autonomous optimisation of grid operations for maximising renewables integration, ensuring dynamic stability, managing complex interactions (grid vehicle-building ecosystems), and optimising energy markets. Phase out incompatible legacy systems where necessary, while always maintaining robust human oversight capabilities for critical functions and emergencies. Deploy highly autonomous AI-based systems (potentially scaling GenAI systems) capable of autonomous grid reconfiguration, energy trading, and load balancing, with operator supervision.

- **Why:** Unlocks the maximum potential efficiency, resilience, flexibility, and renewable hosting capacity of the energy system through holistic, real time, AI-driven optimisation far exceeding human capabilities alone. Reduces operational complexity, enables real-time decision-making, and enhances grid resilience.

- **Who:** TSOs/DSOs (implementation lead within their systems), ai vendors/system integrators (providing advanced technology), market operators, regulators (setting framework and oversight).

- **Activities:** Large-scale deployment of advanced AI control and optimisation systems; significant grid modernisation investments; development of standards for autonomous system interaction; phasing out incompatible legacy control systems; continuous refinement of human oversight strategies. Creates AI-driven control layers with operator supervision.

2. Deploy Advanced AI (Explainable, Robust, Uncertainty-Aware):

- **Elaboration:** Develop and deploy next-generation AI capabilities, including inherently robust and uncertainty-aware models (quantifying their own confidence), with explainability (XAI) as a standard design principle. Fund long-term R&D collaborations to enhance GenAI model transparency, robustness, and uncertainty estimation. Implement highly accurate predictive AI capable of anticipating failures or system disturbances with longer lead times, potentially enabling automated self-healing grid actions. Explore, validate, and deploy novel AI paradigms like causal AI, neuro-symbolic AI, or advanced reinforcement learning. Invest in "moonshot" Generative AI tools for complex long-term scenario planning and energy policy design support.

- **Why:** Pushes the boundaries of grid intelligence, resilience, foresight, and operational efficiency, enabling proactive management, faster recovery from disturbances, and better long-term planning in the face of uncertainty. Increases trust and enables safe integration of GenAI in smart grid operations.

- **Who:** Research institutions, leading ai vendors (development lead), funding bodies (sustained support for high-risk R&D), TSOs/DSOs (early adopters/testers).

- **Activities:** Sustained public and private funding for frontier AI research specifically for energy systems; establish platforms for testing and validating advanced AI concepts; facilitate pathways for deploying breakthrough AI technologies into operational environments; foster interdisciplinary research. Delivers AI models with built-in explainability and probabilistic outputs for critical grid applications.

3. Optimise AI Efficiency & Footprint (Energy-Efficient & Smaller Models):

- **Elaboration:** Make energy efficiency a primary design criterion for AI in the energy sector. Develop and deploy highly optimised AI models ("TinyML" on edge devices, pruned/quantised large models) and specialised, energy-efficient hardware (e.g., neuromorphic chips, ASICs) specifically for grid applications. Invest in foundational AI research focused on low-resource models without performance loss. Drive fundamental research into sustainable AI infrastructure, considering materials, lifecycle impacts, and integration with renewable energy sources.

- **Why:** Ensures that the significant benefits of AI in the energy transition are not undermined by AI's own potentially large energy consumption and environmental footprint, aligning AI deployment fully with sustainability goals. Democratises innovation and lowers the energy footprint of AI in smart grids.

- **Who:** Research institutions (fundamental research), AI developers, hardware manufacturers (innovation lead in efficient design), standards bodies/regulators (setting efficiency standards/targets), TSOs/DSOs (procuring efficient solutions).

- **Activities:** Fund research into Green AI algorithms and hardware; develop benchmarks and standards for AI energy efficiency in the energy sector; incentivise or mandate the use of energy-efficient AI solutions; promote lifecycle assessments for AI infrastructure. Delivers smaller, cost-efficient GenAI models available to a wide range of stakeholders.

5.3.3 Collaboration & Skills:

1. **Foster Global Alliances & Leadership (incl. International Innovation Alliances):**

- **Elaboration:** Establish strategic alliances and joint R&D programmes with international partners (countries, research institutions, industry) on cutting-edge AI in energy topics, with European consortia often taking a leading role where Europe has strengths. Create structured long-term funding frameworks involving EU, EIB, and global partners. Partner selectively with global technology leaders while ensuring European control over critical components and intellectual property. Promote joint investment mechanisms involving EU entities (like the EIB) and global partners for large-scale demonstration projects.

- **Why:** Leverages global expertise and resources, shares the significant costs and risks of frontier R&D, enhances European influence in shaping global AI standards and markets for energy, accelerates progress through international collaboration. Shares innovation risks, increases investment scale, and enhances global influence.

- **Who:** EU institutions (coordination/strategy lead), european consortia (research/industry – leading alliances), eib/national promotional banks, global partners (countries, institutions, companies).

- **Activities:** Identify strategic areas for international collaboration; establish bilateral or multilateral R&D agreements and programmes; facilitate joint ventures and investments; actively participate in international forums on AI and energy. Creates multilateral R&I projects advancing frontier AI in smart grids.

2. **Promote Open Ecosystems:**

- **Elaboration:** Continuously and vigorously promote, fund, and sustain the use and development of open-source AI tools, frameworks, simulation environments, and datasets specifically for the energy sector. Implement policies that favour or require open standards and interfaces in public procurement and funded projects.

- **Why:** Ensures a healthy, competitive, and innovative ecosystem by preventing vendor lock-in, fostering broad participation (especially from SMEs and academia), enabling transparency and reproducibility, and accelerating the adoption of best practices.

- **Who:** EU institutions/funding bodies (policy/support lead), open-source foundations/communities, industry associations, academia, utilities (participation/contribution).

- **Activities:** Provide sustained funding and infrastructure support for key open-source energy AI projects; implement procurement policies favouring open standards/software; promote open science principles in AI research for energy; facilitate community building and governance for open projects.

3. **Achieve Workforce Proficiency (incl. Lifelong Learning & Curriculum Evolution):**

- **Elaboration:** Ensure a sustainable, long-term pipeline of talent fully proficient in developing, deploying, managing, and ethically governing AI systems within the energy sector. Establish lifelong learning platforms integrated with evolving AI and grid technology trends. This requires deeply integrated and continuously updated university curricula, widely accessible lifelong learning platforms offering advanced training and credentials (including on human-AI collaboration), and potentially specialised certifications for AI energy professionals.

- **Why:** Creates and maintains the highly skilled European workforce necessary to innovate, operate, and lead in the increasingly complex, AI-driven future energy system. Develops a future-proof, skilled energy-AI workforce ready to adapt to emerging technologies.

- **Who:** Educational institutions (universities, vocational schools – lead for curricula/platforms), industry (providing input, internships, continuous training), professional associations (certifications), lifelong learning providers.

- **Activities:** Establish mechanisms for continuous curriculum review and adaptation; invest in scalable lifelong learning infrastructure for the energy workforce; develop advanced courses on human-AI teaming and AI ethics in energy; potentially establish professional certifications for AI energy roles. Provides regularly updated learning content, simulation environments, and credentialing systems.

5.3.4 Standards & Interoperability:

1. Establish Global Standards Leadership (incl. Global Harmonisation):

- **Elaboration:** Actively work to position EU-developed ethical principles and technical standards for AI in critical infrastructure, particularly energy systems, as global benchmarks. Lead standardisation efforts within key international bodies (IEC, ISO, IEEE, ITU) by contributing expertise, proposals, and convenorship roles, seeking alignment while upholding stringent EU requirements where necessary (e.g., on privacy, safety, ethics). Engage in IEC, ISO, IEEE to align EU AI energy standards with international frameworks.

- **Why:** Promotes EU values and safety/ethical requirements globally, facilitates international market access for European AI companies, ensures global interoperability based on European-led standards, enhances EU's geopolitical influence in technology governance. Enhances interoperability, cybersecurity, and global market access.

- **Who:** EU institutions (coordination, strategic direction), Member States (supporting eu positions), european standards bodies (CEN/CENELEC, ETSI – leading technical contributions), industry experts (participating in working groups), international standards bodies.

- **Activities:** Develop proactive strategy for international AI standardisation in energy; fund participation of European experts in international bodies; propose new work items based on European R&D and regulatory frameworks; build coalitions with like- minded international partners; align EU and international standards where feasible. Leads to globally accepted EU-led standards and practices.

2. Ensure Seamless Cross-Border Trade:

- **Elaboration:** Implement the necessary harmonised technical standards, data exchange protocols (building on CIM and data spaces), market rules, and regulatory frameworks to allow AI systems to fully coordinate and optimise cross-border energy flows (electricity trading, balancing, congestion management) efficiently, securely, and reliably across Europe.

- **Why:** Creates a truly integrated, efficient, and optimised pan-European energy market, maximising the benefits of shared resources, enhancing security of supply, and facilitating the integration of renewables across borders through AI-driven coordination.

- **Who:** European network operators (ENTSO-E, DSO Entity), ACER (Agency for the Cooperation of Energy Regulators), national regulators, DSOs, TSOs, market operators (framework/implementation lead).

- **Activities:** Develop and adopt harmonised network codes and market rules for AI-based cross-border coordination; implement standardised secure data exchange platforms; ensure interoperability of national AI systems involved in cross-border processes; conduct cross-border simulations and pilot projects.

5.3.5 Societal & Ethical Alignment:

1. **Mainstream Trust Mechanisms:**

- **Elaboration:** Embed consumer trust-building mechanisms – such as easily accessible transparency tools (explaining AI decisions), independent fairness audits, clear
- performance reporting, and effective redress processes – as standard, integrated components of all significant AI-driven grid operations and energy services affecting citizens. Institutionalise regular public engagement processes and the use of robust XAI frameworks as normal practice.
- **Why:** Moves beyond pilot trust initiatives to make transparency, fairness, and accountability integral parts of the AI-driven energy system, essential for maintaining long-term public acceptance and the social licence to operate.
- **Who:** TSOs/DSOs/utilities/energy service providers (implementation lead within their operations), regulators (mandating requirements), technology providers (building tools), consumer groups (monitoring/advocacy).
- **Activities:** Integrate trust tools and XAI features into standard operational systems and customer interfaces; mandate regular fairness audits and public reporting; establish accessible and independent redress mechanisms; incorporate public engagement into system design and review cycles.

2. **Align with EU Green Deal & Ensure Fairness:**

- **Elaboration:** Continuously evaluate, adapt, and fully align AI deployment strategies and associated regulations with the overarching goals of the EU Green Deal, particularly carbon neutrality. Establish and rigorously track metrics measuring AI's net contribution (positive and negative) to CO2 reduction and environmental sustainability. Actively leverage AI to enable and optimise decentralised energy systems (prosumer grids, energy communities) in an equitable manner. Proactively enforce fairness by mitigating biases (e.g., in training data, algorithms) in AI-driven decisions affecting distribution, pricing, or access, and ensure diverse community stakeholders are included in the design and governance of AI systems.
- **Why:** Ensures that AI deployment in the energy sector actively contributes to climate goals and social equity, rather than potentially exacerbating environmental problems or societal inequalities. Aligns technological advancement with core EU policy objectives.
- **Who:** EU institutions/regulators (policy/monitoring lead, setting targets/metrics), TSOs/DSOs/industry (implementation, reporting, bias mitigation), research institutions (developing metrics/fairness techniques), civil society/community groups (advocacy, input on fairness, participation in design).
- **Activities:** Integrate AI impact metrics into Green Deal monitoring frameworks; fund research on quantifying AI's environmental footprint and societal impacts; implement mandatory fairness audits and bias mitigation strategies for relevant AI systems; establish formal mechanisms for stakeholder and community inclusion in AI design and governance processes.

5.4 Summary table of the roadmap actions

The following table summarises the actionable recommendations detailed in Chapter 5, organised by the implementation phase (short-term: 0-2 years, medium-term: 2-5 years, long-term: 5+ years) and strategic category. The main text of Chapter 5 provides detailed elaboration, rationale, and stakeholder involvement for each action.

5.4.1 Phase 1: Short-Term (0-2 Years) – Build the Foundation

Table 3 - Short-Term Actions

Action ID	Action Name	Category
S1.1	Establish EU-wide Smart Grid AI Task Force	Governance & Regulation
S1.2	Clarify AI Act & GDPR Interpretation	Governance & Regulation
S1.3	Launch & Enhance Regulatory Sandboxes	Governance & Regulation
S1.4	Develop Foundational Data Governance	Governance & Regulation
S1.5	Establish Interim Certification & Conformity	Governance & Regulation
S1.6	Evaluate Innovation Barriers in Regulation	Governance & Regulation
S1.7	Mandate Critical Safeguards (Human-in-the-Loop)	Governance & Regulation
S2.1	Develop Common EU Energy Data Spaces (Pilots)	Data & Infrastructure
S2.2	Generate Synthetic Energy Data	Data & Infrastructure
S2.3	Invest in Foundational Infrastructure (Testbeds)	Data & Infrastructure
S3.1	Develop Open-Source EU AI Model (LLM)	Technology & R&D
S3.2	Fund Priority AI Applications & Infrastructure	Technology & R&D
S3.3	Pilot Explainable AI (XAI)	Technology & R&D
S3.4	Initiate Foundational Cybersecurity (Zero Trust)	Technology & R&D
S4.1	Form Initial Consortia & Networks	Collaboration & Skills
S4.2	Launch Visible Open Innovation Programmes	Collaboration & Skills
S4.3	Initiate AI Upskilling & Literacy	Collaboration & Skills
S4.4	Support SMEs & Startups	Collaboration & Skills
S5.1	Develop AI Maturity Framework	Standards

5.4.2 Phase 2: Medium-Term (2-5 Years) –Scale & Harmonise

Table 4 - Medium-Term Actions

Action ID	Action Name	Category
M1.1	Implement EU-wide AI Certification & Labelling	Governance & Regulation
M1.2	Establish Clear Liability Frameworks	Governance & Regulation
M1.3	Refine Data Governance & Consent	Governance & Regulation
M1.4	Update Grid Codes & Procedures	Governance & Regulation
M2.1	Establish Unified EU Digital Marketplaces/Spaces	Data & Infrastructure

M2.2	Scale Data Infrastructure & Federated Learning	Data & Infrastructure
M2.3	Expand HPC & Edge Computing Access/Deployment	Data & Infrastructure
M3.1	Deploy Interoperable AI Systems	Technology & R&D
M3.2	Operationalise AI Agents with Human-in-the-Loop	Technology & R&D
M3.3	Develop AI-Driven Tools (Scale)	Technology & R&D
M3.4	Develop Sector-Specific LLMs	Technology & R&D
M3.5	Promote Energy-Efficient AI ("Green AI")	Technology & R&D
M3.6	Foster Sovereign Capabilities (Platforms/Models)	Technology & R&D
M4.1	Scale Collaborative Ecosystems (Clusters/Hubs)	Collaboration & Skills
M4.2	Establish Co-Funded AI Deployment Programmes	Collaboration & Skills
M4.3	Formalise Public-Private Research Partnerships	Collaboration & Skills
M4.4	Expand Workforce Development (Structured Prog.)	Collaboration & Skills
M4.5	Build Consumer Trust & Engagement	Collaboration & Skills
M5.1	Deploy Minimal Interoperability (MIM) Standards	Standards & Interoperability
M5.2	Strengthen Cybersecurity (Grid-Specific NIS2/AI)	Standards & Interoperability

5.4.3 Phase 3: Long-Term (5+ Years) – Achieve Full Integration & Optimisation

Table 5 - Long-Term Actions

Action ID	Action Name	Category
L1.1	Mature Governance Frameworks (Periodic Reviews)	Governance & Regulation
L1.2	Institutionalise Data Governance (Bodies)	Governance & Regulation
L1.3	Implement Full Accountability	Governance & Regulation
L1.4	Manage Autonomy (Protocols/Oversight)	Governance & Regulation
L1.5	Protect Consumer Rights in Autonomous Systems	Governance & Regulation
L2.1	Achieve Deep Integration & Autonomous Grids	Technology & Infrastructure
L2.2	Deploy Advanced AI (Explainable, Robust, Uncert.)	Technology & Infrastructure
L2.3	Optimise AI Efficiency & Footprint (TinyML)	Technology & Infrastructure
L3.1	Foster Global Alliances & Leadership	Collaboration & Skills
L3.2	Promote Open Ecosystems (Sustain)	Collaboration & Skills
L3.3	Achieve Workforce Proficiency (Lifelong Learning)	Collaboration & Skills
L4.1	Establish Global Standards Leadership	Standards & Interoperability

L4.2	Ensure Seamless Cross-Border Trade (AI Coord.)	Standards & Interoperability
L5.1	Mainstream Trust Mechanisms (XAI/Audits)	Societal & Ethical Alignment
L5.2	Align with EU Green Deal & Ensure Fairness	Societal & Ethical Alignment

5.5 Overall alignment between the actions

The actions are designed to be interdependent, building upon each other across the short, medium, and long-term, creating an overarching storyline.

5.5.1 From Foundational Readiness to Integrated Leadership

The roadmap follows a logical progression:

1. **Phase 1 (Short-Term: 0-2 Years) – Building the Runway:** This phase focuses on creating the essential enabling conditions. It's about laying the groundwork, reducing immediate uncertainties, fostering initial collaboration, and conducting early, contained experiments to build confidence and momentum.

2. **Phase 2 (Medium-Term: 2-5 Years) – Scaling Proven Concepts & Harmonising:** Building on the foundations, this phase involves scaling successful pilots, establishing common standards and rules, strengthening infrastructure, broadening collaboration, and moving towards operational deployment of trusted AI solutions.

3. **Phase 3 (Long-Term: 5+ Years) – Achieving Full Integration & Optimisation:** This final phase aims for maturity and leadership. It involves deploying AI pervasively for optimised, autonomous (where appropriate) grid operations, ensuring long-term ethical alignment and sustainability, establishing Europe as a global leader, and creating adaptive frameworks for continuous improvement.

The key synergies and the narrative flow within the storyline is the one described below.

5.5.2 Phase 1: Laying the Groundwork (Synergies)

- **Governance & Data Hand-in-Hand:** The **AI Task Force (S:1.1)** provides the coordination hub. Clarifying the **AI Act/GDPR (S:1.2)** and establishing **Initial Data Governance (S:1.4)** frameworks reduces legal friction, allowing **Common EU Energy Data Space pilots (S:2.1)** to proceed with more confidence. **AI Risk Clarification (S:1.2)** informs the requirements for **Interim Certification (S:1.5)** and **HITL safeguards (S:1.7)**.

- **Testing Needs Infrastructure & Clarity: Regulatory Sandboxes (S:1.3)** provide the legal space, while **AI Testbeds (S:2.3)** provide the technical space for testing priority **AI Applications (S:3.2)** and **XAI pilots (S:3.3)**. Access to **Synthetic Data (S:2.2)** or data via **Data Spaces (S:2.1)** is crucial fuel for these tests. **Evaluating Innovation Barriers (S:1.6)** helps identify rules needing waivers within sandboxes.

- **Building Blocks for Future Tech:** Developing an **Open-Source EU LLM (S:3.1)** and **Synthetic Data Generators (S:2.2)** provides foundational tools that benefit SMEs, researchers, and future medium-term applications (like Sector-Specific LLMs M:3.4). Investing in **IoT/Edge (S:2.3)** supports near-term pilots and prepares for edge-heavy medium-term deployments.

- **Collaboration Seeds Future Growth:** Forming **Initial Consortia/Networks (S:4.1)**, including **Open Source Collaboration**, and launching **Open Innovation Programmes (S:4.2)** attracts talent and ideas, feeding into pilot projects (S:3.2, S:3.3) and potentially forming the basis for medium-term clusters (M:4.1). **Initial Upskilling (S:4.3)** prepares the workforce for immediate needs and medium-term expansion.

- **Trust Starts Early: Interim Certification (S:1.5)**, piloting **XAI (S:3.3)**, mandating **HITL (S:1.7)**, and developing an **AI Maturity Framework (S:5.1)** are early steps to build operator and regulator confidence, paving the way for broader acceptance later.

5.5.3 Phase 2: Scaling & Harmonising (Synergies- Building on Phase 1)

- **From Pilots to Operations:** Successful pilots (from Phase 1) are scaled into **Interoperable AI Systems (M:3.1)** and **AI Agents with HITL (M:3.2)**. This requires the **Harmonised Standards & Certification (M:1.1)** and **Minimal Interoperability Standards (M:5.1)** developed in this phase. **Clear Liability Frameworks (M:1.2)** are essential for deploying these operational systems.

- **Data Infrastructure Matures:** Initial **Data Space pilots (S:2.1)** evolve into **Unified EU Marketplaces/Data Spaces (M:2.1)**. This requires **Refined Data Governance & Consent tools (M:1.3)**. **Scaled Data Infrastructure & Federated Learning (M:2.2)** and expanded **HPC/Edge (M:2.3)** provide the backbone for training more complex models (like **Sector-Specific LLMs M:3.4**) and deploying edge applications.

- **Standardisation Enables Markets: Harmonised Certification (M:1.1)** and **MIM Standards (M:5.1)** create a predictable market. **Updated Grid Codes (M:1.4)** formally integrate AI operations. **Strengthened Cybersecurity (M:5.2)** builds on initial measures (S:3.4) and aligns with AI Act/NIS2 implementation.

- **Collaboration Deepens & Broadens:** Initial networks (S:4.1) evolve into **Scaled Collaborative Ecosystems & Cross-Sector Clusters (M:4.1)**. **Co-funded Deployment Programmes (M:4.2)** leverage private investment to scale pilots. **Formalised PPP Research (M:4.3)** strengthens the academia-industry link. **Expanded Workforce Development (M:4.4)** addresses the growing need for specialised skills. **Consumer Trust building (M:4.5)** becomes crucial as AI impacts become more visible.

- **Technology Specialises:** Foundational models (S:3.1) are refined into **Sector-Specific LLMs (M:3.4)**. Awareness of energy use drives promotion of **Energy-Efficient AI (M:3.5)**. Strategic investments foster **Sovereign Capabilities (M:3.6)**.

5.5.4 Phase 3: Full Integration & Optimisation (Synergies- Building on Phase 2)

- **Achieving Autonomy & Optimisation:** Scaled interoperable systems (M:3.1) and agents (M:3.2) evolve into **Deeply Integrated & Autonomous Grids (L:2.1)**, leveraging **Advanced AI (L:2.2)**. This requires **Mature Governance Frameworks (L:1.1)**, **Institutionalised Data Governance (L:1.2)**, **Full Accountability mechanisms (L:1.3)**, policies to **Manage Autonomy (L:1.4)**, and robust **Consumer Rights Protection (L:1.5)**.

- **Sustainability & Ethics Mainstreamed:** Promoting **Energy-Efficient AI (M:3.5)** evolves into optimising the **AI Efficiency & Footprint (L:2.3)** as a core requirement. Early trust measures (Phase 1 & 2) are embedded via **Mainstreamed Trust Mechanisms (L:5.1)** and alignment with the **EU Green Deal & Fairness (L:5.2)**.

- **Global Leadership & Seamless Operation:** Harmonised EU standards (M:1.1, M:5.1) form the basis for establishing **Global Standards Leadership (L:4.1)**. This, combined with **Fostering Global Alliances (L:3.1)**, supports European industry internationally. Mature data exchange and interoperability enable **Seamless Cross-Border Trade (L:4.2)**.

- **Ecosystem Maturity:** Expanded workforce development (M:4.4) leads to **Achieving Workforce Proficiency (L:3.3)**. Scaled collaboration (M:4.1) is sustained via **Promoting Open Ecosystems (L:3.2)**.

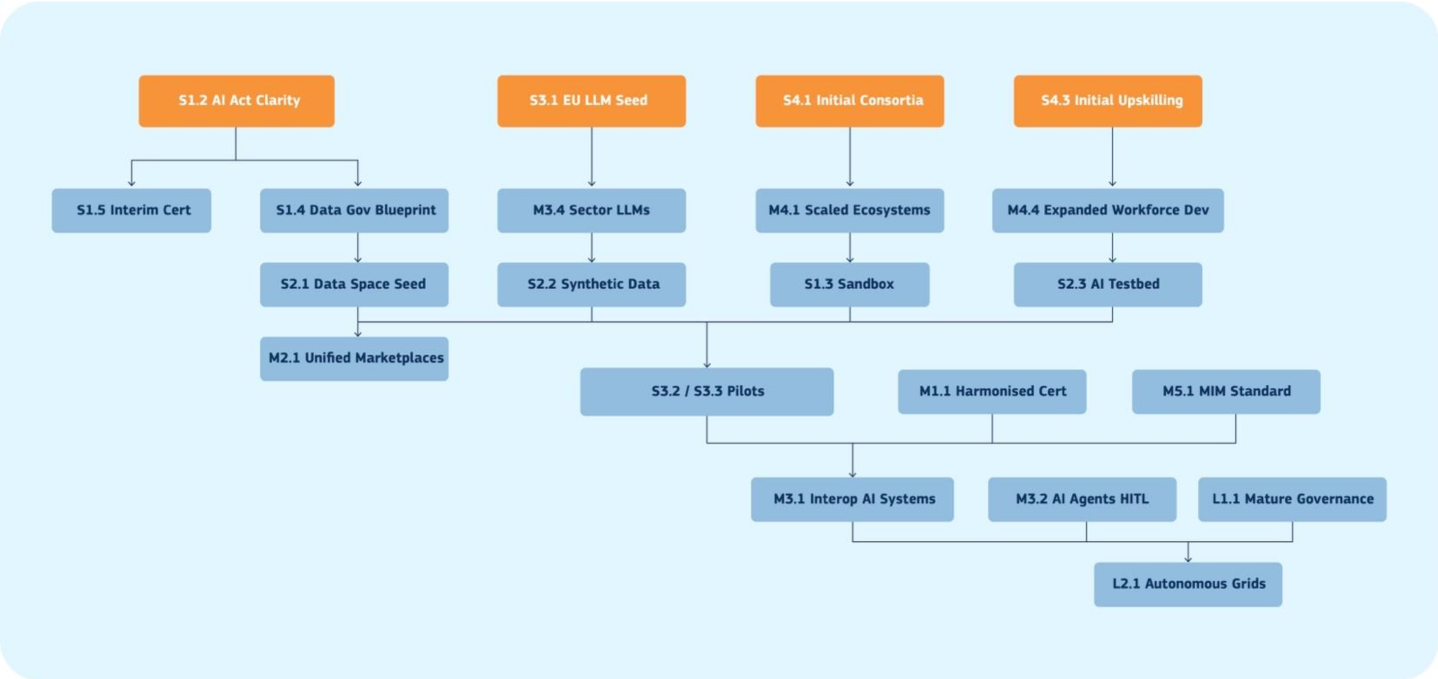

Figure 3 - Roadmap synergies.

5.5.5 Conclusion:

The action plan is not just a list but a structured roadmap where early foundational steps (regulatory clarity, data access, pilot projects, initial standards, basic skills) create the conditions for medium-term scaling, harmonisation, and operational deployment. This, in turn, paves the way for long-term goals of achieving a fully optimised, resilient, ethical, and sustainable AI-powered energy system where Europe plays a leading role. Each step builds trust, capability, and the technical/regulatory infrastructure needed for the next level of integration.

6 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarises the paper's key findings and insights. It offers tailored recommendations for stakeholder groups, addresses the ethics for trustworthy AI and looks at how AI may contribute to a sustainable and resilient European energy sector.

6.1 Introduction: Charting the Course for AI in Europe's Energy Future

This paper has explored the transformative potential of Artificial Intelligence (AI) and Generative AI (GenAI) within the context of Europe's evolving energy landscape. As detailed in previous chapters, the transition towards a decarbonised, decentralised, and digitalised energy system presents both immense opportunities and significant complexities (Chapter 1). Smart grids are fundamental to managing this transition (Chapter 1.2), and AI/GenAI offer powerful capabilities to enhance their efficiency, reliability, flexibility, and resilience (Chapter 3, Chapter 4.1).

However, realising this potential requires navigating a complex interplay of technological advancements, policy frameworks (Chapter 2), infrastructure development, stakeholder collaboration, and ethical considerations (Chapter 4.2). Europe is embarking on a phased transformation – building foundations, scaling and harmonising efforts, and ultimately optimising the integrated system. Success hinges on addressing key gaps identified through strategic analysis – notably in regulatory clarity, data access, skills, infrastructure, standardisation, and trust.

This concluding chapter synthesises the key findings and insights derived from the preceding analysis. It presents a robust and strategically grounded set of actionable recommendations tailored to specific stakeholder groups. These recommendations are designed to bridge the identified gaps, align with the overarching European strategy, leverage necessary organisational structures and systems, build critical skills, foster a collaborative style, and uphold shared values such as trustworthiness, security, and sustainability. They offer a practical guide for unlocking the full potential of AI and GenAI in European smart grids, contributing to a secure, competitive, and sustainable energy future for the continent.

6.2 Overarching Strategic Context

The integration of AI/GenAI into European smart grids is not merely a technological upgrade; it is a strategic imperative aligned with the European Green Deal and the Digital Decade objectives. The journey involves moving from foundational activities (establishing frameworks, piloting technologies) through scaling and harmonisation (standardising approaches, building infrastructure, broader deployment) to full optimisation (autonomous systems, pervasive integration).

Key challenges (Gaps) that must be addressed include:

- **Regulatory Uncertainty:** Ambiguity in the application of the AI Act and GDPR to specific energy use cases.
- **Data Access and Governance:** Siloed, insufficient, or inaccessible data hindering AI model development and deployment.
- **Skills Shortage:** Lack of personnel proficient in both AI and energy systems domain knowledge.
- **Infrastructure Deficits:** Need for enhanced computing (HPC, edge), sensor networks, and communication capabilities.
- **Standardisation Gaps:** Lack of harmonised technical standards and interoperability protocols.
- **Trust and Acceptance:** Building confidence among operators, consumers, and regulators regarding AI's reliability, security, and fairness.
- **Investment Needs:** Significant funding required for R&D, infrastructure, and skills development.
- **Cybersecurity Risks:** New vulnerabilities introduced by interconnected, AI-driven systems.

- **Ethical Concerns:** Potential for bias, lack of transparency, and inequitable outcomes.

A cohesive **Strategy** involving multi-stakeholder collaboration, pilot-driven innovation, phased regulation, standardisation, and building EU sovereign capabilities is essential. This requires aligned organisational **Structures** (e.g., Task Forces, Consortia), efficient **Systems** (funding mechanisms, certification processes, data governance), the development of critical **Skills** and **Staff**, and a collaborative **Style**. This entire transformation must be underpinned by **Shared Values** prioritising trustworthiness, security, fairness, and sustainability.

6.3 Recommendations by Stakeholder Group

The following recommendations provide specific, actionable guidance for key stakeholders, linking actions back to the strategic context and the capabilities required.

6.3.1 For EU Policymakers & Regulators

- **Provide Regulatory Framework and Clarity (Foundation & Harmonisation)**
  - **Action:** Urgently clarify the AI Act's application to energy use cases (especially risk classification, liability, SME pathways) and issue GDPR guidance supporting AI data use. Establish interim certifications and mandate critical safeguards such as Human- in-the-Loop (HITL). Launch regulatory sandboxes for controlled testing. Evolve towards stable, harmonised, yet adaptive EU-wide frameworks, including mandatory certification/labelling and periodic reviews.
  - **Rationale & Context:** Addresses the critical **GAP** in regulatory uncertainty inhibiting investment. Aligns with the **STRATEGY** of phased regulation and building trust. Requires establishing clear regulatory **SYSTEMS** and leveraging the **STRUCTURE** of national regulators and EU bodies. Balances innovation with safety (**Shared Values**).
- **Drive Funding & Investment (Enablement)**
  - **Action:** Create a substantial, dedicated "AI in Energy" funding stream (linking to Horizon Europe, Digital Europe, national programmes). Prioritise foundational needs (grid stability R&D, cybersecurity, edge infrastructure), R&D hubs/Centres of Excellence (CoEs), open-source initiatives, and SME support. Link funding eligibility to collaboration and open/data-sharing commitments. Support strategic investments in EU sovereign capabilities.
  - **Rationale & Context:** Addresses **GAPS** in resources and infrastructure. Directly supports the **STRATEGY** of building EU capabilities and fostering collaboration. Requires efficient funding **SYSTEMS**. Aligns with **OBJECTIVES** of building the foundation and scaling proven concepts.
- **Establish Data Governance (Foundation & Harmonisation)**
  - **Action:** Develop initial data governance frameworks aligned with GDPR. Fund and support Common EU Energy Data Spaces pilots, scaling them into unified marketplaces. Mandate the use of interoperability standards (e.g., IEC CIM+) and open APIs where appropriate. Establish clear rules for secure data access/sharing (via data spaces, trusts, GDPR revisions). Clarify smart meter data access. Consider permanent, independent data governance bodies long-term.
  - **Rationale & Context:** Critical for overcoming the data access **GAP**. Central to the **STRATEGY** of data enablement. Requires clear governance **SYSTEMS** and potentially new **STRUCTURES**. Unlocks data needed for AI while ensuring privacy (**Shared Values**).
- **Champion Standards & Ethics (Trust & Leadership)**
  - **Action:** Fast-track harmonised EU certification/labels. Mandate/incentivise energy efficiency for AI

systems. Promote Explainable AI (XAI) and enforce anti-bias rules. Champion EU ethical standards and technical standards (e.g., MIM) globally. Ensure alignment with the Green Deal and fairness principles.

- **Rationale & Context:** Builds trust (**Shared Values**), addresses **GAPS** in standardisation and ethics. Key to the **STRATEGY** of creating a predictable single market and establishing EU leadership. Requires robust **SYSTEMS** for certification and standard- setting.

- **Foster Skills & Collaboration (Capability Building)**
  - **Action:** Fund Centres of Excellence (CoEs), joint university-industry programmes, and upskilling initiatives. Mandate/incentivise cross-sector collaboration (e.g., Energy- Mobility clusters) and SME participation in funded projects. Support open-source communities.
  - **Rationale & Context:** Addresses the critical **SKILLS GAP**. Essential for building the necessary human capital (**Staff/Skills**). It aligns with the collaborative **STRATEGY** and **STYLE**.
- **Ensure Sovereignty & Competition (Strategic Alignment)**
  - **Action:** Develop strategies and targeted investments (e.g., IPCEI) for EU AI capabilities in critical areas (e.g., foundational models, chipsets). Manage risks from non-EU tech monopolies while enabling global collaboration.
  - **Rationale & Context:** Reinforces EU leadership **OBJECTIVES**. Addresses strategic dependencies (**GAP**). Aligns with **Shared Values** of sovereignty and competitiveness.
- **Facilitate National Alignment (Coordination)**
  - **Action:** Establish and support the EU-wide Smart Grid AI Task Force to align national strategies, funding, testbeds, and sandboxes with the EU framework. Ensure coherent implementation across Member States.
  - **Rationale & Context:** Addresses the **GAP** of fragmented efforts. Provides the necessary coordination **STRUCTURE** and promotes a unified **STYLE**. Crucial for the overall **STRATEGY's** success.

6.3.2 For Energy Companies & Grid Operators (TSOs/DSOs)

- **Invest & Adopt Strategically (Adoption & Modernisation)**
  - **Action:** Allocate specific innovation budgets for AI adoption (e.g., 10% suggested). Invest strategically in enabling technology (edge computing; Zero Trust cybersecurity) and workforce upskilling (AI literacy, oversight skills). Start deploying proven AI in high- value areas (e.g., stability, predictive maintenance) and scale successful pilots. Prioritise standardising data models (IEC CIM) for easier integration.
  - **Rationale & Context:** Necessary to bridge internal capability **GAPS**. Requires developing internal **SKILLS** and adapting **SYSTEMS**. Aligns with the **STRATEGY** of pilot- driven scaling and modernisation.
- **Prioritise Trust & Ethics (Building Confidence)**
  - **Action:** Adopt XAI techniques for critical systems internally and externally. Implement clear human-AI collaboration rules and governance with human oversight (HITL/HOTL). Communicate transparently with consumers about AI use. Implement trust mechanisms as standard practice.
  - **Rationale & Context:** Builds internal/external trust (**Shared Values**), addressing acceptance **GAPS**. Requires changes in operational **SYSTEMS** and **STYLE**. Essential for social licence to operate.

- **Embrace Collaboration & Standards (Ecosystem Integration)**
    - **Action:** Actively participate in the EU Task Force, consortia, R&D hubs, and regulatory sandboxes. Adopt standard protocols (IEC CIM+, MIM). Contribute to and utilise common data platforms/spaces. Engage in open-source development where beneficial. Implement updated grid codes incorporating AI.
    - **Rationale & Context:** Supports the collaborative **STRATEGY** and avoids vendor lock-in (**GAP**). Requires active engagement in ecosystem **STRUCTURES** and adopting common **SYSTEMS/Standards**. Accelerates learning and shares risks/costs.
- **Build Internal Capacity (Internal Capability)**
    - **Action:** Develop internal AI teams or competence centres. Partner with universities for targeted training and talent pipeline development. Ensure staff are proficient in managing, adapting, and leveraging AI effectively, including human-AI teaming.
    - **Rationale & Context:** Addresses internal **SKILLS/STAFF GAPS**. Creates necessary organisational capability to manage and benefit from the **STRATEGY** of AI adoption.

6.3.3 For AI & Tech Developers (including Vendors)

- **Align with EU Needs & Standards (Market Alignment)**
    - **Action:** Design solutions compatible with EU data models (IEC CIM+), emerging certifications, and interoperability standards (MIM). Utilise open interfaces. Seek certification for products.
    - **Rationale & Context:** Ensures market access and interoperability, avoiding vendor lock-in (**GAP**). Aligns with the **STRATEGY** of harmonisation and creating a predictable market. Requires adherence to evolving **SYSTEMS/Standards**.
- **Prioritise Security & Ethics (Trust by Design)**
    - **Action:** Build robust cybersecurity ("Security by Design") and ethics (fairness, transparency) into AI models from the start. Focus on XAI for critical applications. Develop energy-efficient models ("Green AI"), especially for edge deployment.
    - **Rationale & Context:** Meets regulatory/customer demands (**GAP**). Builds trustworthy products (**Shared Values**). Aligns with the **STRATEGY** of responsible AI adoption and Green Deal goals. Essential capability (**Skills**).
- **Collaborate Actively (Ecosystem Role)**
    - **Action:** Partner with energy companies to understand needs and access data (e.g., for sector-specific LLMs). Engage with regulators and standards bodies. Contribute to open-source projects. Partner with SMEs. Create user-friendly explainability tools.
    - **Rationale & Context:** Develops relevant solutions and influences standards (**STRATEGY**). Leverages collaborative **STRUCTURES** and **STYLE**. Contributes to ecosystem health.
- **Address Key Grid Challenges (Value Proposition)**
    - **Action:** Focus product development on solving core energy sector problems: grid stability, cybersecurity, renewables integration, predictive maintenance, demand response, energy efficiency.
    - **Rationale & Context:** Ensures market relevance and impact, aligning with overall energy transition **OBJECTIVES**.

6.3.4 For Academia & Research Institutions

- **Conduct Targeted Research (Advancing Knowledge)**
  - **Action:** Focus research on specific grid AI challenges (stability, security, efficiency, XAI, bias mitigation, federated learning, low-power AI, next-gen optimisation, human-AI collaboration). Develop relevant metrics and benchmarks. Research sustainable/Green AI infrastructure. Develop advanced ethical/governance frameworks for critical AI. Lead open-source development of core algorithms.
  - **Rationale & Context:** Directly addresses knowledge **GAPS**. Advances the scientific frontier needed for the **STRATEGY**. Provides essential tools (**SYSTEMS**) for the community.
- **Develop Talent Pipeline (Building Capacity)**
  - **Action:** Update engineering/CS curricula for "AI in Energy". Run joint Master's programmes with industry. Offer micro-credentials/upskilling. Help establish and staff Centres of Excellence. Ensure graduates understand ethical considerations and human-AI teaming.
  - **Rationale & Context:** Crucial for closing the **SKILLS GAP**. Builds the **STAFF/SKILLS** needed across the ecosystem for long-term success.
- **Enable Innovation & Transfer (Bridging Theory & Practice)**
  - **Action:** Establish realistic simulation/hardware testbeds (TEFs) for AI validation. Partner actively with industry for tech transfer via formalised Public-Private Partnerships (PPPs). Create public benchmarks.
  - **Rationale & Context:** Bridges the **GAP** between research and practice. Provides essential **SYSTEMS/Infrastructure** for validation. Supports the **STRATEGY** of pilot- driven innovation.

6.3.5 For SMEs & Startups

- **Engage & Leverage Resources (Leveraging the Ecosystem)**
  - **Action:** Actively participate in collaborative R&D hubs, regulatory sandboxes, and open innovation programmes. Take advantage of public funding/subsidies and access to open-source tools/datasets and testbeds.
  - **Rationale & Context:** Overcomes resource limitations (**GAP**). Leverages collaborative **STRUCTURES** and funding **SYSTEMS**. Enables participation in the **STRATEGY**.
- **Focus & Innovate (Finding Advantage)**
  - **Action:** Develop specialised AI solutions targeting niche grid applications. Utilise open-source frameworks to lower development barriers.
  - **Rationale & Context:** Finds competitive advantages (**STRATEGY**). Leverages available tools (**SYSTEMS**) to accelerate development.
- **Partner Strategically (Scaling Up)**
  - **Action:** Seek partnerships with larger industry players, academia, and utilities (via consortia/hubs) to access markets, expertise, and data. Understand and leverage simplified compliance pathways.
  - **Rationale & Context:** Overcomes limitations of size/scale (**GAP**). Uses ecosystem **STRUCTURES** for growth.

6.3.6 For Consumers & Energy Communities

- **Engage & Advocate (Participation & Voice)**
  - **Action:** Participate in public consultations, AI pilot projects (e.g., demand response). Advocate for transparency, fairness, and privacy protection in AI systems. Engage with regulators on smart meter data usage concerns.
  - **Rationale & Context:** Ensures consumer interests are represented (**Shared Values**). Contributes to closing trust **GAPS**. Influences **SYSTEMS** and regulations.
- **Demand Transparency & Build Literacy (Understanding & Trust)**
  - **Action:** Seek clear, understandable communication from energy providers about AI use in grid management/billing. Participate in educational initiatives to understand AI's role, benefits, and risks.
  - **Rationale & Context:** Builds understanding and trust (**Shared Values**), addressing acceptance **GAPS**. Empowers informed participation (**STRATEGY**).
- **Empower Communities (Agency & Local Action)**
  - **Action:** Support community-owned data initiatives where feasible. Explore using accessible AI tools for local energy management (e.g., optimising community solar/battery).
  - **Rationale & Context:** Enables local participation and benefit from AI (**STRATEGY**). Maintains local agency over data (**Shared Values**). Leverages data governance frameworks.

For a detailed mapping of these recommendations to the specific short-term (S), medium-term (M), and long-term (L) actions outlined in the Chapter 5 roadmap, please refer to Annex 3.

6.4 Ethical Considerations: Building Trustworthy AI

Throughout the integration process, ethics must remain paramount. Achieving fairness, transparency, accountability, and privacy is not merely a compliance exercise but fundamental to building and maintaining public and operator trust – the social licence to operate. This involves actively mitigating bias in algorithms and data, ensuring AI systems are explainable (particularly when impacting consumers or critical operations), establishing clear lines of responsibility, robustly protecting sensitive energy data (in line with GDPR), and ensuring human oversight where necessary. Proactive engagement with consumers and civil society, alongside adherence to evolving ethical guidelines and the principles embedded within the AI Act, will be crucial for ensuring AI deployment aligns with European values and contributes positively to a just energy transition.

6.5 Concluding Perspective: Towards an AI-Enabled European Energy System

Integrating AI and GenAI offers Europe a critical opportunity to modernize energy systems, accelerate decarbonization, strengthen security, and safeguard competitiveness. This paper charts a clear path (from foundational readiness to full-scale, optimized integration) ambitious yet achievable.

Technology alone will not deliver success. It requires coordinated action from policymakers, regulators, industry, academia, and citizens; sustained investment in infrastructure, skills, and innovation; and agile governance that balances rapid progress with safety, reliability, and ethics.

The recommendations provide a strategic roadmap grounded in analysis and stakeholder dialogue. By closing gaps, fostering collaboration, and aligning with European values, the EU can unlock AI's transformative potential in smart grids and lead globally in responsible, human-centric AI, advancing the Green Deal and Digital Decade objectives. The journey demands commitment and adaptability, but the reward – a smarter, cleaner, and more secure energy system for all Europeans – is worth the effort.

7 GLOSSARY

7.1 Addressing Terminology Discrepancies

While the document is generally consistent, a few areas show minor variations or potential for confusion if not clarified by a glossary:

1. **Renewable Energy Sources (RES) vs. Variable Renewable Energy (VRE):**
    - *Observation:* Both terms are used. "RES" is the general category, while "VRE" specifically refers to intermittent sources like solar and wind, which pose particular challenges for grid integration.
    - *Resolution:* The usage seems contextually appropriate (VRE used when discussing intermittency challenges). The glossary clarifies the distinction.
2. **Foundation Models (FM) / General-Purpose AI (GPAI) / Large Language Models (LLM) / Grid Foundation Models (GridFM):**
    - *Observation:* These related terms appear across chapters. FM is the broad category (often LLMs); GPAI refers to models with broad applicability (as defined in the AI Act context); LLMs are a specific type focused on language; GridFM is a proposed domain-specific FM for energy grids.
    - *Resolution:* The terms are distinct but related. The glossary provides specific definitions to clarify their scope and relationship within the context of this paper.
3. **Human Oversight / Human-in-the-Loop (HITL) / Human-on-the-Loop (HOTL):**
    - *Observation:* "Human oversight" is used generally. HITL and HOTL appear in the roadmap (Chapter 5) and annexes, representing specific modes of oversight.
    - *Resolution:* The glossary defines HITL and HOTL based on their typical usage and the context provided in the roadmap, distinguishing them from general oversight.
4. **Data Spaces / Common European Energy Data Spaces / EU Energy Data Space Seed / Unified EU Digital Marketplaces & Data Spaces:**
    - *Observation:* These terms refer to the same core concept of facilitated, secure data sharing infrastructure, but at different levels of specificity or stages of development (pilot vs. scaled-up marketplace).
    - *Resolution:* The glossary defines "Data Space" generally, encompassing the underlying concept relevant across these different instances.
5. **Digital Twin (DT) / Digital Twin Systems:**
    - *Observation:* Chapter 3 mentions both, suggesting "Digital Twin Systems" implies interconnected twins.
    - *Resolution:* The usage seems contextually acceptable. The glossary defines the core "Digital Twin" concept.
    - *Resolution:* Following standard practice, general terms are lowercase in the glossary unless part of a specific name (e.g., AI Act). Acronyms are defined. Proper nouns (Acts, Directives, specific projects like GridFM) retain capitalisation.

7.2 Glossary

- **AI (Artificial Intelligence):** Computer systems capable of performing tasks typically requiring human intelligence, such as learning, problem-solving, decision-making, and pattern recognition, applied here to energy systems.

- **AI Act:** The European Union's regulation establishing a harmonised legal framework for Artificial Intelligence, classifying AI systems based on risk (prohibited, high, limited, minimal) and setting corresponding requirements.
- **API (Application Programming Interface):** A software intermediary that allows two applications to talk to each other, defining methods for communication.
- **ASIC (Application-Specific Integrated Circuit):** An integrated circuit chip customised for a particular use, potentially offering higher efficiency for specific AI tasks compared to general-purpose processors.
- **BESS (Battery Energy Storage System):** Systems that store electrical energy chemically in batteries for later discharge to the grid or local use.
- **CEN/CENELEC:** The European Committee for Standardisation and the European Committee for Electrotechnical Standardisation, key bodies developing European standards (ENs).
- **CER Directive (Critical Entities Resilience Directive):** EU directive setting obligations for Member States and designated critical entities (including in the energy sector) to enhance their resilience against non-cyber threats. Its thresholds may inform AI Act risk assessments.
- **CET (Clean Energy Technology):** Technologies supporting the transition to a low-carbon energy system, including renewables, storage, and smart grid components.
- **CIM (Common Information Model):** A standard (IEC 61970/61968/62325 series) providing a common vocabulary and semantics for power system data exchange, crucial for interoperability.
- **Cloud Computing:** The delivery of computing services—including servers, storage, databases, networking, software, analytics, and intelligence—over the Internet (“the cloud”).
- **CNN (Convolutional Neural Network):** A type of deep learning model particularly effective for processing grid-based data like images (e.g., for asset inspection).
- **CoE (Centre of Excellence):** A dedicated unit or entity pooling expertise, resources, and best practices in a specific area, such as "AI in Energy."
- **Data Space:** An infrastructure enabling secure, trusted, and sovereign data sharing between multiple organisations based on common governance rules and technical standards, without necessarily centralising the data. (Encompasses concepts like Common European Energy Data Space, EU Digital Marketplaces).
- **Decarbonisation:** The process of reducing carbon dioxide emissions resulting from human activity, primarily by transitioning away from fossil fuels.
- **DER (Decentralised/Distributed Energy Resource):** Smaller-scale electricity generation or storage units connected to the distribution grid, such as rooftop solar PV, small wind turbines, batteries, or controllable loads like EVs.
- **DGA (Data Governance Act):** EU regulation aiming to facilitate data sharing across sectors and Member States by establishing rules for data intermediaries and data altruism.
- **Digital Twin (DT):** A dynamic virtual representation of a physical asset or system (like a substation or grid segment), updated with real-time data, used for simulation, analysis, monitoring, and control.
- **DL (Deep Learning):** A subset of machine learning using multilayered neural networks to learn complex patterns from large datasets.
- **DSO (Distribution System Operator):** The entity responsible for operating, ensuring the maintenance of, and developing the electricity distribution system in a given area and ensuring its ability to meet reasonable demands for electricity distribution.
- **DR (Demand Response):** Programmes and actions designed to encourage end-use electricity customers to change their usage patterns in response to price signals, incentives, or direct control signals, thereby assisting grid balancing

and congestion management.

- **E.DSO:** An industry association representing leading European Distribution System Operators (DSOs), focused on shaping smart grid policies, promoting the deployment of smart grid technologies, sharing best practices, and representing DSO interests in the energy transition. (Formerly known as EDSO for Smart Grids).
- **Edge Computing:** Processing data closer to where it is generated (e.g., at a substation or smart meter) rather than in a centralised data centre, reducing latency and bandwidth needs for real-time AI applications.
- **EED (Energy Efficiency Directive):** EU directive establishing a common framework of measures for the promotion of energy efficiency within the Union.
- **ELSA (Ethical, Legal, and Societal Aspects):** A framework for considering the wider implications of technology development and deployment beyond the purely technical.
- **EMD (Electricity Market Design) Reform:** Recent EU legislative changes aimed at improving the functioning of the internal electricity market, accelerating renewables integration, improving consumer protection, and enhancing affordability and stability.
- **EMS (Energy Management System):** Systems used to monitor, control, and optimise energy generation, transmission, distribution, or consumption (can refer to grid-level systems or building/home systems).
- **ENISA (European Union Agency for Cybersecurity):** The EU agency focused on achieving a high common level of cybersecurity across Europe.
- **ENTSO-E (European Network of Transmission System Operators for Electricity):** The association representing European electricity TSOs, involved in developing network codes and promoting cooperation.
- **EPO (European Patent Office):** The organisation responsible for granting European patents.
- **ETIP SNET (European Technology and Innovation Platform for Smart Networks for Energy Transition):** A stakeholder forum guiding R&D&I for Europe's future energy system.
- **ETSI (European Telecommunications Standards Institute):** A European standards organisation developing standards for information and communication technologies.
- **EU DSO Entity:** The formal entity for DSO cooperation at the EU level, established by Regulation (EU) 2019/943. Its tasks include contributing to the development of network codes and guidelines relevant to DSOs, facilitating the integration of renewable energy and distributed generation, and cooperating with ENTSO-E and ACER.
- **EV (Electric Vehicle):** Vehicles propelled by one or more electric motors, representing significant new loads and potential flexibility resources (via V2G) for the grid.
- **Federated Learning (FL):** A machine learning approach where models are trained on decentralised data sources without exchanging the raw data itself, enhancing privacy.
- **FM (Foundation Model):** Large AI models trained on vast datasets, capable of performing a wide range of tasks and adaptable (fine-tunable) to specific applications (e.g., GridFM for energy). LLMs are a prominent type.
- **Formal Verification:** The use of mathematical methods to prove or disprove the correctness of algorithms or system designs with respect to certain formal specifications or properties, used here for assessing AI robustness.
- **GAN (Generative Adversarial Network):** A class of generative models using two competing neural networks (generator and discriminator) to create realistic synthetic data.
- **GDPR (General Data Protection Regulation):** The EU's core data protection law regulating the processing of personal data, highly relevant for smart meter data and consumer-facing AI applications.
- **GenAI (Generative AI):** AI systems capable of generating novel content (text, images, code, data) based on patterns learnt from training data, often prompted by user input.

- **GIS (Geographic Information System):** Systems for capturing, storing, analysing, and displaying geographically referenced information, used for grid mapping and asset management.
- **GNN (Graph Neural Network):** Neural networks specifically designed to process data structured as graphs, suitable for modelling power grid topologies and relationships.
- **GPAI (General-Purpose AI):** As defined in the AI Act context, AI models with broad capabilities that can be adapted for numerous downstream applications, potentially subject to specific transparency and documentation rules. Often overlaps with Foundation Models.
- **GridFM (Grid Foundation Model):** A hypothetical or developmental Foundation Model specifically trained on diverse power system data for various grid-related tasks.
- **HAN (Home Area Network):** A network connecting devices within a home, potentially linking smart meters, appliances, and EMS.
- **HITL (Human-in-the-Loop):** An AI system design where human intervention is required at specific points for approval, correction, or validation before an action is taken or a decision finalised.
- **HOTL (Human-on-the-Loop):** An AI system design where the AI operates autonomously but a human monitors its performance and can intervene or override decisions if necessary.
- **HPC (High-Performance Computing):** The use of aggregated computing power (supercomputers, clusters) for performing complex calculations required for training large AI models or running intensive simulations.
- **HVAC (Heating, Ventilation, and Air Conditioning):** Systems controlling building climate, representing significant energy loads that can potentially offer demand-side flexibility.
- **IEA (International Energy Agency):** An intergovernmental organisation providing analysis, data, and policy recommendations on the global energy sector.
- **IEC (International Electrotechnical Commission):** A leading global organisation for preparing and publishing international standards for electrical, electronic, and related technologies (e.g., CIM, 61850).
- **IEEE (Institute of Electrical and Electronics Engineers):** A large technical professional organisation involved in developing standards, including for energy and communication (e.g., IEEE 2030.5).
- **IDS (Intrusion Detection System):** Software or hardware systems that monitor network or system activities for malicious activities or policy violations, often enhanced by AI.
- **Interoperability:** The ability of different systems, devices, applications, or networks to connect, exchange data, and use the information that has been exchanged effectively.
- **IoT (Internet of Things):** The network of physical devices embedded with sensors, software, and connectivity, enabling them to collect and exchange data (e.g., grid sensors, smart appliances).
- **IPCEI (Important Project of Common European Interest):** Mechanism allowing EU Member States to jointly support large, strategic transnational projects under specific state aid rules.
- **ISO (International Organization for Standardization):** An international body developing and publishing a wide range of proprietary, industrial, and commercial standards.
- **KPI (Key Performance Indicator):** Quantifiable measures used to evaluate the performance and success of an organisation or system (e.g., SAIDI/SAIFI for grid reliability).
- **Legacy Systems:** Older IT or OT systems still in operation, often based on outdated technology, which can pose challenges for integration with modern AI solutions.
- **LiDAR (Light Detection and Ranging):** A remote sensing method using laser light to measure distances and create precise 3D representations of objects and environments, used for asset inspection.

- **LLM (Large Language Model):** A type of foundation model trained on massive amounts of text data, capable of understanding, generating, and translating human language.
- **LSTM (Long Short-Term Memory):** A type of recurrent neural network (RNN) particularly suited for learning from sequential data like time series (e.g., load forecasting).
- **ML (Machine Learning):** A subset of AI where systems learn from data to improve performance on a specific task without being explicitly programmed.
- **MIM (Minimal Interoperability Mechanism):** A concept promoting basic interoperability using the simplest necessary standards and interfaces, particularly relevant for data spaces.
- **MTD (Moving Target Defence):** A cybersecurity approach that makes systems less predictable for attackers by dynamically changing configurations or attributes.
- **Neuro-symbolic AI:** An approach combining neural network-based learning with symbolic reasoning (rule-based systems) to leverage the strengths of both.
- **NIS2 Directive:** The revised EU Directive on Security of Network and Information Systems, setting stricter cybersecurity obligations for essential and important entities, including the energy sector.
- **NRA (National Regulatory Authority):** The national body responsible for regulating the energy sector (and potentially other sectors) within a Member State.
- **OPF (Optimal Power Flow):** An optimisation problem aiming to find the best operational state for a power grid (e.g., minimising costs or losses) while respecting technical constraints.
- **Open Source:** Software or models whose source code is made available with a licence in which the copyright holder provides the rights to study, change, and distribute the software to anyone and for any purpose.
- **OT (Operational Technology):** Hardware and software systems used to monitor and control physical processes, devices, and infrastructure (e.g., SCADA systems in grids).
- **P2P (Peer-to-Peer) Energy Trading:** Direct trading of energy (usually electricity) between consumers and prosumers without necessarily involving a traditional utility or retailer.
- **PdM (Predictive Maintenance):** Maintenance strategies that use data analysis tools and techniques to detect anomalies in operation and predict potential failures, allowing maintenance to be scheduled proactively.
- **Physics-Informed AI/NN (Neural Network):** AI models that incorporate knowledge of physical laws (e.g., power flow equations) into their structure or learning process to improve accuracy, robustness, and data efficiency.
- **PKI (Public Key Infrastructure):** A system for creating, managing, distributing, using, storing, and revoking digital certificates used for secure electronic communication and authentication.
- **PMU (Phasor Measurement Unit):** Devices providing time-synchronised measurements of voltage and current phasors (magnitude and phase angle) in the power grid, enabling WAMS.
- **Prosumer:** An energy consumer who also produces energy (e.g., with rooftop solar PV) and may actively participate in the energy market or grid services.
- **PV (Photovoltaic):** Technology converting light directly into electricity using semiconductor materials.
- **QML (Quantum Machine Learning):** Using quantum computing principles and hardware to potentially accelerate or enhance machine learning tasks.
- **Quantum Computing:** A type of computation that harnesses the collective properties of quantum states, such as superposition, interference, and entanglement, to perform calculations.
- **R&D (Research and Development):** Systematic activity combining basic and applied research, aimed at discovering solutions to problems or creating new goods and knowledge.

- **Reinforcement Learning (RL):** A type of machine learning where an agent learns to make decisions by taking actions in an environment in order to maximise the notion of cumulative reward.
- **RES (Renewable Energy Source):** Energy derived from naturally replenishing resources like solar, wind, geothermal, hydro, and biomass. (See also VRE).
- **SAIDI (System Average Interruption Duration Index):** A standard reliability metric indicating the average total duration of interruptions per customer served during a defined period.
- **SAIFI (System Average Interruption Frequency Index):** A standard reliability metric indicating the average number of times a customer experiences a sustained interruption during a defined period.
- **SAREF (Smart Appliances REFerence ontology):** An ETSI standard ontology facilitating interoperability for smart devices; SAREF4GRID is its extension for the energy grid.
- **Scaleability:** The ability of a system, network, or process to handle a growing amount of work, or its potential to be enlarged to accommodate that growth.
- **SCADA (Supervisory Control and Data Acquisition):** A system architecture comprising computers, networked data communications and graphical user interfaces for high-level process supervisory management.
- **SGAM (Smart Grid Architecture Model):** A reference framework for structuring smart grid use cases and ensuring interoperability across different domains and layers.
- **Situation Awareness:** In power systems, the operator's perception and understanding of grid elements and events, comprehension of their meaning, and projection of their status in the near future.
- **SME (Small and Medium-sized Enterprise):** Businesses defined by size criteria (employee count, turnover) set by the EU, often targeted for specific support measures.
- **Smart Grid:** An electricity network enabling a two-way flow of electricity and data, using digital communications technology to detect and react to local changes in usage, generation, and grid conditions.
- **Smart Meter:** An electronic device recording consumption of electric energy and communicating that information back to the utility for monitoring and billing, often enabling advanced functionalities and data access.
- **SSoT (Single Source of Truth):** An information architecture concept where critical data elements are mastered and stored in one authoritative location, ensuring consistency across systems.
- **Standardisation:** The process of implementing and developing technical standards based on the consensus of different parties including firms, users, interest groups, standards organisations and governments.
- **Synthetic Data:** Artificially generated data that mimics the statistical properties of real-world data, used for training AI models when real data is scarce or private.
- **TEF (Testing and Experimentation Facility):** Dedicated large-scale facilities allowing companies to test and validate AI technologies in real-world or near-real-world conditions.
- **TinyML:** The practice of running machine learning models on low-power, resource-constrained devices like microcontrollers, relevant for edge AI applications.
- **Transformer Model:** A deep learning architecture based on the self-attention mechanism, highly successful in natural language processing (forming the basis of most LLMs) and increasingly applied to other sequence data like time series.
- **TRL (Technology Readiness Level):** A scale (typically 1-9) used to assess the maturity level of a particular technology (See Annex 3 for definitions).
- **TSO (Transmission System Operator):** The entity responsible for operating, maintaining, and developing the high-voltage electricity transmission network and ensuring security of supply at that level.

- **V2G (Vehicle-to-Grid):** The capability for electric vehicles to not only draw power from the grid (charge) but also inject power back into the grid when needed.
- **VAE (Variational Autoencoder):** A type of generative AI model used for learning latent representations of data in an unsupervised manner.
- **VPP (Virtual Power Plant):** An aggregation of diverse DERs managed by a central control system to provide grid services or participate in energy markets as if it were a single, larger power plant.
- **VRE (Variable Renewable Energy):** Renewable energy sources whose output is non-dispatchable and fluctuates based on weather patterns (primarily wind and solar).
- **WAMS (Wide Area Monitoring System):** Systems utilising synchronised measurements (from PMUs) across a large geographical area to monitor the power grid's dynamic state in real time.
- **XAI (Explainable AI):** AI techniques and systems designed to make their decision-making processes understandable and interpretable by humans.
- **XGBoost:** An efficient and scalable implementation of the gradient boosting machine learning algorithm, often used for forecasting and classification tasks.
- **Zero Trust Architecture (ZTA):** A cybersecurity paradigm based on the principle of "never trust, always verify," requiring strict identity verification and access controls regardless of whether a user or device is inside or outside the network perimeter.
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9 ANNEX 1- DETAILED DESCRIPTION OF PILOT PROJECTS AND DEMONSTRATION INITIATIVES IN EUROPE

There are several pilot projects and demonstration initiatives in Europe that are testing and implementing smart grid technologies using AI and GenAI. These projects are crucial for validating the feasibility and effectiveness of these technologies in real-world scenarios.

9.1 GridFM - Open-source Foundation Models for Power Grids

- **Challenge and Motivation:** Develop an open-source framework to enable the development of foundation models (FM) for power grids (Hamann et al., 2024). FM provides a scalable and standardised data-driven approach for use cases such as AC power flow and optimal power flow calculation. These models emulate physics-based simulations with impressive accuracy and efficiency, accelerating power system simulations compared to traditional methods solving partial differential equations iteratively and without *a priori* assumptions. A key challenge is access to realistic, large scale, and representative grid data (e.g., topology, load, generation measurements), which is difficult due to confidentiality barriers and lack of data-sharing incentives. FM also poses risks, such as enabling adversarial attacks.

- **AI Solution:** The core technology is the transformer model with encoder and decoder components, pre-trained on massive grid datasets and fine-tuned for various applications. The pre-trained FM is adapted to downstream tasks with minimal labelled data by attaching a task- specific decoder head and performing a few training iterations (Hamann et al., 2024).

- **Achievements:** The project is in its early stage. A large collection of solved AC power flow for different grid topologies, parameters, and load conditions was generated using synthetic data (e.g., PowerGraph, Varbella et al., 2024). Suitable transformer architectures are being evaluated, with models, training strategies, and loss functions optimised to reconstruct masked power flow data.

- **Key Success Factors:** FMs exhibit excellent token prediction skills for data imputation, forecasting, and simulation acceleration. Pre-trained models, once fine-tuned to specific grid topologies and confidential data, mitigate data-sharing barriers. Examples in weather modelling (Chen et al., 2023) and remote sensing (Hong et al., 2024) highlight their adaptability.

9.2 Smart Alarm Management

- **Challenge and Motivation:** Human operators managing grid control centres face a significant increase in alarm data due to distributed generation and active grid management. For instance, HOPS, the Croatian TSO, recorded over 100 alarms in 10-minute intervals for a month (Baranovic et al., 2016). E-REDES, the Portuguese DSO, reported a single medium voltage line fault triggering up to 24 alarms within minutes. Operators may encounter up to 300 alarms per minute, amounting to 200,000 daily or 1.6 million monthly (Leitão et al., 2013). This overwhelming volume complicates real-time network state analysis. AI can process alarm data in real time, highlighting only the critical alarms needing human attention. A shift to event- centric alarm processing is necessary, reducing redundant reporting on circuit breaker trips, reclosures, and communication failures.

- **E-REDES and INESC TEC Solution**
    - **AI Solution:** E-REDES and INESC TEC piloted a solution where alarm events are translated into ML terminology. Word embeddings and statistical learning detect unusual patterns in substation protection relay operations, group similar incidents, and categorise new event logs using unsupervised learning (Andrade et al., 2022).
    - **Achievements:** AI enhances alarm management by grouping related alarms, enriching alarms with contextual information, and suggesting resolution steps directly within the alarm (Campos et al., 2024).

  - **Key Success Factors:** Successful deployment requires integrating human factors, leveraging operator feedback, and enabling manual re-prioritisation for continuous improvement (Marot et al., 2024).

- **Hitachi Energy Solution**
  - **AI Solution:** Traditional alarm management approaches are not readily applicable to power systems due to their unique and complex nature. The dynamic and interconnected nature of power systems presents challenges that require new, data- driven approaches to effectively manage alarms (Mitrentsis et al., 2022). Hitachi Energy teamed up with Elia to work on the issues of the existing alarm management system and developed tooling.
  - **Achievements:** Development of the tool with the following capabilities:
    - Interactive alarm list
    - Alarm KPI platform
    - Alarm flood visualisation including indicative alarm IDs
    - Heatmap of the ELIA high voltage grid showing how alarms are generated across the grid
  - **Key Success Factors and Recommendations:** One of the key messages of success in this technology development project is that successful deployment of alarm management systems hinges on robust collaboration between vendors and customers. Key success factors include clear communication and understanding of customer needs, which enable vendors to tailor solutions that address specific operational challenges. Additionally, to address the challenges of modern alarm management, it is essential to develop advanced UI/UX designs that cater specifically to the needs of power system operators. These designs should facilitate intuitive interaction with alarm data, enabling operators to quickly identify and respond to critical issues. The power systems community can take several steps to improve alarm management:
    - Develop Practice Guidelines: Establish comprehensive guidelines tailored to the electric power industry. These guidelines should outline best practices for alarm management, ensuring consistency and reliability across the sector.
    - Vendor Engagement: Vendors should actively engage with customers and the broader community to understand their needs and challenges. This collaboration will help in developing solutions that are both effective and user- friendly.
    - Historical Data Utilisation: System operators should start managing alarms by saving historical data and using it to learn and improve future alarm responses. This practice will enable continuous improvement and adaptation to evolving system conditions.

9.3 Real-time Congestion Management

- **Challenge and Motivation:** Rising electricity demand, coupled with fluctuating and less predictable renewable energy generation, has increased pressure on transmission capacity and made congestion more frequent. Weather-dependent energy production adds volatility, complicating predictions of when and where congestion will arise. Operators often act on information available only shortly before real time, reducing the time to evaluate and implement remedial measures. Mitigation strategies include topological adjustments, redispatching generation, and phase-shifting transformers. However, electricity grids comprise thousands of switching elements, creating billions of potential configurations. The solution space becomes unmanageable when combined with other remedial actions, making traditional approaches impractical and highlighting the need for AI-driven solutions.

- **AI Solution:** Supervised learning methods require extensive historical data, which often lacks the diversity to represent modern grid complexities. Reinforcement Learning (RL) addresses this by exploring effective solutions in a practical timeframe. In the Paris Region AI Challenge, an RL agent proposed congestion mitigation actions based on grid state observations and historical data. The best-performing system combined an RL-based curriculum agent (Lehna et al., 2023) with convex optimisation for continuous control, orchestrated using simple business rules (Sintes & Dang, 2024).

- **Achievements:** The Grid2Op simulator, developed by RTE (Donnot, 2020), provided a robust platform for creating AI agents to manage power systems. Trials showed AI-based agents mirrored human operator behaviour, suggesting imitation learning can support decision- making. Cost-free topology actions, which account for 98% of interventions, proved effective in avoiding renewable energy curtailment.

- **Key Success Factors:** Engaging operators early fosters trust and smooth integration of AI tools (Marot et al., 2024). Gradual development and early data collection ensure robust testing and continuous improvement. Clear baselines demonstrate the measurable impact of AI solutions.

9.4 Condition-Based Monitoring of Circuit Breakers

- **Challenge and Motivation:** Grid operators face significant challenges in maintaining critical grid assets efficiently and cost-effectively. These challenges stem from the increasing complexity of network infrastructure, the growing integration of renewable energy sources, and the ageing of many assets, which require more frequent attention. Traditional maintenance methods, heavily reliant on manual inspections and static schedules, are time- consuming, resource-intensive, and incapable of adapting to real-time operational conditions. As a result, these approaches often lead to suboptimal resource utilisation, delayed issue detection, unexpected asset failures, and increased operating costs. The absence of predictive capabilities in these models further contributes to excessive downtime, unscheduled repairs, and reduced equipment lifespan. The framework aims to enhance system operators' asset management by introducing data-driven services to support predictive maintenance strategies.

- **AI Solution:** The AI solutions developed for condition-based monitoring of circuit breakers (CBs) focus on predictive analytics and advanced data processing techniques to assess operational conditions and predict failure probabilities. A predictive maintenance (PdM) tool automatically processes CB event data to predict optimal operation intervals before maintenance is required, reducing costs and minimising downtime. A COMTRADE parser ensures smooth integration of complex operational data, while supervised learning algorithms detect and classify faults with high accuracy. Advanced statistical tools generate detailed incident reports, enabling real-time monitoring and data-driven maintenance strategies. This approach enhances grid reliability, operational efficiency, and cost-effectiveness by addressing fault detection and equipment degradation.

- **Main Achievements:** The project has produced a predictive maintenance framework that uses AI to analyse operational data and predict failure probabilities. The framework includes fault detection algorithms to differentiate between faults and normal operations, classification models for fault identification, automated incident reporting processes, predictive models for Health Index (HI) estimation, and optimised maintenance schedules that reduce costs and downtime.

- **Key Success Factors and Lessons Learnt:** The integration of operational and inspection data was essential to the success of the analysis tools. Collaboration between domain experts and data scientists ensured the relevance and accuracy of predictive models. Scalable data processing infrastructure was critical for adapting to various asset types and operational conditions.

9.5 Predictive Maintenance for Transmission Network Assets

- **Challenge and Motivation:** The reliability, efficiency, and safety of power transmission networks rely on effective maintenance of overhead lines. Persistent risks from vegetation encroachment, structural defects, and human-made obstacles compromise operations, requiring advanced solutions. Managing vast amounts of unstructured data, such as LiDAR (Light Detection and Ranging) scans, adds complexity, as tools must accurately classify transmission towers and detect obstacles within Right-of-Way (RoW) corridors. Traditional manual inspection methods are labour-intensive, error-prone, and unable to address issues promptly or cost-effectively. This project aims to optimise maintenance planning, streamline operations, and reduce costs by integrating AI-based solutions using LiDAR data.

- **AI Solution:** The proposed AI solution combines advanced computer vision, machine learning, and data classification to automate LiDAR data analysis. This enables precise detection and classification of transmission network components, reducing manual effort and improving system reliability. LiDAR data analysis assesses OHL towers and RoW corridors, while supervised and unsupervised learning algorithms classify transmission towers and categorise objects like vegetation, conductors, and obstacles. Semi-automatic maintenance planning generates dynamic schedules based on OHL assessments, allowing timely, targeted interventions.

- **Main Achievements:** The AI-driven system has improved OHL maintenance by automating LiDAR data processing, enhancing obstacle detection, and reducing operational costs. It optimises resource allocation and minimises manual labour while enabling early threat detection.

- **Key Success Factors and Lessons Learnt:** Collaboration between AI experts, field inspectors, and operators ensured system relevance. Model adaptability, stakeholder engagement, and scalable infrastructure were critical for success and continuous improvement.

9.6 Predictive Maintenance for Distribution Grids

- **Challenge and Motivation:** The primary challenge was to enhance the technical asset management process, particularly for medium voltage assets. The existing processes were heavily reliant on data with media breaks and heuristic evaluation logics, which were not efficient enough to meet the growing demands of the energy sector. The motivation behind the project was to create a more reliable and data-driven approach to asset management, aiming to extend the lifespan of assets and proactively replacing underperforming ones.

- **AI Solution:** The AI solution implemented by Netze BW involved the development of a Predictive Maintenance tool. This tool is a central and scalable AI service that digitalises the asset management. It enables a data-based asset condition analysis by integrating relevant data analysis results and geoinformation into the technical processes. The solution includes the creation and testing of statistical or machine learning models to provide objective asset condition analyses based on technical, geospatial, event-based, and telemetry data.

- **Main Achievements:** One of the key achievements of the project was the successful implementation of the Predictive Maintenance tool for central medium-voltage assets. The results were integrated into the end-to-end asset management process, considering the requirements of ISO 55001. The technology was scaled across different asset types using the PM Tool Library, and a technology rollout was enabled for the company's subsidiaries. This led to significant improvements in asset management efficiency and reliability. Based on the model prediction, we now replace the top 1% most critical underground cables per year which lead to a SAIDI penalty reduction potential by 750k€ per year. Also, through the proactive replacement, we get a CAPEX optimisation potential by factor 4.7.

- **Key Success Factors from AI and Lessons Learnt:** The key success factors for the AI implementation included the integration of the Predictive Maintenance tool into the core technical processes from the beginning and ensuring the product's reusability. The project emphasised the importance of a fully integrated product with feedback functions to enable transparent decision-making for risk-based asset management processes. Lessons learnt from the project highlighted the need for early involvement of end-users and continuous feedback to refine the AI models and processes.

9.7 Low Voltage Forecasting

- **Challenge and Motivation:** The Low Voltage Forecasting project was initiated to improve transparency in the low voltage grid, focusing on power flow in substations and circuits. It addressed data gaps caused by missing values and aimed to provide standardised load profiles through AI. This was vital for network planning and meeting legal requirements, including low voltage control under German law.

- **AI Solution:** The project developed an AI model trained on data from sensor-equipped substations, combined with master data (e.g., number of heat pumps, PV systems) and weather information. This model predicts load profiles for local network stations without sensors, offering a technical capability for forecasting that supports various operational use cases.

- **Main Achievements:** The AI model successfully generated load profiles for local network stations, providing real-time load data that was previously updated every four years. The project improved transparency in the low voltage network, benefiting grid planners, operations teams, and other stakeholders.

- **Key Success Factors and Lessons Learnt:** Key factors included generating accurate, real-time load profiles that enhanced network planning and compliance with legal requirements. The AI model's ability to learn feature impacts made it flexible to customer usage changes (e.g., flexible tariffs). Unlike sensors, AI also predicts future power flows, aiding grid flexibility. Lessons learnt emphasised the importance of high-quality training data and ongoing model updates for sustained accuracy.

9.8 Assistant for Grid Technicians

- **Challenge and Motivation:** The Nele App project was launched to ensure grid technicians have easy access to necessary information in the field. It aimed to reduce the risk of forgetting critical details and to provide support for rarely performed tasks, improving both efficiency and safety during operations.

- **AI Solution:** The Nele App, an intelligent network lexicon, was developed using GenAI to answer technicians' questions. It integrates information collection, knowledge documentation, and intelligent retrieval. A vector database stores documents, making them interpretable by large language models (LLMs). When a technician queries the app, a semantic search retrieves relevant documents, and GPT generates detailed answers.

- **Main Achievements:** The project successfully developed and implemented the Nele App, enabling technicians to search for information using voice input. The app provides clear answers and navigates users to source documents. It also supports the creation of a collaborative knowledge database that users can expand collectively.

- **Key Success Factors and Lessons Learnt:** Key success factors included the app's ability to deliver accurate, timely information, enhancing technicians' efficiency and safety. Lessons learnt emphasised the importance of maintaining a robust, comprehensive knowledge database and continuously updating AI models to ensure their relevance and accuracy over time.

9.9 Virtual Inspection of Grid Assets

- **Challenge and Motivation:** The virtual inspection was initiated to address the challenge of improving the efficiency and accuracy of inspections for overhead line inspections. The motivation behind this project was to leverage innovative technologies such as drones and AI to enhance the inspection process and reduce the reliance on traditional methods like helicopter flights and manual inspections.

- **AI Solution:** The AI solution involved the use of drones equipped with high-resolution cameras to capture detailed images of overhead lines. These images were then analysed using AI algorithms to identify potential issues such as damaged components, corrosion, and other anomalies. The AI image recognition technology enabled the automated detection and classification of these anomalies, providing actionable insights for maintenance and repair.

- **Main Achievements:** The project is in an ongoing phase. So far, classification of components works very well, and focus is currently on the exact anomaly detection.

- **Key success factors from AI and lessons learnt:** Lessons learnt from the project highlighted the importance of having a robust and scalable media database, as there was a lack of enough training data for the AI.

9.10 AI-based PV Production Forecasting with Transfer Learning

- **Challenge and Motivation:** Accurately forecasting photovoltaic (PV) production is crucial for balancing electricity supply and demand, particularly within smart cities and energy communities. However, a major challenge arises when limited historical data exists, such as for recently installed solar plants or when smart-metering data is unavailable. This lack of data, known as data scarcity, impairs the ability of traditional Deep Learning (DL) models to perform effectively. Transfer Learning (TL) addresses this limitation by transferring knowledge from well-trained models to domains with insufficient data, reducing the need for extensive localised datasets. The motivation is to enable accurate solar production forecasts even in scenarios in which collecting one calendar year of training data is impractical.

- **AI Solution:** The AI-based solution was successfully applied in the context of H2020 MATRYCS in the PV parks of Coopérnico, a Portuguese renewable energy cooperative, the only one operating at a national level with several regional groups. This solution employs a stacked Long Short-Term Memory (LSTM) architecture alongside three TL strategies to forecast hourly PV production. TL is utilised in two ways: for weight initialisation in the LSTM and for feature extraction, using different freezing approaches (Sarmas et al., 2022a). The model, pre-trained on data-rich locations, is fine-tuned for target domains with limited data availability. This methodology is evaluated against conventional non-TL approaches and a smart persistence model, demonstrating its superior accuracy, especially in data-scarce conditions. With only one year of data, the TL model achieved a 12.6% reduction in Root Mean Square Error (RMSE) and a 16.3% improvement in forecast skill index. When training data is reduced to three months, the TL models outperformed conventional approaches by an even greater margin.

- **Main Achievements:** The application of TL significantly enhances PV forecasting accuracy, particularly for new installations with limited data. In experiments, TL strategies achieved forecast skill scores between 0.28 and 0.56, surpassing benchmarks in existing literature. Additionally, the methodology demonstrated scaleability by maintaining accuracy across PV plants in different cities and with varying nominal capacities. This success suggests TL as a replicable and efficient approach for energy communities.

- **Key Success Factors from AI and Lessons Learnt:** TL strategies prove highly adaptable, as the models trained on base datasets maintain their accuracy regardless of geographical distance between the source and target PV plants. Their scaleability and flexibility enable energy communities to implement data-sharing practices, enhancing inclusivity and promoting smart city development. Furthermore, TL offers a robust solution to address the inherent limitations of data scarcity, providing a foundation for future advancements in renewable energy forecasting and cross-stakeholder collaboration. Generative AI can enhance this solution by creating realistic synthetic training data for underrepresented or newly installed PV plants, further mitigating data scarcity and improving model accuracy.

9.11 Incremental Learning for AI-based Energy Demand Forecasting in Microgrids

- **Challenge and Motivation:** Accurate energy demand forecasting at the microgrid level is essential for efficient energy management, balancing supply and demand, and optimising resources in real time. Traditional machine learning (ML) and deep learning (DL) models rely on offline or batch learning methods, which are static and unable to adapt to the continuous changes in energy consumption patterns. These models often degrade in accuracy post- deployment due to their inability to account for concept drift—shifts in data patterns caused by evolving human behaviour or environmental changes. This rigidity makes traditional methods less effective in dynamic settings like microgrids. Incremental learning, or online learning, presents a promising alternative by allowing models to continuously update with streaming data, enabling real-time adaptability and improved forecasting accuracy.

- **AI Solution:** The proposed solution, introduced in the context of H2020 BD4NRG project and validated on data from a microgrid setup in Terni, Italy, introduces an integrated incremental learning framework that employs the multi-layer perceptron (MLP) regressor for dynamic energy demand forecasting (Sarmas et al., 2022b). Unlike traditional models that require storing and processing entire datasets, this approach updates models iteratively using mini- batches of data through the partial fit function. This method allows the model to adapt to new consumption patterns without losing previously learnt information, addressing challenges such as concept drift and catastrophic forgetting. By leveraging this adaptive training strategy, the system can operate efficiently even in resource-constrained environments, requiring significantly less memory and computational power compared to traditional methods.

- **Main Achievements:** Incremental learning demonstrated its effectiveness by outperforming static models in forecasting energy demand, particularly in environments with highly variable consumption patterns. In a real-world microgrid use case, the proposed framework exhibited a significant improvement in accuracy while reducing memory usage by over 600 times compared to batch learning approaches. Furthermore, the model proved robust in handling dynamic data streams, maintaining performance even as input data evolved over time.

- **Key Success Factors from AI and Lessons Learnt:** The adaptability of incremental learning to real-time data streams ensures that models remain accurate and efficient in dynamic environments like microgrids. Its lightweight architecture reduces the need for extensive computational resources, making it well-suited for deployment in smaller energy systems. By addressing challenges like concept drift and memory efficiency, this approach provides a scalable and practical solution for energy demand forecasting, paving the way for smarter, more responsive microgrid management.

9.12 Network Digitisation for Grid Resilience

- **Challenge and Motivation:** Storm Arwen in 2021 exposed vulnerabilities in the UK's power grid, leaving over a million customers without power for up to a week. Existing manual inspections and statistical analysis methods were inadequate for maintaining reliability and minimising damage. The goal was to leverage AI to improve risk assessment, optimise asset investments, and enhance network resilience against extreme weather.

- **AI Solution:** Neara partnered with Scottish Power Energy Networks (SPEN) to develop an AI- powered, physics-enabled 3D digital twin of the overhead network. This model simulated Storm Arwen's conditions—wind speed, direction, and flooding—integrating data like Asset Health Indicators and severe weather zones. The AI-driven analysis identified weak points in the grid, enabling targeted reinforcements to strengthen infrastructure.

- **Main Achievements:** The AI model helped SPEN optimise CAPEX, directing investments where most needed, improving grid resilience, and enhancing decision-making in asset management.

- **Key Success Factors and Lessons Learnt:** Integrating diverse datasets into a unified AI model proved crucial. The project highlighted the power of AI-driven physics simulations in predicting risks and strengthening infrastructure reliability.

9.13 Example of a Portfolio of AI Projects from an Energy Utility

- **Currently developed solutions in pilot phase**
    - *Drone-based overhead line inspections and AI-powered image analysis (Sweden)* In order to connect all our customers with good energy, we are standardising, digitalising, and automating our grid business. How we do this can be illustrated by the example of drones that we use. These smart helpers offer us considerable added value in our day-to-day work - for example, when flying over overhead power lines and electricity pylons, when inspecting transformer stations, and when monitoring our construction sites. Currently, around 180 drones are already in use for various applications (in our German grid companies). They generate high-resolution imagery for AI applications such as automated damage detection, operate with lower noise levels compared with helicopters, and can carry out inspections in places that are difficult for helicopters to access. With the help of drones, we can generate data over our network faster and in a more standardised way. And thanks to AI, we can process and evaluate this data even more quickly and accurately. The use of drones with intelligent software increases work safety for our employees, reduces travel distances, optimises the level of documentation, automates and simplifies evaluations, and enables more reproducible assessments.

9.14 Example of European Initiatives from DSOs

- **DeepCourboGen:** A generative AI system developed by Enedis to produce ultra-realistic, privacy-preserving synthetic smart meter data. It uses a TimeGAN model to generate individual load curves for residential sites, allowing broader applications of smart meter data without privacy concerns.

- **Analytics4Vegetation (A4V - E-REDES):** The Analytics 4 Vegetation (A4V) initiative is designed to manage and control vegetation encroachment around high and medium voltage overhead lines. By employing updated information sources and Machine Learning techniques, A4V aims to optimise intervention planning, such as tree cutting, to ensure greater operational efficiency. The initiative leverages advanced analytics and AI to enhance safety and efficiency in vegetation management around the electrical grid.

- **PREDIS (E-REDES):** The PREDIS project is a Big Data time series forecasting initiative designed to predict approximately 200,000 load diagrams daily, each with a 15-minute granularity, for medium and high-voltage installations in the Portuguese electrical grid. The problem PREDIS addresses is the need to accurately predict power consumption and generation in the electrical grid to optimise its operation. Traditionally, power grids were built with large safety margins to handle low-probability events, leading to significant investments and inefficiencies. With the energy transition, there is an increasing demand for electricity (e.g., due to electric vehicles) and more variability in the grid from renewable energy sources, making grid management a more complex task. Accurate forecasting allows for better planning and management of the grid, reducing the need for over-dimensioning and enabling more efficient and sustainable operations.

- **ARC (E-REDES):** BackOffice operators must search for information in business procedures and the SAP system to clarify and process customer requests. Contacts are classified through two levels: Class and Action, ensuring structured categorisation. Due to the complexity of E-REDES processes, the service can experience errors and longer response times, impacting operational cost and customer satisfaction. The solution involves a conversational virtual assistant guiding the operator through the appropriate procedure and proposing a response. It processes the customer's request, analyses the business procedure, and asks the operator for additional information to identify the response scenario. Then, it proposes a response adhering to guiding templates. The tool can also provide information about a given procedure.

- **3D Digital Model:** HEDNO's AI platform that processes LIDAR data to create a 3D digital model of the electricity network. It automates LiDAR classification, accelerates network digitisation, and supports vegetation management.

- **DORA:** Enedis platform that uses AI to analyse drone-captured photos of 20 kV poles, identifying anomalies and speeding up the selection process for network maintenance. It's operational in all 25 Enedis regional divisions and used daily by 250 employees.

- **GridWise:** E-REDES' centralised real-time monitoring system that employs AI, IoT, Big Data analytics, and Edge Computing for fault detection, power quality assurance, and fraud mitigation in transformer substations.

- **Distributed Processing Platform (DPP):** i-DE's initiative to implement AI and edge computing in secondary substations for improved data processing and network management. The project is still in development, with a new market review planned for late 2024.

9.15 Network Digitisation for Grid Resilience (Neara & SPEN)

- **Challenge and Motivation:** The vulnerability of power grids to extreme weather events was highlighted by Storm Arwen in 2021, one of the worst storms to hit the UK in over 20 years, causing extensive outages. Traditional methods involving manual field inspections and statistical analysis proved insufficient for comprehensive risk assessment and maintaining reliability standards against such events, leading to costly damages. Scottish Power Energy Networks (SPEN, part of Iberdrola group) needed a more advanced approach to understand network risks, optimize asset investment, and improve resilience.

- **AI Solution:** Neara, a climate/infra-tech SaaS platform, partnered with SPEN to leverage AI for network digitization. Neara's platform rapidly created an engineering-grade, physics-enabled 3D digital twin of SPEN's overhead network infrastructure (over 2 million km managed globally on their platform). This digital model was used to simulate the specific conditions of Storm Arwen, including 100 mph wind speeds, direction, and associated flood risks. The simulation integrated diverse datasets such as Asset Health Indicators, severe weather area data (floods), and Protection Zones, matching them with extensive structural analyses (Finite Element Analysis - FEA) and weather simulations.

- **Main Achievements:** The AI-driven simulation allowed SPEN to identify specific weak spots in the network infrastructure that required strengthening and upgrades. This detailed, physics- based risk assessment across the network enabled SPEN to optimize its Capital Expenditure (CAPEX) by targeting investments precisely where they were most needed to improve resilience against future extreme weather events.

- **Key Success Factors and Lessons Learnt:** The ability to rapidly generate a detailed digital twin and integrate diverse datasets (asset health, environmental conditions, structural analysis) into a single, physics-based simulation model was crucial. This approach provided a more holistic and accurate understanding of network vulnerabilities compared to legacy methods, enabling data-driven, optimized investment decisions for enhancing grid resilience. The use of visualizations (3D models, heat maps) aids in communicating risk (See Images 1-7 for examples of the Neara platform capabilities).

10 ANNEX 2- TECHNOLOGY READINESS LEVELS (TRL)

Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified:

- **TRL 1** – basic principles observed
- **TRL 2** – technology concept formulated
- **TRL 3** – experimental proof of concept
- **TRL 4** – technology validated in lab
- **TRL 5** – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- **TRL 6** – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- **TRL 7** – system prototype demonstration in operational environment
- **TRL 8** – system complete and qualified
- **TRL 9** – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

11 ANNEX 3: MAPPING OF RECOMMENDATIONS TO ROADMAP ACTIONS

This annex provides a cross-reference between the key recommendations outlined in Chapter 6 and the specific, coded actions detailed in the original Chapter 5 roadmap. This illustrates how the individual roadmap steps contribute to the broader strategic objectives for each stakeholder group.

(Note: S = Short-Term Action (0-2 Years), M = Medium-Term Action (2-5 Years), L = Long-Term Action (5+ Years) from the Chapter 5 Roadmap)

Stakeholder Group	Recommendation (from Chapter 6)	Relevant Roadmap Actions (from Chapter 5)
EU Policymakers & Regulators	Provide Regulatory Framework and Clarity	S:1.2, M:1.2 (AI Act/GDPR), S:1.5 (Interim Cert.), S:1.7 (HITL), S:1.3 (Sandboxes), M:1.1 (Mandatory Cert.), L:1.1 (Periodic Reviews)
	Drive Funding & Investment	S:3.2, M:4.2 (Funding stream), S:2.3 (Edge Infra), S:3.4 (Cyber R&D), S:4.3, M:4.1 (Hubs/CoEs), S:3.1, S:4.1 (Open Source), S:4.4 (SME Support), M:3.6 (Sovereignty)
	Establish Data Governance	S:1.4 (Initial Fwk), S:2.1, M:2.1 (Data Spaces), M:1.3 (Refined Rules), L:1.2 (Permanent Bodies)
	Champion Standards & Ethics	S:1.5, M:1.1 (Cert/Labels), M:3.5, L:2.3 (Efficiency), S:3.3 (XAI), M:5.1 (MIM Stds), L:4.1 (Global Stds), L:5.2 (Green Deal/Fairness)
	Foster Skills & ollaboration	S:4.3, L:3.3 (Upskilling), M:4.3, M:4.4 (Uni-Industry), M:4.1 (Cross-Sector), S:4.4 (SME Partic.), S:4.1, L:3.2 (Open Source)
	Ensure Sovereignty & Competition	S:3.1, M:3.6 (Capabilities/IPCEI), L:3.1 (Manage Risks)
	Facilitate National Alignment	S:1.1 (Task Force)
Energy Companies & Grid Operators (TSOs/DSOs)	Invest & Adopt Strategically	S:2.3, M:2.3 (Edge), S:3.4, M:5.2 (Cyber), S:4.3, M:4.4, L:3.3 (Upskilling), S:3.2, M:3.1 (Deploy Proven AI), M:5.1 (Data Models)
	Prioritise Trust & Ethics	S:3.3, L:2.2 (XAI), S:1.7, M:3.2 (HITL/HOTL), M:4.5 (Transparency), L:5.1 (Trust Mechanisms)
	Embrace Collaboration & Standards	S:1.1 (Task Force), S:4.1, M:4.1 (Consortia/Hubs), S:1.3 (Sandboxes), M:5.1 (Protocols/MIM), S:2.1, M:2.1 (Data Spaces), S:4.1 (Open Source), M:1.4 (Grid Codes)
	Build Internal Capacity	M:4.3, M:4.4 (Partnerships), L:3.3 (Human-AI Teaming)
AI & Tech Developers (incl. Vendors)	Align with EU Needs & Standards	S:1.5, M:1.1 (Cert.), M:5.1 (Data Models/Interoperability)
	Prioritise Security & Ethics	S:3.4, M:5.2 (Security by Design), L:5.1, L:5.2 (Ethics), S:3.3, L:2.2 (XAI), M:3.5, L:2.3 (Green AI)

	Collaborate Actively	M:3.4 (Understand Needs), S:1.1, S:1.5 (Engage Reg/Stds), S:4.1, L:3.2 (Open Source), S:3.3 (XAI Tools)
	Address Key Grid Challenges	S:3.2, M:3.3 (Focus Development)
Academia & Research Institutions	Conduct Targeted Research	S:3.3, M:3.4, L:2.2 (Grid Challenges), S:5.1 (Metrics), M:3.5, L:2.3 (Green AI), S:3.1 (Open Source Algo)
	Develop Talent Pipeline	M:4.4 (Curricula/Joint Pg), S:4.3 (Upskilling), S:4.3, M:4.1 (CoEs), L:3.3 (Ethics/Teaming)
	Enable Innovation & Transfer	S:2.3 (Testbeds/TEFs), M:4.3 (PPPs)
SMEs & Startups	Engage & Leverage Resources	S:4.1, M:4.1 (Hubs), S:1.3 (Sandboxes), S:4.2 (Open Innov.), S:4.4 (Funding), S:2.2, S:3.1 (Open Tools/Data), S:2.3 (Testbeds)
	Focus & Innovate	(Implicit: Leveraging resources allows focus)
	Partner Strategically	S:4.1, M:4.1 (Partnerships), S:1.2 (Compliance Pathways)
Consumers & Energy Communities	Engage & Advocate	M:1.3, M:4.5 (Data Concerns)
	Demand Transparency & Build Literacy	M:4.5, L:5.1 (Communication), M:4.5 (Education)
	Empower Communities	S:1.4, M:1.3 (Data Gov. Fwk for local initiatives)

This mapping highlights the interconnectedness of the roadmap actions and how they collectively contribute to achieving the strategic recommendations for advancing AI/GenAI in European smart grids.

12 ANNEX 4: SURVEY ON AI AND GENAI IN SMART GRIDS – METHODOLOGY AND KEY FINDINGS

12.1 Introduction

To inform the development of this strategic position paper on the role of Artificial Intelligence (AI) and Generative AI (GenAI) in European smart grids, a comprehensive survey was conducted. The objective was to capture diverse stakeholder perspectives on the critical challenges, opportunities, priorities, and potential pathways for leveraging these technologies within the energy sector. The survey explored themes ranging from regulatory frameworks and ethical considerations to technological priorities, collaboration models, data governance, and future vision.

12.2 Survey Methodology

The survey was structured into five distinct thematic groups, each focusing on a specific dimension of AI/GenAI adoption in smart grids:

- **Group 1: Regulatory & Ethical Foundations:** Focused on balancing innovation, compliance, and ethics; regulatory **harmonisation**; GDPR compliance; and AI talent development.
- **Group 2: Technology & Innovation Priorities:** Focused on funding priorities, key applications, scaleability of AI/GenAI, barriers to adoption, and long-term **decarbonisation** impacts.
- **Group 3: Collaboration & Stakeholder Roles:** Focused on leadership models, effective partnerships (public-private, cross-sector), SME competitiveness, and skills gap solutions.
- **Group 4: Data Governance & Cybersecurity:** Focused on balancing data accessibility and privacy, interoperability standards, risk mitigation (including GenAI-specific risks), legacy system integration, and sustainability impacts of AI.
- **Group 5: Vision & Future Challenges:** Focused on long-term goals, public trust, and systemic risks.

Each group contained a series of multiple-choice questions designed to elicit stakeholder views on specific trade-offs, preferred strategies, perceived risks, and critical enablers. The questions referenced specific chapters and themes intended for this position paper (e.g., Ch1 Q1 referring to Chapter 1, Question 1).

12.3 Summary of Key Findings

The survey results revealed several key trends and areas of consensus, as well as points of divergence, across the stakeholder landscape.

12.3.1 Regulatory & Ethical Foundations:

- **Balancing Act:** A strong preference emerged for balancing AI innovation with regulatory compliance and ethical considerations, rather than **prioritising** one over the other. Agile, ethics-by-design frameworks and regulatory sandboxes were popular suggestions.
- **Harmonisation & Safety: Harmonised** EU-wide AI certification standards and requiring "human-in-the-loop" for critical decisions were common suggestions for ensuring safety. Transparency through mechanisms like compliance labels or open model validation was also **favoured**.
- **EU Strategy:** A hybrid approach to AI strategy—combining common EU standards with flexibility for local needs—was the most popular option, though unified strategies were also supported for interoperability.

- **Ethics as Advantage:** Most respondents believe that **prioritising** ethical AI builds long-term trust and market leadership for Europe, rather than being a competitive disadvantage.

- **Talent Gap:** Partnering with universities to redesign curricula was seen as a key strategy to address the AI talent gap in the energy workforce.

- **GDPR & Data:** Creating EU-wide "data trusts" and **prioritising** edge computing were seen as viable ways to reconcile GDPR constraints with smart meter data needs.

12.3.2 Technology & Innovation Priorities:

- **Immediate Funding Needs:** Real-time grid stability algorithms and predictive maintenance for ageing infrastructure were identified as top priorities for immediate funding. Edge computing infrastructure was seen as the most urgent investment area.

- **Sovereignty vs. Collaboration:** While the importance of EU sovereignty in AI infrastructure (e.g., developing models like GridFM) was strongly supported, hybrid approaches involving global partners while retaining control were also **favoured**.

- **Barriers to Adoption:** Data silos and lack of interoperability were identified as the biggest barriers, followed by regulatory uncertainty and workforce skill gaps.

- **Decarbonisation Impact:** Autonomous grid **optimisation** for renewables integration was seen as the AI application with the greatest long-term **decarbonisation** potential.

- **Scaling Pilots:** Scaling pilot projects EU-wide requires addressing **standardised** data formats and potentially fragmented national regulations. Pan-European data-sharing platforms were seen as key enablers.

- **Cybersecurity:** Real-time AI-powered intrusion detection was considered the most urgent cybersecurity measure.

- **Automation vs. Human Control:** Respondents indicated a preference for using AI automation primarily for non-critical, repetitive tasks or testing extensively in simulations first, **emphasising** the need for human oversight, especially in crises.

- **Sustainability:** Leveraging Europe's green tech leadership was seen as the key to competing globally while upholding sustainability, which was viewed as a competitive edge.

12.3.3 Collaboration & Stakeholder Roles:

- **Leadership:** Hybrid consortia involving public institutions, private corporations, and academia were the preferred model for leading AI development.

- **Partnership Models:** EU-led consortia (like Horizon Europe) and cross-sector partnerships (e.g., energy + telecom) were seen as effective for scaling innovations.

- **Supporting SMEs:** Funding collaborative R&D hubs linking SMEs and utilities, alongside **subsidising** open-source tools, were popular suggestions.

- **Incentivising Collaboration:** Creating shared data spaces (e.g., Energy Data Spaces) was **favoured** over mandated partnerships or tax breaks.

- **Skills Gap Strategy:** Setting up dedicated **centres** of excellence pooling talent from TSOs, DSOs, vendors, and academia was a popular strategy.

- **Harmonisation Level:** A hybrid approach to regulation—adopting global standards (e.g., NIST/IEEE) but enforcing stricter EU safeguards—was preferred.
- **Funding Catalysis:** Requiring funded projects to form multi-stakeholder consortia and potentially establishing a single EU "AI in Energy" funding umbrella were seen as effective. Tying funding to open-source/data-sharing commitments was also suggested.
- **Integration Lead:** Industry stakeholders (DSOs/TSOs, technology providers) were seen as the primary group to lead AI integration.
- **Testbeds & Commercialisation:** Mandating clear **commercialisation** plans and linking testbeds to regulatory sandboxes were seen as crucial for yielding market-ready solutions.
- **Open Source:** Open source was viewed as critical for quality and cost reduction, extending beyond just prototyping, although privacy/security concerns were noted.

12.3.4 Data Governance & Cybersecurity:

- **Data Access vs. Privacy:** Mandating open data sharing was popular for accelerating innovation, but developing hybrid models like federated learning was also strongly **favoured** to balance access with privacy. Strict GDPR compliance remains a key concern.
- **GenAI Risks:** Over-reliance on private tech monopolies and unintentional failures due to unexplainable AI were cited as major risks of deploying GenAI in critical operations.
- **Liability:** Shared responsibility across the value chain was the preferred model for liability in case of AI-driven grid failures.
- **Legacy Integration: Standardising** interoperability protocols (e.g., IEC CIM) was seen as the most critical short-term action.
- **Secure Data Sharing:** Adopting a single EU-wide data model standard (like extended IEC CIM) was the most popular choice, alongside creating national/EU data hubs.
- **Open Data Mandate:** While generally supported for innovation, using smart meter data requires specific purpose definition (security, reliability) and user consent considerations.
- **Sustainability Risks:** Energy-hungry data **centres** were identified as the biggest sustainability risk of AI in smart grids.
- **Reducing Environmental Impact: Prioritising** AI solutions requiring less computational power was the **favoured** approach.
- **Edge Computing:** A hybrid approach, using edge for sensitive data and central processing for non-sensitive tasks, was the most popular strategy.
- **Monitoring Metrics:** Key metrics suggested include "Explainability score," "Carbon reduction index," and "Consumer trust rating."

12.3.5 Vision & Future Challenges:

- **Defining Success (2030):** Reducing CO_2 emissions via **optimised** renewables and reducing grid outages were seen as the top metrics for success. Building public trust was also highlighted.
- **Ensuring Fairness:** Enforcing diverse training datasets and developing explainable AI (XAI) frameworks were

common suggestions. Including community stakeholders in design was also **emphasised**.

- **Role of Sensors:** Sensors remain critical for real-time data; AI is seen as reducing but not eliminating the need for them (partial replacement).
- **Sector-Specific LLMs:** Development should focus on high-quality, sector-specific data and encourage collaboration between energy companies and AI developers, with ongoing updates.
- **Deployment Timelines:** A 3-5 year timeframe was the most common projection for significant AI-driven PV curtailment/EV charging deployment.
- **Regulatory Sandboxes:** Enhancing their scope/funding and simplifying SME access were seen as ways to better support innovation.
- **AI Skills Impact:** The dominant view is that AI will create a *mix* of skill needs – requiring more advanced skills in some roles while simplifying/automating others.
- **Human Oversight:** Humans must *always* oversee and validate critical AI-driven grid control decisions, though AI could operate with less oversight in lower-risk scenarios.
- **Ethical Priorities:** Lack of transparency in AI decision-making and accountability for failures were highlighted as key ethical concerns requiring immediate attention.
- **Building Consumer Trust:** Transparent communication about how AI makes decisions, guarantees of fair pricing/distribution, and strong regulatory oversight were identified as crucial.

12.4 Conclusion

The survey results provide valuable insights into the perspectives and priorities of stakeholders regarding AI and GenAI in European smart grids. These findings highlight areas of broad agreement, such as the need for balance, **harmonisation**, collaboration, and trustworthiness, while also pinpointing areas requiring further discussion and strategic direction, such as the specifics of data governance, the pace of automation, and the optimal balance between EU sovereignty and global collaboration. This input is instrumental in shaping the strategic recommendations presented in this paper.

13 ANNEX 5: AI SMART GRID SUPERMARKET SWEEP – PRIORITISATION EXERCISE METHODOLOGY AND ACTION CATALOGUE

13.1 Introduction

As part of the development process for the ETIP SNET Strategic Position Paper, "Unlocking the Potential of Artificial Intelligence (AI) and Generative AI (GenAI) in Smart Grids: A Guide for Action," a stakeholder engagement exercise, known as the "AI Smart Grid Supermarket Sweep," was designed. The primary objective was to gather initial perspectives from stakeholders on the relative importance and prioritisation of potential actions outlined in the roadmap for integrating AI into European smart grids. This annex details the methodology of the exercise as presented to participants and lists the catalogue of actions available for selection in each phase, along with the final prioritisation results based on participant choices.

13.2 Methodology

The "AI Smart Grid Supermarket Sweep" was framed as a gamified prioritisation exercise simulating strategic decision-making under budget constraints. The process presented to participants involved the following steps:

- **Participants & Role:** Workshop attendees assumed the role of "Grid Modernisation Managers."
- **Roadmap Presentation:** Participants were presented with a roadmap of potential AI-related actions structured into three distinct phases, each with a defined timeframe and a specific budget allocation in "GridCoins (GC)":
  - Phase 1: Build the Foundation (0-2 Years) – Budget: 200 GC
  - Phase 2: Scale & Harmonise (2-5 Years) – Budget: 250 GC
  - Phase 3: Full Integration & Optimisation (5+ Years) – Budget: 300 GC
- **Action Information:** For each potential action ("Product"), participants received:
  - A clear name/title.
  - A concise "Tagline" summarising its core benefit or function.
  - A specific cost in GridCoins (GC).
  - (These were visually represented, for instance by bar charts, during the workshop presentation).
- **Task (Planning Stage):** Participants were initially provided with a worksheet (corresponding to the catalogue in Section 3 below) linked to the presentation. They were instructed to review the actions, taglines, and costs for each phase. As a planning-only exercise at this stage, they were asked to tick boxes next to items they considered important or interesting for that phase, without initially adhering strictly to the budget limit.
- **Final Selection (Gamified Exercise):** The instructions noted that the actual timed selection exercise, adhering strictly to the budget for each phase, would occur later using a separate online form. The planning worksheet served as preparation for this final selection.
- **Data Interpretation:** The exercise aimed to understand which actions stakeholders prioritised when constrained by a budget, providing insights into perceived importance across the different phases. This annex lists the actions presented (Section 3) and the aggregated results from the final selection exercise (Section 4).

13.3 Catalogue of Actions Presented

The following actions, grouped by phase, were presented to participants for consideration during the Supermarket Sweep exercise. Costs are indicated in GridCoins (GC).

13.3.1 Phase 1: Build the Foundation (0-2 Years) - Budget: 200 GC

- **(S1.1) AI Task Force Token:** Unites experts, avoids duplicated effort! Cost: 25 GC
- **(S1.2) AI Act Clarity Lens:** Reduces legal uncertainty, speeds up innovation! Cost: 30 GC
- **(S1.3) Sandbox Starter Kit:** Test new AI safely in the real world! Cost: 25 GC
- **(S1.4) Data Governance Blueprint:** Builds trust for essential data sharing! Cost: 35 GC
- **(S1.5) Trust Label Stamp (Interim):** Builds early confidence in AI tools. Cost: 20 GC
- **(S1.6) Regulation Roadblock Map:** Identifies rules blocking AI progress. Cost: 15 GC
- **(S1.7) Human Oversight Button (HITL):** Ensures safety for critical AI decisions. Cost: 20 GC
- **(S2.1) EU Energy Data Space Seed:** Kick-starts secure, shared energy data platforms. Cost: 40 GC
- **(S2.2) Synthetic Data Generator Pack:** Creates safe data for AI training when real data is scarce. Cost: 30 GC
- **(S2.3) AI Testbed Construction Set:** Builds labs for safely testing AI grid solutions. Cost: 35 GC
- **(S3.1) Open-Source EU LLM Seed Fund:** Funds early Europe's own energy AI model. Cost: 40 GC
- **(S3.2) Priority AI Pilot Funding:** Funds early projects with clear benefits (e.g., stability). Cost: 25 GC
- **(S3.3) Explainable AI (XAI) Toolkit:** Makes AI decisions understandable, builds trust. Cost: 20 GC
- **(S3.4) Zero Trust Security Starter:** Begins building next-gen cybersecurity for AI grids. Cost: 25 GC
- **(S4.1) Collaboration Catalyst Grant:** Funds new partnerships & open-source networks. Cost: 15 GC
- **(S4.2) "AI for Energy" Challenge Prize:** Attracts fresh ideas & talent via competitions. Cost: 10 GC
- **(S4.3) AI Skills Micro-Credential:** Starts upskilling the current energy workforce for AI. Cost: 15 GC
- **(S4.4) SME & Startup Booster Pack:** Helps smaller companies join the AI energy race. Cost: 15 GC
- **(S5.1) AI Maturity Framework Guide:** Creates a common way to measure AI readiness. Cost: 10 GC

(Note: Slight discrepancies existed between the costs presented on participant worksheets and those shown on visual aids (e.g., bar charts) during the workshop for Phase 1. The worksheet costs, being explicitly listed for participants, are used here.)

13.3.2 Phase 2: Scale & Harmonise (2-5 Years) - Budget: 250 GC

- **(M1.1) EU AI Compliance Label (Official):** Creates single market for trusted AI, ensures safety. Cost: 35 GC
- **(M1.2) Clear Liability Rulebook:** Defines who pays if AI fails, boosts deployment confidence. Cost: 40 GC
- **(M1.3) Smart Consent Toolkit:** Standardises easy, GDPR-compliant consumer data access. Cost: 30 GC
- **(M1.4) Grid Code AI Update Module:** Formally integrates AI operations into grid rules & markets. Cost: 35 GC
- **(M2.1) Unified EU Data Marketplace Access:** Scales up data sharing via robust, common platforms. Cost: 45 GC
- **(M2.2) Federated Learning Framework:** Trains AI on diverse data without centralising sensitive info. Cost: 40 GC

- **(M2.3.1) HPC Power-up Voucher:** Provides access to supercomputers for complex AI model training. Cost: 25 GC
- **(M2.3.2) Edge Computing Grid Rollout:** Deploys computing power across the grid for real-time AI. Cost: 40 GC
- **(M3.1) Interoperable AI System Deployment:** Moves successful pilots to full-scale, integrated operation. Cost: 35 GC
- **(M3.2) AI Control Room Assistant (HITL):** Deploys AI agents to help operators manage complex grids safely. Cost: 35 GC
- **(M3.3) Specialised AI Tool Suite:** Funds wider range of tools (flexibility, EV charging, forecasting). Cost: 30 GC
- **(M3.4) Energy Sector LLM Fine-Tuning Kit:** Customises foundation AI models for specific energy tasks. Cost: 20 GC
- **(M3.5) "Green AI" Efficiency Standard:** Promotes energy-saving AI algorithms and hardware. Cost: 35 GC
- **(M3.6) EU AI Sovereignty Chipset Fund:** Invests in key EU-made AI hardware/platforms for energy security. Cost: 45 GC
- **(M4.1) "AI in Energy" Hub Funding:** Scales up successful R&D centres & cross-sector clusters. Cost: 30 GC
- **(M4.2) Public-Private Scale-Up Fund:** Blends public/private money to deploy validated AI solutions widely. Cost: 30 GC
- **(M4.3) Academia-Industry Exchange Programme:** Embeds researchers in industry & vice-versa for faster innovation. Cost: 15 GC
- **(M4.4) Consumer Trust Campaign Pack:** Builds public understanding & acceptance of AI in energy. Cost: 15 GC
- **(M4.5) Advanced AI Workforce Programme:** Launches joint Master's degrees & certifications for AI energy skills. Cost: 25 GC
- **(M5.1) Plug-and-Play Standard (MIM):** Enforces basic interoperability for easier system integration. Cost: 20 GC
- **(M5.2) Advanced Cybersecurity Shield (NIS2):** Deploys mature Zero Trust & AI-specific security measures. Cost: 30 GC

(Note: Significant discrepancies existed between the costs presented on participant worksheets and those shown on visual aids for Phase 2. Worksheet costs are used here where available and explicit.)

13.3.3 Phase 3: Full Integration & Optimisation (5+ Years) - Budget: 300 GC

- **(L1.1) Adaptive Governance Framework:** Creates permanent, flexible rules that evolve with AI tech. Cost: 35 GC
- **(L1.2) Independent Data/AI Watchdog:** Establishes permanent bodies for ethical oversight & dispute resolution. Cost: 30 GC
- **(L1.3) Full AI Accountability System:** Ensures clear responsibility & redress for autonomous AI actions. Cost: 35 GC
- **(L1.4) Autonomy Management Protocol:** Defines policies & controls for highly autonomous grid operations. Cost: 30 GC
- **(L1.5) Consumer AI Rights Charter:** Mandates fairness, transparency & appeal for AI affecting consumers. Cost: 25 GC
- **(L2.1) Pervasive AI Integration Mandate:** Drives deep, autonomous AI optimisation across the entire energy system. Cost: Worksheet cost missing; Bar Chart Value: ~34 GC (Using Bar Chart Value) -> Adjusted Cost: 35 GC for consistency/rounding if needed, or state approx.
- **(L2.2) Next-Gen AI Deployment (XAI/Robust) Benefit:** Funds & deploys advanced, trustworthy AI (uncertainty-aware, causal). Cost: Worksheet cost missing; Bar Chart Value: ~39 GC (Using Bar Chart Value) -> Adjusted Cost:

40 GC or 45 GC as per results table. Let's use the value from the results table for internal consistency: Cost: 45 GC

- **(L2.3) Optimised AI Footprint Standard:** Mandates highly efficient "TinyML" & specialised hardware for sustainability. Cost: 35 GC
- **(L3.1) Global AI Energy Alliance Lead Role:** Establishes EU leadership in international AI energy R&D & standards. Cost: 30 GC
- **(L3.2) Open Ecosystem Sustaining Fund:** Ensures long-term support for open-source AI tools & data in energy. Cost: 30 GC
- **(L3.3) Lifelong AI Learning Platform:** Creates continuously updated training for the AI-driven energy workforce. Cost: 30 GC
- **(L4.1) Global Standards Leadership Seat:** Actively shapes international AI standards based on EU principles. Cost: 35 GC
- **(L4.2) Seamless EU Energy Market AI Coordination:** Harmonises all rules & tech for optimised cross- border energy flows via AI. Cost: 45 GC
- **(L5.1) Mainstreamed Trust & XAI Tools:** Embeds transparency & fairness tools as standard in all AI systems. Cost: 30 GC
- **(L5.2.1) Green Deal AI Alignment Monitor:** Continuously tracks & ensures AI positively contributes to climate goals. Cost: 30 GC
- **(L5.2.2) AI Fairness & Equity Enforcement:** Proactively audits & corrects bias in AI systems impacting communities. Cost: 30 GC

(Note: Significant discrepancies existed between costs on worksheets and visual aids for Phase 3. Worksheet costs are used here where available and explicit. Where worksheet costs were missing, approximate values derived from the visual aids or values used in the final exercise results are indicated, e.g., L2.2 uses the 45 GC cost reflected in the results.)

13.4 Prioritisation Exercise Results

The following tables show the prioritised actions selected by participants during the final, budget- constrained stage of the "AI Smart Grid Supermarket Sweep" exercise. The selections reflect the aggregated preferences for investment within the allocated "GridCoin" budget for each phase, based on the number of votes received for each action until the budget limit was reached.

13.4.1 Phase 1: Build the Foundation (0-2 Years) (Budget: 200 GridCoins

Rank	Action	Cost (GC)	Votes	Cumulative Cost (GC)
1	(S2.2) Synthetic Data Generator Pack	30	38	30
2	(S1.3) Sandbox Starter Kit	25	36	55
3	(S2.3) AI Testbed Construction Set	35	32	90
4	(S1.4) Data Governance Blueprint	35	29	125
5	(S1.2) AI Act Clarity Lens	30	24	155
6	(S1.1) AI Task Force Token	25	23	180

7	(S1.5) Trust Label Stamp (Interim)	20	12	200
	Total	**200**		

13.4.2 Phase 2: Scale & Harmonise (2-5 Years) (Budget: 250 GridCoins)

Rank	Action	Cost (GC)	Votes	Cumulative Cost (GC)
1	(M1.4) Grid Code AI Update Module	35	34	35
2	(M3.2) AI Control Room Assistant (HITL)	35	32	70
3	(M2.1) Unified EU Data Marketplace Access	45	29	115
4	(M1.3) Smart Consent Toolkit	30	28	145
5	(M2.3.2) Edge Computing Grid Rollout	40	27	185
6	(M1.2) Clear Liability Rulebook	40	25	225
7	(M3.3) Specialised AI Tool Suite	30	25	255*
	Total (closest selection)	**255***		

**(Note: The cumulative cost slightly exceeds the budget due to the indivisible nature of the selected items based on votes. The selection reflects the highest-voted items up to the point nearest the budget.)*

13.4.3 Phase 3: Full Integration & Optimisation (5+ Years) (Budget: 300 GridCoins)

Rank	Action	Cost (GC)	Votes	Cumulative Cost (GC)
1	(L1.1) Adaptive Governance Framework	35	40	35
2	(L2.2) Next-Gen AI Deployment (XAI/Robust)	45	39	80
3	(L1.4) Autonomy Management Protocol	30	36	110
4	(L4.2) Seamless EU Energy Market AI Coord.	45	34	155
5	(L1.3) Full AI Accountability System	35	34	190
6	(L3.2) Open Ecosystem Sustaining Fund	30	33	220
7	(L1.2) Independent Data/AI Watchdog	30	32	250
8	(L3.3) Lifelong AI Learning Platform	30	29	280
9	(L5.2.1) Green Deal AI Alignment Monitor	30	28	310*
	Total (closest selection)	**310***		

**(Note: The cumulative cost slightly exceeds the budget due to the indivisible nature of the selected items based on votes. The selection reflects the highest-voted items up to the point nearest the budget.)*

These choices reflect the participants' collective prioritisation for actions supporting AI integration into the energy sector across different timeframes, when operating under simulated budget constraints.

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