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Inter-sectoral cooperation on cross-cutting issues

Impact of Artificial Intelligence on the digital and data transformation in the electricity sector

Note by the secretariat

Summary

The intermittent nature of renewable energy resources such as solar and wind amid the increasing demand from industrial and residential sectors, provide rationale for rethinking the existing energy systems through integration of demand side management, peak load shifting, deployment of short-term (few hours) and long-term (seasonal) energy storage options (such as batteries or clean fuels such as hydrogen). These require advanced digital technologies to maintain overall electricity grid balance, regulate frequency, and ensure stability. Digital technologies and data hold tremendous potential to accelerate clean energy transitions across the energy sector. Digitalization can help cut investment needs, reduce operational and fuel source related costs, improve efficiency and resilience, and reduce emissions.

Advances in digital technologies and services and increased connectivity accelerate the digital transformation of energy, particularly in electricity networks: over the period from 2015, a 50 per cent growth of grid-related investment in digital technologies is observed, expected to reach 19 per cent of total grid investment in 2023. There is an increasing focus on the distribution segment, which currently represents more than 75 per cent of the total digital spend on grid upgrades. There was a substantial upswing in investment in electric vehicle charging infrastructure market, valued at USD 25.83 billion globally in 2023 and expected to have a compound annual growth rate of more than one-fourth between 2024 and 2030.

Energy market participants have technologies to hand that provide real-time scheduling of all generation assets across large geographical areas to optimize the lowest cost to serve the demand. However, the sector is just starting to see the equivalent on the demand side, where a mainstream market is yet to take shape to provide the same level of optimization for renewable resources, storage, and the capacities that they offer at the consumer's (or prosumer's) end.

Further efforts by policymakers and industry will be necessary to realize the full potential of digitalization to accelerate clean energy transitions. This includes the implementation of enabling standards, policies and regulations that prioritize innovation and interoperability while addressing risks to cybersecurity and data privacy. This document, prepared by the Task Force on Digitalization in Energy, focuses on Artificial Intelligence as a technology to meet not only the energy trilemma goals of sustainable, affordable and secure energy, but also with the focus on the digital transition as it applies to the electricity sector of the energy value chain.

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I. Introduction

1. The rapid transformation of the energy sector through decarbonization, decentralization and digitalization bring opportunities and potential applications of emerging technologies for its planning and operation.[1] In particular, the rising potential of data and analytics have been fundamental in providing new optimization capabilities.[2]

2. Digitalization, through the declining costs of information and communication technologies, as well as advances in computing power, is leading to an increasing availability of diverse data types and advancements in analytics in the electricity sector. Coupled with more variable and non-dispatchable energy generation sources and the rising number of actors (as well as assets), across the sector increases complexity and drives demand for data analytics, including advanced methods in AI such as Machine Learning (ML) and Deep Learning (DL). Increasingly, the use of AI-based predictions and optimization is used across the whole value chain of energy sectors, may it be in the digital twin energy modelling, forecast of renewable electricity generation, weather-dependent gas consumption, or the availability of capacity in electricity, gas, and heating networks. The digitalization process unlocks multiple opportunities across the energy sector, including enhanced system operation and planning with advanced measurement and monitoring systems, holistic forecasts and predictive maintenance, demand-side opportunities, and optimized cybersecurity systems.

II. Artificial Intelligence – an overview

3. The technology known as AI is not new and dates back to the 1950s. It is an area of research that has fascinated computer scientists since Alan Turing proposed his Imitation Game in 1950. Whenever there is a transformative shift in the way society views the world (be it local or global), and especially when that shift is driven by technological changes, there is a need to understand the implications of that change. The emergence of AI is impacting an increasing range of sectors and is expected to affect global productivity, as well as equality and inclusion. The impacts of AI to the energy sector, both as an enabler and a new source of risks, require a thorough understanding of the relevant technology first. Based on that, it is possible to develop the required methods, evolve processes (including policy and regulation) and enhance constituent data sources in order to ensure its use towards sustainable energy systems.

4. The Organisation for Economic Co-operation and Development defines AI system as:

“[A] machine-based system that can, for a given set of human defined objectives, make predictions, recommendations, or decisions influencing real or virtual environments”[3]

5. A definition of AI system from the European Union Artificial Intelligence Act, reads:

“[A] machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments”[4]

6. Different AI systems vary in their levels of autonomy and adaptiveness after deployment. As such, Artificial Intelligence is a broad field that includes the areas of Machine Learning, Deep Learning, and more recently, Generative AI. Sometimes these terms are used interchangeably to describe systems with intelligent behavior, and their relative positions and key areas of application in the electricity sector are outlined in Figure I.

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[1] See: ECE/ENERGY/GE.6/2022/4−ECE/ENERGY/GE.5/2022/4.

[2] See: GEEE-9.2022.INF.3 and ECE/ENERGY/GE.6/2023/4−ECE/ENERGY/GE.5/2023/4.

[3] https://mneguidelines.oecd.org/RBC-and-artificial-intelligence.pdf

[4] https://www.europarl.europa.eu/doceo/document/TA-9-2024-0138-FNL-COR01_EN.pdf

Figure I
AI application areas for the electricity sector

Smart grid management and optimization

☐ Efficiency enhancement
☐ Reliability improvement
☐ Sustainability focus
☐ Real-time analysis
☐ Predictive maintenance
☐ Demand response

Smart generation services

☐ Output forecasting
☐ Renewable energy integration
☐ Storage solutions
☐ Plant optimization
☐ Capacity forecasts

Energy trading, market design and operations

☐ Market trend prediction
☐ Automated bidding
☐ Risk management
☐ Market transparency

Data management and data security

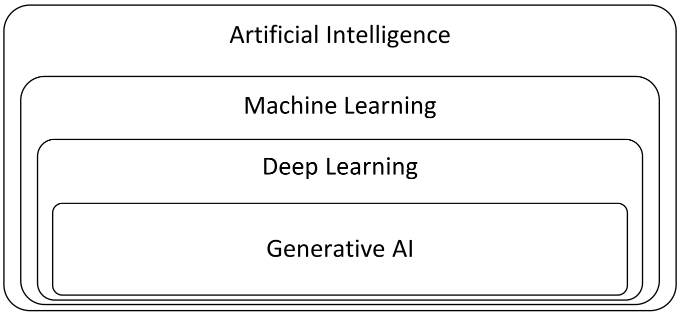
☐ Cybersecurity measures
☐ Operational data analysis
☐ System interoperability
☐ Compliance and governance

Delivered energy and managed services

☐ Rates design
☐ Balanced EV integration
☐ Demand forecasting
- Residential
- Commercial
- Industrial

7. AI may be classified in several ways, the families of algorithms used to develop, the applications for which AI is used, the abilities reproduced by the technology, as examples. The most adequate approach to classify AI may be driven by the objectives of the study in which it will be used.[5] Taxonomies of AI are presented in Figure II.[6]

Figure II
An illustration of the nested positions for the areas of Generative AI, DL, and ML within the field of AI



8. ML refers to a class of algorithms that use data to learn rules and find generalized predictive patterns. There are three main categories of ML and approaches are traditionally classified as:

(a) Supervised learning: algorithms that learn from a set of inputs and labelled outputs to make predictions, which can be either real-valued (regression) or discrete class labels (classification, e.g., predicting and forecasting energy demand);

(b) Unsupervised learning: algorithms that learn patterns, similarities, differences, and structures of unlabelled data (e.g., anomaly detection for predictive maintenance);

(c) Reinforcement learning: algorithms that learn the optimal result for a set of defined rules by exploring and evaluating different options and possibilities. This type of machine learning is akin to human trial and error (e.g., optimal operations for heating, ventilation, and air conditioning, HVAC, systems).

9. As the nature of learning systems continues to evolve, there are approaches that do not fit neatly into these three categories and require new descriptors (e.g., semi-supervised

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[5] Samoili, S., López Cobo, M., Gómez, E., De Prato, G., Martínez-Plumed, F., and Delipetrev, B., AI Watch. Defining Artificial Intelligence. Towards an operational definition and taxonomy of artificial intelligence, EUR 30117 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17045-7, doi:10.2760/382730, JRC118163.

[6] Sarker, I.H. Deep Learning: A Comprehensive Overview on Techniques, Taxonomy, Applications and Research Directions. SN COMPUT. SCI. 2, 420 (2021). https://doi.org/10.1007/s42979-021-00815-1

learning, self-supervised learning), but this categorization remains useful when considering the potential application space for AI.

10. DL is a branch of machine learning involving methods that use artificial neural networks. In this context, “deep” refers to the use of a network hierarchy containing multiple layers, which serve to transform data into useful abstract representations that are learned automatically. This is a key differentiation from traditional ML methods, which rely on human-identified data transformations.

11. Generative AI is one subset of DL that learns the structure and patterns of data to then generate new data that has similar characteristics. Generative AI algorithms typically utilize unsupervised or semi-supervised learning, which combines supervised and unsupervised approaches by using both labelled and unlabelled data. Semi-supervised learning is important in cases where obtaining adequate labeled data are prohibitively difficult or expensive, but large amounts of unlabeled data are easier to acquire.[7] Large Language Models (LLMs), like GPT, are a form of generative AI that learn the grammatical structure and contextual relationships between words by training on a vast amount of textual data. They are considered foundation models since they are trained on a wide range of data such that they can be applied across broad use cases.[8]

III. Applications of Artificial Intelligence in the electricity sector

12. As digitalization progresses and as organizations becomes more aware of the value of data generated by their connected assets, and in response transform their processes accordingly, AI can help deal with these large volumes of data and unlock value in the entire chain, from data creation to better decision-making.

13. The emerging needs brought about by the transformation of electricity systems, which could potentially be addressed through AI, may be grouped as follows:

(a) The increasing complexity of planning and operating electrical grids and electricity markets due to the higher number of actors and services. The current electric system was not designed to accommodate diversified and distributed power generation sources, particularly renewable generation with variable production patterns;

(b) The increasing utilization of sensors such as smart meters and internet-of-things (IoT) technology in grid assets lay the foundation for new business opportunities that extract value from collected data and, eventually, may improve energy efficiency and/or decrease costs for consumers and companies;

(c) The transformation of the functioning of electricity wholesale and retail markets. New market schemes, e.g., local markets or energy communities with peer-to-peer trading, require fast mechanisms for resource allocation and billing.[9]

14. In this document, the use of AI in electric grids is grouped into the following areas outlined in Figure I, i.e.:[10] Management and Optimization; Generation and Generation Services; Energy Trading, Market Design and Operations; Data Management and Data Security; Delivered Energy and Managed Services.

15. Balancing the electric grid is a complex and crucial task that ensures a stable and reliable supply of electricity. The primary goal is to ensure that electricity supply meets

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[7] https://www.ibm.com/topics/semi-supervised-learning

[8] https://cset.georgetown.edu/article/what-are-generative-ai-large-language-models-and-foundation-models/

[9] F. Heymann, H. Quest, T. Lopez Garcia, C. Ballif, M. Galus, ‘*Reviewing 40 years of artificial intelligence applied to power systems – A taxonomic perspective*’, Energy and AI, Volume 15, 2024, 100322, ISSN 2666-5468, https://doi.org/10.1016/j.egyai.2023.100322. https://www.sciencedirect.com/science/article/pii/S2666546823000940, last accessed 29 May 2024.

[10] See IRENA, ‘Artificial Intelligence and Big Data’ , 2019 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_AI_Big_Data_2019.pdf?rev=13acc202641648b1b1b24ea17dacd72e

demand in real-time and in planning hour-ahead, day-ahead, etc. This process is what is meant by “balancing” the grid.

16. In addition to real-time tools used to assist in this balancing, like Automatic Generation Control (AGC), load shedding, demand management, the accuracy of load and generation forecasts are of great importance. With the diversification of generation sources, including behind-the-meter, smart buildings, microgrids, etc., the traditional models used to forecast loads and generation are being challenged and, at times, no longer have the needed accuracy as these models were generally based on historical pattern matching. AI models can better deal with the increased complexity and more accurately predict load and generation and potential capacity. AI models could encompass various techniques including ML and DL as well as hybrid models that combine different AI approaches.

17. In network operation planning (hour-ahead, day-ahead, week-ahead, etc.) ML models could be used to optimize such planning thus reducing the time required and the risk of errors for such complex calculations.

Grid management and optimization

18. The power grid is a complex and living system and its complexity is increasing with the additions of non-traditional elements like Inverter-Based Resources (energy storage, solar-based generation, charging infrastructure for electric vehicles, etc.). Hence, it is becoming increasingly difficult for a human operator to recognize patterns, fully comprehend and decode what is happening especially when disturbances happen.

19. Using AI to optimize grid planning, design, operation, and performance monitoring and enhancing the capacity of existing transmission and distribution lines, as well as extending the lifetime of equipment, will be key to supporting the energy transition. As the electricity grid becomes ever more integrated and decentralized, the responsibility for system optimization is now at both the higher and lower voltage levels, and distribution grids become important to long-term planning. Maintaining grid stability and ensuring the security of supply can become more complex, hence automation of previously manual processes and system checks can have a significant impact.

20. While achieving a fully automated grid where no human intervention is needed remains a distant ambition, AI empowers human operators with real-time insight allowing faster and enhanced decision-making in network control. AI could assist grid operators by analysing huge amount of data and:

(a) Find the root cause of a disturbance and suggest course of action to remediate;

(b) Parse through alarms, determine and prioritize the root ones as opposed to those triggered by the cause;

(c) Predict potential problems before they occur and suggest mitigation actions;

(d) In case of large disturbances or blackout, AI could analyse many possible recovery scenarios and suggest optional actions based on levels of acceptable risk;

(e) Even in normal operations, AI could help optimize power flows on the grid and thus reduce congestion and/or costs.

21. In addition to these benefits in operations, AI could also contribute significantly to the processes associated with equipment maintenance and help reduce the administrative aspect of maintenance (move from systematic maintenance to maintenance based on real asset condition), improve assets management (move from asset replacement based on generic timeframe to replacement based on real asset condition) and optimize maintenance schedules for field crews. This segment needs to have comprehensive and well-managed data including equipment maintenance records, equipment and sensor data, market information, commodity updates, weather forecasts, images and videos.

Generation services

22. As more generation, like wind and solar, becomes dependent on weather, any improvement on the forecasting of these renewable resources will help both the operations and the market. AI models could be used to better predict the power output of, e.g., solar and

wind generation by learning from historical weather data, real-time measurements of wind speed and global irradiance from local weather stations, sensor data, and images and video data (for example, satellite images of cloud cover).

23. For system operators, accurate short-term generation forecasting can improve unit commitment, increase dispatch efficiency, and reduce reliability issues, and therefore reduce the operating reserves (including fuel) needed in the system.

24. In addition, these more accurate short-term forecasts could be used in conjunction with local battery storage, vehicle-to-grid (V2G) or with virtual power plants (VPPs), charging and discharging to help reduce curtailment of renewable and improve the reliability of the grid. It could also help renewable generators with their bid in the wholesale and balancing markets and help reduce penalties; and, when integrated with grid operations would give flexibility to grid operators and improve grid reliability and resiliency. AI can help operate these technologies in a more efficient way, maximizing renewable electricity integration (including the reduction of generation forecast errors), minimizing prices and maximizing returns for the owners of the storage system.

25. As grids are working to accelerate the integration of renewable energy systems to lower carbon emissions and provide both resiliency and consumer independence through optimized energy management and storage, AI can support the dynamic timescales needed to coordinate the generation, storage and dispatch of electricity when demand is at its peak. The complexity created by the integration of expensive generation, storage, management and communication systems can be mitigated by cooperating AI technologies as part of the integration processes.

26. To bring the full capability of a future grid, the cost of installations, inspections and interventions are expected to grow with the expansion of the grid networks (e.g., cables, poles, transformers, software, etc.). ML algorithms can help operators understand events as they happen in real-time, be able to respond just as dynamically and predict future events.

27. Holistic analysis of these integrated systems requires well documented records from construction planning and siting to asset management and failure reports, to maintenance schedules and power production forecasts. At the same time, such an analysis would favor the reliable and economic integration of renewable energy resources into the grid.

Energy trading, market design, and operations

28. AI is most effective at identifying patterns in large datasets and optimization processes. As the grid expands towards a distributed generation network, IoT devices that are promoting a new era of energy networks, are generating hundreds of terabytes of data every day.[11] Only a small percentage of this data, around 2 per cent, is kept on a consistent basis.[12] To open up a range of energy services including behind-the-meter (BTM) energy transactions, these distributed assets must play a part in grid balancing and power quality optimization.

29. Demand response (DR), while not a new market device, is still nascent in the energy market context, as most DR programmes are operated through a manual arrangement between grid operators and equipment owners. Grid-scale batteries can contribute to grid and ancillary services (e.g., frequency control) and when integrated with distributed and IoT devices, provide opportunities for new market designs such as VPPs.[13]

30. The speed and complexity of electricity markets, with intraday markets, capacity markets, and integration of new, often smaller, players, etc., are increasing.

31. AI could help to optimize close to real-time market operations by relying on large streams of data, enabling rapid response to market changes. Better prices forecasting, aggregation and more flexibility in trading could be gained from use of AI. As markets are

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[11] https://explodingtopics.com/blog/data-generated-per-day

[12] Volume of data/information created, captured, copied, and consumed worldwide from 2010 to 2020, with forecasts from 2021 to 2025, Petroc Taylor, 2023, Statista.com. https://www.statista.com/statistics/871513/worldwide-data-created/

[13] https://www3.weforum.org/docs/WEF_Harnessing_AI_to_accelerate_the_Energy_Transition_2021.pdf

evolving, AI could support the development of new algorithms, new trading schemes and new market rules.

32. The data required for these applications include equipment and sensor data, market, commodity, and weather data. VPPs can take advantage of other digital technologies, such as Blockchain.[14,15]

Data management and data security

33. Digitalization has been identified as the key to linking the various segments of the energy sector, into the most reliable, affordable and cleanest system possible.15 Digital technologies automate complex processes, coordinate disparate systems, facilitate information sharing across distributed systems, and play a fundamental role in driving a coordinated transition. However, without real-time data, advanced analytics and automation, the complex energy systems of the future will become impossible to manage. The key is to ensure that the datasets are continuously and consistently updated and managed in such a way to keep the integrity of the provenance.[16]

Delivered energy and managed services

34. Demand (load) forecast is the other end of the balancing equation. Accurate demand forecasting, together with renewable generation forecasting, can be used to optimize economic load dispatch as well as to improve demand-side management and efficiency.

35. Traditional historical load demand patterns are no longer considered as reliable being challenged by climate changes, customer behavior, inverter-based resources, distributed energy resources (DER), etc.

36. There is a great potential in combining better generation forecasts with power demand forecasts, to optimize both short-term and longer-term system planning and operation leading to more optimal operations (optimized transmission limits, reserves, etc.) and better long-term grid investments.

37. On the customers' end, AI applications can help understand consumption habits and contribute to better load management in view to optimize energy management of buildings, or even a community reducing their electricity bill and helping the grid operator and the asset planners. AI can be applied in the building stock context to optimize electricity usage in HVAC units by using sensor data and occupancy data to determine typical usage and to understand the building's thermal behaviors (potentially with smart home technologies).

38. In the context of industry and data centres, AI is being used to help optimize electricity consumption as well as predicting potential threats and vulnerabilities.[17] AI can be used to reduce power demand and to also shift peak demand to match times of high renewables generation, allowing demand to follow supply. AI can help to better schedule solar and wind power and storage to minimize curtailment and provide more local capacity.

39. Utilities (i.e., energy providers) can use AI for rate design and impact analysis of consumer rate classifications correlated to peak demand. As access to high-resolution data increases, dynamic pricing scenarios become less future ambition and more current state-of-the-practice.

40. As the grid continues to grow in complexity to become ever more a system of systems, there will be many more opportunities for AI to assist in managing that complexity.

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[14] https://unece.org/sites/default/files/2022-07/ECE_ENERGY_GE.6_2022_4_ECE_ENERGY_GE.5_2022_4_Final.pdf

[15] Khatoon, A.; Verma, P.; Southernwood, J.; Massey, B.; Corcoran, P. Blockchain in Energy Efficiency: Potential Applications and Benefits. Energies 2019, 12, 3317. https://doi.org/10.3390/en12173317

[16] Werder, K., Ramesh, B., & Zhang, R. (Sophia). (2022). Establishing Data Provenance for Responsible Artificial Intelligence Systems. ACM Transactions on Management Information Systems, 13(2), 22:1-22:23. https://doi.org/10.1145/3503488

[17] https://www.digitalrealty.com/resources/articles/data-center-ai

IV. Data for Artificial Intelligent applications

41. The energy sector relies significantly on data and this trend will accelerate, due to which both short-term strategic decisions and long-term operational efficiency are influenced. Infrastructure development, integration of renewable sources, and efficient energy flow management all benefit from data-driven insights.

42. The following details the pivotal aspects of data management in the energy industry, emphasizing the need for robust governance and innovative strategies for safeguarding and optimizing data assets.

Importance of data

43. In terms of operational optimization, data plays an important role as a catalyst for energy providers to fine-tune operational efficiency. This involves using real-time data to swiftly respond to fluctuations in energy demand and to optimize grid performance. Effective data utilization facilitates the development of agile energy distribution systems, vital for sustaining stability and efficiency in energy supply.

44. Data plays a pivotal role in facilitating seamless integration of renewable energy sources into the grid. Energy systems can adeptly manage the variability and intermittency of renewable energy sources through leveraging data, ensuring stable supply of energy.

45. For example, an intensive research and development activities are ongoing in the high 500-1500oC temperature demanding industrial sectors to develop energy storage technologies (compressed carbon dioxide, volcanic rocks, chemical conversion energy storage), which is deemed to replace the use of fossil fuels with renewable energy. AI is one of the most important constituent parts which assess industrial energy demand and renewables intermittence and decides on the load shift and optimal energy storage based on the renewable energy surplus and / or electricity price in the market.

46. Data analysis provides support for informed decision-making on critical sector activities including policy development, risk mitigation, and future investment planning. This depth of insight enhances flexibility and resilience amid evolving energy landscapes. Data-driven decisions aid in forecasting energy demands and adjusting strategies accordingly.

Privacy and data protection

47. The increasing digitization of energy systems introduces significant privacy concerns, particularly with the widespread deployment of smart meters that track detailed consumption data. While beneficial for efficiency, these technologies pose risks related to personal privacy and data security. Smart meters, while enhancing operational insights, raise questions about the privacy of individual energy consumption patterns. As energy systems become more interconnected and data-driven, safeguarding consumer privacy becomes paramount.

48. Energy companies are required to adhere to stringent data protection laws such as the General Data Protection Regulation (GDPR). These regulations mandate the safeguarding of consumer data, ensuring privacy and protecting against unauthorized data breaches. Compliance with these regulations is not only a legal obligation but is also critical for maintaining consumer trust and credibility. To comply with these regulations, energy companies must implement advanced security measures, conduct regular audits, and ensure that all data handling practices are transparent and secure. These measures are essential to protect sensitive data from cyber threats and to maintain the integrity of energy systems. By investing in robust cybersecurity protocols and transparent data management practices, energy providers can mitigate risks and build resilience against potential data breaches or cyberattacks.

Open data initiatives

49. Initiatives for open data play a vital role in enhancing transparency within the energy sector by enabling public access to data. This transparency fosters accountability and encourages constructive feedback from consumers and regulatory bodies. It is crucial for building public trust and creating a collaborative environment for policy development.

50. By facilitating public access to energy data, these initiatives fuel the development of innovative technologies and solutions geared towards enhancing energy efficiency and encouraging sustainable practices. Open data serves as an invaluable asset for researchers and innovators, offering them opportunities to delve into novel approaches to energy conservation and management.

51. Open data initiatives empower a diverse range of stakeholders, including researchers, entrepreneurs, and the wider public, to interact with energy data, thereby nurturing a more knowledgeable and involved community. This inclusive engagement is fundamental for democratizing access to energy information and equipping consumers with the knowledge to make informed decisions about their energy usage.

Commercial versus open access data

52. Privately-owned commercial data, such as proprietary information on energy production and grid technologies, is closely protected to preserve competitive advantages. This data constitutes a cornerstone for the strategic planning and commercial prosperity of private energy enterprises.

53. Conversely, open access data serves broader societal interests by enriching public knowledge and supporting both academic and commercial research endeavors. It promotes the widespread dissemination of knowledge and encourages a collaborative approach in tackling challenges in the energy sector.

54. Achieving equilibrium between safeguarding commercial interests and promoting public access stands as a pivotal endeavour. This balance propels innovation while honouring the proprietary rights of data owners, ensuring the optimal utilization of data benefits while safeguarding competitive positions.

Critical infrastructure and personal data

55. The safeguarding of critical infrastructure information (CII) and personally identifiable information (PII) is paramount to mitigate the risk of potentially severe breaches and to protect individual privacy. This protective measure is central for preserving the security, reliability, and dependability of energy systems, crucial for both operational continuity and consumer confidence.

56. Establishing rigorous security measures and protocols is imperative to shield this sensitive information from evolving cyber threats and unauthorized access attempts. By deploying multi-layered security protocols, energy entities can enhance the resilience of their energy systems, ensuring effective protection against diverse forms of cyberattacks.

57. Negotiating the intricate landscape of regulations poses significant challenges for companies aiming to uphold legal requirements in relation to data protection, while effectively securing sensitive infrastructure and personal data. Compliance with these multifaceted regulations is not only essential for legal adherence, but also paramount for maintaining operational stability and mitigating potential risks.

Data volume and quality

58. The effectiveness of AI models in predicting energy patterns and optimizing grid operations hinges on access to large volumes of high-quality data. These technologies are dependent on extensive data sets to improve accuracy and efficiency in energy management.

59. The volume and quality of data directly impact the predictive accuracy and reliability of AI and machine learning models in the sector. Ensuring high-quality data enables these models to perform optimally, resulting in improved decision-making and operational efficiencies.

60. Acquiring sufficient data of adequate quality often requires substantial investments in technology and infrastructure for data capture, storage, and processing. These investments are essential for enhancing the capabilities of AI and ML applications in the energy sector.

Synthetic data

61. Synthetic data offers a practical alternative to real data, particularly in situations where using authentic data may compromise privacy or security. This data, generated through

sophisticated algorithms simulating real-world data patterns, preserves confidentiality while replicating genuine data intricacies.

62. The adoption of synthetic data facilitates the development and training of robust ML models without the inherent risks associated with exposing sensitive information. Synthetic data can be customized to meet specific requirements and scenarios, presenting a versatile and secure avenue for model training, ensuring optimal performance.

63. Synthetic data generation addresses the challenge of balancing the need for extensive data for training with stringent privacy and security regulations. It empowers the utilization of advanced data analytics tools while safeguarding user privacy and preserving data integrity, thus aligning with evolving privacy paradigms and regulatory frameworks.

Governance and standard practices

64. At the core of effective data governance, lies the establishment of precise guidelines pertaining to data ownership, usage rights, and data handling practices. These guidelines serve as a compass, guiding ethical and responsible data utilization within the energy sector.

65. Upholding standard practices is imperative to ensure alignment with legal standards and promote transparency in data management. This commitment to transparency not only fosters consumer and stakeholder trust but also mitigates risks associated with data handling. By adhering to these principles, organizations cultivate a culture of accountability, laying the foundation for ethical data governance.

66. As technology continues to evolve, governance practices must undergo continuous refinement to accommodate emerging data types and evolving data management technologies. This adaptability is essential for staying ahead of potential challenges and seizing new opportunities in data utilization. With the ongoing digitalization of the energy sector, understanding and managing the intricate interplay between data utility, privacy, security, and efficiency grows increasingly imperative. The need for sophisticated data governance frameworks and innovative data management strategies is pivotal for unlocking the potential of data to shape the future of sustainable and resilient energy systems.

V. Potential benefits and barriers of Artificial Intelligence

Benefits

67. Research on role of AI in achieving the Sustainable Development Goals,[18] identifies 134 targets that AI can enable and potentially 59 targets where AI may be an inhibitor. As AI potential is being unlocked by the generation of big data and increased processing power, it could enable fast and intelligent decision-making, leading to increased grid flexibility and integration of variable resources both in operations and in planning. Some of the benefits include:

(a) Better analysis: (i) Real-time operations rely on a large amount of accurate and timely data. To deal with a vast amount of data, AI can help and improve data analysis. For example, during alarms AI could help analysing the root cause; (ii) Grid operators could optimize system performance and make more informed decisions with advanced analysis; (iii) AI could analyse data patterns to predict natural disasters and their impact on the grid allowing for proactive measures like rerouting power or securing critical assets;

(b) More efficient planning: AI is great at simulating scenarios, at predicting outcomes and at considering more inputs and would enhance the planning phase. AI could, for example, simulate more extreme weather scenarios. AI could enhance the planning process and improve resource allocation, optimized generation, etc., including optimize siting and construction of assets, energy flows and potentially accelerate such transactional models as peer-to-peer energy trading;

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[18] Vinuesa, R., Azizpour, H., Leite, I. *et al.* The role of artificial intelligence in achieving the Sustainable Development Goals. *Nat Commun* **11**, 233 (2020). https://doi.org/10.1038/s41467-019-14108-y

(c) Assets management: (i) By using data from monitored critical assets, AI can detect early anomalies, potential failures and maintenance needs leading to maintenance based on asset real conditions instead of systematic maintenance; (ii) Timely maintenance will minimize unplanned outages and extends the lifespan of the asset. AI could also assist in asset management during its entire life cycle and provide potential optimization of maintenance schedules;

(d) Drive regulation innovation: National regulatory authorities can enhance their regulatory frameworks by leveraging the increased granularity and accuracy of data provided by operators who utilize advanced AI-enabled data management and processing capabilities. In particular, the enhanced ability of operators to monitor individual network components can reduce the information asymmetry faced by regulators, providing them with a more comprehensive overview of the performance of various network assets. This, in turn, can foster the development of new incentives schemes for proactive network management.

Barriers

68. While AI can contribute to deal with increased complexity of the electric grid planning and operations, market design and operations and create value with the data becoming more available from digitalization, some concerns and barriers would need to be addressed to capture the full value of AI. Some barriers include:

(a) Data Privacy and Security: (i) Privacy concerns arise due to the large-scale data collection required for AI training. Sensitive information must remain confidential; (ii) Cybersecurity becomes critical as AI systems interact with grid components. Protecting against data breaches and unauthorized access is essential;

(b) Availability of data: (i) Sufficient historical data and data diversity are needed to train models and may not be sufficiently available due to poor data curation and lack (or limitation) of data sharing; (ii) Frameworks to share sensitive data (CII and PII) must be developed along with balancing cross-industry standardization with allowing free market forces to exist;

(c) Legacy Infrastructure: Many power grids still rely on legacy infrastructure. Integrating AI into existing systems can be challenging and will require substantial investment;

(d) Skill development and availability of skilled workers: The availability of workers trained in AI and data with a good understanding of the grid environment will be a challenge. Skills development policies are important and training personnel, including network operators, to work effectively with AI will be essential for successful adoption;

(e) Lack of Transparency: (i) AI models often operate as “black boxes”, making it difficult to understand their decision-making process. Social media and mainstream news outlets can be sources of misinformation about the potential ‘hazards’ of technologies like AI; (ii) Research has shown that AI errors (‘hallucinations’) may have unintended consequences and compromise safety and reliability. Bad actors who are expert at the uses of advanced technologies like AI, can use it to disturb energy systems and create malicious data to train legitimate AI models.

VI. Ethics applied to Artificial Intelligence

69. Integrating AI into the energy sector brings significant benefits, and also raises important ethical issues that need further assessment to ensure the responsible and fair use of AI.[19] The main principals of AI ethics are as follows:

(a) Responsibility (“take responsibility for AI generated influence on others”): (i) Prevent and limit damage or negative AI use in energy sector side effects. Side effects can occur with an AI intervention; therefore, they need to be identified as much as possible to prevent damage or negative effects. (ii) Prevent misuse of AI generated knowledge and make

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[19] https://spectrum.ieee.org/ai-ethics-governance

sure that data, measured effects, or reports are clear to the intended users to avoid misunderstandings of the results;

(b) Integrity ("influence with integrity"): (i) Make sure all AI generated actions are based on integrity, independently, objectively and professionally, without being influenced by external forces such as for example, contracts, external pressure or power relations. (ii) Be open about AI generated results and on what level of qualifications, knowledge, skills and resources it is based. Indicate what AI can generate or not at a professional level;

(c) Respect ("influence with respect to other target groups"): Respect the privacy of the target group AI may influence as penetration to the private life of the target group may influence their behaviour, as the target group may be particularly vulnerable. AI action should consider the potential impacts of the discrimination; therefore, the AI generated decisions should be based on legislation, regulations and a moral compass;

(d) Expertise ("influence based on sufficient experience"): AI should ensure a high quality of professional conduct and should follow the limits of potential competence and limitations of AI expertise and use only methods for which AI is qualified through education, training or experience;

(e) Data ("use lawful, reliable and valid data with due account of privacy and data security"): (i) AI should work with lawfully obtained data and respect local legislation such as GDPR. Developing an AI should not only act according to the letter but also according to the spirit of the law. For example, developing an AI should be clear that the right permissions will be received, and that these are given consciously, autonomous, informed and thoughtfully. (ii) Know the reliability of AI generated and used data and then respond accordingly, reporting confidence intervals and being careful with AI generated actions or conclusions and interventions based on data with low numbers. Inform if the AI used data is insufficiently reliable or valid. (iii) AI systems rely on huge amounts of data, including personal and commercial information, and it is therefore essential to ensure that this data is collected, stored, and used in accordance with the established legal framework and ethical principles.

70. These main aspects of ethics need to be clearly understood and strictly followed when AI is used in the electricity sector.

71. Other observations made previously by the Task Force on Digitalization in Energy on the importance of using big data in an integral way for comprehensive and holistic analytics,[20] include:

(a) Cybersecurity. AI systems are an integral part of the energy infrastructure and create an attack surface subject to cyberattacks. Robust security measures must be in place to protect sensitive data and critical infrastructure;

(b) Transparency and accountability. AI algorithms are complex enough to make it difficult to trace how decisions are made. It is therefore necessary to assess the limits of accountability and to identify who is responsible for decisions generated by AI, especially when they may have an impact on society and the environment;

(c) Bias and fairness. AI systems can inadvertently accept biased data and lead to unfair outcomes, which requires AI auditing to detect and manage potential biases;

(d) Equal access. It is essential to ensure that AI systems are inclusive and inclusive of as many and as diverse groups as possible, including marginalised populations;

(e) Environmental impact and sustainability. The development and deployment of AI systems requires significant energy resources, which can lead to increased energy consumption and carbon emissions, and it is therefore necessary to balance the benefits of AI with its potential environmental impacts. AI can only be used if it is considered sustainable, so that it does not cause collateral damage to the environment.

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[20] https://unece.org/sites/default/files/2022-08/GEEE-9.2022.INF_.3-DataAnalytics_rev.pdf, last accessed 1 June 2024.

(f) The human factor. Human oversight is necessary in energy decision-making to ensure that ethical considerations are taken into account. Humans should have a decisive say in key decisions;

(g) Impact on employment. The deployment of AI in the energy sector may lead to job losses. Strategies for workforce transition and up-skilling are needed to mitigate negative employment impacts and ensure just transition;

(h) Resilience and adaptability. The energy sector needs to be ready to adapt to evolving AI technologies and their impact, and to remain resilient to potential disruptions.

72. These ethical issues require multi-stakeholder engagement including policymakers, civil society, industry, and technology providers, among other. Ongoing dialogue and a commitment to ethical principles are essential to responsibly exploit the full potential of AI in the energy sector.

VII. Reducing energy consumption in data centres with Artificial Intelligence – a case study summary

73. Data centres are the backbone of digital world, yet they require enormous amounts of energy, particularly for cooling systems. This growing demand has prompted the exploration of AI to enhance energy efficiency. Reinforcement learning (RL), a type of AI where systems learn optimal behaviors through trial and error, has shown significant promise in this area. By continuously adjusting based on real-time data, RL helps in optimizing operations to reduce energy consumption without sacrificing performance.

74. Google DeepMind, developed an RL-based AI system to optimize cooling processes in their data centres. This system collected data from thousands of sensors and used ML models to predict cooling needs. By dynamically adjusting cooling settings, Google achieved a 40 per cent reduction in energy used for cooling and improved overall data centre efficiency by 15 per cent. These improvements not only resulted in cost savings but also significantly reduced Google's carbon footprint, aligning with their sustainability goals.

75. Similarly, Telus and the Vector Institute partnered to enhance the energy efficiency of Telus data centres using an AI-driven Energy Optimization System (EOS). This system, built on model-based reinforcement learning (MBRL), was designed to fine-tune HVAC systems, optimizing temperature control based on real-time conditions and weather forecasts. In a pilot test, EOS reduced electricity consumption by nearly 12 per cent annually. Moreover, by open sourcing their algorithm, Telus and the Vector Institute have enabled other organizations to adopt these innovative techniques, promoting wider energy savings and environmental benefits.

76. These case studies illustrate the transformative potential of AI in making data centres more sustainable. By utilizing AI for predictive adjustments and operational optimization, companies can achieve substantial energy savings, reduce operational costs, and contribute to global efforts in reducing carbon emissions. The success stories of Google and the collaboration between Telus and the Vector Institute serve as compelling examples of how advanced technologies can address some of the most pressing environmental challenges in the industry.

VIII. Conclusions and recommendations for policymakers

77. Figure I is introduced to give context to the areas that need strong policy support to accelerate the advancement of AI, yet with enough caution to ensure fairness and equity to all stakeholders and beneficiaries alike.

78. Key areas where policy can support the progress of rational integration of AI into the electricity sector, include:

(a) Education:

(i) Across all application areas identified in this document, a level of upskilling from the electricity sector workforce will be needed to successfully use AI technologies. From planners and administrators to market operators and field operations technicians. Certainly, a level of mathematics and software skills are needed to develop new and optimized AI models. As these skills are taught and fine-tuned in the next generation of AI developers and understanding the use of integrity and morality needs to be instilled;

(ii) There is a crucial need to develop specialized expertise in both digital and electro-technical domains to effectively align strategic grid objectives with AI system implementation. This blend of skills is currently lacking, forcing grid operators to rely on expensive consulting services, which inflate the cost of digitalization efforts. Furthermore, attracting digital-skilled professionals to the electricity sector is challenging, as many are drawn to more financially rewarding roles within the IT sector;

(iii) Addressing concerns about job displacement due to the application of AI systems requires significant investments in upskilling and developing a future-ready workforce. Ensuring that the existing workforce can adapt to new technologies and workflows is essential for a smooth and just transition;

(iv) Policy recommendations to tackle these challenges include:

  a. Promoting life-long learning initiatives to equip professionals with the necessary skills to navigate the evolving technology landscape;

  b. Establishing cross-cutting partnerships between energy stakeholders, technology providers, and academia can facilitate knowledge transfer and foster AI applications deployment in the electricity sector.

(b) Data:

(i) In the new landscape of ever-voluminous big data, the opportunities for training advanced models to understand more granular patterns in the energy value chain (e.g., energy consumption, user behavior, asset alarms, equipment failures) advance commensurate to market factors (e.g., growth of cloud computing, customer experience improvements, automation of manual tasks). These advancements must be understood to be fully applied. This includes the implementation of enabling standards, policies and regulations that prioritize innovation and interoperability while addressing risks to cybersecurity and data privacy. Identifying cross-industry applications of data, ensuring data provenance, protecting and promoting democratization of clean and complete ground truth data and training data sets, and ensuring the security of the data can all be pathways towards the successful application of AI.

(c) Regulation and Economic Incentives:

(i) The adoption of AI requires significant investments from electricity operators, primarily driven by the need to address electricity grid challenges such as the integration of renewable energy sources. Currently, these challenges are often met with conventional grid capacity expansion strategies rather than investing in digital infrastructure, which could unlock grid flexibility and minimize expansion costs. This preference is largely due to regulatory frameworks that do not adequately incentivize network development and innovation, making digital investments less attractive and remunerative. To overcome this, several direct and indirect measures can be recommended:

  a. Direct measures:

    i. Increase funding for innovation: providing greater financial incentives for innovation projects is vital to stimulate investment in AI technologies. By offering higher remuneration for projects that demonstrate innovative solutions and technological advancements, regulators can incentivize electricity grid operators to prioritize digitalization initiatives;

ii. Requalify digital infrastructure expenditure as capital expenditures: treating digital investments as capital expenditures rather than operating expenses allows electricity grid operators to recover costs over a longer depreciation period, making these investments more financially viable. This approach aligns digital investments with traditional capital planning and recovery processes, thus integrating them into the broader financial strategies of grid operators.

b. Indirect Measures:

i. Develop specific performance indicators: create performance indicators to measure the benefits of digitalization, such as improvements in flow management efficiency and reductions in system losses. These indicators can form the basis of a performance-based reward system, motivating operators to adopt digital technologies and advanced AI applications that lead to measurable improvements in operational efficiency and service quality;

ii. Incentivize predictive maintenance and condition monitoring: Encourage the adoption of predictive maintenance and condition monitoring practices, which use advanced data analytics and sensor technologies to predict potential failures and assess asset conditions in real-time. This proactive approach helps extend asset lifespan, optimize maintenance schedules, and reduce operational costs. By shifting the focus from reactive to preventive maintenance, operators can ensure higher network reliability and efficiency while fostering adoption of innovative digital technologies;

iii. Introduce operations and maintenance remuneration schemes: implementing schemes that provide financial incentives for maintaining and upgrading assets beyond their depreciation period, encourages operators to focus on long-term asset sustainability and efficiency rather than premature replacement. By offering rewards for extending asset life, regulators can promote better asset utilization and performance optimization while indirectly promoting Digital technologies investments.

(d) Benefits and Barriers

(i) The advancements previously discussed can be both enablers and inhibitors to the successful application of AI. It is also not the solution to the digital and data transformation for Energy, as there are many potential solutions. To do this a comprehensive set of tools and techniques, and policies to support their use, will be required. More research is needed to identify and frame where AI technologies can provide additional benefits to the electricity and the larger energy sector within the 2030 Agenda for Sustainable Development and beyond. Further work is also needed to ensure that any barriers to the successful use of AI are identified, and mitigation solutions can be developed and implemented.

79. Conversely, it is worth noting that technologists can support policymakers in the following ways:

(a) Usage of ‘technology-speak’ within the correct context – Technologists tend to use a short-hand language when speaking with colleagues about their area of expertise. Indeed, this is useful when discussing a complex topic among experts. This can be difficult to navigate for those coming to the technology for the first time. A better language translation is needed to ensure that non-technology persons are brought into the conversation in an equitable fashion. Potentially, this could be part of the education process discussed above;

(b) Context-awareness – AI, like any other technology, is not a silver bullet and will not solve all problems in the energy sector alone. Technologists can become passionate about their ownership of a given solution. Understanding the context in which the technology is being applied in an unbiased way will help all stakeholders in the conversation;

(c) Navigating the landscape of misinformation – There is quite a bit of misinformation about seemingly futuristic technologies like AI. It can be helpful to understand what AI is and is not. Understanding this in an approachable, actionable way can accelerate the acceptance of AI as a technology for those who are still unconvinced as to its applicability.