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The use of AI for improving energy security

Exploring the risks and opportunities of the deployment of AI applications in the electricity system

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Preface

Modern civilisation is critically dependent on access to electricity. Electricity systems underpin practically all the essential life functions we take for granted. Most economic activity would be impossible without access to electricity. However, existing grid systems were not designed to handle present – let alone future – electricity demand. At the same time, climate change urgently demands drastic changes to our energy systems. Developing and modernising grid infrastructure requires substantial investment, and securing necessary funding for these projects is complicated by finite resources and competing budget priorities. Attempting to make necessary changes to electricity systems without causing interruptions to the critical services they are already providing makes this an even more complex challenge.

Artificial intelligence (AI) applications have potential to solve many of the challenges facing the grid. They can fulfil a range of functions throughout the electricity system, making electricity cheaper and more reliable. In many cases, the deployment of AI simply extends existing methods and approaches. For example, AI applications that help increase electricity market clearing can build on many existing data applications. AI tools can also open up new ways of interacting within the electricity grid, such as dynamic charging and discharging of electric vehicle batteries to provide flexible storage. These opportunities could help improve the overall energy security of the electricity system. However, the deployment of AI applications could also give rise to cybersecurity risks, the risk of unexplained or unexpected actions, or supplier dependency and vendor lock-in. The speed at which AI is developing means many of these risks are not yet well understood. This report provides an overview of state-of-the-art AI deployment in the electricity system and discusses the risks and opportunities AI tools may bring for electricity systems.

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Executive summary

Background and context

Electricity systems around the world are under pressure due to aging infrastructure, rising demand for electricity and the need to decarbonise our energy supplies at pace. AI applications could help address these pressures and increase overall energy security. For example, AI applications can reduce peak demand through demand response, improve the efficiency of wind farms and facilitate the integration of large numbers of electric vehicles into the power grid. However, the widespread deployment of AI applications could also come with heightened cybersecurity risks, the risk of unexplained or unexpected actions, or supplier dependency and vendor lock-in. The speed at which AI is developing means many of these opportunities and risks are not yet well understood.

Study objectives and research approach

The aim of the study was to provide insight into the state of the art of AI applications for the power grid and the associated risks and opportunities. We conducted a focused scan of the scientific literature to find examples of relevant AI applications to determine the state of the art in the United States, the European Union, China and the United Kingdom (UK).

We then used a Python-based power system model called PyPSA to explore the extent to which different AI applications can improve energy security. For mapping the risks, we first created a risk taxonomy. We also invited external stakeholders from policymaking and research organisations to participate in a backcasting exercise, where we discussed the key enablers that would contribute to certain positive and negative outcomes out to 2050.

Primary findings

There has been a significant acceleration in the development and deployment of AI, and this includes energy-related applications. AI applications are already being deployed in electricity systems in the United States, the European Union, China and the UK (which are the jurisdictions we considered in this report). While general AI-related policies are being formulated, far less policy activity covers the nexus between AI and energy specifically.

Overall, our research points to the effectiveness of behind-the-meter AI applications, such as AI-driven load shifting, in strengthening energy security.[1] We did not find evidence of the effectiveness of front-of-meter AI applications,[2] although this may be due to the limitations of our approach. In addition, we found that combining different AI applications would not necessarily lead to an improvement in energy security across the board. Instead, we saw a trade-off between different aspects of energy security. For

1 Front-of-meter applications cover energy-related activities that take place in the utility side of the grid. These activities are centralised and large-scale: D'haen (2023).

2 Front-of-meter applications cover energy-related activities that take place in the utility side of the grid. These activities are centralised and large-scale: D'haen (2023).

example, we found that a combination of AI applications in the European electricity system make electricity more affordable in some countries, while lowering affordability in others (though still leading to an overall improvement in affordability across the system).

Our study confirms there are several risks associated with deploying AI applications in the electricity system. We compiled a risk taxonomy that includes cybersecurity risks, jurisdictional or territorial sovereignty issues, the risk of unexplained or unexpected actions, unethical or illegal decision-making by the model, failure in human-machine interaction, supplier dependency, and vendor lock-in. Many of these risks are not unique to the electricity system but acquire additional gravity due to the critical nature of the electricity system. In most cases, these risks cannot be addressed through a single action, but instead require continuous commitment to safe and secure deployment.

Policy recommendations

Based on the research, we propose several policy recommendations that could help guide the deployment of AI applications in the electricity system and ensure that we are able to take advantage of the opportunities offered by AI while limiting its risks.

Policymakers

As with other emerging technologies, the deployment of AI applications in the electricity system confronts policymakers with a challenging and fast-changing policy environment. **Policymakers will need to stay informed of these developments.** This will require information sourced from different stakeholder groups through public hearings and reports.

In the jurisdictions we discussed, we saw that there are different bodies of regulation – notably AI regulation, energy regulation and critical infrastructure regulation – that partially address AI applications in the electricity system, but do not cover it directly. **Policymakers will need to investigate whether existing regulatory frameworks adequately cover AI applications in energy and clarify or add to them where necessary.**

Our backcasting exercise showed that stakeholder participation and buy-in of the AI transition is necessary to realise the full benefits of AI. **Policymakers must develop and maintain dialogue with a range of societal stakeholders.** To ensure this dialogue is representative, policymakers should also try to engage stakeholders that are harder to reach.

Policymakers need to be aware of the market dynamics of AI applications in the electricity system. For example, they must consider the commercial pressures that may drive energy companies to rapidly implement AI applications without due regard for the risks. They also need to consider tendencies towards consolidation and concentration in the market for AI applications.

Regulators

AI applications developing very rapidly. **Regulators should keep an eye on the market and stay up to date with the latest developments.** This will require regulators to actively track new developments, instead of passively reacting to market developments. Horizon scanning of developing technology could be helpful to spot AI applications in early stages of development and can help regulators develop their position on these applications before they become commercialised.

Regulators should stay on top of the state of AI deployment in the electricity system. To this end, **regulators should create a mandatory reporting of deployment of AI applications in the electricity system.** They could then analyse this data to gauge the speed and nature of AI deployment and use it to assess whether further targeted regulatory action is needed.

Interactions between an AI application and the rest of the system in which it is implemented can lead to unexpected effects. Increased understanding of these interactions can help reduce risk. **Regulators should develop sandboxes where AI applications can be tested before their deployment in the electricity system.** This may involve advanced simulations of the electricity system where AI applications can be stress-tested. The ethical dimensions of AI applications could be tested through procedural AI evaluation methods.

Deployment of AI applications in the electricity system touches on several regulatory domains. For example, AI regulators, energy regulators, market regulators and the regulators of other critical infrastructure systems also have a role to play in the successful regulation of AI in energy. To avoid gaps or duplication in regulatory efforts, **relevant regulators should have regular meetings and set up channels to exchange knowledge.**

Energy companies

Ultimately, the decision to deploy a specific AI application will be taken by individual energy companies. **These companies should consider the risk/opportunity trade-off in the deployment of AI applications**. An important first step is to ensure that they have access to the expertise (either in-house or through a third party) to assess this trade-off for a specific AI application in a specific context. They should also consider the potential for supplier dependency and vendor lock-in, and the difficulties that may arise from trying to reverse deployment of AI applications.

Linked to this, **energy companies should proactively share their intention of deploying AI applications with the regulator**. While we consider that there should be mandatory reporting of AI deployments to the regulator, we acknowledge that this may be difficult to enforce ex ante. Energy companies should therefore engage with the regulator proactively and in good faith.

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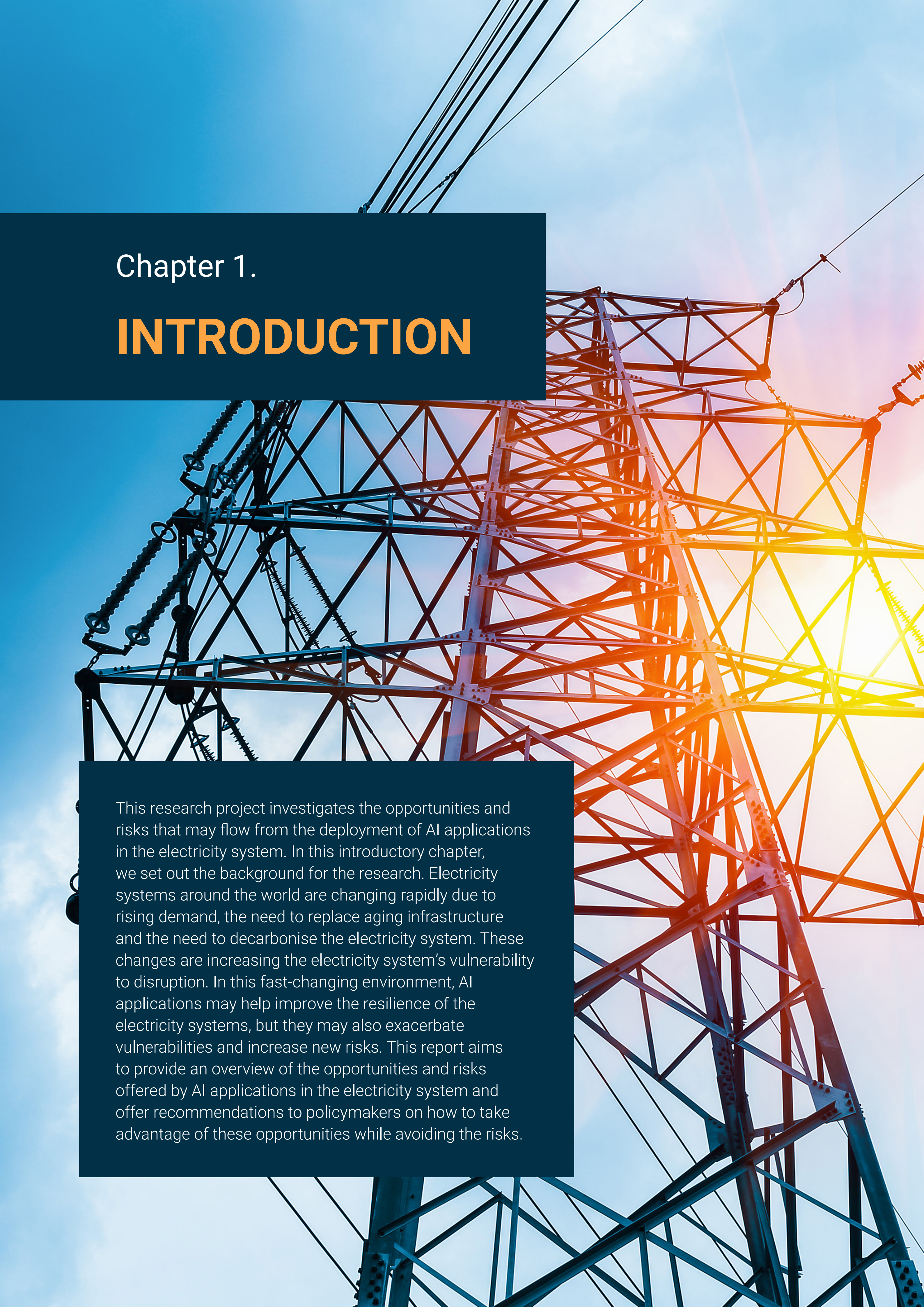
Abbreviations and acronyms

AI	Artificial intelligence
AIRMP	Artificial Intelligence Risk Management Playbook
AITO	Artificial Intelligence and Technology Office
APM	Asset performance management
ATLAS	Adversarial threat landscape for artificial-intelligence systems
BTM	Behind-the-meter
CCGT	Combined cycle gas turbine
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent emissions
DER	Distributed energy resources
DERMS	Distributed energy resource management systems
DLR	Dynamic line ratings
DoD	US Department of Defense
DoE	US Department of Energy
DSM	Demand-side management
EDCS	Electrical distribution control system
EDIHs	European Digital Innovation Hubs
ENTSO-E	European Network of Transmission System Operators for Electricity
GHG	Greenhouse gas
GRID	Grid Resilience Innovation and Development
GW	Gigawatt
GWh	Gigawatt-hours
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IIOT	Industrial internet of things
IOT	Internet of things
IFOM	In-front-of-the-meter
LMP	Locational marginal price
ML	Machine learning
MW	Megawatt
MWh	Megawatt-hours
NREL	National Renewable Energy Laboratory
R&D	Research and development
SET Plan	Strategic Energy Technology Plan
UHV	Ultra-high voltage
UK	United Kingdom
USD	United States dollar
VPP	Virtual power plant



Chapter 1.

INTRODUCTION

This research project investigates the opportunities and risks that may flow from the deployment of AI applications in the electricity system. In this introductory chapter, we set out the background for the research. Electricity systems around the world are changing rapidly due to rising demand, the need to replace aging infrastructure and the need to decarbonise the electricity system. These changes are increasing the electricity system's vulnerability to disruption. In this fast-changing environment, AI applications may help improve the resilience of the electricity systems, but they may also exacerbate vulnerabilities and increase new risks. This report aims to provide an overview of the opportunities and risks offered by AI applications in the electricity system and offer recommendations to policymakers on how to take advantage of these opportunities while avoiding the risks.

1.1. The changing nature of electricity systems

Our lives are fundamentally dependent on electricity systems. With each flick of a switch, press of a button or tap on a screen, we tap into a complex system of infrastructures that powers our world and shapes our routines. Other essential critical infrastructure, such as our water and food supply, communications, payments and transport, depend on access to electricity.

Because the world faces a climate emergency, there is an urgent need to decarbonise the electricity system. This will significantly change how the electricity system operates. In general, this implies a move away from generation by large, centralised power plants and energy transmitted over long distances to end-users, towards a more spread-out approach to power generation, where energy is produced closer to the point of consumption, using a variety of sources and technologies.[3] This reorganisation also reshapes electricity markets, away from the traditional hierarchical value chain – where electricity is produced by generation companies and then distributed to consumers – to one where players become both producers and consumers of electricity.[4] Finally, there will be a rise in electrification across the economy – deployment of electric vehicles and heat pumps are key examples of this – further increasing the importance of the electricity system.[5]

At the same time, the electricity system is already stressed. Much of the world's electricity infrastructure is aging, which poses challenges for reliability and safety.[6] Existing electricity grids were not built to handle even current levels of electricity consumption.[7] Moreover, there is a shortage of funding for grid modernisation. Developing and upgrading grid infrastructure requires significant amounts of investment and securing funding can be challenging. According to the International Energy Agency (IEA), to meet climate targets and support the energy transition, the world must build 80 million kilometres of grid infrastructure by 2040 – doubling the entire extent of existing grid infrastructure.[8] This requires annual investment in grid infrastructure – which so far has hovered around 300 billion USD per year – to double to 600 billion USD per year.[9]

3 However, there are some projects that seek to connect regions with high renewable energy potential to faraway regions with high electricity demand. For example, British company Xlinks aims to build long-distance power transmission lines between Morocco (which has a high level of solar irradiation capacity) and the UK (which has a high electricity demand): Hook (2021).

4 Gržanić et al. (2022).

5 Huismans and Voswinkel (2023); IEA (n.d.b.)

6 IEA (2023a).

7 For example, the European Commission identified the strengthening of electricity grids as a key enabler for the energy transition: European Commission (2024); Similarly, the US Department of Energy found that there is an urgent need to strengthen electricity transmission infrastructure: US Department of Energy (2024b).

8 This involves either replacing existing outdated infrastructure, upgrading existing infrastructure to increase its capacity, or building new transmission capacity: IEA (2023a).

9 IEA (2023a).

1.2. Increasing vulnerabilities in the electricity system

Electricity systems are incredibly complex. They consist of a network of physical infrastructure, including electricity generation assets, transmission assets, distribution assets and consumption assets. This physical infrastructure is connected through communication networks. In addition, there are human operators that keep the system going.[10]

The challenges the electricity system faces are only increasing its complexity. Many renewable energy sources like solar and wind have variable generation patterns that depend on the weather, season and time of day.[11] This creates variability in the generation of electricity that makes it difficult to consistently manage supply. At the same time, consumers have become more active in generating and storing electricity – for example by deploying solar energy and battery storage units. This gives consumers more flexibility in drawing electricity from the grid, making it harder to predict demand.

Such changes associated with the energy transition will fundamentally transform electricity systems even as they continue to provide critical services. The system is particularly tricky to manage because it requires near-instantaneous production, delivery and consumption of electricity. Any shock to the system is felt immediately and can cause cascading failures, such as brownouts and blackouts.[12] The scale of the transformation required will create new grid dynamics that operators are unfamiliar with. Lessons learned from previous disruptions may therefore be of little value as the system is reshaped by the energy transition.[13]

1.3. Deployment of AI applications

The complexity of electricity systems, as well as the speed at which they operate, make it increasingly difficult for human operators to keep up.[14] AI techniques will likely become critical to dealing with this complexity.[15] AI is an umbrella term for a wide variety of statistical and algorithmic techniques. It can be used to identify trends in large amounts of data and control processes, make decisions or predictions, and interact with its environment based on data. It does so through the use of algorithms and advanced computational techniques to enable a system to understand and process data, learn from experience, make decisions and take actions in response to changing conditions and stimuli.

The deployment of AI techniques is the next step in the realisation of the 'smart grid'. This is a long-standing vision, defined by the US Department of Energy (DoE) as a 'fully automated power delivery network that

10 Duan and Ayyub (2019).
11 Sinsel et al. (2020).
12 IEA (2020).
13 Capitanescu (2023).
14 Prostejovsky et al. (2019).
15 Kroposki et al. (2017).

monitors and controls every customer and node, ensuring a two-way flow of electricity and information between the power plant and the appliance, and all points in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time market transactions and seamless interfaces among people, buildings, industrial plants, generation facilities and the electric network'.[16]

AI applications will interact with other digitalisation techniques in the electricity system. For example, there is a close connection between AI applications and the internet of things (IoT). The IoT is a network made up of sensors and smart devices that act as nodes, each generating data that can be shared, collected and analysed. The large amounts of data generated through IoT applications in the electricity system can be fed into AI algorithms to achieve faster and more optimal decisions.[17]

The efficiency gains that flow from digitalisation could generate significant savings.[18] For example, the IEA predicts that proper digitalisation of grid infrastructure could save 1.8 trillion USD in global grid investment by 2050 while ensuring smoother integration of renewables and minimising supply disruptions. Even so, current global investment falls short of what is required to achieve net zero emissions by mid-century, which calls for annual grid investment to be doubled to around 750 billion USD by 2030.[19] If AI can generate grid investment savings, it could help decision-makers understand which investments will generate the best 'bang for buck' in reaching net zero targets.

1.4. Opportunities, risks and policy options for deploying AI applications in electricity systems

The pressures on electricity systems and resulting vulnerabilities present a critical challenge for our societies. AI applications can help address some of these pressures. However, because this is a nascent technology, the potential opportunities and risks of deploying AI are not well understood. This lack of understanding is particularly problematic in critical infrastructure like the electricity system, where suboptimal use of AI could have large and widespread impacts. This research seeks to fill these gaps and has the following aims:

1. Review the state of the art of AI applications in electricity systems, including the current state of the technology, the level of deployment of AI applications in relevant jurisdictions, and the policy landscape in these jurisdictions.
2. Assess the opportunities AI applications can offer to alleviate pressures, address vulnerabilities or improve overall functioning of electricity systems.
3. Evaluate the potential risks that flow from the use of AI applications in electricity systems.

16 US Department of Energy (2003).

17 Entezari et al. (2023).

18 The IEA estimates that digital technologies could save 1.8 trillion USD in grid investment globally out to 2050 by extending the lifetime of grids, while also helping to integrate renewables and minimising interruptions in supply: IEA (2023b).

19 IEA (2023b).

In this report, we rely on the concept of energy security as a metric to capture the opportunities and risks related to deploying AI in the electricity system. For the purposes of this report, we base our definition of energy security on that developed the Asia Pacific Energy Research Centre (the 'four A's') [20] but extend the concepts of accessibility and acceptability to cover additional questions relevant to AI applications:

- **Availability** means that the energy required to fulfil the needs of the economy and society is available at all times.
- **Affordability** relates to the price of the energy provided. A lower energy price will increase energy security for consumers, as it will be cheaper for them to procure the energy required to meet their needs.
- **Accessibility** deals with sourcing and transporting energy supplies, and the geopolitical challenges this may entail. In this report, we extend this concept to cover issues that can limit a country's control over AI applications or its electricity system.
- **Acceptability** deals with environmental issues and debates around sustainability. In this report, we extend this concept to include the societal acceptability of AI applications.

We used these four dimensions as yardsticks to measure the performance of AI applications against. When we talk about opportunities offered by AI applications in the electricity system, we mean ways to improve the availability, affordability, accessibility or acceptability of energy. Conversely, risks related to AI applications threaten to reduce the availability, affordability, accessibility or acceptability of energy.

1.5. Structure of the report

Chapter 2 analyses the current state of deployment of AI applications in the electricity system. We assess the different roles that AI applications can fulfil, and provide examples of deployment in the United States, the European Union, China and the UK. We also explore the policy landscape in these jurisdictions.

Chapter 3 discusses the opportunities that AI can provide to improve energy security. To do so, we rely on a power system model of the synchronous grid of Continental Europe to simulate different scenarios with and without the deployment of AI. More details on the methodology for this quantitative analysis are available in a technical report that complements this policy report.[21]

Chapter 4 addresses the risks associated with deploying AI applications in the electricity system – first through a taxonomy of risks to map the breadth of the threat landscape, and then through a backcasting exercise, where expert participants imagined a positive and a negative future scenario relating to the deployment of AI in the electricity system and worked back to the present day to uncover relevant risks and potential mitigations.

Chapter 5 provides key policy recommendations for policymakers and concludes the report.

The annex to the report provides an overview of the methodology and the limitations of our approach.

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20 Asia Pacific Energy Research Centre (2007); while we rely on the definition by the Asia Pacific Energy Research Centre, the literature contains a range of definitions for energy security: Ang et al. (2015).

21 Arciniegas Rueda et al. (2023).

Chapter 2.

THE STATE OF THE ART

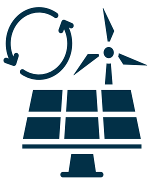
In this chapter, we provide an overview of the state of the art of the deployment of AI systems in the electricity system. First, we highlight different ways AI applications can be integrated into the electricity system. We then provide examples of the commercial deployment of AI applications in the United States, the European Union, China and the UK. Finally, we look at the policy landscape relating to the use of AI in energy applications in the same jurisdictions.

2.1. AI in the electricity system

The deployment of AI techniques in the electricity system is the latest step in advancing electricity system automation.[22] Historically, these improved control techniques have been based on advances in applied mathematics, control theory, computer science, operational research, telecommunications and the availability of more powerful computational facilities.[23] In practice, it is hard to draw a clear line between advanced statistical methods and AI. In many instances, energy companies have been using automation, big data analysis and statistical methods for many years. However, improvements in AI techniques, underpinned by big increases in computing power, mean that AI applications being developed today are significantly more powerful and versatile than previous generations of electricity system automation.

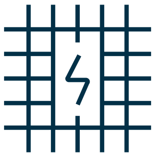
Given the broad progress in AI, there are many different ways AI can be integrated in the electricity system. In many cases, the deployment of AI techniques is simply an extension of existing methods and approaches. AI can be used to improve the performance of existing applications, such as through the optimisation of existing hardware or design of new hardware solutions.[24] One example is dynamic line ratings (DLR), where the maximum carrying capacity of a transmission line is adapted to climatic conditions to improve operating performance. This technique already exists, but it benefits greatly from enhanced forecasting and decision-making enabled by AI techniques.[25] AI can also open up new ways of interacting within the electricity grid. For example, large-scale integration of electric vehicles into the grid, and ways to ensure the grid makes optimal use of the flexible storage they offer, is very difficult to achieve without a parallel rollout of AI techniques.[26]

In this report, we classify AI applications according to six categories (as summarised in Figure 1):



Wind and solar generation forecast: AI models can analyse vast amounts of data from various sources, such as weather patterns, historical energy output and geographical information, to predict solar and wind energy generation more accurately.[27] Moreover, AI can continually learn and adapt to changing conditions, leading to progressively more accurate predictions over time.[28] Localised predictions with high granularity can improve the efficiency of individual assets.[29] For example, AI can help optimise wake steering in wind farms, whereby the angle at which the turbine faces the wind is changed to redirect the turbulent wake generated by the turbine and increase efficiency.[30]

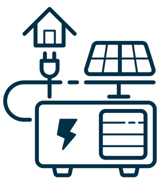
22 Unbehauen (2009).
23 Glavic et al. (2017).
24 techUK (2021).
25 IRENA (2020).
26 techUK (2021).
27 Meenal et al. (2022); Kumari and Toshniwal (2021); Voyant et al. (2017).
28 Lai et al. (2020).
29 Yonekura et al. (2018).
30 Neustroev et al. (2022).



Grid stability and reliability: AI integration can enhance operations by detecting faults, scheduling maintenance and analysing usage data. This can reduce maintenance costs and required infrastructure investment.[31] AI can be used for more accurate management of grid voltage and frequency levels,[32] which are essential to preventing instability and potential blackouts, especially in complex grids with diverse energy sources.[33] AI systems can also be used to balance electricity systems at a more granular level – for example in managing microgrids.[34]

Demand forecast: AI can improve demand forecasting by analysing historical power usage alongside factors such as weather patterns, economic activities and consumer behaviour. This approach allows more accurate predictions of future power demand.[35] AI's ability to process real-time data from smart meters and IoT devices allows for continuously updated and timely forecasts. AI excels in identifying complex patterns in energy usage – including seasonal variations and peak usage times – that might be overlooked by traditional methods.[36]

Demand-side management (DSM): One key dimension of the smart grid paradigm is activation of the demand side, whereby previously passive electricity consumers start to play a more active role in responding to changes in the electricity system.[37] For example, in demand response applications, consumers are financially incentivised to reduce their electricity demand in response to supply shortages. AI can help streamline DSM by anticipating periods of high demand and initiating measures to balance grid load.

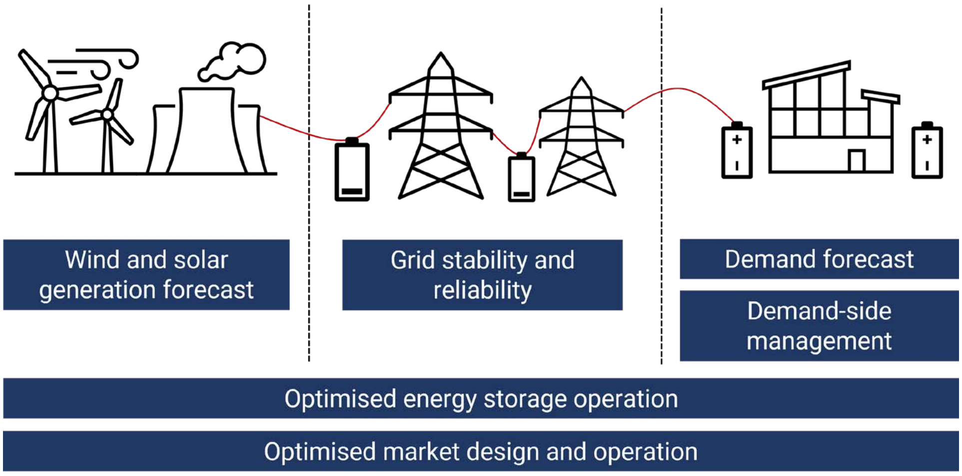


Optimised energy storage operation: Efficient use of energy storage can help balance the fluctuating output of solar and wind. AI applications can use predictive analytics to determine optimal times for charging and discharging energy storage based on energy demand forecasts, electricity pricing and renewable energy generation, thus ensuring energy is stored or released at the most beneficial times.[38]

31 Shin et al. (2021).
32 Diao et al. (2019); Zhang et al. (2022).
33 Wu et al. (2017).
34 Wu and Wang (2021); Mohammadi et al. (2022).
35 Bedi and Toshniwal (2019).
36 Perera and Kamalaruban (2021).
37 Pelka et al. (2022).
38 Abdalla et al. (2021).

Optimised market design and operation: AI can help improve the operation of the electricity market. By leveraging AI in locational marginal pricing,[39] electricity prices can be set more accurately at different locations within the grid, reflecting the true cost of electricity delivery, including congestion and losses.[40] AI algorithms analyse vast amounts of data, including grid topology, load patterns and generation capacities, to determine optimal prices at each node. AI can also speed up the electricity market by quickly analysing bids and offers, matching supply with demand in real time.[41] This rapid clearing is crucial to incorporating a higher share of variable renewable energy, such as wind and solar, as it allows the market to adapt swiftly to changes in generation and demand.[42]

Figure 1: Categories of AI application



Source: Adapted from IRENA (2019).

39 Locational marginal pricing, also called nodal pricing, adopts the marginal pricing principle used in micro-economics, and prices electricity at each network node for each time interval. The LMP is then the overall operating cost to the entire system to serve one additional megawatt of demand at a given node: Tan et al. (2022).

40 Jami et al. (2023).

41 Kahawala et al. (2021).

42 Hu et al. (2018).

2.2. Commercial deployment of AI applications in the electricity system

AI applications are already being deployed around the world. In this section, we provide examples of deployment in the United States, the European Union, China and the UK. We selected these countries because of the size of their investments in AI and scale of deployment. Our literature review shows that in these countries, the deployment of AI tools in the electricity system is already quite advanced and covers most of the key categories we identified in the previous section. The overview below provides a selection of relevant deployments for the countries analysed across the different categories of application. However, we do not seek to provide a comprehensive overview of what each of these countries is doing in terms of commercial AI application. Table 1 summarises which categories of AI application we found in the United States, the European Union, China and the UK.

Table 2: Overview of AI applications and jurisdictions

	US	EU	China	UK
Wind and solar generation forecast	X		X	X
Grid stability and reliability	X	X	X	X
Demand forecast	X	X		X
Demand-side management	X	X		X
Optimised energy storage operation	X	X		X
Optimised market design and operation		X	X	X

Source: RAND analysis.

United States

The US private sector has made major strides in developing AI applications for deployment in the electricity system. In many cases, these are the result of joint ventures and partnerships between established energy companies and relatively young start-ups in the AI space:

Wind and solar generation forecast: Splight provides advanced weather forecasting for renewable energy using AI techniques. It combines data generated by the energy company with third-party weather information to produce forecasts from one minute to two weeks ahead.[43]

Grid stability and reliability: AI is also being deployed in generation optimisation and grid balancing processes. Notable platforms include the National Renewable Energy Laboratory's (NREL) REopt software – which uses AI algorithms to optimise the design and operation of renewable energy systems across buildings and microgrids – as well as AutoGrid Flex and Enbala's virtual power plant (VPP) solutions, which are AI-driven distributed energy resource management systems (DERMS).[44] General Electric has made significant progress in utilising AI through its Autonomous Tuning software, which utilises digital twin gas turbine models to reduce emissions and save fuel.[45]

Demand forecast: Companies like C3 and Bidgley have crafted algorithm-based load forecasting solutions that utilise historical demand data and network related inputs to provide energy suppliers with millions of daily, real-time predictions and improved operational decision-making.[46] Additionally, a cross-sector partnership between IBM and Oncor developed an AI-driven load forecasting system that predicted energy demand and modified energy usage across 3.2 million advanced meters.[47]

Demand-side management: DSM has been shaped by partnerships between software companies and energy suppliers, like General Electric Digital's 2021 acquisition of Opus One Solutions Energy Corporation to integrate renewables and distributed energy resources (DERs) across the electric grid.[48]

Optimised energy storage operation: AI is also changing energy storage. Tesla's AI-driven Autobidder platform manages over 1.2 GWh of energy capacity and oversees real-time trading and control of energy assets.[49]

43 Lago (2023).
44 AutoGrid (n.d.); PR Newswire (2019); AutoGrid (2019); PV Magazine (2018a); Nafkha-Tayari et al. (2022).
45 NREL (n.d.); Power Magazine (n.d.).
46 Hand (2019).
47 Callaway (2018); Energy Digital Magazine (2020).
48 Holman and Mulaney (2021).
49 Lambert (2021).

European Union

The commercial sector across EU member states has seen significant integration of AI into energy processes:

Grid stability and reliability: Dutch company TenneT developed the crowd balancing platform Equigy, which uses blockchain technology and AI algorithms to analyse data from DERs, predict their energy production and consumption patterns and effectively integrate DERs into the grid.[50] AutoGrid's Flex VPP platform was deployed in the Flandres Centre in Dunkirk, France, which houses a 25 MW lithium-ion system. VPP provided Total SE with frequency regulation capabilities and the ability to provide stability to the French power grid in real time.[51]

Demand forecast: Several demand forecasting tools have been produced in recent years. Norway's Statnett and Sweden's Svenska kraftnät developed the AI-centred modern area control error (MACE) concept, which utilises optimisation algorithms, automatic reserves and available transmission capacities to exchange reserves across bidding zones.[52]

Demand-side management: The Enel X Connect platform, developed by Italy's Enel, is a digital platform that optimises energy demand through big data analysis and artificial intelligence.[53]

Optimised energy storage operation: Finnish start-up Capalo AI is developing an AI application to enhance management of flexible energy assets like energy storage systems and electric vehicle charging stations. This technology helps energy storage assets respond to changes in the electricity system, making it easier to integrate variable renewables into the electricity grid.[54]

Optimised market design and operation: Several energy suppliers are producing generation optimisation software. ABB developed Ability Genix, which uses the industrial internet of things (IIOT) to contextualise industrial data and improve operational efficiency, while their asset performance management (APM) solution uses AI and ML to train and deploy predictive and prescriptive models, promoting optimal asset performance.[55] Siemens' Energy Thrust is a neural network based self-optimisation software for wind turbines, which can be used to update older wind turbines, allowing them to produce up to 5% more electricity annually.[56] Since 2021, grid balancing tools have also risen to prominence in the commercial sector.

50 TenneT (n.d.); PV Magazine (2021).
51 Traub (2021).
52 Presthus (2018).
53 Enel (n.d.).
54 Lawrence (2023).
55 ABB (n.d.).
56 Siemens (2014).

China

AI has been deployed extensively in the Chinese electricity system. The Chinese electricity grid previously deployed AI in backbone networks for the purposes of industrial users, but it is now being rolled out to support individual consumers.[57] However, public information about these initiatives is relatively limited:

Wind and solar generation forecast: The Chinese National Meteorological Information Centre has developed a national wind and solar resources climate prediction model that uses AI techniques to provide predictions on key variables affecting renewable energy production, such as wind speed, solar radiation and local temperature.[58]

Grid stability and reliability: State Grid, a Chinese state-owned electric utility company, has tested AI solutions to minimise electricity disruptions in a community of around 200 families near Urumqi in the Western Xinjiang province. Each node in the electricity grid was equipped with AI capabilities that could decide how power should be routed. These capabilities can automatically locate and fix faults without human intervention. These techniques would allow the grid to recover from a blackout in three seconds, rather than the current six to ten hours.[59] China has also deployed AI to inspect powerlines at the outer edge of the network. It performs on-site image and video analysis and promptly raise alarms when a discrepancy is detected. A seperate AI system at the main site continuously optimises the algorithms deployed at the edge of the network.[60] Another application uses AI-based infrared detection to monitor and identify heat fluctuations in ultra-high voltage (UHV) powerlines.[61]

Optimised market design and operation: The Chinese State Grid constructed the first provincial-level digital power grid in the country's Jiangsu province. The virtual power grid combines IoT applications, the BeiDou Navigation Satellite System and AI applications. This system makes it easier to determine optimal grid operating conditions. It also makes it possible to automatically determine the location of power failures through analysis of subtle anomalies in power consumption data.[62]

57 Chen (2022).
58 Hayley and Lewis (2023).
59 Chen (2022).
60 Xu and Hua (2019).
61 Global Times (2023).
62 Xinhua (2024).

United Kingdom

The UK commercial sector has made significant progress on integrating AI into the energy sector:

Wind and solar generation forecast: Open Climate Fix is a non-profit product lab that has developed AI models providing granular, near-term forecasts of solar irradiation to predict and improve the output of solar power generation. In particular, the AI models improve prediction of cloud formation, which traditional weather models do not do well. These models are being tested for deployment by the National Grid electricity system operator (ESO).[63]

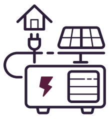
Grid reliability and stability: AI is also contributing to the cyber and physical security of energy assets. Darktrace Enterprise's cyber immune system, used by companies like Open Energi, utilises AI to intelligently identify emerging anomalies and threats, and secure energy networks and digital infrastructure.[64] RWE's 174 MW Robin Rigg offshore wind farm in Scotland uses tidal access forecasting and advanced pattern recognition to help pinpoint and maintain the most profitable turbines and efficiently identify and resolve anomalies.[65]

Demand-side management: DSM has been bolstered through mechanisms like Open Energi's Dynamic Demand 2.0 platform, which responds to peak price charges, fluctuations in grid frequency and system imbalance prices to optimise daily electricity use. EDF Energy's PowerShift utilises demand side response schemes, allowing customers to combine energy generation sources and adjust their energy usage in response to demand.[66]

Demand forecasting: Recent developments in demand forecasting have provided insights into asset management and helped promote reliable electricity and a resilient power grid. For example, in 2020, Scottish Power Energy Networks began using AI-powered software developed with Sia Partners to maximise the capacity of its distribution network, predict energy demand and facilitate its transition to becoming a distribution system operator.[67]

Optimised market design and operation: GridBeyond has developed a real-time forecasting solution that utilises advanced trading strategies and analytics to optimise revenues and savings, while the company's cloud-based Point platform automatically adjusts power consumption to balance the grid.[68]

63 Salian (2024).
64 Doran and Britton (2018); DarkTrace (2015).
65 Memija (2023).
66 AggNet (2018); PV Magazine (2018b).
67 Lempriere (2020); Whaley and Pope (n.d.)
68 GridBeyond (n.d. a); GridBeyond (n.d. b)



Optimised energy storage operation: By the end of 2024, Highview Power plans to build the world's first commercial-scale liquid air energy storage plant to boost renewable power generation within the UK. £250 million will be used to construct a storage plant with 30 MW capacity that can store 300 MWh of electricity. AI was used to produce a digital twin of the liquid air energy storage facility and will help optimise operation of the plant and maximise its efficiency and revenue streams.[69] VPPs are being developed throughout the UK, serving as storage systems, bolstering renewable energy rollout and supporting net zero targets.[70]

69 Dempsey (2022); Messenger (2023).

70 OctopusEnergy (n.d.); Renewable Energy World (2021); Slye (2022).

2.3. Policy on AI in the electricity system

Policymakers around the world are grappling with the implications of AI applications in the electricity system, and countries are beginning to develop individual approaches to reaping the benefits of AI while limiting the risks. In this section, we provide an overview of the policy actions of selected countries. We observe that the United States and the European Union have the most advanced policy frameworks for the deployment of AI in their electricity systems. China is developing extensive regulation on generative AI, but this does not directly apply to energy systems. The UK, meanwhile, appears to have had less targeted policy activity since the release of its AI strategy in 2021.[71]

2.3.1. United States

Most US policy documents on energy security – including the Energy Security and Independence Act of 2022 and the 2023 DoD Operational Energy Strategy – do not explicitly mention AI.[72] Future AI initiatives could pave the way for the integration of AI into federal energy and infrastructure policies. Additionally, the National Institute for Standards and Technology (NIST) developed the voluntary AI Risk Management Framework for responsible AI use and risk mitigation across all sectors.[73]

The US DoE plays an active role in developing and managing AI applications for energy systems. The National Artificial Intelligence Initiative Act of 2020 highlights the DoE's Artificial Intelligence Research Program as a mechanism for developing AI tools and capabilities within the Department and wider energy sector.[74] The DoE also has an Artificial Intelligence & Technology Office (AITO),[75] and developed the AI Risk Management Playbook (AIRMP) as a reference guide to AI risk identification and recommended mitigations.[76] Finally, it has developed the DoE AI use case inventory, which highlights AI applications specific to energy.[77] In October 2023, the Biden administration released an executive order on AI,[78] directing the Secretary of Energy to issue a public report outlining AI's potential to improve planning, permitting, investment and operation of the power grid.[79]

2.3.2. European Union

The European Union is currently finalising the world's first comprehensive AI law. The proposed AI Act takes a risk-based regulatory approach and aims to balance innovation with maintaining citizens' rights through the promotion of trustworthy AI.[80] It considers deployment of AI applications in electricity system management and operation to be

71 HM Government (2021).
72 Govtrack (n.d.); United States Department of Defense (2023).
73 NIST (2023).
74 United States House of Representatives (2020).
75 United States Department of Energy (n.d.a).
76 United States Department of Energy (n.d.b).
77 United States Department of Energy (2023a).
78 White House (2023).
79 Executive order 5.2(g)(i): White House (2023).
80 European Parliament (2023).

high-risk.[81] Accordingly, these applications would be subject to compliance with mandatory requirements and an ex-ante confirmatory assessment.[82]

AI is only mentioned in passing in EU energy policy. In the European Green Deal, AI is listed as a critical enabler for attaining sustainability goals and overcoming environmental barriers.[83] In the EU Security Union Strategy, AI is considered both an enabler and a tool to anticipate and mitigate future risks, with no direct connections made to energy or infrastructure protection.[84] With the goal of developing a sustainable, secure, transparent and competitive market for digital energy services, the European Union has adopted a Digitalisation of Energy Action Plan that aims to enable structural cooperation between the energy-focused European Digital Innovation Hubs (EDIHs) and Artificial Intelligence Testing and Experimentation Facilities (AI TEFs) established under the Digital Europe Programme and the EU network of innovators and research institutions set up under the Strategic Energy Technology Plan (SET Plan).[85]

2.3.3. China

China has been a leader in developing binding national regulations on AI.[86] So far, these regulations have mostly focused on the social dimensions of AI. For example, China has created a regulation on the administration of deep synthesis internet information services that prohibits generation of 'fake news' and makes it mandatory for synthetically generated content to be labelled.[87] China has also released a draft generative AI regulation.[88] The Chinese National Energy Commission (NEC) is the highest-ranking State Council agency responsible for drawing up energy policy. In March 2023, the NEC promoted the application of AI for use in intelligent decision-making in the electricity system.[89]

2.3.4. United Kingdom

The UK's 2021 National AI Strategy refers to the development of AI for energy as a key priority. AI is also mentioned as a mechanism to optimise electricity, reduce costs and meet climate goals.[90] However, AI is not mentioned in the 2022 British Energy Security Strategy or the 2023 Energy Security Plan.[91] In a separate announcement, the UK government allocated £4 million to developing AI solutions relating to the electricity system.[92] This seems to indicate that there are a number of parallel efforts on AI and energy within the UK government, and that these efforts could be more streamlined and integrated in order to avoid duplication.

81 Recital 34 draft AI Act: European Commission (2021).
82 Chapter 2 draft AI Act: European Commission (2021).
83 European Commission (2019).
84 European Commission (2020).
85 European Commission (2022).
86 Sheehan (2023).
87 Cyberspace Administration of China. (2022).
88 Gong and Qu (2023).
89 National Energy Administration (2023).
90 HM Government (2021).
91 HM Government (2022); Department for Energy Security and Net Zero (2023).
92 Department for Energy Security and Net Zero et al. (2023).

Chapter 3.

THE OPPORTUNITIES

In the previous chapter, we highlighted a wide range of possible applications of AI in the electricity system. In this chapter, we demonstrate some of the ways in which AI can improve energy security in the electricity system. We do this through a quantitative approach based on a power system optimisation tool, where we compare four different cases of the deployment of AI applications to a benchmark scenario in which no AI applications are deployed in the electricity system. Our results show that AI applications can indeed have a positive impact on energy security if they are widely deployed in the electricity system. However, in some cases there are trade-offs between different objectives relating to energy security.

3.1.
Power system optimisation

In order to assess the opportunities of AI applications, we relied on a power system model called PyPSA.[93] This opensource model is designed to provide great flexibility and adaptability for users, and is easily scalable to large networks and long time series.[94] We developed a benchmark scenario where no AI applications are deployed, three scenarios where a particular AI application is widely implemented, and a final scenario where the three different AI applications are combined. Table 2 provides an overview of these scenarios. For each scenario, we measured the performance of the AI applications against the benchmark, using metrics for each of the dimensions of energy security described in Table 3. Our methodology for power system optimisation is outlined in annex A to this report and the technical report of this research project.[95]

Table 3.1: Overview of scenarios

Scenario name	Description
Benchmark	The benchmark scenario covers the coldest week of winter 2013 in the European electricity system with no AI applications.[96]
Scenario 1: AI-driven load reduction	Scenario 1 features energy consumption reductions across the commercial and industrial sectors resulting from more efficient control of heating, ventilation and air conditioning (HVAC) using AI.
Scenario 2: AI-driven load shifting	Scenario 2 features widespread deployment of AI applications that automatically adjust electricity consumption time to reduce the peak demand.
Scenario 3: AI-driven wind wake steering	Scenario 3 features wake steering of wind turbines[97] coupled with AI technology increasing the net wind plant power production and reducing fatigue loads due to wake turbulence.
Scenario 4: Combined scenario	Scenario 4 features AI-driven load reduction, AI-driven load shifting and AI-driven wind wake steering. It therefore combines scenario 1, 2 and 3.

Source: RAND analysis.

93 Github (2023).

94 We rely on PyPSA-EUR, which is a model of the European electricity system. Our findings are therefore primarily related to the European electricity system and cannot necessarily be extrapolated to other electricity systems. Our reasons for choosing PyPSA-EUR are outlined in Annex A.

95 Arciniegas Rueda et al. (2023).

96 Saroj (2022).

97 A wind farm control strategy in which upstream wind turbines are misaligned with the wind to redirect their wakes away from downstream turbines.

Table 3.2: Relevant metrics within PyPSA

Energy security dimension	Relevant metric within PyPSA	Description of metric
Availability	Reserve margin	The amount of excess capacity available in a power system to meet unexpected increases in demand or unexpected outages of power plants or other energy resources
Accessibility	Fossil fuel dependency	The degree to which a society or economy relies on fossil fuels such as coal, oil and natural gas to meet its energy needs
Acceptability	CO_2 equivalent emissions (CO_2e)	Greenhouse gas emissions from power generation during the study period
Affordability	Locational marginal price (LMP)	The cost of generating and transmitting electricity to a specific location

Source: RAND analysis.

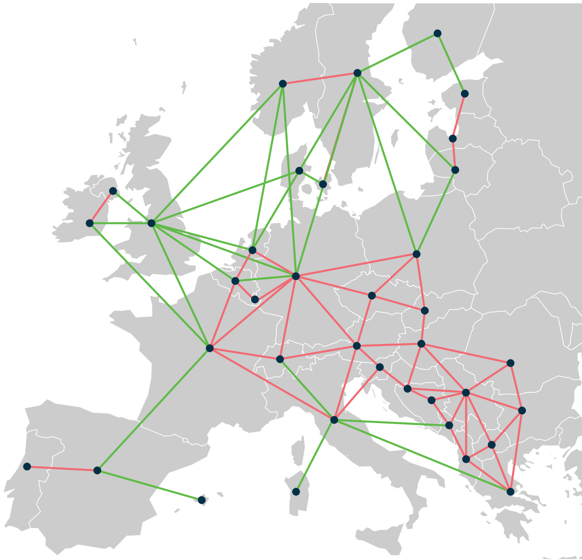
3.1.1. Benchmark

In our benchmark scenario, we constructed a network of the electric grid across 33 European countries.[98] Our benchmark scenario is designed to represent a situation where the electricity system is under stress and has reduced energy security, reflected by low availability, affordability, accessibility and acceptability of energy.

We used this benchmark scenario to isolate, as far as possible, the impact of AI applications from other variables. In a system that already has high energy security, the contribution of AI applications may be hard to distinguish from normal operation. In a scenario with low energy security, it is easier to identify any improvements that could be linked to the introduction of an AI application as the only change between the benchmark scenario and the test scenario.

For our benchmark scenario, we selected the week from 16 January 2013 to 22 January 2013, when the EU system reached its maximum load for the year.[99] We then applied this data to the European grid topology as of 2020 and used the model to find the cheapest solution to match supply and demand in this network by minimising system costs. We only optimised power plant and storage dispatch for existing resources without adding new capacity to the system. Figure 3.1 represents the resulting network in the benchmark scenario. The green connections indicate that the electricity system is functioning as normal, while the red connections show where the electricity system is facing stress and struggles to adequately match supply with demand.

Figure 3.1: Geographical representation of the modelled grid



Source: RAND analysis.

98 These countries included Albania, Austria, Bosnia and Herzegovina, Belgium, Bulgaria, Switzerland, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, UK, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Montenegro, North Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Sweden, Slovenia and Slovakia.

99 Saroj (2022); This particular year was selected as the data needed to run PyPSA-Eur was already curated by the developers. Data curation of additional years was beyond the scope of this project, and we recommend it as an area of further research.

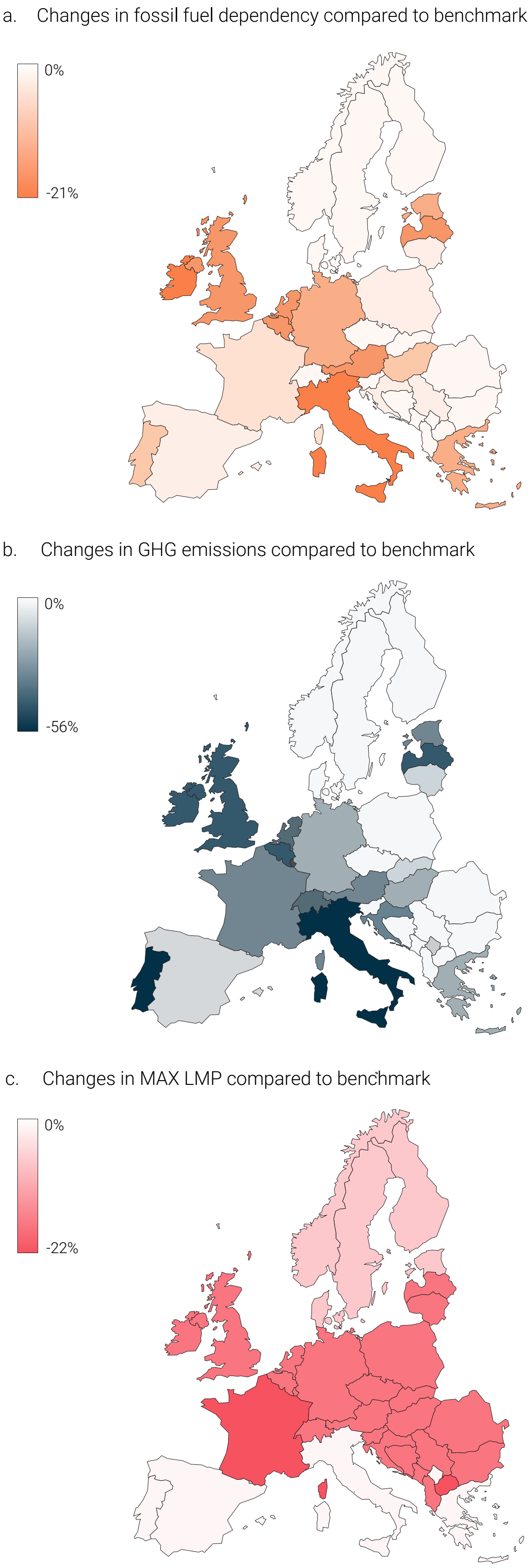
3.1.2. Scenario 1 (S1): AI-driven load reduction

In this scenario, we analyse the impact of energy consumption reductions across the commercial and industrial sectors resulting from the large-scale deployment of AI applications controlling HVAC units more efficiently. This is a form of DSM. The magnitude of the impact varies between countries, from more than 10% to negligible. Figure 3.2 illustrates changes from the benchmark for accessibility, acceptability and affordability. Although all three energy security metrics improved compared to the benchmark at the system level, the distributional impact on individual countries varied. For maximum LMP, France and UK showed the biggest reductions from the benchmark, while Spain and Portugal did not change at all.

We observed that in S1 (load reduction), the countries experiencing the greatest impact are not the same across all security metrics. One possible explanation is that countries with larger dispatchable fossil generation fleets are likely to benefit most from changes on dispatchable load profiles triggered by AI-driven load reductions. Italy, for instance, is the second largest importer of natural gas after Germany. Both Germany and Italy see significant energy security improvements in accessibility and acceptability. Our exploratory analysis does not allow us to explain the relative differences between countries, such as variations in affordability among countries with apparently similar circumstances, such as Latvia and Estonia, for example. Teasing out these differences would require more scenarios than those developed here.

In summary, our exploratory analysis has raised important insights at the European level but is more restricted at the national level, given the nature of the applied scenarios. In the case of S1, AI-driven load reduction seems to have an overall positive impact across all the energy security metrics without significant trade-offs across.

Figure 3.2: Distributional impact in S1 (load reduction) compared to benchmark



Source: RAND analysis.

3.1.3. Scenario 2 (S2): AI-driven load shifting

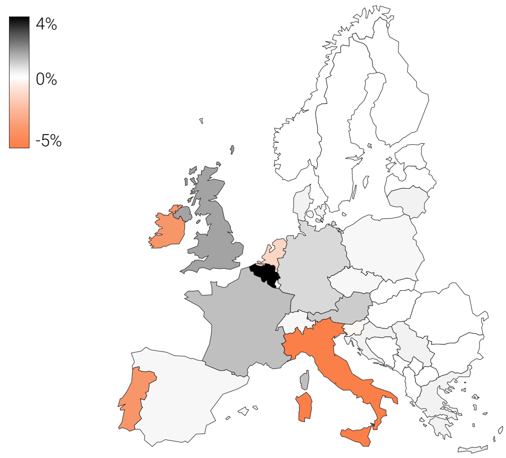
In this scenario, we assume that AI applications can automatically shift electricity consumption within a day, based on the cost or carbon-intensity of electricity.[100] A flexible load is a controllable load, where more or less energy can be used at a given time. Load shifting is a form of optimised market design and operation, combined with responsive demand. It is valuable in today's energy markets because it helps energy market operators to better manage peaks and incorporate intermittent renewable energy sources into the grid.[101]

The analysis reveals that S2 (load shifting) did not significantly alter fossil fuel dependency or GHG emissions compared to the benchmark. This can be attributed to total amount of combined cycle gas turbine (CCGT) generation remaining unchanged. However, the reduction of peak load led to an improved reserve margin, with more excess generating capacity available to meet unexpected shocks. In addition, the price of electricity showed fewer extreme fluctuations due to a smoother, less peaked demand curve.

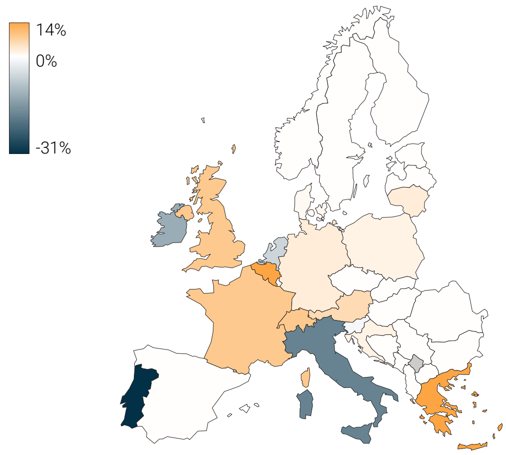
Figure 3.3 illustrates changes from the benchmark for accessibility, acceptability and affordability. Although fossil fuel dependency and CO_2e metrics did not change compared to the benchmark at the system level, the magnitude and direction of change for each country varied. Some countries showed more improvement than the system-wide reduction, while others did not change at all, or even worsened compared to the benchmark. For example, Italy's fossil fuel dependency fell by 5% reduction, while Belgium's increased by 4%. Regarding maximum LPM, France showed the most significant reductions from the benchmark, while Spain and Portugal worsened by 5%. This result further highlights a potential trade-off between countries and could be an area of further research.

Figure 3.3: Distributional impact in S2 (load shifting) compared to benchmark

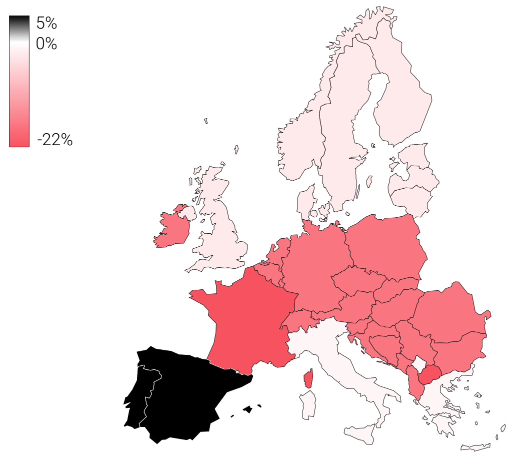
a. Changes in fossil fuel dependency compared to benchmark



b. Changes in GHG emissions compared to benchmark



c. Changes in MAX LMP compared to benchmark



Source: RAND analysis.

100 For example, a washing machine that incorporates AI applications can turn on when electricity demand and electricity prices are low, instead of turning on immediately when the owner presses the start button: Khorram et al. (2020).

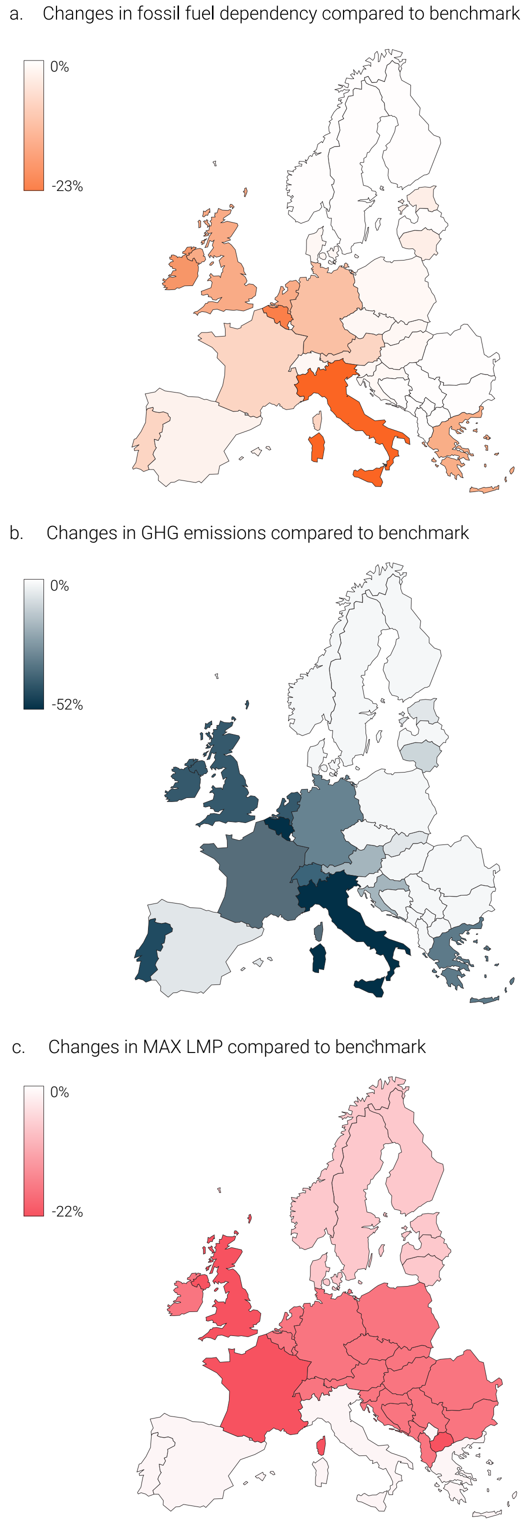
101 Scott (2019).

3.1.4. Scenario 3 (S3): AI-driven wind wake steering

In this scenario, we assume wide deployment of AI-enabled wake steering in wind farms. Wind turbine wakes cause significant energy loss during generation from downstream turbines due to reduced wind speed. The magnitude of power loss due to the wake effect varies depending on the distance between turbines and their layout pattern, but literature reports that it could be as much as 23%.[102] Wake steering is a wind turbine control strategy where the turbines are misaligned with the wind direction, deflecting the wakes from downstream turbines and leading to improved performance for the wind farm. Wind-wake steering is already enabled through improved wind and solar generation forecasting.

In contrast to the other scenarios, AI applications relating to wind wake steering did not display significant differences from the benchmark across all metrics (Figure 3.4). The magnitude of improvement observed was minimal. Nonetheless, it is important to acknowledge that the impact of wind generation efficiency is expected to increase as the grid undergoes decarbonisation and incorporates new wind developments.

Figure 3.4: Distributional impact in S4 (all combined) compared to benchmark



Source: RAND analysis.

102 Adaramola et al. (2011); Choney (2022); Fairley (2019).

3.1.5. **Scenario 4 (S4): Combined scenario**

The final scenario assumes that the three different AI applications are deployed simultaneously. We modified all input parameters discussed above and then optimised the system to evaluate the change in energy security metrics from the benchmark scenario. This combined scenario yielded unexpected findings. We anticipated that the combination of AI applications targeting different aspects of the electricity system would result in this scenario outperforming all others. However, only the reserve margin metric exhibited the highest performance, while the average and maximum LMPs were worse than those of S1 (load reduction). Other metrics remained on par with S1. This outcome can be attributed to the predetermined load profile strategy, which focused on reducing the peak load. While successful in improving the reserve margin, it neglected optimisation around the price signal after load reduction. This highlights the complex dynamics that may exist between different AI applications and the goals towards which they try to optimise. Combining different AI applications may lead to outcomes that are worse on some metrics than deploying a single AI application. This highlights the need for careful consideration of interactions between applications to avoid adverse impacts on the electricity system.

3.2. Policy insights

Table 4 provides an overview of the outcomes of the different scenarios. Based on our quantitative analysis, we find that behind-the-meter AI applications can measurably improve energy security. Importantly, because these applications are implemented on the demand side, the benefits of this increased energy security can also accrue to consumers. For example, AI-driven load reduction can have system-wide benefits by reducing the need to bring additional power generation online, and therefore lead to reduced energy bills for the individual consumer. However, our study implies that some AI implementations generate trade-offs among the different energy security metrics.[103] When different AI technologies are implemented together, interactions between the applications may result in adverse effects on energy security. Policymakers should recognise that the impact of AI applications on energy security is not necessarily additive and that there could be trade-offs whereby optimising for one metric can result in suboptimal results for another.

Behind-the-meter AI applications can also play an important role in the development of microgrids and other localised power setups. While these concepts are not new, the increased performance of AI applications can make them more practical and cheaper to implement. Policymakers should recognise that progress in AI could reinvigorate debate on the relative merits of a centralised versus a decentralised electricity system. While the potential of a more decentralised system for

Table 3.3: Overview of scenario outcomes

Energy security		**Scenarios**				
Category	Metric	Benchmark	BTM applications		IFOM applications	BTM and IFOM applications
			S1 Load reduction	S2 Load shifting	S3 Wind wake steering	S4 All combined (S1 + S2 + S3)
Accessibility	Fossil fuel dependency	46.5%	38%	46.6%	46.4%	38%
Availability	Reserve margin	21.0%	43%	32.4%	21%	57%
Acceptability	Kilotons of CO_2e emissions	10036	7970	10032	10022	7934
Affordability	Average LMP	€42,68	€38,36	€42,13	€42,66	€39,36
	Max LMP	€53,53	€45,89	€49,28	€53,54	€47,09

Source: RAND analysis.

103 For example, in S2 (AI-enabled load shifting), we saw an improvement across the whole system on the energy security metric of availability and affordability, but a simultaneous decline in accessibility. In the same scenario, we saw a system-level improvement in affordability, but the individual country-level breakdown revealed that while most countries were better off, some were not.

increased resilience and participation has been discussed for more than twenty years,[104] there has so far been little progress on implementing this in practice. The rapid improvement in AI capabilities could accelerate the transition towards a more decentralised electricity system.[105] Policymakers should take this into account when setting out the general policy directions for the future of the electricity system.

We were only able to model one front-of-meter AI application, namely wind-wake steering. We found little to no indication of a positive impact on energy security from this application. Based on this single scenario, we are unable to provide a detailed quantitative assessment of the potential of front-of-meter applications to improve energy security.

Future areas of research

Our research was bound by the limitations of the PyPSA model. For a more complete picture of the potential benefits of AI applications for energy security, future research should cover more detailed modelling of relevant AI applications. For example, we assumed in our scenarios that the respective AI applications had a 100% implementation rate across the European electricity system. This crude assumption could be refined by adding sub-scenarios covering different levels of implementation in time and geographical coverage. In addition, our modelling was limited by the available data. For our benchmark scenario, we found that 2013 was the latest year for which curated data was available through PyPSA. The European electricity system has changed significantly in the past 10 years. To increase the relevance of the assessment, researchers should have access to up-to-date data on the state of the electricity system.

Future research should also assess the energy security impact of front-of-meter AI applications, particularly those that implemented at a central node of the currently centralised electricity system. The impact of some of these AI applications could be very large, but may be hard to assess through the method we applied. For example, AI applications for market clearing deployed by electricity exchanges could play a key role in the future functioning of the electricity market.[106] However, we did not find a satisfactory way to model this type of application through PyPSA, or to assess its potential for increasing energy security.

AI applications are not the only digital technologies that could have a significant impact on the electricity system. For example, there is growing interest in applications based on quantum technology. The rising number of inputs and outputs to the grid may make it too complex to be computationally solvable even on current supercomputers. Breakthroughs in quantum computing, combined with developments in AI, could change this. US Senators Cornyn and Padilla introduced the Grid Resilience Innovation and Development (GRID) Act, which would direct the US DoE to conduct further research into how quantum applications can make the electricity grid more resilient.[107] More research is also needed to assess the interplay between different enabling digital technologies and the impact they may have on the future development of the grid.

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104 For an overview of the dynamics at play, see: Mehigan et al. (2018).

105 NREL (2022).

106 Pagnier et al. (2022).

107 Cornyn (2023).

Chapter 4.

THE RISKS

In the previous chapter, we demonstrated that AI applications can have a positive impact on energy security. However, even if AI applications can improve certain dimensions of energy security, policymakers and technology developers should ensure that the expected improvements in the efficiency and reliability of the electricity system do not come at the cost of unacceptable risks or increased vulnerabilities. To understand these trade-offs, we first developed a taxonomy of risks. We then ran a backcasting exercise, where we imagined a positive and a negative future outcome of the deployment of AI in the electricity system. We show that the introduction of AI applications in the electricity system could present a range of risks. However, the probability of these risks materialising and their potential impact if they did are not well understood.

4.1. Risk taxonomy

To understand the scope of risks associated with the deployment of AI in the electricity system, we first created a risk taxonomy – a structured framework for categorising risks. Table 5 outlines the six categories of risk we identified. Annex A provides relevant methodological details on this approach.

Table 4: Risk taxonomy

Risk	Description
Cybersecurity breach or intrusion	AI applications make it possible for hackers to launch cyberattacks on the electricity system, for example by poisoning the model's data flow. Adversaries may also use AI tools to aid their offensive cyber activities, for example through AI-enabled spearphishing attacks (whereby someone's communication is very closely imitated).
Jurisdictional or territorial sovereignty issues	Electricity systems typically span multiple jurisdictions. Deployment of AI applications could give rise to complex legal issues at the intersection of different legal frameworks. For example, AI applications could lead to liability questions with large financial implications.
Unexplained or unexpected actions	AI applications could interact with underlying electricity systems in complex ways and decisions taken by the AI may be hard to explain. This impenetrability may make it harder to diagnose and resolve faults in the system.
Unethical or illegal decision-making	AI-based decision-making may lead to unethical outcomes. For example, an AI system may decide to reduce demand from energy-inefficient homes, which are likely to house vulnerable people. AI applications could also aid in illegal behaviour, for example market manipulation.
Human-machine interaction, reliance and trust	AI applications can reduce the need for human operators in the electricity system. However, when the capabilities and behaviours of AI applications are not well understood, it is possible to put too much trust in these systems. In such cases, there may no longer be enough skilled human operators to intervene and override an AI application when necessary.
Supplier dependency and vendor lock-in	The development of AI applications for electricity systems will likely be a highly specialised market with only a few suppliers. Energy companies may become dependent on a single supplier with outsized and undue influence over the energy company.

Source: RAND analysis.

4.1.1. Cybersecurity breach or intrusion

The first category of risk involves cybersecurity breaches and intrusions into sensitive systems. As electricity systems have become increasingly digitalised, the risk and consequences of cybersecurity attacks have increased.[108] For example, there are indications that foreign actors have infiltrated the US and European electricity systems.[109] While most of these cyberattacks remain limited to cyber espionage and intelligence gathering operations, a few attacks have had kinetic effects – most notably a series of cyberattacks on the Ukrainian electricity system starting in 2015.[110] AI has a complex relationship to cybersecurity offers both offensive and defensive opportunities:

- **Specific attack vectors**: AI applications in the electricity system may present a number of specific attack vectors. For example, adversaries might engage in data poisoning attacks on AI models by tampering with a dataset's content or associated labels. This tactic enables them to embed hidden vulnerabilities in AI models trained on the compromised data, making detection challenging. This could lead to, for example, incorrect calculation of the generation available to meet demand, creating artificial constraints on the system.[111] Adversaries might also use data poisoning to introduce a specific trigger into an AI model. In this case, the model operates as expected under standard conditions, but it will produce the adversaries' desired output in response to the trigger.[112] For example, if weather forecast data include temperatures higher than 35 degrees Celsius, the model is triggered to trip certain key transmission lines which, in combination with the high cooling demand that day, could lead to blackouts.
- **General offensive capabilities**: Adversaries can use AI techniques to attack the electricity system in ways that are not specific to the energy industry, by simultaneously increasing the complexity and lowering the cost of offensive cyber operations. For example, AI can create highly sophisticated and targeted spearphishing campaigns. By analysing vast amounts of data, AI algorithms can customise phishing messages that are more likely to deceive individuals into providing sensitive information or access.[113]
- **General defensive capabilities:** On the defensive side, energy companies can use AI tools to monitor their networks for disturbances that may indicate a compromise.[114] This could help avoid 'living off the land' attacks, whereby attackers infiltrate the system for extended periods of time and only trigger an attack at an opportune time.

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108 Casanovas and Nghiem (2023).

109 For example, US authorities have warned that Chinese actors compromise and maintain persistent access to US critical infrastructure: CISA (2024); Similarly, thousands of cyberattacks are launched on the European electricity system every week and the sector does not have adequate cyber defences to deal with them: Jack (2023).

110 SANS-ICS and E-ISAC (2016); Pearson (2023).

111 MITRE (n.d .a).

112 MITRE (n.d. b).

113 MITRE (n.d. c)

114 Aldossary and Alasaadi (2021).

4.1.2. Jurisdictional or territorial sovereignty issues

Electricity grids often span multiple countries, states or regions. The deployment of AI applications can lead to potential complications and vulnerabilities arising from jurisdictional or sovereign boundaries. There are several particularly salient issues relating to jurisdictions:

- **Complex legal frameworks:** There is little to no dedicated regulation of AI applications in the electricity system. None of the jurisdictions we discussed in section 2.3 currently have dedicated policies on AI applications in the electricity system. Instead, these applications must comply with a complex patchwork of existing general-purpose regulations, including those on privacy and data protection, cybersecurity, energy, as well as critical infrastructure protection regulations and general private law requirements. The situation becomes even more complex when these applications involve the sharing of data between different organisations and across national borders.[115] The complexity of the legal landscape may slow the development of beneficial AI applications due to large compliance costs.[116]
- **Legal liability**: In cases where AI-driven systems malfunction or cause accidents, determining the jurisdiction for liability and litigation can be complex, especially if the supply chains and data transfers involved span multiple countries.[117]

115 Niet (2022).

116 Heymann et al. (2023).

117 Hacker (2023).

4.1.3. Unexplained or unexpected actions

AI-based decision-making can be incredibly complex, and it can be hard to understand and explain how an AI application arrived at a certain outcome. There are concerns stemming from unexpected or unexplainable actions performed by AI-enabled systems, a challenge often referred to as the 'black-box' problem. This poses a number of risks:

- **Unpredictable system behaviour**: AI applications in the electricity system are likely to incorporate a wide range of data streams and take decisions in close to real time. If an AI system makes decisions or takes actions that are not anticipated or understood by operators, it could lead to unpredictable outcomes that pose risks to operational reliability and efficiency.[118]
- **Challenges in fault diagnosis and resolution**: In the event of a system failure or anomaly, the lack of transparency in black box AI systems makes diagnosing and resolving the issue more difficult, potentially prolonging outages or other problems.[119]
- **Cascading effects**: Electricity systems are tightly coupled with other critical infrastructure and are prone to cascading effects. These dynamics could be amplified by widespread AI deployment, as unexpected action by one AI application feeds into other decision-making processes. This could lead to widespread disruptions across critical infrastructures.[120]

118 Machlev et al. (2022).
119 Machlev et al. (2022).
120 Maas (2021).

4.1.4. Unethical or illegal decision-making

Ensuring transparency in decision-making processes is crucial to prevent unethical or illegal outcomes. In situations where humans play a minimal role, clear rules and expectations become essential, as there is no human to serve as a common-sense or ethical check.

- **Unethical decision-making**: If AI applications are designed to achieve the most economically optimal outcome, they will optimise for this outcome regardless of ethical considerations.[121] For example, an AI tasked with limiting peaks in electricity demand may decide to automatically reduce the demand of energy inefficient homes, which are more likely to house people who are already disadvantaged.
- **Privacy violations**: Energy companies have access to large volumes of personal data. By matching addresses with energy consumption data, it is possible to gain detailed insight into the daily lives of individuals. Training AI models requires a large amount of data and combining these different data streams into a single training set could lead to privacy violations.[122]
- **Market manipulation**: In jurisdictions with liberalised electricity markets, the price of electricity is set by market actors based on the forecasted balance between supply and demand. AI applications can be used to manipulate these markets. For example, AI-driven high frequency trading can be used to execute large volumes of transactions at very high speeds. In doing so, traders can front-run the market by acting on relevant information before it is available to others. AI systems can also be used in illegal trading strategies. For example, the manipulator can place and then cancel orders at a rapid pace to create misleading signals on supply or demand, influencing the market prices in favour of the manipulator. The manipulator could also leverage botnets created out of hacked IoT appliances to slightly alter the total demand of the power grid to shift electricity prices in favour of specific market players.[123]
- **Biased decision-making**: Additionally, AI systems can develop quirks through pattern-seeking. For example, the AI model could begin to associate older callers with follow-up complaints, leading to biased decisions against this group. There have been documented cases where similar systems were manipulated to insult specific groups, provide misleading information or exhibit racist biases. These examples emphasise the need for stringent oversight and continuous training to prevent harmful outcomes.

121 Gratch and Fast (2022).
122 Mireshghallah et al. (2020).
123 Shekari et al. (2021).

4.1.5. Human-machine interaction, reliance and trust

Interaction between AI-enabled systems and human operators or supervisors may also create risks. AI technologies, especially expert systems, have immense potential to enhance the effectiveness and efficiency of complex systems. There may be added pressure to supplant human operators with AI-enabled systems in for-profit energy providers.

- **Unexpected events:** Many common AI algorithms are good at finding underlying patterns in data that may be difficult for humans to spot. This makes them good at predicting future outcomes based on past data. However, an AI may not perform well in situations that differ substantially from its training data. In the context of the electricity system, this can make AI applications well-suited to the management of regular operations, but they may struggle to adjust generation and flow rates during unexpected spikes in demand or natural disasters.
- **Loss of oversight:** To save costs on expensive human operators, energy companies may decide to introduce AI applications and reduce the number of human operators. However, without a proper understanding of the possible effects, this could lead to a loss of oversight where human supervisors are unable to step in in case of a failure.
- **Long-term decisions**: Trust issues may also impact long-term decisions such as network investment plans that outline investment in the electricity system several decades into the future. Grid regulators may put excessive trust in AI-based simulations of future power demand, environmental conditions or other relevant factors. If the limitations of these simulations are not well understood, this could give rise to flawed investment decisions.

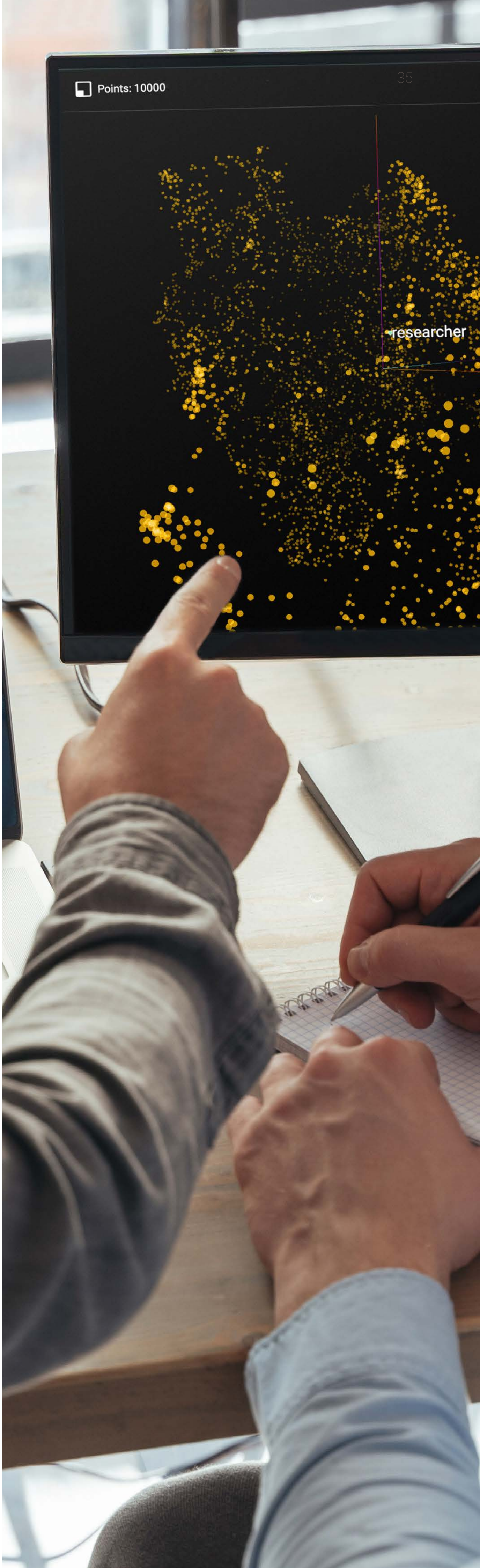
4.1.6.
Supplier dependency and vendor lock-in

The market for energy-related AI applications is still developing. However, given the large computational requirements of power system management, there is tendency towards using large foundation models.[124] This can give rise to various challenges:

- **Concentration:** The substantial costs involved in generating, training and deploying large-scale AI models could create monopolisation among key players. Given the highly specific characteristics of the electricity industry, this market is likely to feature only a few suppliers.[125]
- **Vendor lock-in:** Once it is deployed, an AI application could become a critical part of a company's IT stack and decision-making process. It may be very hard to undo its integration, particularly for front-of-meter applications that affect many system nodes. This dynamic can also make electricity companies dependent on the vendor of a particular AI application.
- **Undue influence:** The combination of the concentration of the market among a small number of players and the lock-in effect created by the deployment of a particular AI application can give suppliers undue influence over energy companies. For example, a vendor's decision to deprecate one of their AI applications could have a material impact on operation and decision-making in electricity systems in which it is deployed.

124 Huang et al. (2023).

125 Vipra and Korinek (2023).



4.2. Backcasting exercise

In addition to developing the risk taxonomy, we conducted a backcasting exercise where we envisaged a positive outcome and a negative outcome of deploying AI applications and identified the key policy dynamics that would lead to these potential outcomes out to 2025, 2030 and 2050. Annex A provides relevant methodological details on this approach.

4.2.1. Positive outcome

In the first scenario, we discussed a potentially positive outcome of future AI deployment. The scenario description was the following:

> *'The European transmission system operators use AI to more efficiently secure and manage an integrated European grid under the auspices of a central EU regulator. The AI-enabled grid manager directs the actions of a series of regional maintainer systems, each responsible for securing and maintaining the energy infrastructure across a 150-square-kilometre zone. AI systems are well integrated into a working public-private partnership. Human operators/supervisors are trained and equipped to maintain an appropriately meaningful level of human control over the system. The system was tested most recently by the Great Storm of 2048, a major storm front that tore through Western Europe causing widespread power outages. Conventional response efforts were complicated by significant flash flooding. Fortunately, each regional maintainer AI was trained to undertake predictive maintenance across the network. They also monitor weather and environmental data to estimate where future disruptions or damage are likely to occur. To effect maintenance or repairs, the regional AIs can dispatch semi-autonomous robotic repair drones. These deployments are coordinated by the overall grid manager. As a result, the AI grid-manager stockpiled spare parts, while the regional AIs pre-positioned semi-autonomous repair drones. The grid manager system can direct deployment of temporary transmission nodes in the worst affected areas. It also coordinates the deployment of repair drones under the guidance of its subordinate regional management AIs to effect repairs in areas that are unsafe for human repair personnel.'*

The participants then discussed each of the three different time horizons, starting with the third horizon and working back to the present:

Third horizon (2050): The participants agreed that for this future to be realised, it is essential that regulators have the skills to understand the dynamics of changing technology and what they mean for regulation. Given the speed of technological change in AI, they must be able to do this quickly. This would require a highly technocratic bureaucracy with expert understanding of relevant technologies and would probably also demand extensive collaboration between governments and industry, so that governments can respond more rapidly to developments in the private sector. Furthermore, if we assume that progress in AI is set to continue at an exponential rate, by this time horizon human operators would probably not be able to keep up, even if they were experts. We may reach a situation where regulators need AI techniques to regulate AI. This prompted some participants to question whether this scenario truly presented a positive outcome, because it would reduce human oversight too much. The participants also discussed the implications for resilience of an electricity system where AI applications are widespread. The participants argued that AI applications could make a decentralised electricity system built around islandable microgrids a viable option, making it easier to limit cascading failures. Finally, the pervasiveness of AI applications in this time horizon assumes that there has been large buy-in from the population, which would be possible only if the AI applications met rigorous standards of trustworthiness, reliability and privacy.

Second horizon (2035): The participants argued that the second horizon is when AI begins to move from niche applications to widespread deployment. This is when the disruptive effect of these technologies truly starts to play out. To avoid a public backlash against these disruptions, strong public buy-in is important for this transition. One participant suggested that, as part of policy design to achieve a positive transition to AI in the electricity system, policymakers should engage in a long-term strategic 'wargame', supported by civil society through societal and political movements. This wargame would enable policymakers to develop a holistic approach to AI policy and create buy-in across stakeholder groups. In addition, this time horizon should see large R&D investments into trustworthy and reliable AI applications. Government and corporations in particular will have to improve their understanding of how AI applications can fit into the legacy structure of the electricity system. In this time horizon, policymakers will also need to decide how they frame the relationship between AI policy and the energy transition, which is the other great transition the electricity system will be undergoing simultaneously. Given its complexity, it is unlikely that an electricity system based on variable renewables could work without AI.

First horizon (2025): The participants argued that this initial time horizon would feature lots of social engagement and political coalition building to generate an overall social vision of what AI could offer. The participants stressed that the deployment of AI applications should not be rushed. Not only could an AI-induced failure in the electricity system cause widespread harm to the economy and society, but it would also destroy societal buy-in for AI applications in general (including those that could have significant benefits). Participants generally agreed that governments should work with companies to develop frameworks for developing and testing trustworthy and reliable AI applications.

4.2.2.
Negative outcome

In the second scenario, we discussed a potentially negative outcome of future AI deployment. The scenario description was the following:

> *'Belgian government officials are alerted to a pattern of brownouts and unscheduled load shedding across the electricity grid. Driven by promises of efficiency, electricity infrastructure companies shifted several years ago to a networked AI model, replacing most of its human workforce. By networking with other AI-enabled energy managers, the AI was essentially able to reliably supply the national energy grid on a just-in-time model, thereby increasing efficiency. The human operators in the system are unable to find any faults within the system operation itself. The conclusion reached by company representatives is that criminals must be drawing power in those neighbourhoods for illicit data mining. This conclusion is rejected by the security services and a very public impasse is reached. The unscheduled load shedding occurs with increasing frequency over the following weeks as Europe descends into a sub-zero winter. Political tensions grow between the government and lower-income residents in the affected neighbourhoods. Spurred by calls of injustice, a loosely affiliated hacking collective based in a neighbouring country breaches the secure servers of Enerdyne, the firm that trained the AI, and exfiltrates sensitive data. Publishing the entire model online as a method of protest, the collective demands a moratorium on the use of AI in vital service delivery. After four weeks of unexplained load shedding, and several dozen fatalities, the problem seemingly resolves itself. It is only months later that a detailed examination of the leaked training data by a University of Le'Ron research team identifies the cause. A data-poisoning attack enacted years earlier has caused the AI to self-impose overly conservative limits on production, artificially imposing load limitations while hamstringing the engineers' ability to intervene.'*

The participants then worked their way back through the three time horizons to determine different pathways that could have led to this outcome:

Third horizon (2050): The participants found that the effects of an AI-related outage in the electricity system could have an even larger impact than the scenario suggests. For example, in this scenario the effects of the crisis are limited to the electricity system, yet this system is interconnected with other critical infrastructure such as the water system. The participants argued that risks from AI applications should be considered together with vulnerabilities the electricity system already faces. For example, the bottlenecks in the production and repair of power grid transformers exist today, are not AI-specific, and are well known in the industry. There are also significant gaps in our current understanding of how an AI-enabled electricity system would work. For example, there is a lot of uncertainty over whether it is possible to black start an electricity system run largely by AI applications.[126] It may be that if a critical AI application causes a blackout, we are no longer

126 A black start of the power grid refers to the procedure of restarting energy generation units and restoring power in the network without relying on external electric power transmission networks, typically used after a total or partial shutdown.

able to manually black start the electricity system because the relevant analogue control options no longer exist. On the other hand, it is possible that AI applications can help facilitate black starts by allowing the grid to disaggregate into islanded microgrids that are able to progressively restart in case of a black out. Issues such as these need to be clarified urgently. If we deploy AI and are not entirely sure how it would behave in critical conditions, we may end up with a system that has both AI applications and very expensive human overrides for when there is a failure. In addition, current operation of the system depends a lot on human expertise built up over years. Once humans are no longer in the loop but merely on the loop, these skills may disappear very quickly – and human operators may be less effective at stepping in even if they have the technical capacity to do so.

Second horizon (2035): The participants argued that the key dynamics that set us up for a negative future outcome were related to a lack of performant regulations, as well as economic incentives to prioritise the rapid deployment of AI applications in the electricity system over safety and security concerns. It is important to consider the supporting infrastructure of regulations as well. It may be that regulations are tough on paper but lack a trained workforce to support their implementation, monitoring and enforcement. The participants argued that it would be important to have a clear, obvious and widely applicable yardstick against which to measure the desirability of AI applications during this rapid deployment. The participants discussed AI ethics but concluded that many ethical issues are inherently unsolvable.[127] Instead, they agreed that the explainability of decisions made by the AI application would be useful as a yardstick.

First horizon (2025): To avoid a negative future outcome, the participants agreed that the dynamics between governments and corporations must change. In particular, there needs to be more sharing of information and expertise between governments and corporations, for example through the increased use of public-private partnerships. At the same time, there is a need for level-headedness in the policy debate. While AI applications may hold great potential benefits for the electricity system, it is possible that the technology will not be able to meet the lofty expectations placed on it.

127 For example, there is no universally accepted answer to the 'trolley problem', where a runaway trolley is on course to collide with five people on the track, but a bystander has the option to intervene and divert the trolley to a different track, thereby colliding with just one person: Kamm (2020).

4.3. Policy insights

Based on the risk taxonomy and the backcasting exercise, we were able to generate insights on the risks presented by AI, and potential mitigations.

The risk taxonomy covers a wide range of risks, which shows that the scope of potential risks is large. This is due to the disruptive nature of AI and how it is fundamentally changing decision-making in the electricity system. At the same time, however, the risk taxonomy is not exhaustive, and there may be additional categories of risk that we have not covered. To understand the potential risks arising from the deployment of AI applications in the electricity system, we need to assess the wider landscape of AI risk, while considering the specificities of the electricity system.

AI applications can hide a lot of underlying complexity, which could lead to normal accidents.[128] Increasing the explainability of AI applications can make it easier to trace the chain of decision-making, which is particularly important in critical infrastructure systems. Increased explainability can also raise the trust and societal acceptance of AI applications in the electricity system. Combining different AI applications could further increase complexity. To limit the emergent risks that may flow from interactions, it may be helpful to keep different AI applications separate until government and companies have a solid understanding of their risk profile.

In many cases, AI is a double-edged sword. AI applications can be instrumental in the integration of renewable energy sources into the electricity grid and the development of islandable microgrids, which increase the sustainability and resilience of the electricity system. On the other hand, they have vulnerabilities that can be exploited by adversaries, for example through data poisoning attacks.

The backcasting exercise shows that decisions about risk depend on commercial considerations. Energy companies will be under commercial pressure to improve their efficiency and reduce costs. This may lead to the premature deployment of AI applications before the technical risks are fully understood. Policymakers may consider ways to limit the effects of this commercial pressure while encouraging innovation, for example through the development of mandatory sandboxes where potential AI applications can be extensively tested before their deployment into the electricity system.

The electricity system is interconnected with other infrastructure systems. For example, a blackout could cause issues with the water system, because the latter depends on pumps powered by electricity. When designing policy approaches to mitigate the risks of AI applications in the electricity system, policymakers need to engage with a wide range of stakeholders from different industries to ensure they understand relevant interconnections.

128 Normal accidents can occur in systems that are so complex and tightly coupled that it generates unexpected interactions that lead to a chain reaction of failures: Perrow (1999).

4.4.
Future areas of research

Several of the risks we identified are related to the complex nature of the decisions and actions of AI applications in the electricity system. These risks could be at least partially remediated by making AI applications more explainable and removing or mitigating the black box nature of AI systems. This is particularly important where AI systems are deployed in critical infrastructure such as the electricity system.[129]

The backcasting exercise showed that cultivating public understanding and fostering buy-in from societal stakeholders are essential to successfully deploying AI applications. Given the arcane nature of both the electricity system and AI, creating this understanding and buy-in may prove challenging. More research is needed to identify the right audience, the right message and the right approach to doing so.

For our analysis of the risks, we have used a qualitative approach based on a combination of literature reviews and futures methods. This approach has given us an initial overview of the landscape of risks associated with the deployment of AI applications in the electricity system. However, we have not explored how the impact of the risks on energy security can be quantified (in contrast to our assessment of the opportunities, where we did use a quantitative approach). Conducting this analysis would constitute a valuable next step in research of risks related to AI deployment in electricity systems.

129 Laplante et al. (2020).

Chapter 5.

CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1. AI applications could help improve energy security

AI appears to have much to offer in terms of balancing the competing pressures and opportunities the electricity system faces. Its ability to rapidly detect patterns in large amounts of data from a range of sources, and to make decisions with that information much faster than a human could, seem well suited to complex electricity systems.

These systems could use the help. More is being asked of aging electricity infrastructure, as growing populations and changing demand patterns put pressure on systems not designed to meet these challenges. Moreover, a warming climate, and the extreme weather that comes with it, not only increases demand for electricity, but also increases risks to the infrastructure that supplies it. Added to this, rapidly changing technologies raise the costs to energy companies of updating their infrastructure, while also raising the opportunity cost – as the risk of investments being quickly rendered obsolescent is higher now than in the past. The business model is changing, and this presents fundamental and even existential questions for companies in energy generation and supply.

AI's potential to sift through and balance supply and demand across an increasingly stressed system, isolate problems before they spread, and identify where the greatest gains from new investment might be found, has already prompted some energy suppliers to introduce AI into their operations. These gains may only become sharper and more apparent as AI technology improves, and our means of testing those gains become more refined.

5.2. The benefits mainly lie behind the meter

This study sought to test the potential for AI to improve the level of energy security in electricity systems. The research team found significant potential benefits of applying AI BTM – i.e. applications installed on consumer premises that work directly to make energy consumption more efficient. For example, we found that AI applications that aim to improve the efficiency of HVAC installations could have a significant positive impact on the overall energy security of the system. AI applications that guide demand response and help consumers react more dynamically to changing electricity prices also had a clear impact.

However, the research team found negligible benefits from in-front-of-the-meter (IFOM). Nevertheless, our analysis showed that AI-driven wake steering of wind turbines did not markedly improve energy security. This is surprising: we expected the benefits of AI to be seen more broadly throughout the system. We also noted that the combination of different IFOM and BTM AI applications led to trade-offs between the benefits offered by the different applications.

5.3. The risks of AI should not be overlooked

Despite these opportunities, the deployment of AI applications in the electricity system also comes with risks. Our research points to cybersecurity risks, jurisdictional or territorial sovereignty issues, the risk of unexplained or unexpected actions, unethical or illegal decision-making by the model, failures in human-machine interaction, supplier dependency and vendor lock-in. Commercial pressures may drive electricity companies to deploy AI before it is mature or save costs on human oversight. It may be difficult to undo the implementation of AI application in the electricity system. Policymakers, regulators and energy companies should therefore carefully balance the opportunities and risks offered by specific AI applications.

5.4. Our approach has limitations

The research team faced some obstacles and limitations in undertaking this research. Our quantitative modelling was limited by the availability of sufficiently complete generation and consumption data for the European electricity system, as well as useable data or projections for the performance of AI applications. We also found a surprising reticence among experts, both within and outside the energy industry, to speak to the research team about the pros and cons of AI. In some cases, this appeared to be due to a dearth of potential participants who felt comfortable engaging with both the AI and the energy supply sides of this research, highlighting a potential knowledge gap. It may also be that this is a commercially sensitive area, which could be a reason for some potential participants' reluctance to engage.

This speaks to the importance of further research in this area to assist policymakers in understanding where there are opportunities, what the best options are for accessing them, and how best to minimise risks.

5.5. Policy recommendations

Based on the research, we propose a number of policy recommendations that could help guide the deployment of AI applications in electricity system and ensure that we are able to take advantage of the opportunities offered by AI while limiting its risks.

5.5.1. Policymakers

As with other emerging technologies, the deployment of AI applications in the electricity system confronts policymakers with a challenging and fast-changing policy environment. **Policymakers will need to stay informed of these developments.** This will require sourcing information from different stakeholder groups through public hearings and reports.

In the jurisdictions we discussed, we saw that there are different bodies of regulation, notably AI regulation, energy regulation and critical infrastructure regulation, that partially address the issue of AI applications in the electricity system but do not cover it directly. **Policymakers will need to investigate whether the existing regulatory frameworks adequately cover AI applications in energy and clarify or add to the existing frameworks where needed.**

Our backcasting exercise showed that stakeholder participation and buy-in of the AI transition is necessary to realise the full benefits of AI. **Policymakers need to develop and maintain a dialogue with a range of societal stakeholders.** To ensure this dialogue is representative, policymakers should also try to engage stakeholders that are harder to reach.

Policymakers need to be aware of the market dynamics of AI applications in the electricity system. For example, they need to consider the commercial pressures that may push energy companies towards a rapid implementation of AI applications without due regard for the risks. They also need to take into account the tendencies towards consolidation and concentration in the market for AI applications.

5.5.2. Regulators

AI applications are being developed very rapidly. **Regulators should keep an eye on the market and stay up to date with the latest developments.** This will require the regulator to actively look out for new developments, instead of passively reacting to market developments. Horizon scanning activities of technology developments could be helpful to spot AI applications in the early stages of developments and can help regulators develop a position on these applications before they become commercialised.

Regulators should stay on top of the state of AI deployment in the electricity system. To this end, **regulators should create a mandatory reporting of deployment of AI applications in the electricity system.** They could then analyse this data to gauge the speed and nature of the deployment of AI and use it to assess if further targeted regulatory action is needed.

The interactions between an AI application and the rest of the system in which it is implemented can lead to unexpected effects. Better understanding of these interactions can help reduce the risks associated with the deployment of AI applications. **Regulators should develop sandboxes where AI applications can be tested before their deployment in the electricity system.** This may involve advanced simulations of the electricity system where AI applications can be stress-tested. The ethical dimensions of AI applications could be tested through procedural AI evaluation methods.

The deployment of AI applications in the electricity system touches on several regulatory domains. For example, AI regulators, energy regulators, market regulators and the regulators of other critical infrastructure systems also have a role to play in the successful regulation of AI in energy. To avoid gaps or duplication in regulatory efforts, **relevant regulators should have regular meetings and set up channels for exchanging knowledge.**

5.5.3. Energy companies

Ultimately, the decision to deploy a specific AI application will be taken by individual energy companies. **These companies should consider the risk/opportunity trade-off in the deployment of AI applications**. An important first step is to ensure that they have access to the expertise (either in-house or through a third party) to assess this trade-off for a specific AI application in a specific context. They should also consider the potential for supplier dependency and vendor lock-in, and the difficulties that may arise from trying to reverse deployment of AI applications.

Linked to this, **energy companies should proactively share their intention of deploying AI applications with the regulator**. While we consider that there should be mandatory reporting of AI deployments to the regulator, we acknowledge that this may be difficult to enforce ex ante. Energy companies should therefore engage with the regulator proactively and in good faith.

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Annex A: Methodology

In this annex, we set out the methodology underpinning the various aspects of the report. Given the complexity of the power system optimisation exercise, we have produced a separate technical report that accompanies this policy report. This technical report provides more information on the Python-based power system model and gives a detailed, step-by-step overview of how we applied it.[130]

A.1 Literature review (Chapter 2)

We began our research with a review of the literature on AI applications in the electricity system. To structure our approach to the literature review, we used an iterative process. We first conducted a high-level review, which focused on papers that provide an overview of a relevant segment of the literature. This gave us a first idea of the different ways in which AI applications can be deployed in the electricity system. Based on this high-level overview, we decided to use a categorisation of AI applications with six elements:

- Wind and solar generation forecast
- Grid stability and reliability
- Demand forecast
- Demand-side management
- Optimised energy storage operation
- Optimised market design and operation.

These categories necessarily abstract some distinctions in the literature. For example, we grouped AI applications on predictive maintenance, which are sometimes treated as a separate category in the literature, under 'grid stability and reliability'.

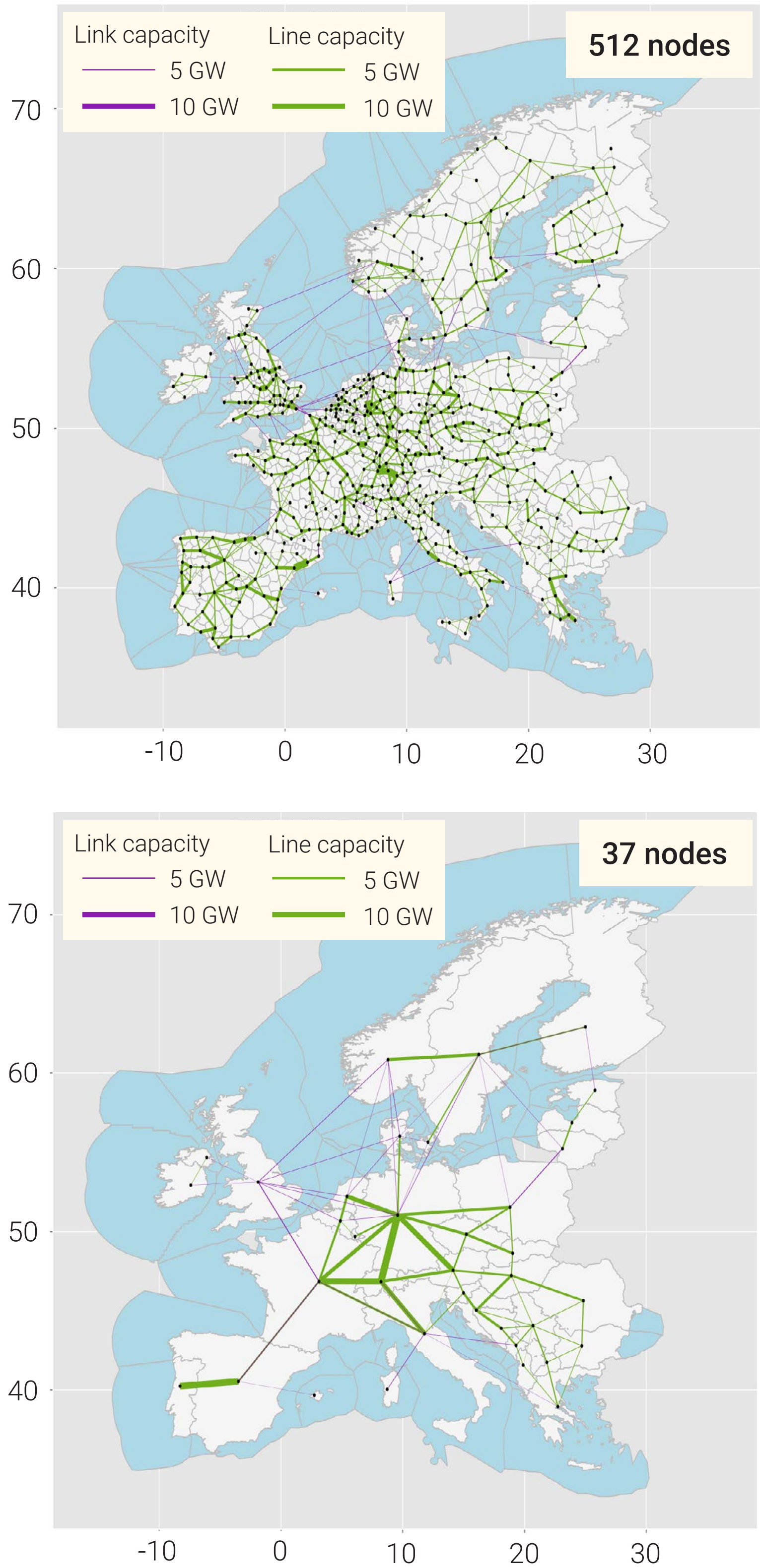
A.2 Power system optimisation (Chapter 3)

To quantify the potential for AI to improve energy security, we used the PyPSA-Eur power system optimisation tool. We selected this as the most suitable model for our research due to the following features:

- **Data availability:** Power system modelling requires a wide range of input data including the grid network topology, electricity demand, power plant type and capacity and renewable energy generation profiles based on location-specific weather patterns. These datasets should reflect appropriate geographical and temporal resolution to simulate the real-time balance of power supply and demand, as well as considering limitations from physical infrastructure and operational constraints. PyPSA-Eur incorporates a workflow to build a model of the European power system and necessary input data from open sources. In addition to links to the different data sources, PyPSA-Eur developers have also made available a fully curated dataset for 2013.
- **System requirements and flexibility:** Power system modelling can be computationally challenging and demand large computational resources to solve large-scale problems. Our interest was to identify a flexible modelling application so that the system could be customised as needed and made feasible for use with the computational resources available at RAND. PyPSA-Eur provides network simplification, or a clustering feature, that enabled us to balance necessary network resolution with our computing system capabilities. Figure A.1 below shows how, with PyPSA-Eur, a system of 512 nodes can be clustered into 37 nodes.

130 Arciniegas Rueda et al. (2023).

Figure A.1: Clustering of European power grid



Source: Neumann et al. (2020).

- **Configurable and easily modifiable input parameters:** PyPSA-Eur is highly configurable as it allows the users to select the analysis scope, customise assumptions and define policy goals. It is easy to modify and select target counties, reference year, time periods, temporal resolution, demand, GHG reduction goals, cost assumptions, weather dataset, etc.
- **Power system optimisation**[131]**:** The mathematical optimisation model is widely used in the power sector, from electricity market operation to long-term energy planning and modelling climate mitigation strategies.[132] PyPSA-Eur can optimise the dispatch of generation and storage and the capacity of generation, storage and transmission infrastructure to yield the cost-optimal energy system operation subject to various constraints, such as reliability, transmission capacity limit, fulfilling CO_2 emission reduction targets and others. This approach allows the user to explore the impact of changes in fuel prices or electricity demand on the power system. The model input and output satisfy the context and granularity of energy security parameters.
- **Scenario analysis:** The objective of our analysis is to quantify the difference between energy security outcomes with and without the AI applications on the power system. This requires modifications to input data to reflect the impact of different AI applications to able to test different scenarios. PyPSA-Eur is modular, making inputs and system parameters relatively easy to modify.

Our approach consisted of the following steps [133]:

- **Constructing a benchmark case for the European electricity system:** This benchmark is intended to reflect a time when the electricity system is very constrained, resulting in low energy security.
- **Selecting three different AI applications for testing:** We focused on applications with a high technology readiness level, as these could be deployed and adopted in the short term. We then modelled these applications in PyPSA by capturing how each AI application impact could be reflected on the grid (such as energy savings potential, generation efficiency improvement, energy density improvement) and mapping the characteristics of the AI application to the variables of the model (Table A.1).
- **Running scenarios**: We ran the benchmark scenario as a baseline on one hand, and the scenarios with AI applications added on the other hand. This generated different model outcomes with and without the inclusion of AI applications.
- **Comparing model outcomes:** We compared the performance of model outcomes in relation to the energy security metrics outlined in Table A.1. This allowed us to investigate whether, and how much, AI applications could affect the selected energy security metrics of the European electricity system compared to a benchmark scenario (Table A.2).

131 While PyPSA provides other features such as power flow and contingency analysis, to explore the behaviour of the power grid, we limited ourselves to power simulation and the use of other features was out of scope.

132 Roald et al (2023).

133 For more information on PyPSA-Eur and our methodology, please see the technical report.

Table A.1: Modelled AI applications

AI application	Category
AI-driven load reduction	Demand-side management
AI-driven load shifting	Optimised market design and operation, combined with DSM
AI-driven wind wake steering	Wind and solar generation forecast

Source: RAND analysis.

Table A.2: Energy security metrics

Energy security element	Metric	Definition
Availability	Reserve margin	The amount of excess capacity available in a power system to meet unexpected increases in demand or unexpected outages of power plants or other energy resources
Accessibility	Fossil fuel dependency	The degree to which a society or economy relies on fossil fuels such as coal, oil and natural gas to meet its energy needs
Acceptability	CO_2 equivalent emissions (CO_2e)	GHG emissions from power generation during the study period
Affordability	Locational marginal price (LMP)	The cost of generating and transmitting electricity to a specific location

Source: RAND analysis.

A.3 Risk taxonomy (Chapter 4)

The next stage in this research was the development of a taxonomy to identify and evaluate the risks associated with integrating AI technologies into the electricity supply and management grid of European countries. This taxonomy was developed using a four-step methodology. The first methodological step was to undertake a systematic review of emergent principles for the ethical and safe use of AI, drawing on existing scholarly literature and government documentation. The research team also reviewed literature related to AI risks and management approaches. This step principally utilised a combination of key words to search Google Scholar, Scopus and IEEE, supplemented by a snowballing stage to identify further references.

The results of this literature review informed the generation of five core categories of risk. Each category was then subjected to deeper qualitative analysis, drawing on operations research methods. The purpose of this step was to more directly link serious risks identified in the literature with the operational context of European energy markets.

The third step was to develop the taxonomy for evaluating and categorising these key risks. Drawing on existing literature, the research team developed 14 categories, divided into four themes. These themes were risk (how and why the AI function becomes dangerous to the system's effectiveness), impact (quantifying the nature of the potential impact of the risk), likelihood (the likelihood of the risk being realised, and the potential steps leading to its realisation), and response (the human and organisational actors responsible for the safe and effective development and use of the AI-enabled system). This design ensures that policymakers could use the taxonomy to map out an exploration of risks associated with future applications of AI into their energy markets.

The final step in this methodology was a series of internal reviews, leveraging RAND researchers who were unaffiliated with the project but had relevant expertise. The feedback from these consultations was then integrated into the taxonomy. This step helped ensure that the analysis and taxonomy of key risks associated with the integration of AI into critical energy infrastructure was of high quality and applicability to policy professionals.

A.4 Backcasting workshop (Chapter 4)

Backcasting is a planning method used in futures and foresight studies that starts with defining a potential future and then works backwards to identify the steps necessary to reach that future state. It was originally developed in the 1970s as an alternative planning methodology to estimate future electricity supply and demand.[134] Since then, backcasting has been widely applied across different policy domains.[135] Unlike traditional forecasting, which extrapolates future developments based on current trends, backcasting begins with the end goal and does not assume that the future will be a direct continuation of the past or the present. This technique allows planners and strategists to think creatively about the future, exploring innovative solutions and strategies that might be required to achieve a preferred future while avoiding potential pitfalls that would lead to a sub-optimal outcome.

In our research, we invited three subject matter experts to participate in a backcasting exercise to imagine futures in which AI applications have been widely deployed in the electricity system.[136] The study team prepared two scenarios for discussion. The first scenario addressed a positive outcome, where the deployment of AI applications in the electricity system had led to a significant increase in energy security. The second scenario covered a future in which the deployment of AI applications had reduced the energy security of the electricity system. We discussed both scenarios using the three-horizons framework.[137] The two scenarios are drafted to reflect the state of the world in the third horizon, which is furthest in the future. The discussion starts with the participants identifying the key policy enablers that underpin the realisation of this scenario in this time horizon. The participants then work their way back to the present, discussing the second and first horizon and highlighting for each what policy requirements are key to realising the subsequent time horizon. This enables the participants to draw out how policy needs to change to arrive at the scenario outlined in the third time horizon, and it creates a roadmap for possible actions to lead to this outcome.

134 Robinson (1982).

135 Quist and Vergragt (2006).

136 The authors would like to thank John Kendall (DCI Consulting), David Marti (Pour Demain) and Felipe Castro Barrigon (European Commission) for their participation in this workshop and their useful insights.

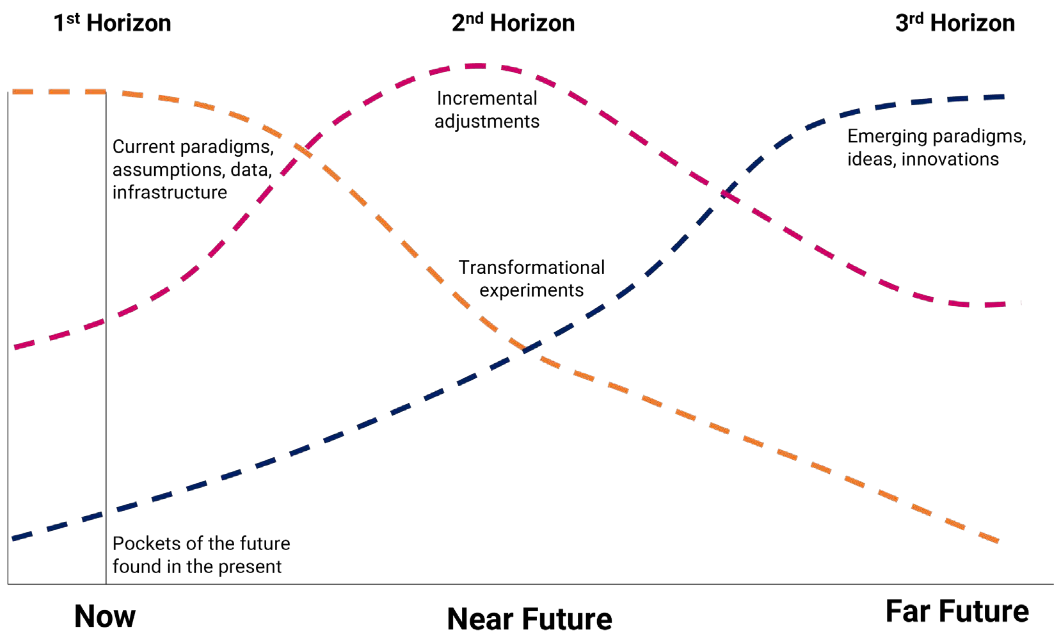
137 Curry and Hodgson (2008).

During the backcasting exercise, we used the following time horizons:

- **First horizon**: The first horizon represents a situation that is just a few years out. In this time horizon, immediate actions and short-term strategies are developed, typically focused on optimising and improving current operations. In our report, the first horizon represents the year 2025. In this timeframe, we see growing deployment of AI applications in the electricity system. However, these applications are generally not very complex and mainly speed up or improve existing processes.
- **Second horizon**: The second horizon discusses the near future – for the purposes of our report, the year 2035. In this horizon, simple AI applications are in widespread use throughout the electricity system, and there is an initial deployment of complex AI applications that enables entirely new forms of interaction. The number of human operators has been reduced and the scope of their role has shrunk. Nevertheless, humans maintain oversight over AI processes.
- **Third horizon**: The third horizon looks out at the far future. It emphasises the new, the transformative, the visionary and breaks with past traditions and current assumptions. In this horizon, the electricity system functions in a completely automated way. The speed and complexity of the deployed AI applications is now too high for humans to play a meaningful supervisory role. In practice, human operators are no longer in the loop. In our report, the third horizon represents the situation in the year 2050.

Figure A.2. captures the three horizons in a diagram, with time along the x-axis, and the relative presence of non-AI applications (orange), simple AI applications (pink) and more complicated AI application (blue) along the y-axis.

Figure A.2. Three horizons



Source: RAND analysis.

A.5 Limitations of the methodology

This report explores the state of the art of the deployment of AI applications in the European electricity system, as well as the opportunities and risks associated with this deployment. The scope of the report is bounded in several ways:

- The field of AI technologies is large and under continuous development. This report aims to provide an overview of the different ways in which AI can be applied in the electricity system. However, it is not meant to be exhaustive. It is possible that developments that occurred after the time of writing render will have outdated some of the findings or recommendations made by this report.
- We limit our quantitative analysis to AI applications at technology readiness levels 8 and 9, because these are the only levels that can be modelled with any reasonable certainty. We also look at short-term impacts on energy security, as we are not able to model long-term impacts to a reasonable degree of certainty.
- The report only looks at the electricity system. It excludes other forms of energy provision, such as the natural gas pipeline network and networks for the provision of heating oil. Neither does it consider infrastructure that provides necessary inputs to the electricity system, such as networks for supplying coal to coal-fired power plants.
- We rely on the concept of energy security as a measure to define the opportunities and risks associated with AI applications in the electricity system. However, this approach has limitations. The academic literature has a wide range of definitions of energy security, and our breakdown of the concept into availability, affordability, accessibility and acceptability may not exhaustively cover what readers understand by energy security. Energy security is also not a unitary concept, and it is possible that AI applications improve a particular dimension of energy security but lead to reduced energy security in others.[138] In many cases, assessment of whether an AI application offers net opportunities or risks will depend on the relative scale of impact on the dimensions of energy security, as well as their political salience – and in practice, these would be highly context-dependent.[139]
- In chapter 3, we discuss the opportunities provided by the deployment of AI in the electricity system by modelling. The model we use is abstract and the dynamics of the power system are highly simplified. The findings should not be seen as definitive findings on the scale of the benefits and opportunities offered by the deployment of AI in the electricity system. In addition, the modelling is based on the current design of the electricity system and only allows us to explore the short-term impacts of the deployment of AI applications in the electricity system.
- Because the model only considers the European electricity system, the core focus of the report is on the European context. Given the many technical and engineering differences between different electricity systems, the findings of this section of the report cannot be applied to other electricity systems without further consideration of the local context.

138 For example, an AI application may increase the availability and affordability dimensions of energy security but reduce the acceptability and accessibility of power (concretely, this could be an AI tool for quickly bringing fossil fuel peaking power plants online that is solely developed by a Chinese vendor).

139 For example, an AI application may lead to a small increase in the availability of power but have larger negative impact on the acceptability of power (concretely, this could be an AI tool that in case of a surge in demand pre-emptively shuts down the power supply to households who use the most power to prevent blackouts. While this application may have a low acceptability, a government could decide that this is outweighed by the increase in availability).