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Deutsche Energie-Agentur (dena)

Harnessing Artificial Intelligence to Accelerate the Energy Transition

WHITE PAPER

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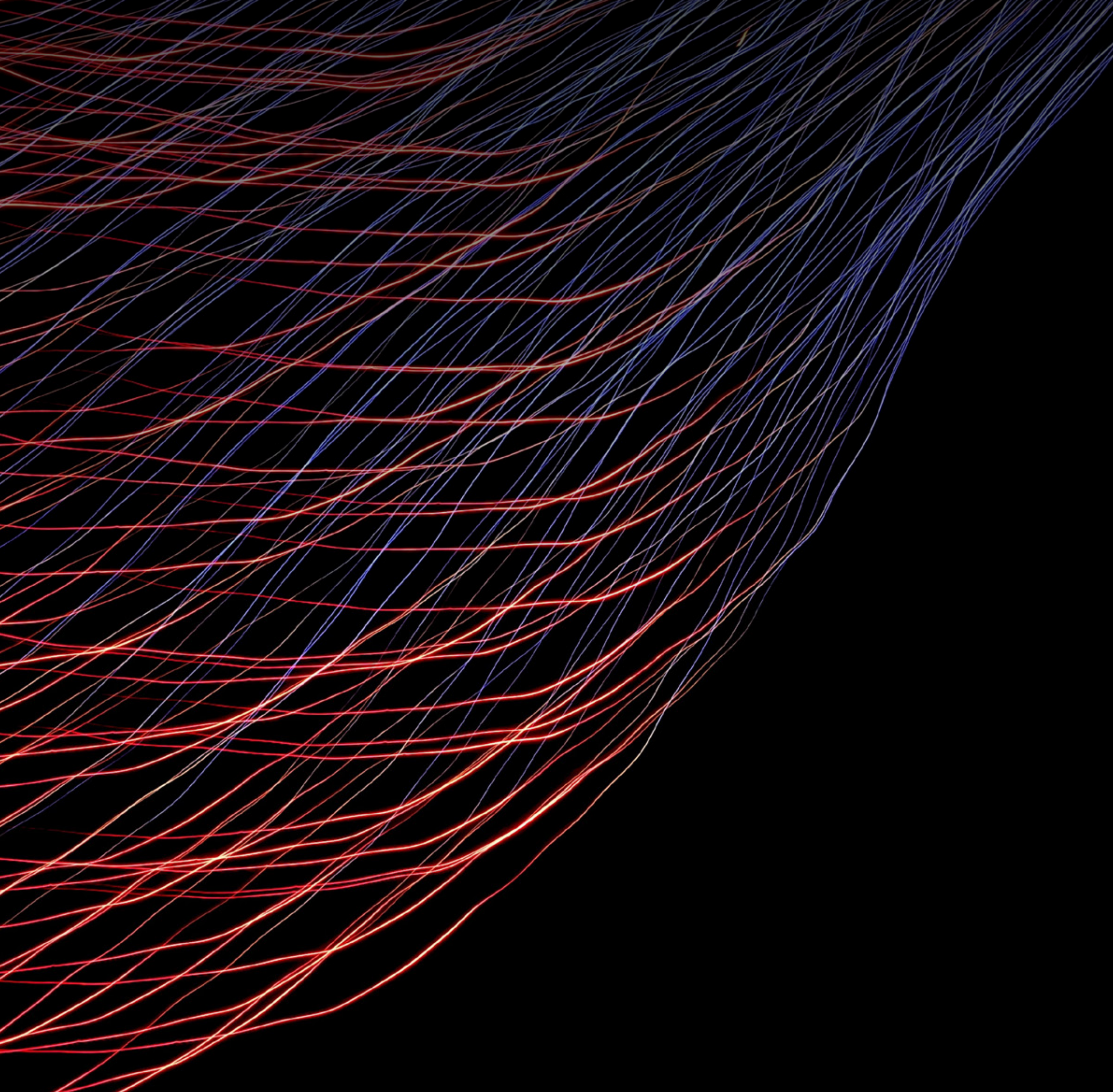

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It is increasingly clear that speeding up the transition to a low-carbon economy is not only essential but urgent, and the energy sector is at the heart of this challenge. This white paper comes at a critical moment. The first instalment of the IPCC's sixth Assessment Report issued in August 2021 and increasingly visible signs of a changing climate over recent years, including heat waves, floods and fires, have focused the minds of policy-makers, corporates and investors alike. New emission reduction targets are emerging every week and many organizations are moving existing targets to nearer time frames. Some companies are even setting carbon-negative targets.

With the 26th UN Climate Change Conference of the Parties (COP26) looming, we expect the rate of climate target announcements to continue at pace. What is less clear is how different stakeholders and the world overall can act at the speed and scale required to meet climate goals. The aim of this white paper is to gather consensus and provide public recommendations for adding another powerful tool to tackle the climate challenge – how to use artificial intelligence (AI) to best enact a fast, equitable and lowest-cost energy transition.

The World Economic Forum's Global Future Council (GFC) on Energy Transition, BloombergNEF (BNEF) and the **Deutsche Energie-Agentur** (dena), the German Energy Agency, ran a series of roundtables from March to May 2021 for leading experts from the energy and AI sectors to accelerate the uptake of AI for energy. This white paper contains a synopsis of the discussions and recommendations from those roundtables, namely, the most important applications of AI for accelerating the energy transition (Section 2), a set of nine "AI for the energy transition" principles that we recommend are adopted (Section 3), and recommended actions for key stakeholders in the public and private sectors (Section 4). This white paper aims to contribute to enhancing an understanding of, as well as trust in, AI technology for the energy industry.

The nine "AI for the energy transition" principles aim at creating a common understanding of what is needed to unlock the potential of AI across the energy sector and how to safely and responsibly adopt AI to accelerate the energy transition. We hope these principles can inspire the development of a collaborative industry and policy environment.

We want to take this opportunity to thank all the participants for their time and contribution to the roundtables and for their valuable input to this white paper and the AI principles.

Executive summary

The efforts to decarbonize the global energy system are leading to an increasingly integrated and electrified energy system, with much more interaction between the power, transport, industry and building sectors. The move to decarbonize the energy supply is also leading to high levels of decentralization in the power sector. This will require much higher levels of coordination and flexibility from all sector players – including consumers – in order to manage this increasingly complex system and optimize it for minimal greenhouse gas emissions.

AI has tremendous potential to support and accelerate a reliable and lowest-cost energy transition, with potential applications ranging from optimizing and efficiently integrating variable renewable energy resources into the power grid, to supporting a proactive and autonomous electricity distribution system, to opening up new revenue streams for demand-side flexibility. AI could also be a crucial accelerator in the search for performance materials that support the next generation of clean energy and storage technologies. However, despite its promise, AI's use in the energy sector is limited, with it primarily deployed in pilot projects for predictive asset maintenance. While it is useful there, a much greater opportunity exists for AI to help accelerate the global energy transition than is currently realized.

The nine "AI for the energy transition" principles (see below) aim at creating a common understanding of what is needed to unlock the potential of AI across the energy sector and how to safely and responsibly adopt AI to accelerate the energy transition. The principles are split into three areas: those that *govern* AI use, those that will help *design* AI to be fit for purpose, and those that *enable* AI's deployment and are aimed at helping to create collaborative industry and policy practices.

"AI for energy transition" principles

Governing

- Risk management
- Standards
- Responsibility

Designing

- Automation
- Sustainability
- Design

Enabling

- Data
- Incentives
- Education

1 Why AI is needed for the energy transition

Global energy systems are in transformation, and several key trends are driving AI's potential to accelerate energy transition.

The global energy system is currently undergoing a massive transformation, and in the decades ahead, it will continue to become more decentralized, digitalized and decarbonized. To reach the commitments made under the 2015 Paris Agreement – limiting the global temperature rise to well below 2°C – this transition must accelerate. In recent years, the energy sector has become increasingly digital and it is clear that further digitalization will be a key feature of the energy transition and an essential driver of the sector's progress towards ambitious climate goals.

The energy transition must be swift and coordinated; digitalization is needed as an enabler

> To reach the commitments made under the 2015 Paris Agreement – limiting the global temperature rise to well below two degrees Celsius – the energy transition must accelerate.

To achieve deep decarbonization, it will be necessary to shift swiftly to an energy system with no or very little carbon dioxide emissions. The efforts to decarbonize our energy system are leading to an increasingly integrated and electrified energy system with much more interaction between the power, transport, industry and building sectors, and a system that will consist of interdependent energy and telecommunication networks. To accelerate the shift towards a widespread, affordable, low-carbon energy supply, there is a need for greater optimization of every aspect of this energy system, as well as greater coordination and cooperation between each component. This requires a better understanding of, and better mechanisms to monitor and control, the ways in which power grids, buildings, industrial facilities, transport networks, and other energy-intensive sectors integrate and interact with one another.

This is where digitalization comes in: it is the key to linking the different sectors into the most reliable, affordable and cleanest system possible. Optimizing each sector separately would exclude flexibility-generating options and reduce the scope for system-wide transformation processes that would maximize the benefits of digital technology for the full energy system, as well as more broadly for the economy, the environment and society.[1] Digital technologies already automate complex processes, orchestrate disparate systems, and facilitate information sharing in the energy sector, and software already plays a significant role in managing our energy systems. With the explosion in the availability of data, and as performance continues to improve, digital technologies will play an increasingly central role in driving a swift and cost-efficient energy transition. These technologies will facilitate performance improvements and cost savings through a combination of automation, optimization, and the enabling of new business and operational models both within and beyond the traditional value chain of generation, transmission, distribution, trade and consumption.

Decarbonizing the power sector is the starting point for full-system decarbonization

The transformation of the energy system will include a rapid expansion of the renewable power supply and vast clean electrification of heat, industry and transport. As electric vehicle (EV) adoption grows, battery storage costs decline, and buildings and heavy industry turn to net-zero electricity, the share of global energy demand met by electricity is projected to grow by 60% from 2019 to 2050. Electricity will increasingly be used to provide heating and cooling (e.g. heat pumps), transport (e.g. EVs) and even raw materials such as hydrogen (electrolyzers). As electricity supplies more sectors and applications, it will become the central pillar of the global energy supply. This will create both new opportunities for value creation and put new pressures on our current systems of power generation, transmission, trade and distribution.

This transition requires significant investment

> …favourable solar, wind and storage economics have become a significant driver of the rapid decarbonization of the power sector.

In BNEF's New Energy Outlook 2020, a long-term economic transition scenario on the future of the energy economy, 56% of power generation could be provided by solar and wind in 2050 – a massive 7.6 TW of solar and 4.6 TW of wind.[2] This scenario assumes no further policy support from today's levels and reflects the fact that favourable solar, wind and storage economics have become a significant drivers in the rapid decarbonization of the power sector, even without strong carbon prices or net-zero targets.

According to BNEF estimates, this Economic Transition Scenario would require $15.1 trillion investment in solar, wind and batteries, and $14 trillion power grid investment by 2050.[3] Even with these historic investments, the scenario outlined above would likely lead to an estimated 2.2°C global warming by 2050. To achieve global net-zero emissions by 2050, every sector of the energy economy needs to eliminate emissions completely. This, according to BNEF's net-zero scenario, would require investments in energy infrastructure to total between $92 trillion and $173 trillion between 2020 and 2050.

The future power system looks highly decentralized

The move towards greater proportions of renewable energy generation has two main practical consequences: the future power system will host more power from intermittent power generators (since solar panels only produce when the sun is shining, and wind turbines when the wind is blowing), and it will be more decentralized. In BNEF's Energy Transition Scenario, 13% of all global power capacity in 2050 will comprise distributed small-scale photovoltaic (PV) energy and batteries, up from 4% today.[4] This will accelerate an ongoing trend of shrinking median power plant size, with BNEF expecting the median power plant size to shrink over 80%, from 944 MW today (which corresponds to a large, natural gas-fired power plant) to 158 MW in 2050.

13%

The proportion of 2050's power generation that could be small-scale distributed rooftop solar

-83%

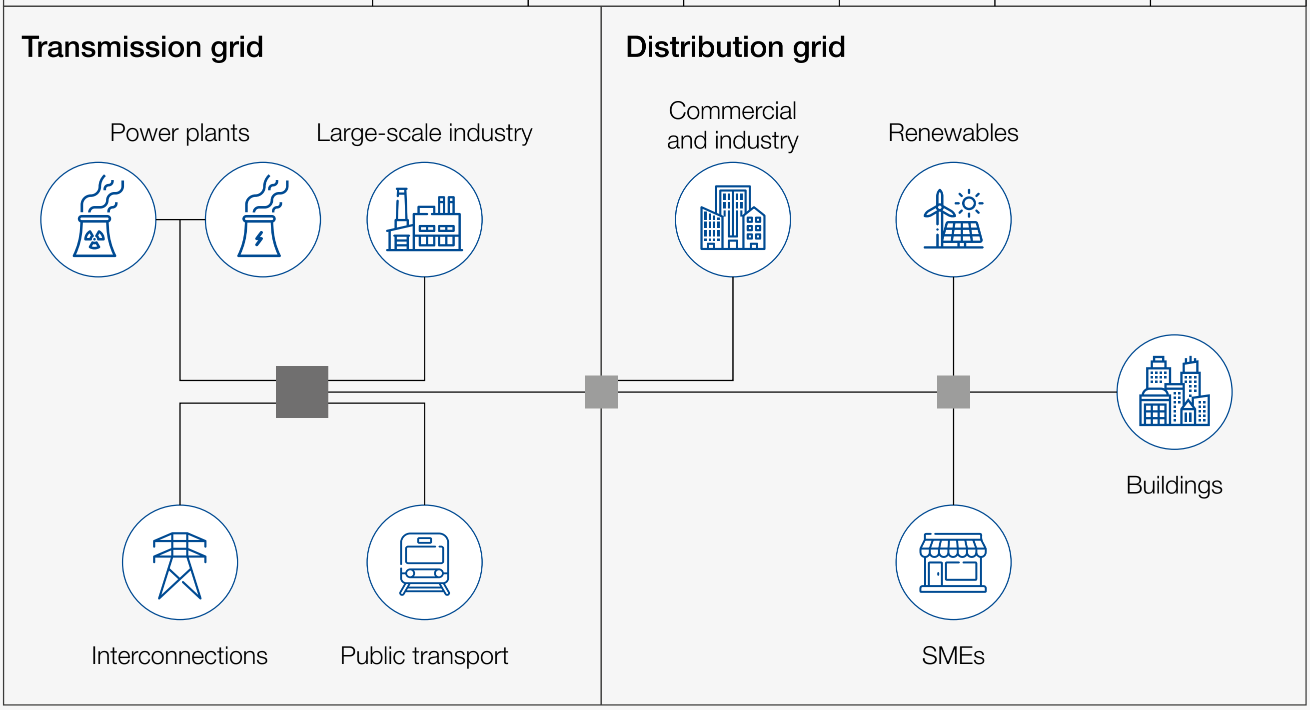
The shrinkage in median power plant size by 2050

The complexity of managing the power system will increase significantly

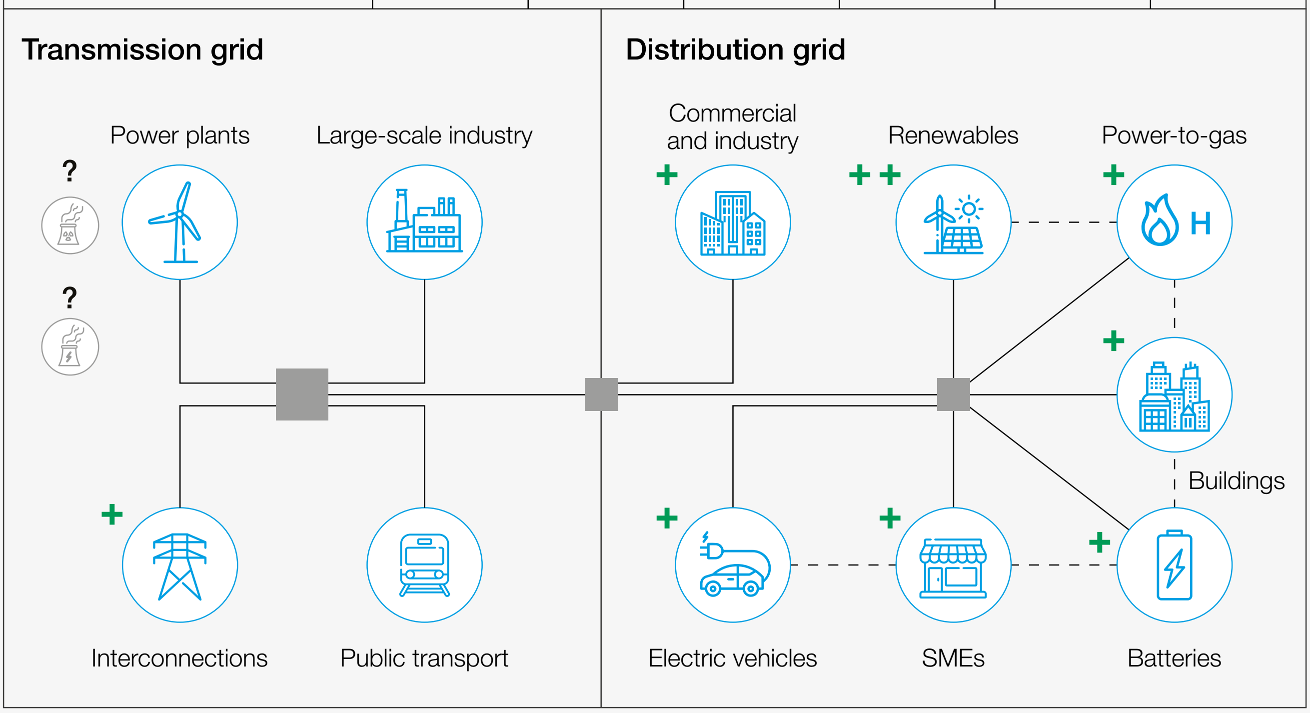
Extrapolating from current deployment trends and taking into account decarbonization targets, it is clear that in the future there will be vastly more physical assets connected to the power grid and, in particular, the distribution grid, where power flows are becoming increasingly dynamic and multidirectional (see Figure 1). These assets might generate power to sell back to the grid (e.g. solar homes), use large amounts of power at once (e.g. EV fast charging) causing demand to spike, or the assets might be connected to the grid without grid operators being aware (e.g. smart home devices). These dynamics could challenge the grid's stability and performance, leading to issues such as power frequency imbalances, blackouts and brownouts, and significant capacity overbuild. Without real-time data, advanced analytics and automation, the increasingly complex power and energy systems of the future will become impossible to manage.

FIGURE 1 | **Transformation of global power systems**

2020	Coupling of sectors	Electric vehicles[i]	Renewables[ii]	Heat-pump demand	Global share of flexible load	Battery storage[iii]
	Low	12 million	1.5 TW	Low	<1%	11 GW



2050	Coupling of sectors	Electric vehicles[i]	Renewables[ii]	Heat-pump demand	Global share of flexible load	Battery storage[iii]
	High	836 million	12 TW	High	8%	1.3 TW



[i] Includes battery, electric and plug-in hybrid passenger cars only (excludes commercial cars and two- or three-wheelers).
[ii] Solar and wind only (excludes other renewable energy sources).
[iii] Includes utility-scale and behind-the-meter lithium ion battery storage.

Source: Adapted from dena (2020). Figures BNEF (2020).

Artificial intelligence can substantially contribute to accelerating the energy transition[5]

> Even if AI were to reduce required energy transition investment by a few percent, this would drive billions of dollars in savings.

AI refers to the broader concept of machines being able to carry out tasks normally requiring human intelligence (such as image and speech recognition, decision-making etc.). AI is not a single technology or product, but rather a set of techniques, mathematical models and algorithms with the ability to extract insights from large datasets, identify patterns and predict the probabilities of potential outcomes of complex, multivariate situations.[6] AI is often confused with automation, but the two are distinct (albeit related): automated systems perform repetitive tasks following a programmed set of rules, while AI identifies patterns and insights in data and "learns" to do this more accurately and effectively over time.

Data, software and automation already play a significant role in the energy sector; however, AI exceeds the capabilities of traditional software. Some use cases of AI already exist within the industry, but in order to address the challenges outlined above, we believe that AI technologies will need to be deployed at a much larger scale and at a much faster pace to speed up the energy transition and lower the associated costs if we are to rapidly, safely and economically transition away from fossil fuels.

The economic value of AI for the energy transition is difficult to estimate, given that it has the potential to be widely adopted across the energy value chain to enable entirely new revenue streams through new business models, and given that some of its benefits will come in the form of avoided costs (e.g. lowering equipment replacement costs through the predictive maintenance of existing assets). Considering the levels of investment required to deliver the energy transition, even if AI were to reduce the required investment or shave peak energy demand by a small percentage, this would drive billions of dollars in savings for the industry and consumers alike.

BOX 1

Selected examples of the value of AI for the energy transition

$1.3 trillion

The reduced clean energy power generation investment, 2020-2050, resulting from every 1% of demand-side efficiency, according to BNEF's net-zero scenario.[7] AI could achieve this by enabling greater energy efficiency and helping to flex demand.

$188 billion

Without intervention, increased air temperatures due to climate change could reduce the lifetime of power grid equipment and could cut the lifetime of transformers by 10 years, according to scientific studies.[8] BNEF analysis shows that this could cause an additional $188 billion in replacement costs between 2020 and 2050 globally.[9] AI can help operators avoid this additional cost by keeping transformers within optimal operating ranges.

6-13%

Across a range of developed markets, BNEF found that the lack of intelligent flexibility would increase power system costs by 6-13% in 2040[10] (study based on Germany, Spain and the UK). AI can help control and balance this intelligent flexibility, for example, with AI-enabled electric battery charging and batteries, thereby reducing system costs, optimizing system build-out while minimizing curtailment, and reducing reliance on fossil fuel plants for backup.

2

Applications of AI for the energy transition

AI is a powerful tool which can manage the complexity of the global energy transition and achieve greater system efficiency, therefore lowering costs and increasing the speed of the transition.

AI technology has the potential to rapidly accelerate the energy transition, particularly in the power sector. In this section, we identify some of the most promising AI applications for the energy transition across four focus areas: renewable power generation and demand forecasting, grid operation and optimization, energy demand management, and materials discovery and innovation.

AI applications can be further classified based on the data inputs they use. AI can use many forms of input data: audio, speech, images, videos, data gained from sensors, data collected manually or robotically, etc. According to dena's 2020 analysis[11,12] of fields of applications for AI in the energy industry (see Figure 2), the majority of AI applications fall in the following categories of data:

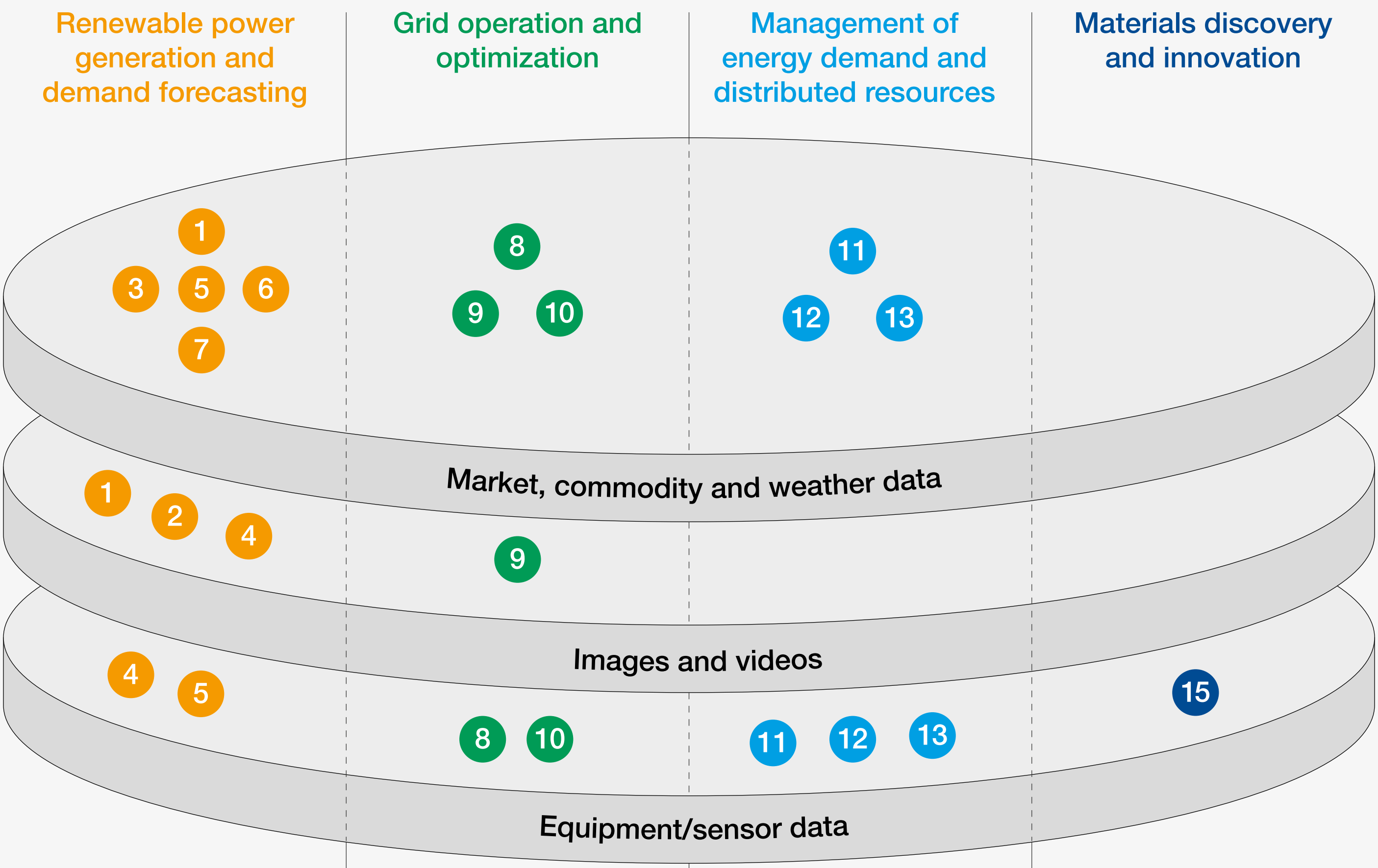
Market, commodity and weather data
Using data collected from various sources, e.g. electricity consumption data, electricity price data, and weather data, AI is employed to recognize patterns and/or provide probabilistic predictions of future outcomes based on patterns identified within the data. The data used is often time series data, which is a series of data points that have been collected over regular time intervals and ordered chronologically.

Images and videos
Using image and video data for AI to recognize objects or conditions in images (e.g. using satellite images to determine cloud cover patterns and, in turn, predict the output of a solar plant).

Equipment and sensor data
Using input data from equipment and "smart" devices that combine sensors with communications and networking capabilities to enable real-time digital connectivity and coordination of physical assets. These systems of sensing and device-level control are a prerequisite for the intelligent coordination and automation of the energy system using AI.

Figure 2 shows the most promising applications of AI for the energy transition and classifies them according to the type of input that is used. A specific application can use several input types. The applications are then explained in more detail in the following sections.

FIGURE 2 | Applications of AI for the energy transition, classified by type of data



1 Siting of solar and wind farms
2 Construction of power plants
3 Improvement of product design
4 Prediction of asset failures and outages
5 Optimization of maintenance schedules
6 Power production forecasts
7 Power demand forecasts

8 Grid design and planning
9 Equipment operation and maintenance
10 Monitoring of grid performance

11 Intelligent management of distributed renewables and devices
12 Optimization of electricity consumption of equipment/buildings
13 Operation of virtual power plants (VPP)

14 Autonomous materials discovery
15 Automated material synthesis and experimentation

Source: dena analysis (2020)

1 Renewable power generation and demand forecasting

As renewable power generation grows, both in absolute terms and as a share of the power supply, it will become essential to better predict solar and wind power generation, to improve capacity factors and production uptime at solar and wind plants, and to accurately forecast power demand. From power plant siting and design through to power scheduling and dispatch, AI has a role to play.

There is great potential in combining better generation forecasts with power demand forecasts, to optimize both short-term and longer-term system planning and operation.

The 1 **siting of solar and wind farms** has a major influence on the capacity factor of these power plants. Companies are already using AI to identify sites with the most favourable sun and wind resources and the best access to existing grid infrastructure. When 2 **power plant construction** begins, AI can also be useful in managing and accelerating costly build schedules by, for example, optimizing the sequencing of equipment delivery to sites or using computer vision to identify inefficient or dangerous worksite processes. AI can even help 3 **improve product design** for new ergonomic wind turbine blades, PV panels, or power electronics and control systems.

When power plants start generating electricity, operators are required to carry out regular maintenance. This can cost anything from 1% of power generation costs (e.g. for utility-scale solar) to 20% (for offshore wind farms), according to an analysis from BNEF.[13] Failing to carry out maintenance can lead to system malfunctions and failures, resulting in downtime and additional repair costs. AI is increasingly being integrated into operations and maintenance processes to improve their efficacy by 4 **predicting failures and outages**, helping to reduce unnecessary maintenance and optimize lifetime maintenance, and avoiding or delaying costly equipment replacement. AI can also 5 **optimize maintenance schedules**, which can save significant costs for remote sites such as offshore wind farms. Using sensors which monitor the assets' health in real time, AI triggers an alarm if anomalies are detected.

It is relatively difficult to predict when and how much power will be generated from solar and wind farms. To effectively integrate the most renewable electricity into the grid and to capture lucrative power purchase agreements, operators are using AI to better 6 **forecast power production** from solar and wind farms. AI can predict the power output of solar and wind assets by learning from historical weather data, real-time measurements of wind speed and global irradiance from local weather stations, sensor data, and images and video data (for example, satellite images of cloud cover). These short-term power generation forecasts can then be fed into operating systems that schedule local battery storage plant charging and discharge to help reduce curtailment of solar and wind farms.

7 **Forecasting power demand** is complex and when badly done it leads to blackouts or renewable curtailment. AI is good at spotting complex patterns and, using historic consumption data, it can be helpful in predicting consumer demand, both at the individual and aggregate level.

There is great potential in combining better generation forecasts with power demand forecasts, to optimize both short-term and longer-term system planning and operation – whether for short-term power generation scheduling or long-term grid investments. Robust demand and generation forecasts on all timescales (weekly, day-ahead, hourly, and intra-hour) are critical to reducing the dependency on fossil-fuelled standby "buffer" plants and proactively managing the growth of variable energy sources and increasing the variable renewable capacity that can be accommodated in the grid.

2 Grid operation and optimization

Current plans to reach net zero by mid-century imply a massive increase in renewable generation capacity and expansion of transmission infrastructure within a relatively short period of time. Due to the long lead times to plan and commission new transmission infrastructure (lead times of as much as ten years for a new transmission line have been reported for the US), the deployment of new transmission capacity might become a bottleneck. Using AI to optimize grid operation and enhancing the capacity of existing transmission and distribution lines, as well as extending the lifetime of existing equipment, will be key to supporting the energy transition. In addition, in an integrated and decentralized energy system, responsibility for system optimization happens at both the higher and lower voltage levels, distribution grids become more important, and maintaining grid stability and ensuring the security of supply become more complex. AI can be helpful in grid planning to optimize infrastructure build by extending the lifetime of expensive grid equipment and keeping the whole grid system stable, even as more renewables are integrated.

BNEF found that at least $14 trillion needs to be invested in new grid infrastructure/grid replacements by 2050 to support the electrification of buildings, industry and transport and to strengthen the distribution grid so that it can integrate and communicate with many more renewable energy sources. AI has an important role to play in strategic decision-making on 8 **grid design and planning.** It can use historic grid data and electricity generation and demand forecasts to best decide what grid equipment to build where, and how to size the transformers and wires most efficiently. AI can also use climate change data and forecasts to advise on which parts of the grid should be reinforced or moved to best avoid or minimize disruptions and blackouts, including those caused by climate change in the form of extreme weather events (heat, cold, storms, floods, etc.).

When the grid is in operation, AI can be used for a range of important 9 **equipment operations and maintenance** activities. If the grid is to grow by millions of kilometres, as is expected in a future low-carbon integrated energy system, the cost of regular manual inspections will grow commensurately. Computer vision and robotics can enable remote inspection of the grid by analysing video footage taken by helicopters or unmanned drones. These systems can be trained to spot rotting poles, bird nests on wires, and overgrown vegetation, directing maintenance crews to the spots that require condition-based interventions. Machine learning can also help operators understand the performance of transformers and predict anomalies and failures, saving time and money.

Rising global temperature, extreme weather events and increasing forest fire risks are increasing the cost of grid maintenance and the frequency of blackouts. With increasing occurrence of extreme weather phenomena, AI may support the mitigation of these events by identifying critical conditions for equipment early, based on weather forecast and historical grid performances. Rising temperatures will reduce the lifetime of grid equipment, cutting transformer lifetimes by up to ten years. AI can use climate data and transformer operations data to design optimal operation ranges for transformers, keeping them within safer parameters and avoiding over-utilization, therefore extending the lifetime of transformers and other equipment.

Beyond equipment maintenance, AI will play an important role in 10 **monitoring grid performance** and helping to operate the grid more efficiently. Monitoring the grid in real time using a "digital grid twin", with AI helping to identify patterns and modelling the behaviour of power lines, could significantly facilitate the penetration and integration of renewable electricity. Thousands of sensors are already installed on transmission grids to understand how they are performing. Doing the same for distribution grids would be very expensive, but much more distribution grid data is necessary if it is to become a major part of an intelligent system. AI offers an alternative way of monitoring system stability by modelling electricity characteristics through providing missing information based on what sensor data is available. AI can also help enhance the utilization of the transmission capacity of a power line by responding to real-time temperature measurements to determine the upper limit that the line can safely carry (instead of using static limits based on theoretical and conservative temperature assumptions). This could increase the transmission capacity of existing infrastructure significantly.

To maximize the benefits of AI for distribution grid system control, several obstacles will have to be overcome, including a lack of readily available datasets with the quality and quantity of data required for training AI models. This is in part due to widespread sensor deployment being a relatively recent phenomenon, but it is also the result of a lack of data access due to competitive or privacy reasons, as well as a lack of sufficiently accurate data labelling. The standardization and pooling of high-quality training data (e.g. images of defects) can help remedy this situation.

Another key challenge, as with any other data-driven application, is balancing data privacy versus data usage (e.g. smart meter data) and ensuring compliance with applicable data protection regulations (e.g. General Data Protection Regulation). The proposal of the European Commission for the Artificial Intelligence Act, for example, classifies AI systems intended to be used as safety components in the management and operation of critical infrastructure as high-risk.[14] Since their failures may affect human life and health on a large scale and considerably disrupt public life and economic activities, the supply of water, gas, heating and electricity are attributed to this group, and AI applications must therefore meet high standards before they are permitted to be used. While this proposal is helpful for classifying risks and harms from AI implementation, it could raise the complexity and cost of regulatory compliance for the energy industry.

3 Management of energy demand and distributed resources

AI can help increase the penetration and use of distributed renewables and has the potential to significantly accelerate their deployment. It is also being used effectively in improving energy efficiency in buildings, factories and data centres. Being able to reduce, manage, aggregate and manipulate energy demand will be an important factor in how effectively and cheaply the sector can decarbonize.

“ AI can help a household to optimally switch between battery power, on-site solar generation and grid power, thereby solving the customer’s needs, whether that be minimizing costs or maximizing self-consumption.

AI is effective at spotting patterns in large datasets and optimizing processes. This is what makes it ideal for 11 **intelligently integrating distributed renewables and batteries**. AI could play a significant role in orchestrating the interplay between distributed renewables and batteries, and other storage devices. For example, AI can help a household to optimally switch between battery power, on-site solar generation and grid power, thereby solving the customer’s needs, whether that be minimizing costs or maximizing self-consumption.

AI is being used by factories and data centres to help 12 **optimize electricity consumption** through learning how equipment behaves and identifying ways to reduce electricity. In buildings, AI can optimize the electricity usage of heating and air conditioning units, for example, by using sensor data and computer vision to determine occupancy levels and better understand a building’s thermal behaviours. AI is useful not only in reducing power demand but also in shifting it to match times of high renewables generation, allowing demand to follow supply. This could reduce the carbon footprint of the consumer and could be an important enabler for consumers to switch to 24/7 carbon-free electricity. AI could also help absorb solar and wind power that might otherwise be curtailed. Hyperscale data centres are particularly active in what they refer to as “renewables matching”.

AI can play an important role not only in reducing or shifting energy demand but also in opening up the energy services market to a range of consumer and industrial devices. The future energy system will work best, and will have the lowest cost, if distributed energy consuming and generating devices get to play a part in grid balancing and power quality optimization. Today, large industrial equipment in factories is already participating in demand response markets, but often this is arranged manually between grid operators and equipment owners. Grid-scale batteries can, depending on market design, contribute to ancillary services such as frequency control, but smaller behind-the-meter assets are rarely able to participate. Digitalization and AI provide two new opportunities for 13 **operating distributed energy resources and devices as “virtual power plants” (VPP)**. First, they offer the ability to aggregate and orchestrate *small power plants* and *distributed energy resources* to provide grid services otherwise inaccessible to them. Second, through automation and the autonomy of small distributed *devices* (such as fridges or EVs), they enable consumers to help support the grid while maintaining the utility of their devices and, in some cases, gain compensation for the grid services provided by them.

VPPs can help small-scale assets access markets and services that they otherwise would not have access to and can include any combination of small-scale batteries, wind turbines, solar PV panels, EVs, biogas generators and more. Their core component is software for monitoring, forecasting and dispatching energy, and AI is useful here because of its ability to forecast asset performance, energy demand and power prices. It is also helpful in creating autonomous systems capable of making rapid, data-driven decisions about whether a physical asset should bid for a grid service. Other digital technologies, including blockchain, can also help scale VPPs by making it easier for new assets to connect automatically to a local VPP network and be securely identified and paid for grid services performed.

AI could also enable smaller electricity-consuming and generating assets in the home to better serve grid operators. Owners of EVs, batteries, smart thermostats or fridges may not want to contribute microservices to operators by, for example, helping to reduce power demand during a heatwave, due to concerns it would impact their device availability. AI could allow consumers to enable their equipment to ramp up or down while still being fully available when their owner needs them. And AI systems are not only useful in the planning and optimization process; they can also make many decisions autonomously, faster and more accurately than humans. Rather than a customer manually operating a system to charge their EV when asked to by the power operator, an AI-enabled control system manages the charging rate and time to benefit both the EV owner and the grid operator. For example, AI responds to time-varied and/or locational marginal prices in the power market to minimize costs.

4 Materials discovery and innovation

The development of high-performance, low-cost materials for clean energy generation and storage has been recognized as a priority for the energy transition. However, the process of discovering, developing and deploying advanced materials, which need to satisfy complex performance specifications, is highly capital intensive and often takes years to complete.

AI could become a powerful tool to generate novel molecular structures which satisfy specific requirements for certain applications. In a process called (14) **autonomous materials discovery**, AI can be used to screen potential materials at the molecular level, identifying high-potential candidates for a given problem by predicting the properties of these materials. AI is also being combined with robotics and used for (15) **automated synthesis and experimentation** to test the properties of these molecules and their performance under a range of conditions. The feedback from these experiments is then used to inform the discovery cycle. Accelerating molecular discovery, characterization and utilization processes could significantly reduce the time and lower the cost required to deploy new materials.

More advanced materials innovation is required to develop catalysts used in carbon capture, utilization and storage (CCUS) technology. The cost and energy requirements to convert CO_2 into products are highly dependent on catalysts, often using expensive or scarce metals, which prohibit scale-up. Other potential innovation areas include energy-efficient materials (e.g. phase-change materials that can store and release heat), thermoelectric materials that can convert heat into electricity, new solar panel materials capable of improved sunlight energy, conversion and new battery materials and chemistries that improve performance and/or durability. For materials used in the manufacturing of solar PV panels, it typically takes 25-35 years from the first report of a novel material until it is manufactured for commercial application on a large scale.[15] AI could cut that time and grow the pipeline of new materials moving from the lab to the market.

3 “AI for the energy transition” principles

Common guiding principles are needed to unlock the full potential of AI for the energy transition.

In the previous sections, we summarized the significant potential that AI offers to accelerate the energy transition. But this potential won’t be realized without concerted multistakeholder action. During a roundtable series conducted between March and May 2021 with leading AI and energy industry experts, participants highlighted several cross-cutting issues that are preventing AI from being adopted rapidly at scale in the industry. Based on these discussions, we have established the following nine “AI for the energy transition” principles, key consensus principles that, if adopted by the energy industry, technology developers and policy-makers, would accelerate the uptake of AI solutions that serve the energy transition. The following principles aim at creating a common understanding of what is needed to unlock the potential of AI across the energy sector, and how to safely and responsibly adopt AI to accelerate the energy transition. We hope these principles can inspire the development of a collaborative industry and policy environment around AI for the energy transition.

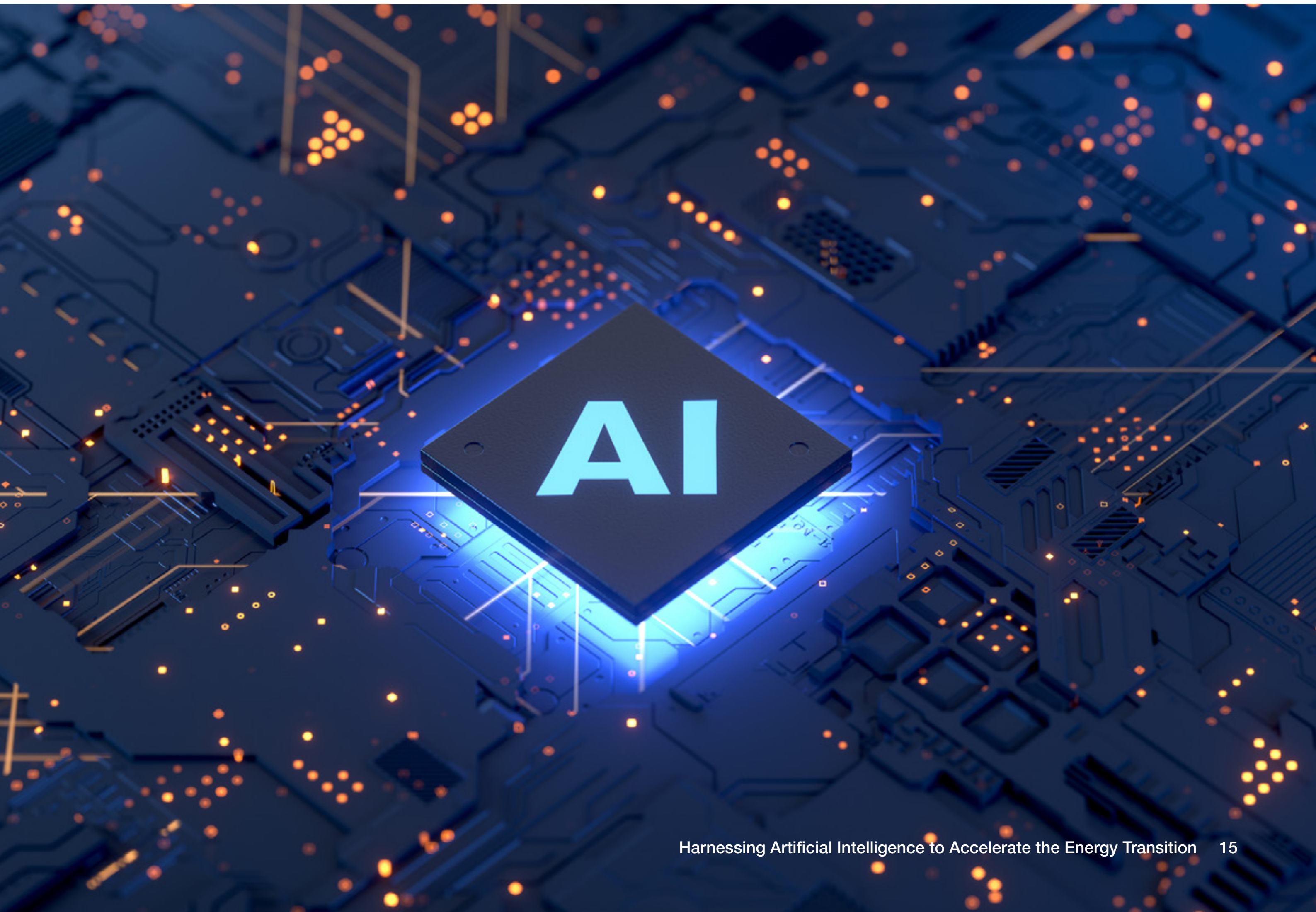
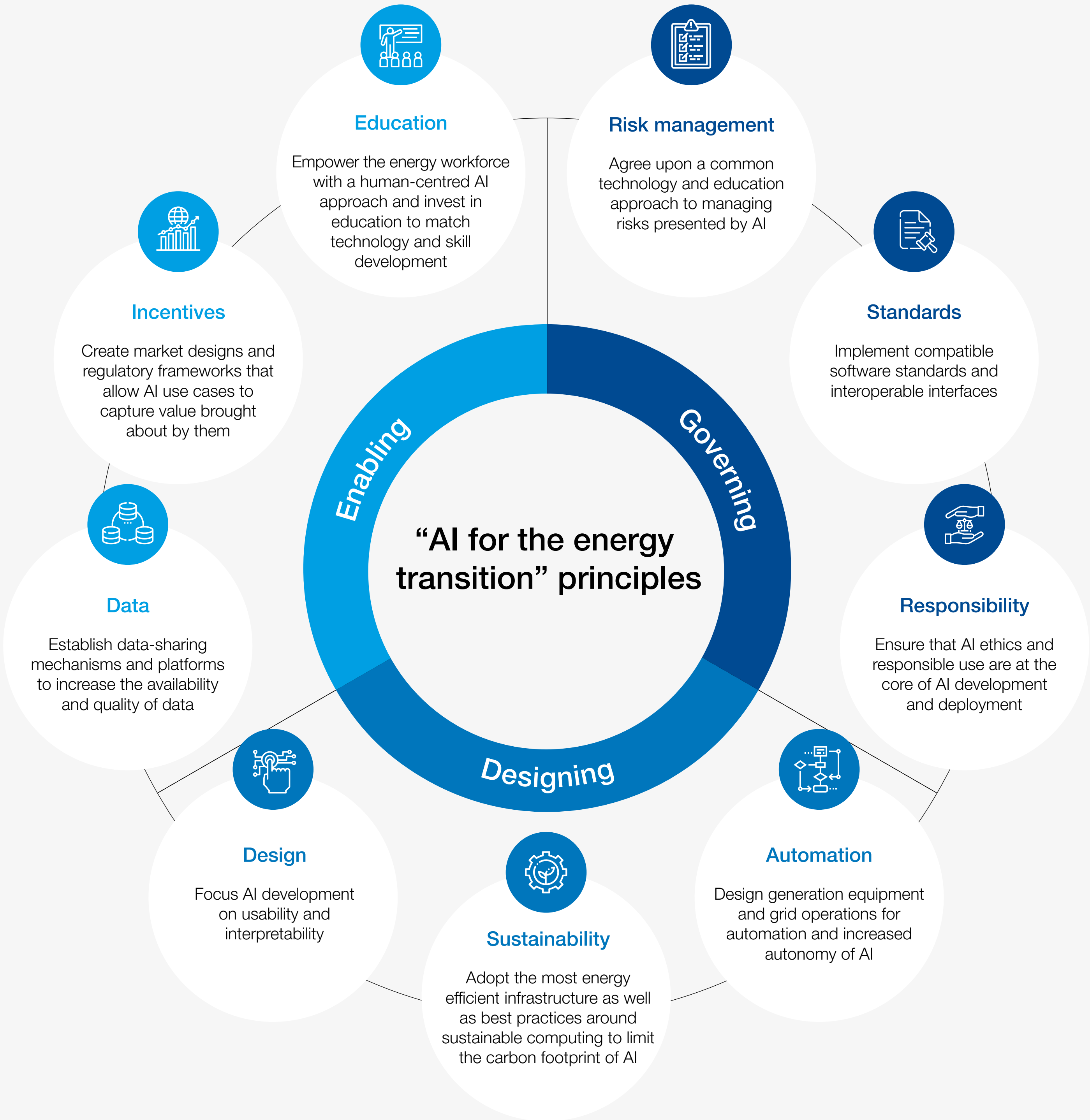


FIGURE 3 | “AI for the energy transition” principles



Source: The World Economic Forum

Designing

Principle 1: Automation – design generation equipment and grid operations for automation and increased autonomy of AI

The complexity of managing future energy systems will not always allow for manual human control. AI will be needed in increasingly decentralized future energy systems that integrate not only electricity but also other sectors (mobility, heat, industry), and where a growing number of complex, close to real-time decisions have to be made. The autonomy spectrum ranges from *augmented automation* with AI solely assisting in human decision-making, to full *autonomy* with AI making decisions autonomously without human supervision. To enable AI's full benefit, grid operations must move towards automation and increased autonomy as standard, and new power system equipment must be designed and set up ready for automation. This will require minimum technology standards for new grid-connected installations and updates to grid operation procedures.

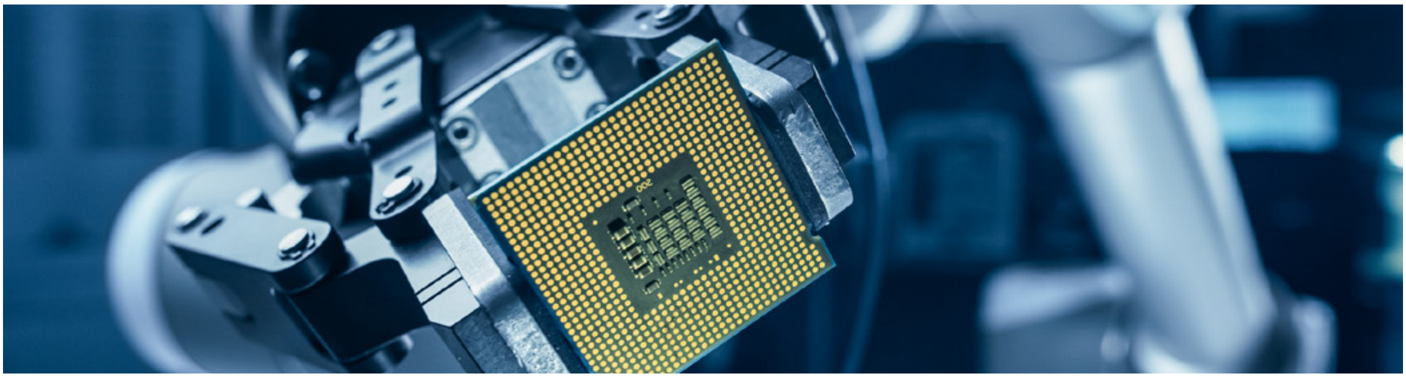
Principle 2: Sustainability – adopt the most energy-efficient infrastructure as well as best practices around sustainable computing to limit the carbon footprint of AI

In this white paper, we highlight the substantial potential for AI to contribute to sustainability goals and accelerate the energy transition. We believe that the sustainability advantages of AI outweigh its own carbon footprint by far. Nevertheless, training and running some machine learning models (e.g. deep learning models) can be computationally intensive, requiring electricity both for computation and for cooling. As the energy industry starts to adopt AI, energy efficiency and sustainability criteria should be taken into consideration, and the energy or emission costs of developing, training and running models should be reported in a standardized way.

As AI finds its way into the energy sector, we must insist that the sector adopts the most energy efficient infrastructure, as well as best practice approaches, tools and methodologies for building energy-efficient models and sustainable computing. This includes running algorithms on hardware powered by green electricity, recycling waste heat, managing computing resources in an energy-optimized way, and using best practice development techniques (e.g. for the tuning of hyperparameters in models) or recycling models across different applications or domains. This will lead to continuous improvements in energy-efficient AI.

Principle 3: Design – focus AI development on usability and interpretability

While the industry will hire more data scientists and carry out internal workforce training, this will not be sufficient in the near term if AI remains accessible to specialists only. AI must be easy to interpret and use for everyone so it can become an integrated base layer for a variety of operational tasks. This will involve developing AI algorithms that explain how they were trained and developed, designing AI algorithms that explain their actions, and building low-code tools that are easy and quick to use and amend by non-experts.



Enabling

Principle 4: Data – establish data standards, data-sharing mechanisms and platforms to increase the availability and quality of data

A critical step to enabling greater data exchange is to agree on common data standards across the energy sector.

Today, the power system is not suitably monitored to provide real-time, granular operations data, particularly at the distribution level. Supervisory Control and Data Acquisition (SCADA) data (the basis of most power monitoring) is not sufficiently frequent or detailed to use for advanced AI algorithms. We need more sensors and better communications networks to build a modern data infrastructure that will allow for the full benefits of digitalization to be realized.

Where sufficient data exists, it is often in different formats, not labelled appropriately, stored on-site, and not shared with third parties.

A critical step to enabling greater data exchange is to agree on common data standards across the energy sector. Once these are put in place, secure, trust-based systems for data sharing within the energy sector can be adopted, for example, through wider cloud and blockchain adoption or anonymized data aggregation activities moderated by regulators. At the regulatory level, the trade-offs between the benefits of using data and protecting data privacy need to be carefully balanced with concessions made when necessary (e.g. to make it an option to use smartmeter data when aggregated and anonymized).

Principle 5: Incentives – create market designs and regulatory frameworks that allow AI use cases to capture the value that they create

AI can make more decisions and faster decisions than humans can, creating new opportunities to make and capture value within energy systems. In the absence of regulatory frameworks that adequately value behind-the-meter device flexibility, there is little incentive to scale up these use cases. AI applications will only scale once there are clear value propositions for customers and other market participants, and only regulators can establish the foundational structures and frameworks to unlock these economic and societal value propositions. But there is currently no agreement on how to value AI-driven applications. For instance, the value of automated demand-response bidding from behind-the-meter devices or AI-assisted microtransactions that optimize local behind-the-meter consumption cannot currently be fully captured.

Principle 6: Education – empower consumers and the energy workforce with a human-centred AI approach and invest in education to match technology and skill development

For AI to contribute meaningfully to the future power system, it needs to earn trust from the engineers, employees and managers who run it. Everyone should feel comfortable with AI being part of their workflows, even if they are not developing the AI tools themselves. Other industries have succeeded in doing this by redesigning teams to bring together the necessary knowledge and skillsets. For the power sector, this might mean teams comprising energy engineers and data scientists, where the latter drive the development of AI capabilities and the former integrate the outputs of AI systems into grid management processes and maximize their operational value.

The successful deployment of AI-based solutions by the end user will also involve education. Educating consumers on how their data is used in these algorithms, and what the limits of AI are, should help them best interact with it.

Governing

Principle 7: Risk management – agree upon a common technology and education approach to managing risks presented by AI

> Working on common approaches around evaluating and managing the risks related to AI will be critical to establishing trust and transparency in algorithms.

Recent EU regulation considers AI for energy a high-risk application. For AI applications to scale within the energy sector, regulators and industry leaders need to understand and mitigate potential risks that AI might pose. Regulatory options include common quality control procedures when building and deploying AI; designing decentralized control structures (ensuring that only a small part is affected in case of an incident); certifying AI systems and/or system operators for safety; and conducting algorithmic audits. Technology options include AI-based security layers (i.e. using AI systems to detect manipulative behaviour within the market) and automated logging of AI systems' activities and decisions.

Working on common approaches around evaluating and managing the risks related to AI will be critical to establishing trust and transparency in algorithms. Setting clear perimeters within which algorithms operate can decrease risks when compared to conventional human processes; however, the perceived risks are still lower when a human is in control. Education around AI risks and AI risk management will be critical for regulators, policy-makers, energy sector employees and citizens.

Principle 8: Standards – implement compatible software standards and interoperable interfaces

The increasing number of integrated devices and behind-the-meter assets means that the sector increasingly needs to agree upon standard protocols for software communication and machine interfaces. Today, there are many different standards and protocols for different geographies and parts of the energy system (e.g. grid communications, smart meters, EV chargers), which results in a lack of interoperability.

This fragmentation will only increase as we attempt to integrate a growing variety of appliances and installations into the grid, leading to sub-optimal outcomes and a grid that is a "whole less than the sum of its parts". All energy system stakeholders and market participants, including regulators, grid operators and equipment manufacturers, should adopt common standards and design and install interoperable "plug and play" devices.

Principle 9: Responsibility – ensure that AI ethics and responsible use are at the core of AI development and deployment

As AI adoption has accelerated across industry sectors, so too have concerns about the risks of unsafe or unethical AI. To ensure beneficial outcomes and avoid societal harms, AI applications in the energy sector must adhere to the OECD's five core AI principles: inclusivity, fairness, transparency, robustness, and accountability. In practice, this means taking a risk-based approach whereby AI's governance and risk management practices are implemented according to the potential for harm of a given use case, with particular attention to high-risk use cases, sensitive personal data and vulnerable populations. AI risk is best managed when ethical considerations are core to the technology and system design processes, when AI systems are thoroughly documented and rigorously tested prior to and throughout implementation, and when organizational processes are designed for the rapid identification and mitigation of emerging issues. As the industry expands its broader AI technology and management capabilities, it must proactively ensure that AI ethics and responsible use considerations are fully integrated into AI development and deployment processes.

4

Recommendations and outlook

Companies and policy-makers must play an active role in governing and shaping the use of AI in the energy sector in a responsible way, and creating an enabling environment to unlock AI's full potential.

Building on the "AI for the energy transition" principles: What needs to happen next? How can these principles be operationalized, and who needs to act?

The energy industry would benefit from approaching AI-related technology governance in a proactive and collaborative way. The coming years will be crucial for encouraging innovation in this domain and democratizing access to new low-carbon technologies across the energy system. As a prerequisite for this, and digitalization more broadly, the industry will have to adopt common data standards, if not already adopted. Increased collaboration among energy sector actors could include R&D collaborations, sharing of best practice approaches to operationalize AI principles, and showcasing use cases. Collaboration could also help build trust between developers and users of AI technologies as well as with consumers and regulators interfacing with AI systems.

Energy companies/utilities executives will need to think about whether and how they make use of AI (e.g. which challenges AI can help solve and, therefore, which processes, products and services will benefit most from it). Company leadership will need to build an understanding of what the AI principles established earlier in this white paper, and any relevant regulations, mean for their organization, and how they can translate this into concrete product design, day-to-day operations, and decision-making processes. Companies can start by exploring best practices for known use cases. It will be a strategic decision for companies whether to adopt AI solutions by procuring them from external providers or to develop the necessary capabilities and solutions in-house. In either case, companies will need to invest in capacity building to ensure that staff are capable of managing the integration of AI systems and realizing their full value.

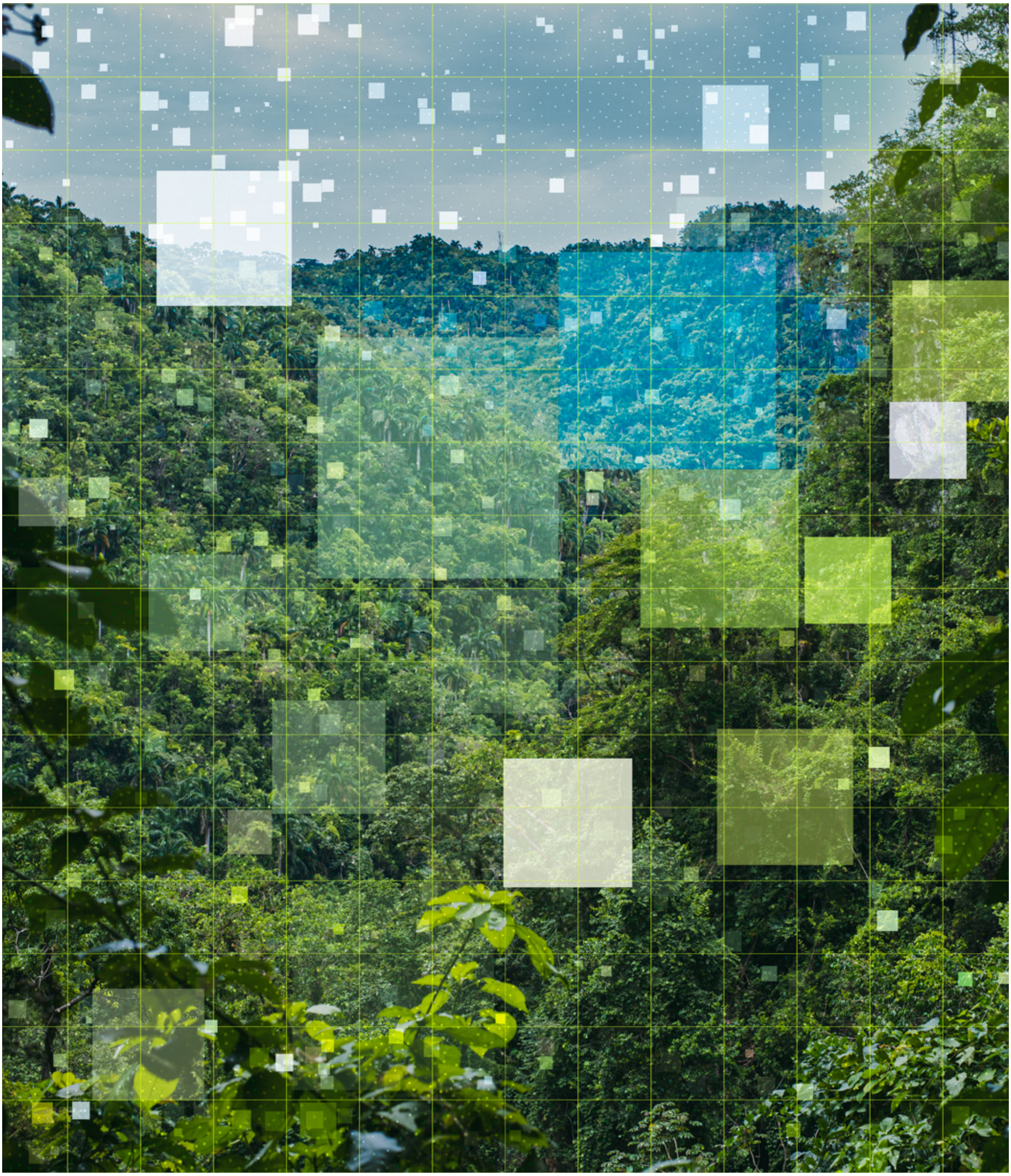
As the management and operation of grids becomes increasingly complex, in particular on the distribution grid level, grid regulators and operators must review the potential of a range of digital technologies (e.g. machine learning, quantum computing, blockchain technology, etc.) to augment the way grids are operated. As the power system decarbonizes and decentralizes, there is a need to rethink grid management and an opportunity to consider new and more decentralized architectures for grid access, operation and management decisions. Suggestions include moving away from the traditional manual command-and-control management approach (with a central system operator), towards technology-enabled decentralized decision-making, which will allow for faster decision-making and the automatic addition of smaller distributed assets to the grid (e.g. using blockchain, digital identity and smart contracts).

Policy-makers and system operators will need to review existing market designs and create advanced electricity markets that reward both variable low-carbon generation, as well as flexible demand. To do this, a truly level playing field for distributed generation vis-à-vis larger-scale power generation units needs to be created and regulatory hurdles removed. As many AI use cases in the energy sector relate to small-scale distributed energy resources, these need to have unrestricted access to the energy markets and the corresponding value pools, to market AI-assisted flexibility, for example.

In regional and national energy system modelling and infrastructure planning, planners should consider the role(s) that AI-enabled, intelligently distributed energy resources could play. To date, energy modelling often ignores distribution grids and overlooks the potential for them to act as a source of grid flexibility and become valuable participants in the grid management process. Integrating these sources, and getting a better understanding of how they can support the transition, can lead to a more informed decision on infrastructure investments such as grid extension and modernization, or the deployment of new, centralized power generation units.

National governments should consider building clearer regulations for energy data (e.g. how it should be protected and who has the right to use it) and make sure that access to this data is equitable and fair. If data is to become a commodity for the energy transition, then governments should lay out clear and simple design rules to make it quick to collect, safe to store, easy to use, and equitably distributed. When designing new regulations, it is critical to consider the level of bureaucracy that this adds, as this might create significant entry barriers for start-ups and smaller players.

As part of this equitable distribution of data, governments could direct or incentivize industry organizations and public entities to manage and fund central databases of industry data. When secure, anonymized and aggregated, these datasets would enable AI algorithm training and potentially reduce algorithm biases that often result from poor quality or limited quantities of data.



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Endnotes

1. World Economic Forum, *System Value Framework,* 2020, https://www.weforum.org/projects/system-value, (link as of 9/8/21).
2. BloombergNEF, *New Energy Outlook 2020*, https://about.bnef.com/new-energy-outlook/, (link as of 9/8/21).
3. Ibid.
4. Ibid.
5. This white paper focuses on the applications of AI that were considered to have a high potential to support the energy transition. The intention is not to give a comprehensive overview of all applications throughout the energy sector, e.g. for conventional power generation technologies.
6. Strictly speaking, machine learning is a current application or subset of AI that allows machines to learn from data without being programmed explicitly. In this white paper, the two terms are used interchangeably.
7. BloombergNEF, *New Energy Outlook 2021*.
8. Fant et al., "Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure", *Energy*, 15 March 2020, vol 195, https://www.sciencedirect.com/science/article/pii/S0360544220300062, (link as of 9/8/21).
9. BloombergNEF, Flexibility Solutions for High-Renewable Energy Systems, 2018/2019, https://data.bloomberglp.com/professional/sites/24/2018/11/UK-Flexibility-Solutions-for-High-Renewable-Energy-Systems-2018-BNEF-Eaton-Statkraft.pdf, https://assets.bbhub.io/professional/sites/24/Flexibility-Solutions-for-High-Renewable-Energy-Systems-Spain-Outlook.pdf, (links as of 25/08/2021).
10. BNEF Power Grid Long Term Outlook, 2021' https://www.bnef.com/insights/25591
11. Deutsche Energie-Agentur (dena) - German Energy Agency, Artificial Intelligence - from Hype to Reality for the Energy Industry, 2020, https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2020/dena_ANALYSIS_Artificial_Intelligence_-_from_Hype_to_Reality_for_the_Energy_Industry.pdf (link as of 25/08/2021)
12. Deutsche Energie-Agentur (dena) - German Energy Agency, Artificial Intelligence for the Integrated Energy Transition, 2019, https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/dena-REPORT_Artificial_Intelligence_for_the_Integrated_Energy_Transition.pdf (link as of 25/08/2021).
13. BloombergNEF, 1H 2021 Wind O&M Price Index, https://www.bnef.com/login?r=%2Finsights%2F26811, (link as of 9/8/21).
14. Artificial Intelligence Act (21 April 2021), Proposal for a Regulation of the European Parliament and of the Council, laying down harmonised rules on Artificial Intelligence (Artificial Intelligence Act) and amending certain Union legislative acts, 2021, *European Commission*, EUR-Lex - 52021PC0206, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELLAR:e0649735-a372-11eb-9585-01aa75ed71a1, (link as of 9/8/21).
15. Ibid.

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