Empowering change: generative AI's role in redefining energy efficiency

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Abstract:

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As generative AI (gen AI) becomes integrated across industries, its impact is particularly promising in sectors like energy and energy-intensive industries, which have historically been forerunners in adopting digital technologies and are well-positioned to leverage the transformative potential of gen AI.

This article highlights the potential for gen AI to enhance energy efficiency and sustainability within these industries, addressing the critical "energy trilemma" of high costs, supply uncertainty, and carbon emissions. The presented analysis suggests that while gen AI holds promise for optimising energy management - through applications like smart grids, predictive maintenance, and energy consumption analytics - the successful adoption of this technology requires a well-defined strategy. Many companies fall into the trap of launching multiple, uncoordinated pilot projects, which dilutes effectiveness and can lead to skepticism about AI's long-term value.

Key insights from the article emphasize that gen AI when aligned with a company's overarching digital strategy, has the power to substantially reduce energy consumption and costs, improve operational resilience, and support decarbonisation efforts. To maximise these benefits, organisations must develop a clear, actionable roadmap for gen AI adoption, starting with targeted pilot projects focused on energy efficiency. The article introduces the AIDE (AI-Driven Energy Efficiency) adoption framework, which outlines a structured approach covering strategic goal setting, risk management, technology integration, and continuous evaluation. By methodically addressing risks such as data quality, cybersecurity, and AI biases, energy-intensive industries can not only improve their energy efficiency but also enhance their competitiveness in a rapidly evolving market.

The transformative potential of gen AI

The transformative potential of gen AI

Over

70

years of gradual advancements in operational performance.

Although the recent surge in artificial intelligence (AI) adoption across consumer products and applications may feel like a sudden revolution, it is, in fact, the culmination of over 70 years of gradual advancements in operational performance. This steady progress was significantly accelerated by the development of transformer technology in 2017, along with breakthroughs in computational power and data accessibility, ushering in a new era of generative AI (gen AI) (Vaswani et al., 2017). This latest frontier of AI is generating considerable excitement within the business community, as gen AI is expected to revolutionise the economy and our everyday lives in the upcoming years.

While it is premature to fully grasp the transformative effects AI may have across various industries, its presence is far from new in sectors like e-commerce and financial services – where its application – now in the form of gen AI - is rapidly expanding (Vulkan, 2020). Gen AI's potential impact is also anticipated in critical areas such as healthcare and sustainability, which are essential for human well-being (Oxford Global Resources, 2023). Energy is one of the critical areas linked to sustainability addressing the global challenges of environmental degradation and resource depletion (International Energy Agency, 2023). Gen AI holds promise for fostering a more sustainable energy system; however, it is crucial to acknowledge both its opportunities and inherent challenges. While gen AI can enhance energy efficiency and optimisation, it also introduces complexities that require careful management, underscoring the necessity for a balanced and strategic approach.

The energy sector has long been a forerunner in adopting digital technologies, leveraging them to enhance operational efficiency, decision-making, and sustainability. According to the Digitalization and Energy report by the International Energy Agency (2017), power utilities began exploring digital solutions as early as the 1970s, using emerging technologies to improve grid management and operations. Similarly, oil and gas companies integrated digital tools to optimize exploration and production processes, while energy-intensive industries turned to process controls and automation to boost quality and yields while reducing energy consumption.

This trend toward digital adoption continues to gain momentum, especially as organisations embrace advanced technologies like gen AI. Industry leaders increasingly recognise the potential of gen AI solutions to drive sustainability, efficiency, and profitability in their operations. Insights from the Artificial Intelligence Index Report 2024 by Stanford University (2024) reveal that interest in AI is surging among world-leading companies. The drive to adopt advanced technologies like gen AI is not only spurred by industry needs but also supported by proactive government initiatives. For instance, the Dutch Government's Knowledge and Innovation Covenant (KIC) provides funding to businesses leveraging gen AI to accelerate the energy transition (NWO, 2024). Such initiatives aim to foster innovation, overcome adoption barriers, and encourage the integration of advanced technologies into energy systems.

The reason behind this momentum is the strong reliance of these industries on data and analytics for innovation, especially as they navigate increasingly complex operational processes, such as optimising supply chain operations, enhancing energy efficiency through real-time monitoring, implementing predictive maintenance to reduce downtime, integrating advanced energy management systems, and streamlining production workflows to minimise waste and emissions. Gen AI introduces a new level of intelligence to data processing, thereby streamlining decision-making and empowering employees with access to knowledge and skills previously beyond reach.

This article outlines the critical factors for successfully integrating emerging gen AI technologies across energy-intensive industries - such as energy, mining, oil and gas, chemicals, and agriculture - by emphasizing the need for a strategic and sustainable approach. For instance, in the energy sector, advanced technologies can optimize grid management, while in chemical manufacturing, gen AI can model and enhance industrial processes. These examples highlight the transformative potential of such innovations, making them a key consideration for future development.

However, realising this potential is contingent upon devising a clear digital strategy. A frequent oversight for companies is to initiate multiple pilot projects across various organisational sectors without first establishing a coherent strategy and identifying priority areas for initial implementation. Furthermore, the sustainability of developing and using gen AI systems must be considered. The International Energy Agency (2024) projects that by 2026, data centers could use twice as much energy as two years ago – and as much as Japan consumes today. Companies must, therefore, critically evaluate whether gen AI is the optimal solution for their specific challenges or if more traditional approaches might prove more effective and cost-efficient.

To navigate beyond the prevailing gen AI hype, as described by the Gartner Hype Cycle for AI (Gartner, 2024), organisations must ensure that the gen AI use cases they choose are strategically aligned with their broader goals and industry priorities. For energy and energy-intensive industries, focusing on energy efficiency as an entry point for employing gen AI could offer a viable and impactful starting point. This approach tackles the core challenges of the energy trilemma by empowering organisations to proactively manage their energy demands in alignment with global shifts towards decarbonisation.

Leveraging gen AI for energy efficiency: a pathway through the energy trilemma

Leveraging gen AI for energy efficiency: a pathway through the energy trilemma

In the current energy landscape, organisations are confronted with the so-called energy trilemma: high energy costs, uncertainty of energy suppl y due to geopolitical tensions, and carbon emissions. These challenges are particularly pronounced within the energy and energy-intensive industries, where the unpredictability of supply can complicate investment decisions, inflate operational costs, and destabilise market prices. In Europe, the surge in energy costs has severely affected these industries, leading to a downturn in production and a rise in imports of energy-intensive goods. Moreover, reducing carbon emissions is not only critical for meeting environmental goals but also for compliance with global regulations, adding another layer of complexity to energy management.
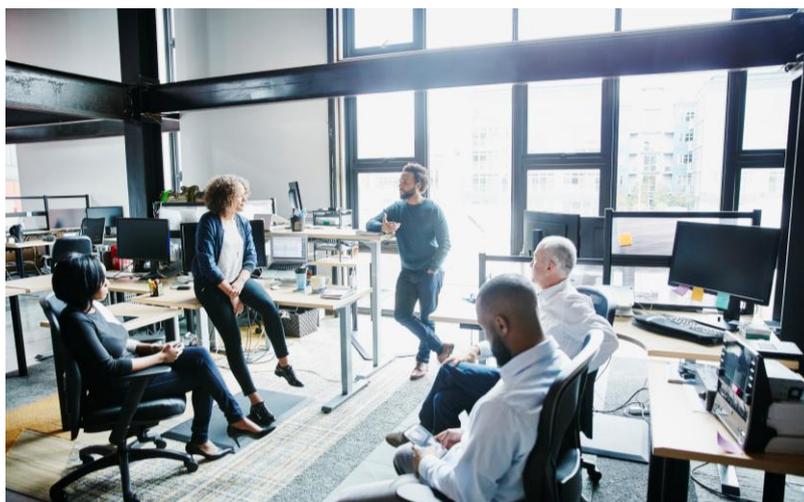
To effectively address this trilemma, it is crucial for companies to thoroughly assess their current and future energy needs to enable more strategic and data-driven management of energy demand. Yet, despite the widespread adoption of AI technologies across the sector, most current applications remain concentrated in trading, asset optimisation, and customer analytics, rather than in direct improvements to energy efficiency (Strategy&, 2025). Industry analyses show that only a small share of AI initiatives explicitly target reductions in energy use or system losses. The majority still focus on short-term performance or revenue outcomes, reflecting an emphasis on profitability over efficiency. This pattern highlights a broader structural gap. Efficiency-driven AI solutions often require deeper data integration, cross-functional collaboration, and alignment with sustainability metrics — areas that are complex and challenging to operationalise effectively. Consequently, digital investments in the sector have produced productivity gains but limited measurable impact on energy efficiency. Yet this gap also represents a strategic opportunity. Energy efficiency remains one of the least developed but most valuable fields for gen AI application, capable of delivering parallel gains in cost, resilience, and emissions reduction.

This gap is increasingly recognised at the policy level. A recent PwC white paper Transforming Energy Demand presented at the Davos Economic Forum in January 2024, calls for a strategic shift towards better management of energy demand and improved energy efficiency. The paper suggests that implementing these strategies could lower energy intensity by 31% and potentially result in savings of up to $2 trillion annually by 2030 (International Business Council, PwC, et al., 2024). Embracing demand-side initiatives, such as enhancing energy efficiency, offers distinct advantages including cost reductions, minimised emissions, and increased resilience against price volatility and supply interruptions. The European Union champions this approach through its "Energy Efficiency First" principle of its strategy for sustainability and climate neutrality, which mandates that energy efficiency solutions be prioritized in all planning, policymaking, and investment decisions across sectors (European Commission, 2024).

At the same time, the International Energy Agency in its **World Energy Outlook 2023**, highlighted underinvestment in energy efficiency and noted that novel solutions to improve energy efficiency are frequently overlooked. However, with the introduction of gen AI technology, this scenario might be changing. Focusing on gen AI for energy efficiency is strategically sound due to several factors. Gen AI's ability to process extensive datasets and provide predictive analytics allows organisations to optimise energy use in real-time, significantly reducing consumption, costs, and carbon emissions. The scalability of gen AI means successful strategies can be quickly expanded across different locations, multiplying the benefits of initial investments.

Energy trilemma

High energy costs

Carbon emissions   Supply uncertainty
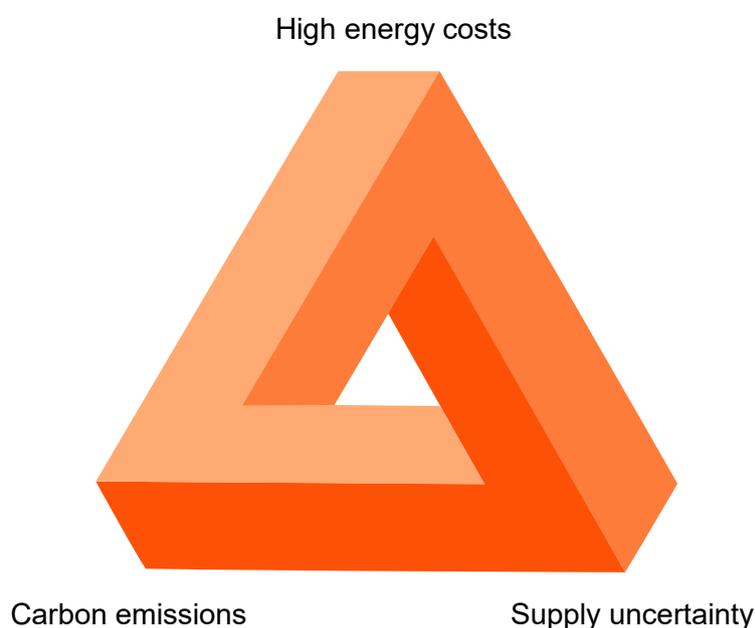
Thus, leveraging gen AI for energy efficiency is a direct, impactful, and scalable solution to address the urgent challenges posed by the energy trilemma where it is most needed - in the energy and energy-intensive industries. Some examples include the following:

Smart grid management. Gen AI optimises electricity distribution and generation within smart grids, improving load balancing and minimising energy wastage according to real-time data and forecasts. It allows grid operators to anticipate demand fluctuations and adjust supply dynamically, ensuring a stable and efficient energy flow. Gen AI also aids in integrating renewable energy sources, balancing their intermittent nature with traditional energy sources to maintain grid stability and reliability. Techniques such as predictive maintenance are employed to prevent equipment failures and reduce downtime, ensuring equipment remains in peak condition. For example, through this new release of Senseye Predictive Maintenance with gen AI functionality, Siemens will make human-machine interactions and predictive maintenance faster and more efficient (Suarez, 2024). This solution leverages existing machine and system knowledge to select optimal actions, boosting maintenance worker efficiency. It fosters greater productivity and sustainability, while also addressing skill shortages by capturing and sharing expert knowledge from an aging workforce, thereby empowering less-experienced employees.

Energy consumption analytics. Gen AI algorithms analyse energy usage patterns and recommend optimisations to minimise energy consumption without affecting productivity. These systems can also predict peak loads and adapt processes to reduce energy costs. Already in 2016, Google's DeepMind developed an AI framework that reducedGoogle's data center cooling energy consumption by a staggering 40% just with a deep learning technology (Okyere, 2024).

Optimised energy storage management. Gen AI can predict the optimal times for charging and discharging energy storage systems based on anticipated energy prices, demand forecasts, and renewable energy availability. This allows for more efficient use of stored energy, reducing reliance on less efficient and more expensive energy sources during peak times. For instance, in managing thermal energy storage systems, gen AI can enhance efficiency by precisely aligning storage cycles with fluctuations in energy demand and generation, ensuring minimal waste and maximum sustainability.

Automated industrial process optimisation. Gen AI can model and simulate industrial processes in sectors like chemical manufacturing, steel production, and others, identifying inefficiencies and proposing alterations to reduce energy consumption. This could involve optimising reaction conditions, material feed rates, and operational sequences to minimise energy use while maintaining or enhancing output quality. These approaches leverage AI's predictive and generative capabilities to not only enhance current systems but also to innovate new processes and designs for better energy management and sustainability. Recent applications in engineering and EPC projects show that AI-driven design optimisation can cut documentation and rework effort by 30–40%, accelerating project timelines and improving long-term operational efficiency (Strategy&, 2025)

More efficient cooling of buildings. Gen AI-driven solutions can improve building cooling processes by integrating real-time environmental data, building usage patterns, and energy demand forecasts. This results in adaptive cooling systems that optimise energy use without compromising comfort. These advancements can significantly reduce energy waste in energy-intensive industries, particularly in facilities with large-scale cooling needs.

Advanced material development. Gen AI aids in discovering new materials and chemical processes that are more energy efficient. IBM Research (2024), for example, uses gen AI to identify and develop new polymer structures that could lead to more sustainable materials.

Optimisation of renewable energy layouts. Gen AI can assist in designing the layout of renewable energy installations, such as wind farms and solar arrays, to maximise energy capture based on historical weather patterns and geographical data. By simulating different configurations, gen AI can identify the most efficient arrangement of turbines or panels, considering factors like wind shadow or potential shading from other structures, which could otherwise reduce the efficiency of energy production. These applications utilise the generative and predictive power of AI to tailor energy production and distribution strategies, significantly boosting efficiency and sustainability in the energy sector.

Predictive and adaptive building design. Gen AI can generate multiple building designs that optimise materials and structural elements for energy efficiency based on climate data, building usage patterns, and geographic location. This can significantly reduce the energy required for heating, cooling, and lighting over the building's lifetime.

These applications not only enhance current systems but also innovate new processes and designs, leading to improved energy management and sustainability. In doing so, gen AI empowers organisations to proactively tackle the energy trilemma, turning the challenges of today into the achievements of tomorrow.

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Potential risks of deploying gen AI in energy and energy-intensive industries

Potential risks of deploying gen AI in energy and energy-intensive industries

However, alongside its potential, gen AI brings a complex array of risks that organisations must navigate to fully leverage this technology without compromising security or operational integrity, such as:

Data privacy

It is crucial to protect sensitive information from unauthorised access to prevent potential breaches.

Cybersecurity

Gen AI systems are vulnerable to backdoor attacks, which may remain undetected, necessitating strong defences against cyber threats.

Fairness and bias

There is a risk of gen AI generating biased outcomes or being exploited to circumvent safeguards intentionally placed within systems.

Transparency and traceability

It can be challenging to identify the origins and reasoning behind AI-generated decisions, which complicates efforts to spot hidden biases or make necessary corrections.

While gen AI poses common risks across various sectors, certain risks are particularly pronounced within energy and energy-intensive industries and should be carefully thought through. Those are:

Data quality and availability

The effectiveness of gen AI applications relies on the availability of high-quality, comprehensive data. In energy sectors, obtaining consistent and detailed data can be challenging, and poor data quality may impair the gen AI's decision-making capabilities.

Accuracy and reliability

For energy and energy-intensive industries, the accuracy of gen AI outputs is vital. Inaccurate AI predictions can lead to energy inefficiencies or wastage, contradicting sustainability and cost-efficiency goals. It is essential for these AI systems to not only provide accurate outputs but also be supplemented with human oversight for final decision-making.

Integration complexity

Integrating gen AI solutions into existing infrastructures can be technically challenging. This complexity arises because these systems must seamlessly interact with well-established processes, making the implementation demanding yet critical for success.

Over-reliance on AI

Depending too much on gen AI for energy management can create vulnerabilities, particularly if AI systems fail or are disrupted. Organisations should ensure system resilience and have contingency plans to maintain operations during AI downtimes.

Evolving beyond the hype: setting the stage for long-term gen AI benefits
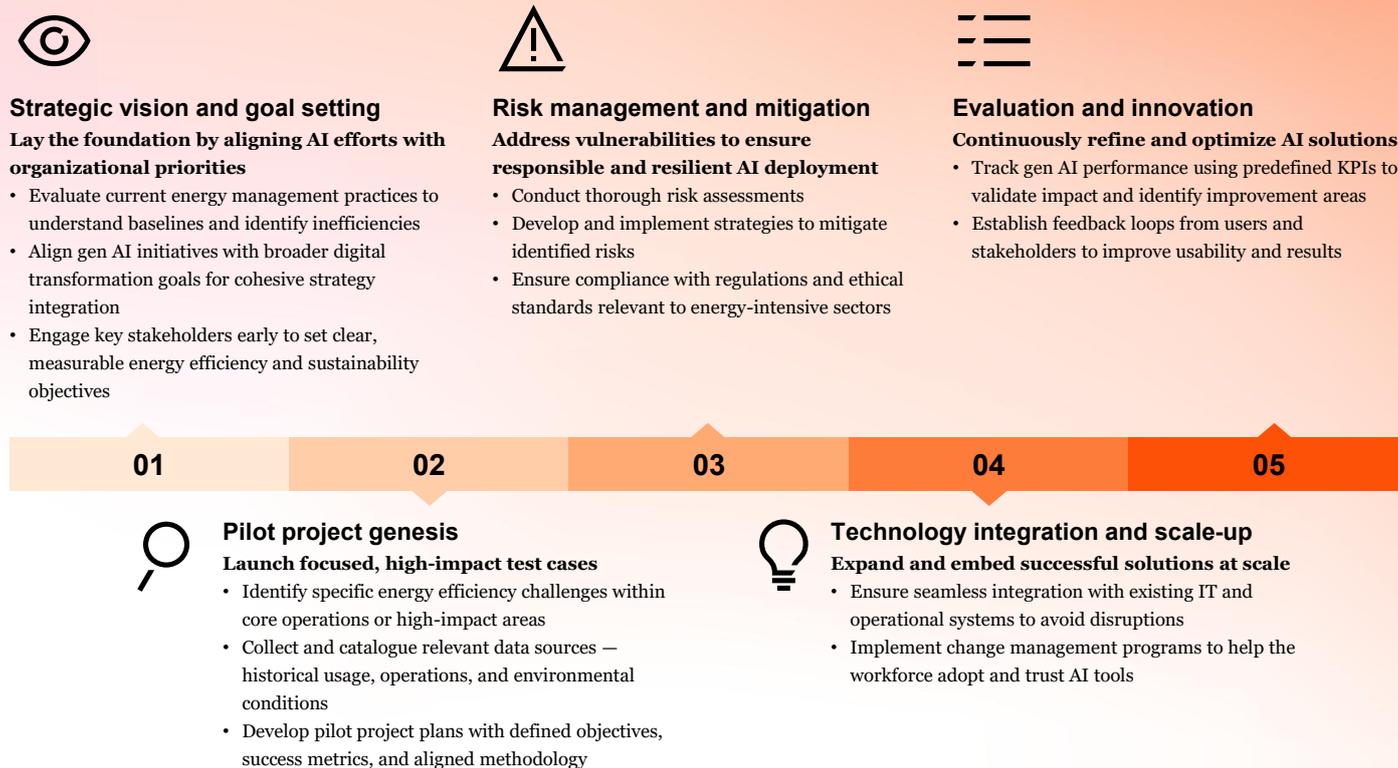
Evolving beyond the hype: setting the stage for long-term gen AI benefits

Amara's Law suggests that the initial impact of new technologies tends to be overestimated, while their long-term potential is often underestimated (Brooks, 2017). This is particularly evident in the early overexcitement surrounding gen AI, where the allure of limitless possibilities can lead companies to prematurely launch numerous pilot projects across different sectors without a cohesive strategy. This scattered approach often results in poor implementation and fails to leverage the technology's potential, especially in industries that depend on intricate processes and face significant risks and challenges with new technologies. Consequently, it fuels scepticism and reluctance to further incorporate the technology into operations.

However, the rapid advancements in gen AI are not just fleeting trends. In fact, leaders in energy and energy-intensive industries should be at the forefront of exploring how gen AI can benefit their operations. These industries, characterised by their technical complexity, can achieve substantial gains from the efficiencies and innovations that gen AI offers.

To effectively leverage this technology and avoid potential pitfalls, it is essential for companies to begin with a robust digital strategy, incorporating an economically sensible gen AI pilot project that aligns with both strategic objectives and industry priorities. Straightforward solutions often prove to be the most effective. A practical starting point with gen AI applications could be improving energy efficiency, which directly addresses the main challenges of the energy trilemma: high energy costs, carbon emissions, and supply uncertainty.

Adopting gen AI for energy efficiency solutions requires a well-structured approach. The AIDE (gen AI-Driven Energy Efficiency) adoption roadmap, illustrated in Picture 1, provides a comprehensive guide for companies to secure a strategic, risk-managed, and scalable implementation tailored to meet the specific needs of energy and energy-intensive industries.

Strategic vision and goal setting
Lay the foundation by aligning AI efforts with organizational priorities
- Evaluate current energy management practices to understand baselines and identify inefficiencies
- Align gen AI initiatives with broader digital transformation goals for cohesive strategy integration
- Engage key stakeholders early to set clear, measurable energy efficiency and sustainability objectives

Risk management and mitigation
Address vulnerabilities to ensure responsible and resilient AI deployment
- Conduct thorough risk assessments
- Develop and implement strategies to mitigate identified risks
- Ensure compliance with regulations and ethical standards relevant to energy-intensive sectors

Evaluation and innovation
Continuously refine and optimize AI solutions
- Track gen AI performance using predefined KPIs to validate impact and identify improvement areas
- Establish feedback loops from users and stakeholders to improve usability and results

| 01 | 02 | 03 | 04 | 05 |

Pilot project genesis
Launch focused, high-impact test cases
- Identify specific energy efficiency challenges within core operations or high-impact areas
- Collect and catalogue relevant data sources — historical usage, operations, and environmental conditions
- Develop pilot project plans with defined objectives, success metrics, and aligned methodology

Technology integration and scale-up
Expand and embed successful solutions at scale
- Ensure seamless integration with existing IT and operational systems to avoid disruptions
- Implement change management programs to help the workforce adopt and trust AI tools

Picture 1. AIDE adoption roadmap could enable stakeholders to strategically plan and implement gen AI solutions, aligning with the broader digital strategy.

The AIDE adoption roadmap entails five essential phases:

1. Strategic vision and goal setting:

Organisations should begin by thoroughly evaluating current energy consumption and management practices. It is crucial to engage key stakeholders to align on strategic objectives and set clear, measurable goals for implementing gen AI. These objectives should align with the broader digital strategy, facilitating an integrated digital transformation.

2. Pilot project genesis:

Selecting initial pilot projects based on potential impact and feasibility is essential. Companies should identify and catalog all relevant data sources, including historical energy usage, operational data, and external environmental factors. Developing detailed project plans with clear objectives, methodologies, timelines, and performance metrics ensures that pilots align with the digital strategy, maintaining a cohesive approach to technology adoption and scaling.

3. Risk management and mitigation:

Conduct thorough risk assessments to identify potential issues related to data quality and privacy, accuracy, reliability, and integration complexity of the AI systems. Develop and implement strategies to mitigate these risks and ensure compliance with industry regulations and ethical standards. Align risk management practices with the overall digital and operational risk framework.

4. Technology integration and scale-up:

Ensure seamless integration of gen AI solutions with existing IT and operational systems to minimise disruptions. Design systems with scalability in mind, allowing successful pilot solutions to expand across multiple sites and departments. Implement comprehensive change management strategies to support workforce adaptation to new technologies, enhancing overall digital infrastructure.

5. Evaluation and innovation:

Regularly evaluate gen AI system performance against established key performance indicators to identify areas for improvement. Establish feedback loops to gather insights from users and stakeholders, enabling continuous refinement of AI applications. Stay updated on technological advancements and emerging trends in AI to foster ongoing digital transformation and innovation.

The AIDE roadmap provides a high-level overview of the journey towards adopting gen AI-driven solutions for energy efficiency. Each phase of this journey is complex, involving numerous questions that stakeholders must address. Although the process of integrating gen AI requires continuous evaluation and adjustment, it offers substantial benefits by transforming energy management in the digital era.

However, embarking on this complex yet fascinating journey often starts with a challenging first step. To navigate this initial phase, organisations should consider these strategic questions as they strive to adopt gen AI-driven solutions for energy efficiency.

1. How does the adoption of gen AI align with our long-term strategic goals and digital transformation vision?

Establishing clear, measurable goals that align with the company's broader strategic objectives and digital strategy ensures cohesive implementation and a unified approach to technology adoption.

2. What are the specific energy efficiency challenges we aim to address with gen AI, and which business units or processes will benefit most from its integration?

Identifying core energy inefficiencies and pinpointing the areas with the highest potential for impact helps define targeted objectives for gen AI systems, ensuring focused and effective deployment.

3. How do we balance the investment in gen AI with the anticipated return on investment, and what strategic partnerships or collaborations could enhance our initiatives?

Analysing the cost-benefit ratio is crucial for justifying the investment, and leveraging external expertise and technology can accelerate the adoption and effectiveness of gen AI solutions.

4. How will we measure and report on the impact of gen AI on our energy efficiency goals, and what future trends in AI and energy management should we be prepared for?

Developing a robust framework for monitoring and reporting aligns with setting clear, measurable goals, and staying informed about emerging technologies and industry trends helps in maintaining a forward-looking strategy.

5. What strategic partnerships or collaborations could enhance our gen AI initiatives?

Leveraging external expertise and technology can accelerate the adoption and effectiveness of gen AI solutions.

By thoughtfully addressing these questions, organisations can embark on a transformative journey, unlocking the full potential of gen AI to drive sustainable energy practices and secure a more efficient and resilient future.

In conclusion, the adoption of gen AI is not merely a technological upgrade but a strategic imperative for energy and energy-intensive industries. It offers a pathway to overcoming current and future challenges, driving innovation, and achieving significant operational improvements. By following the AIDE adoption roadmap and addressing key strategic questions, organisations can ensure a successful integration of gen AI systems, leading to enhanced energy efficiency, reduced carbon footprint, and a stronger competitive position in the market. The journey may be complex, but the potential rewards make it an essential endeavour for any forward-thinking organisation.

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Thank you

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