Artificial Intelligence and Big Data for Planning, Operating, and Restoring Sustainable Distribution Systems

Pioneering the Future of Sustainable Grids Through Data-Driven Intelligence

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DRIVEN BY CLIMATE CHANGES AND THE GLOBAL energy demand growth, transitioning to sustainable, reliable, and affordable energy is one of the most pressing challenges. Artificial intelligence (AI) and big data (BDA) are revolutionizing the energy sector by accelerating renewable energy integration, enabling more intelligent energy management, enhancing grid resilience, and reducing industry carbon footprints. This article explores how AI and BDA are leveraged to optimize power distribution grid planning, operation, and restoration to improve the sustainability, efficiency, and reliability of distribution systems. Specifically, the following topics are discussed: (1) emerging AI and BDA technologies for anticipating sustainable energy integration trend and

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maximizing renewable energy interconnection; (2) advanced forecast, energy management and control strategies methods using AI and BDA that exploit the carbon-free feature of renewable energy; and (3) leveraging AI and BDA to enhance grid resilience in response to extreme weather events and large-scale blackouts. We show that with vast amounts of data, AI and BDA technologies can help engineers, operators, and policymakers develop sustainable planning, operation, and restoration strategies, ensuring a more efficient, resilient, and low-carbon future.

Introduction to Sustainable Distribution Systems

Background of Renewable Energy Integration

The burning of fossil fuels for electricity generation, transportation, and industrial processes is the largest source of carbon dioxide emissions globally. These emissions contribute to global warming, rising sea levels, and inducing more extreme weather events. To slow down climate change and resource depletion, evermore countries have announced pledges to achieve a sustainable future and set up net-zero goals to reduce the use of fossil fuels. Renewable energy sources (RESs), for example, photovoltaic (PV) panels and wind turbines, generate electricity without emitting carbon dioxide, making them critical for replacing fossil-fuel-dependent power plants and reducing the energy sector's carbon footprint. Prompted by supportive policies and technological advancements, renewable power capacity across the globe has significantly increased over the past decade and is expected to continue surging in this decade. According to the Renewables 2024 report released by the International Energy Agency, 5,500 GW of renewable energy capacity are anticipated to be installed worldwide between now and 2030 to empower the sustainable transition of various sectors.

Opportunities and Challenges Brought by RESs

To facilitate the sustainable transition, the penetration level of renewable distributed energy resources (DERs), such as rooftop PV panels and micro wind turbines, continues to grow in sustainable distribution systems. As carbon-free generators that are geographically dispersed in sustainable distribution systems, the interconnection of renewable DERs brings vast opportunities to distribution system operators (DSOs), including decarbonization, sustainability, cost efficiency, and decentralization.

- *Decarbonization*: Using natural resources like wind and solar, renewable DERs generate electricity without directly emitting carbon dioxide and other pollutants. The carbon-free nature of distributed RESs is indispensable for DSOs to minimize their carbon footprints and achieve their net-zero development goals.
- *Sustainability*: Renewable DERs significantly reduce DSOs' reliance on fossil fuels and diversify the generation mix. Renewable DERs enable distribution systems to transit to a sustainable future as the resources used by renewable DERs are replenished naturally and not depleted over time.
- *Cost efficiency*: Driven by technological advancements and economies of scale, the manufacture, installation, operation, and maintenance costs of renewable DERs have drastically decreased over the past decades. As one of the cheapest energy sources in sustainable distribution systems, renewable DERs help DSOs improve operation efficiency and reduce the electricity bills of their customers.
- *Decentralization*: Dispersed across the sustainable distribution system, renewable DERs reduce DSOs' reliance on electricity from upstream grids, thereby enhancing the reliability of the electricity supply. Under extreme weather events, renewable DERs can serve as localized backup power sources when the connection to upstream grids is interrupted, improving the resilience of sustainable distribution systems.

However, there is no such thing as a free lunch. Although renewable DERs generate electricity without carbon dioxide emission, integrating them has brought significant challenges to DSOs, including uncertainty, intermittency, behind-the-meter visibility, and controllability.

- *Uncertainty*: As the generation of renewable energy heavily depends on weather conditions, the power outputs of renewable DERs are highly volatile and uncertain in sustainable distribution systems, as shown in Figure 1. Accurate prediction of renewable DER power is inherently intricate, which poses great challenges for DSOs to maintain the stability and reliability of sustainable distribution systems.
- *Intermittency*: Wind and solar irradiance are not consistently available all day, making the power generation of renewable DERs intermittent. For example, solar generation could change rapidly in the daytime and be unavailable at night. The intermittency of renewable DERs makes it challenging to operate sustainable distribution systems.
- *Behind-the-meter visibility*: Besides utility-scale renewable DERs, many on-site renewable DERs, such as rooftop PV panels, are customer owned and installed behind the meter. Due to a lack of monitoring devices, DSOs have limited visibility for behind-the-meter renewable DERs, including

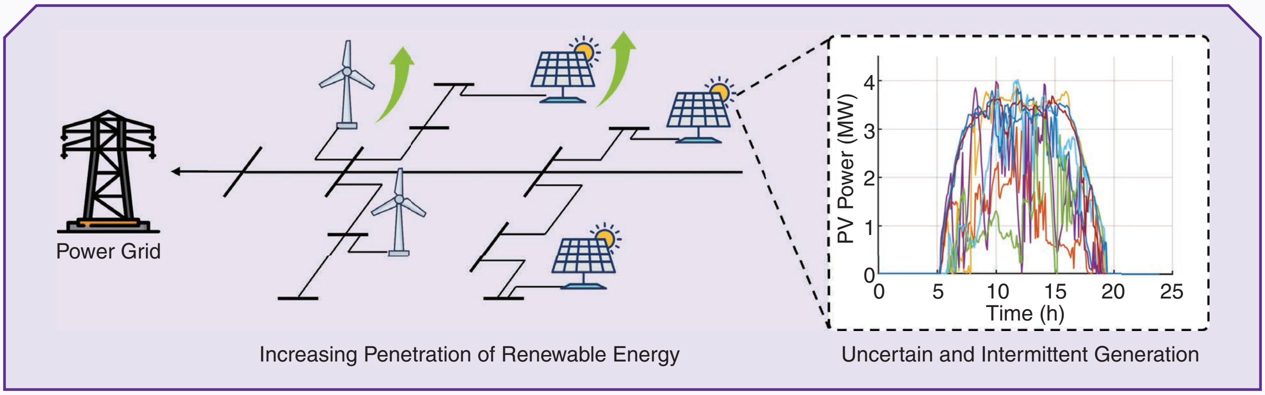

figure 1. Increasing penetration of renewable DERs with uncertain and intermittent generation.

their locations, behaviors, and impacts on the grid. The lack of visibility significantly increases the complexity of managing behind-the-meter DERs in sustainable distribution systems.

- *Controllability*: Unlike conventional generators, renewable DERs lack remote monitoring and control capabilities, especially residential ones. The increasing penetration of uncontrollable DERs requires DSOs to implement sophisticated energy management strategies to maintain a dynamic supply-demand balance in sustainable distribution systems.

Emerging AI and BDA Technologies for Renewable Energy Integration

Traditionally, without penetration of renewable DERs, DSOs use empirical and model-based optimization approaches for the planning, operation, and restoration of the distribution system. However, these methods fall short in handling the challenges brought by renewable DERs in a sustainable distribution system. To fully leverage the benefits of renewable DERs, DSOs need advanced decision-making tools. Luckily, with the development of smart grids, the number of sensing, metering, and communication devices is also increasing. These devices continuously monitor grid conditions and collect operational data systemwide, enabling DSOs to dispatch flexible resources in the sustainable distribution system proactively. With the advancement of AI and BDA technologies, novel data analysis tools and decision-making tools are developed to help DSOs accommodate renewable DERs in sustainable distribution systems. The application of AI and BDA technologies covers a wide range of areas, including forecasting, resource allocation, smart grid management, and blackstart restoration.

- *Forecasting*: With historical renewable generation data, BDA technologies such as statistical analysis and machine learning can be applied to extract the generation patterns of renewable DERs. Driven by BDA, the accuracy of both the long- and short-term renewable generation forecasts has been substantially improved. With more accurate forecast results, DSOs can make better planning, operation, and restoration decisions to unleash the potential of renewable DERs in sustainable distribution systems.
- *Resource allocation*: After forecasting the long-term growing trend of renewable DER penetration, the DSO can use BDA technologies to analyze the hosting capacity of renewable DERs in a sustainable distribution system, which is the foundation of optimal resource allocation in system planning. With the help of AI technologies, DSOs can identify and upgrade key infrastructures, maximizing renewable integration with minimum cost.
- *Smart grid management*: The short-term prediction of renewable DER generation allows DSOs to orchestrate flexible resources in sustainable distribution systems to reduce operation costs and avoid breaching constraints. AI technologies can be incorporated into solving the energy management problem and the volt/var control (VVC) problem, supporting DSOs to exploit the carbon-free benefit of renewable DERs.
- *Blackstart restoration*: With real-time measurements, DSOs can leverage BDA technologies to detect anomalies, identify vulnerable devices, and diagnose faults in sustainable distribution systems. AI technologies further help DSOs control renewable DERs to energize the local grid and support customers during extreme weather events. The blackstart process can also benefit from AI's capability of processing high-dimensional information and making real-time decisions.

In the remainder of this article, we discuss specific topics about renewable DER integration in the sustainable transition of distribution systems, with the "AI and BDA in Sustainable Distribution System Planning," "AI and BDA for Sustainable Operation of Distribution Systems," and "AI and BDA for Restoration of Sustainable Distribution Systems" sections covering the planning, operation, and restoration phases, respectively. For each topic, we explore the applications of AI and BDA technologies to address challenges and promote renewable DER integration. Finally, the "Conclusion and Path Forward" section concludes the article and discusses future research directions.

AI and BDA in Sustainable Distribution System Planning

Renewable DER interconnection is the first step to exploiting their sustainability benefits. In this section, we discuss the planning problems in sustainable distribution systems. Focusing on renewable DER integration, we discuss three topics: forecasting the integration trend of renewable energy, analyzing the hosting capacity of renewable DERs, and upgrading infrastructures for renewable DER interconnection. The challenges brought by renewable DERs and the solutions provided by AI and BDA technologies are elaborated on for each topic.

BDA-Based Long-Term Projections of Renewable Energy Integration

The growing penetration of renewable energy is an inevitable trend in the sustainable transition of the energy sector. However, in different distribution systems, the rate of renewable DER penetration is different, impacted by multiple technological, economic, and political factors. Thus, forecasting the long-term penetration trend of renewable DERs is crucial for DSOs in planning and achieving sustainable energy goals. An accurate projection of renewable DER growth helps DSOs upgrade existing devices and invest in new devices correctly, making the most of limited budgets. Traditionally, the future penetration of renewable DERs is estimated by simple exponential growth models. However, as mentioned earlier, renewable DER integration is driven by multiple factors, including technology readiness, economic development, and policy support, which calls for more complicated long-term projection technologies.

For long-term projections, DSOs need to use BDA technologies to analyze data from various sources, including local historical data and adjacent sustainable distribution systems. Representing data with primary modes, the dynamic mode decomposition algorithm is a powerful tool for predicting the long-term generation potential of renewable DERs, which is robust to noises in historical renewable generation data. To account for multidiscipline-driving factors like economic growth trends and energy consumption trends, quantum harmony search can be applied to the forecast model to improve the prediction accuracy of renewable DER penetration growth. Convolutional neural networks are promising candidates to capture the intraregional variations in solar and wind resources based on data from adjacent sustainable distribution systems. If DSOs want to predict renewable DER integration with confidence intervals, probabilistic approaches, such as Bayesian neural networks, are promising in representing the future with probability distributions.

BDA-Driven Renewable DER Hosting Capacity Analysis of Sustainable Distribution Systems

As most existing distribution systems are not initially designed to accommodate a high penetration level of distributed generators, the interconnection of renewable DERs to the distribution system must be carefully evaluated; otherwise, overinterconnection could cause operational issues like overvoltage and thermal overloading. Thus, DSOs must develop effective hosting capacity assessment methods for renewable DERs. The renewable DERs hosting capacity refers to the maximum capacity that can be reliably integrated without violating the system's voltage limits and thermal capacities. However, assessing renewable DER hosting capacity is complicated, especially for those connected to the secondary side of sustainable distribution systems.

Traditional hosting capacity analysis methods require detailed modeling of the distribution system. An incremental capacity sequence is assumed for a renewable DER, and then power flow is calculated sequentially to check for constraint violation, as shown in Figure 2. The finalized renewable

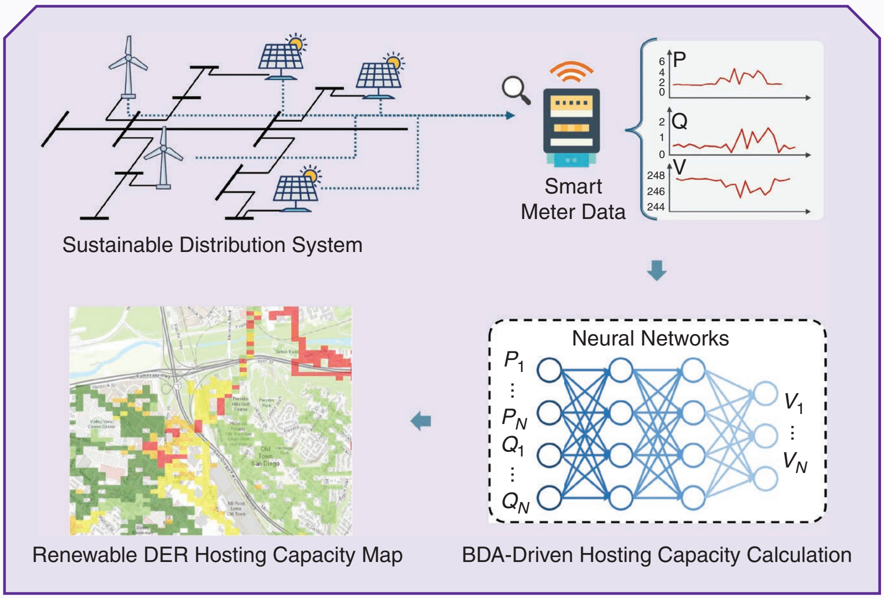

figure 2. BDA-driven hosting capacity calculation of renewable DERs in sustainable distribution system. P: active power; Q: reactive power; V: voltage.

DERs hosting capacity is the maximum capacity without breaching the constraints. Although this method is straightforward, it requires iterative power flow calculation, resulting in two issues. First, to accurately assess the hosting capacity of renewable DERs at different locations, numerous runs of power flow are needed, which takes considerable time. Thus, evaluating the renewable DER hosting capacity in an extensive region is computationally expensive. Second, the secondary distribution system configuration is usually incomplete or erroneous, making it difficult to characterize the impact of renewable DERs with physical models.

The widespread deployment of smart meters has significantly improved the observability of distribution systems, especially the secondary side. Although the physical model is unavailable, DSOs can use BDA technologies such as multilayer perceptron neural networks to extract the nonlinear mappings from renewable DER power to system voltage from smart meter data. With the trained multilayer perceptron neural network, given a renewable DER penetration, DSOs can directly estimate voltage profiles and calculate the hosting capacity, as shown in Figure 2, without the time-consuming power flow calculation processes. As BDA technologies significantly improve computation efficiency, DSOs can now evaluate their renewable DER hosting capacity maps more frequently. This fundamentally differs from traditional situations, where hosting capacity maps are only updated quarterly or annually. The timely updating of hosting capacity maps considers the latest upgrade of the distribution system, significantly enhancing its usefulness and reliability.

AI-Aided Infrastructure Upgrade Strategies in Renewable-Rich Distribution Systems

As the penetration of renewable DERs increases, the hosting capacity of the sustainable distribution system will gradually be used up. To accommodate more renewable DERs for carbon footprint reduction and sustainable transition, distribution system infrastructures such as distribution transformers and voltage regulators must be upgraded. Such upgrades, however, require significant investment, emphasizing careful and comprehensive planning strategies. The balance between an immediate increase of renewable DER hosting capacity and long-term investments necessitates multiobjective optimization formulations. As the upgrade decision of each device is described by a binary variable, the planning problem of a sustainable distribution system is usually modeled as a mixed-integer programming problem. Solving mixed-integer programming problems is usually intricate as it involves a tree search process, for example, branch and bound, where computational complexity grows exponentially. Another challenge arises from the uncertainty of renewable DER generation, which needs to be described in a probabilistic sense. However, accurately depicting the behaviors of renewable DERs in the future is difficult, as we mentioned before.

AI techniques can be applied to determine the optimal infrastructure upgrade strategy for sustainable distribution systems to accommodate more renewable DERs. For example, imitation learning has proven effective in mixed-integer programming problems. Learning from human experts' experience, neural networks can mimic decision-making logic and explore discrete upgrade strategies quickly. With the digital twin model of the sustainable distribution system as an environment, reinforcement learning techniques can be implemented to bypass the optimization of planning problems. During training, the reinforcement learning agent tests numerous upgrade strategies and evaluates their performance in promoting renewable DER integration. When applied in the real world, the trained reinforcement learning agent can directly produce an infrastructure upgrade plan that is suitable for the current grid situation and long-term renewable DER projection. As for the uncertainty of renewable DERs, quantile regression neural networks can provide a probabilistic description of renewable generation based on historical data, and it is easy to embed such a neural network into the optimization framework. With the help of AI technology, the decision-making process for the planning of sustainable distribution systems can be largely simplified. DSOs can easily identify and implement the most effective infrastructure upgrade strategy, allowing for the continuous interconnection of renewable DERs to sustainable distribution systems.

AI and BDA for Sustainable Operation of Distribution Systems

With renewable DERs interconnected, DSOs must carefully operate them, reducing carbon footprints without breaching constraints. In this section, we discuss the operation of sustainable distribution systems with a high penetration level of renewable DERs. As the prerequisite of distribution system operation, we first discuss the short-term forecasting of renewable DER power outputs, driven by BDA technologies. Then, we discuss the energy management problem and the VVC problem in sustainable distribution systems, which are supported by AI technologies.

BDA-Based Renewable Energy Forecast in Sustainable Distribution Systems

The accurate forecast of renewable energy generation guarantees that the optimal solutions obtained for energy management and VVC are effective. However, a renewable DER generation forecast is complicated and challenging. First, the forecasting of renewable DER generation also relies on high-quality and high-resolution meteorological and generation data. However, real-world measurements are usually noisy and incomplete, necessitating the preprocessing of historical data. Moreover, as discussed in the "Introduction to Sustainable Distribution Systems" section, the generation of renewable DERs is uncertain and intermittent, making it challenging to predict. As weather-dependent generators, renewable DERs are highly sensitive to meteorological conditions. Sudden weather changes, such as passing clouds, could cause rapid shifts in the power output, which is hard to capture with forecast models.

Advanced BDA preprocessing techniques such as outlier detection and missing-value imputation are widely applied to improve data quality in sustainable distribution systems. Anomalies are usually few and different. For example, a sudden surge of PV generation during a cloudy day could be suspicious. Outlier detection algorithms, such as isolation forest, can be applied to identify data points that are severely influenced by noises and measurement errors. After removing the outliers, the missing value must be imputed to preserve the integrity of renewable DER data. Regression-based algorithms, such as autoregressive integrated moving average, are common choices for generating plausible values. With missing-value imputation, the historical data forms a complete time series, allowing forest models to capture the time correlation of renewable DER generation.

The power outputs of renewable DERs exhibit temporal and spatial correlations. For an individual renewable DER, its generation at one time step is inherently close to the previous time steps. To capture this temporal correlation, the long short-term memory network, which tends to "remember" relevant information over long sequences and "forget" irrelevant data, is a promising approach. In this way, both the short-term fluctuations (e.g., rapid weather changes) and long-term trends (e.g., daily or seasonal cycles) of renewable DER generation are sufficiently considered for accurate predictions. For renewable DERs in a geographic vicinity, their power outputs are likely to follow the same pattern because they share the same weather conditions. A convolutional long short-term memory network forecasts the power output of a group of renewable DERs in the sustainable distribution system, considering their spatial dependencies. Using BDA-driven spatiotemporal forecast models, DSOs can effectively capture the complex, nonlinear, and interconnected nature of renewable DER generation, paving the way for downstream optimization tasks.

AI-Aided Energy Management for Sustainable Distribution Systems

In traditional distribution systems, DSOs' goal for energy management is usually to minimize the operational cost. Considering the net-zero target and the sustainable transition of the system, nowadays, DSOs also emphasize the reduction of carbon footprints in their operation goals. As the electricity generated by renewable DERs is carbon-free, a straightforward idea for DSOs is to apply maximum power point tracking algorithms, letting renewable DERs inject as much power as possible. However, operational issues such as overloading and reverse power flow could arise if renewable DER generation is not orchestrated. When renewable DERs are relatively concentrated in one area with a sustainable distribution system, their uncontrolled power injection could cause an overloading current at upstream transformers and lines. Persistent overloading current is undesirable as it will accelerate the degradation of insulation materials. Furthermore, not all devices can allow reverse power flow, which flows from renewable DERs to upstream nodes. For example, legacy overcurrent relays might fail to detect fault current and falsely trip if reverse power flow is not controlled.

In a sustainable distribution system, the DSO solves the energy management problem to maximize the utilization of renewable energy, with the flexibility provided by battery energy storage systems and responsive demands. As the BDA-driven forecast of renewable DER generation is more accurate within shorter time frames, DSOs usually solve the energy management problem iteratively, according to the latest forecast results. However, as trigonometric power flow equations are nonconvex, conventional optimization methods cannot guarantee solution accuracy and speed simultaneously. Thus, it is essential to use the vast measurements collected by smart meters every day and develop advanced AI-aided energy management algorithms for sustainable distribution systems. As the only intractable part is the power flow equations, a natural thought is to let AI deal with it. As shown in Figure 3, a promising approach is to train an AI model that replicates the nonconvex and intractable power flow equations with their convex and tractable counterparts. By properly selecting activation functions, a trained AI model can be translated into a group of convex functions or piecewise linear functions, which are tractable for optimization solvers. To this end, the energy of renewable DERs can be optimally managed, ensuring that no constraint is violated.

Mathematically, an AI model with at least one hidden layer and sufficient neurons can approximate any continuous function to arbitrary precision, while approximation errors are unavoidable in practice. A novel AI training technique called *end-to-end learning* can improve AI's performance in managing renewable DERs in sustainable distribution systems. By backpropagating the optimal solution gradient, the end-to-end learning framework tailors the AI model for the optimal coordination of renewable DERs and other flexible resources. In this way, the carbon-free feature of renewable DERs can be fully exploited without threatening the safety of sustainable distribution systems.

AI-Aided VVC in Renewable-Rich Distribution Systems

The increasing penetration of renewable DERs in sustainable distribution systems could not only cause overloading and reverse power flow problems but also over- and undervoltage. Unlike the first two problems, which are mainly handled through the energy management problem, voltage problems are usually resolved by the VVC problem. Although the power set points are carefully orchestrated for renewable DERs and other devices in the sustainable distribution system, in real time operation, voltage fluctuations always exist due to renewable DER power uncertainty and intermittency. Traditionally, voltage regulation is carried out by substation transformers with load tap changers, in-line voltage regulators, and capacitor banks. However, these switch-based legacy voltage regulation devices are insufficient for dynamic voltage support for renewable-rich distribution systems. Thus, DSOs are looking for VVC support from renewable DERs to address voltage fluctuations in short time frames. To damp voltage fluctuations, renewable DERs must dynamically adjust their reactive power in response to voltage changes, following a "volt-Q" rule. As the voltages are highly related to the active power fluctuations of

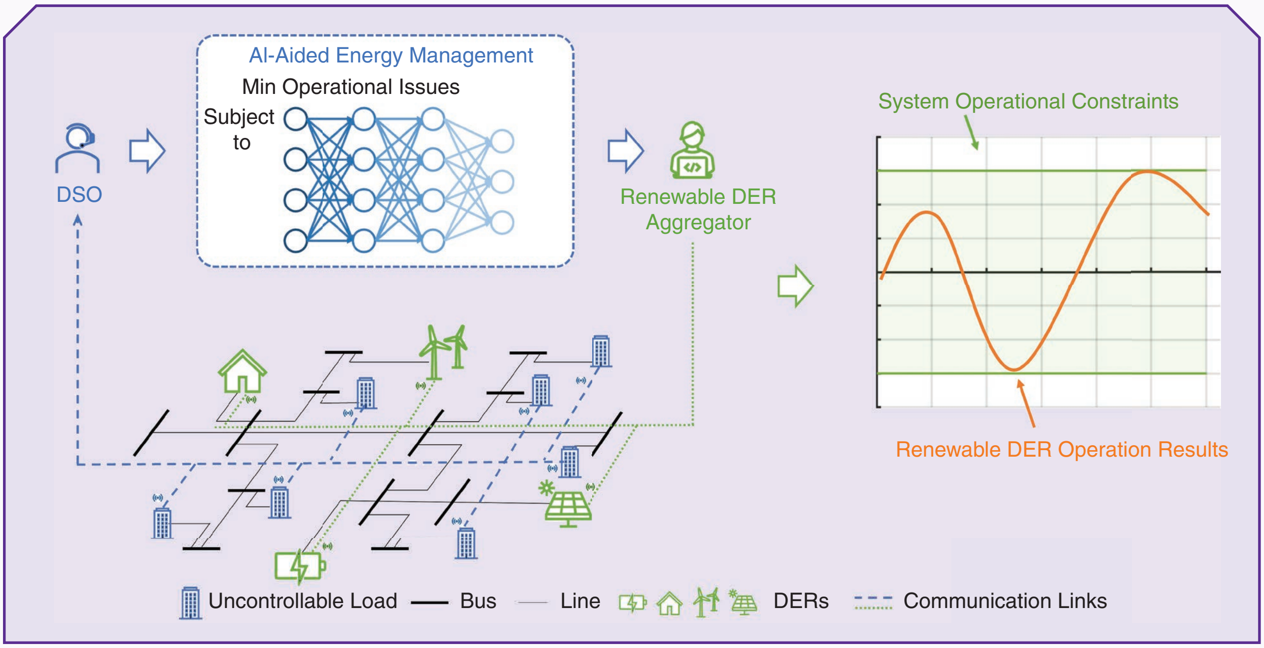

figure 3. AI-aided energy management of renewable DERs in sustainable distribution systems. min: minimal.

renewable DERs, a more direct way is to establish a "P-Q" rule, as prescribed in IEEE Standard 1547.

Determining the P-Q rule for renewable DERs is critical in improving the voltage profiles of the sustainable distribution system. Although the relationship between voltages and power injections can be derived from power flow equations, the computational burden is high. A more effective approach is to train an AI model to capture voltage sensitivities from historical data. Taking grid conditions as the input, deep neural networks can estimate the voltage equilibrium as the output. The trained AI model is supposed to reflect the impact of renewable DER active and reactive powers on the voltage profile. To this end, assuming that the P-Q rule is an affine function, the P-Q slopes of renewable DERs can be determined by an optimization problem. Following the optimized P-Q rule, renewable DERs adjust their reactive power autonomously to improve the sustainable distribution system's voltage profile, significantly simplifying the VVC process. Moreover, as the physics laws are the same, a trained AI model can be retuned for another sustainable distribution system with few-shot data if system configurations are similar.

AI and BDA for Restoration of Sustainable Distribution Systems

Besides supporting the daily low-carbon operation of sustainable distribution systems, renewable DERs can also serve as localized backup power sources during extreme weather events and blackouts. In this section, we discuss the utilization of renewable DERs in the restoration of sustainable distribution systems. In this section, we focus on the postoutage situational awareness, optimal sectionalization blackstart restoration of sustainable distribution systems in the presence of renewable DERs, and discuss the solutions provided by AI and BDA technologies.

BDA-Based Postoutage Situational Awareness and Sustainable Distribution System Sectionalization

In a report released by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information, in 2024, 27 weather and climate disasters were recorded, each resulting in more than US$1 billion in damage and collectively causing 568 fatalities, which is the eighth-highest toll in records stretching back to 1980. Extreme weather events strain distribution systems, leading to more frequent and prolonged blackouts than ever before. It is imperative for DSOs to minimize the impact of power outages. When an outage happens, the DSO needs to gather information to understand the status and future trends of renewable DER generation, load, and network topology, which is called the *post-outage situational awareness of the sustainable distribution system*. With a clear picture of system status, DSOs can further sectionalize the system into networked microgrids powered by renewable DERs to maximize the continuous power supply to customers.

Postoutage situational awareness of the sustainable distribution system includes the monitoring and forecast of the resources in the grid. Renewable DER operational awareness, which includes the forecasting of renewable generation and monitoring of inverter operations, is paramount in the restoration of sustainable distribution systems. Meteorological information, historical data, and real-time measurements can be leveraged by BDA technologies to accurately predict renewable DER generation, as discussed in previous sections. Inverter monitoring tells the DSO which renewable DERs have grid-forming capabilities and assesses the performance of inverters in the restoration process. BDA-driven load awareness provides important information for designing the load recovery sequence, which needs to be orchestrated with renewable DERs' capability. Network awareness requires the use of real-time monitoring data and distribution system-state estimation to improve system observability. With BDA-driven situational awareness of sustainable distribution systems, DSOs can optimize their sectionalization and restoration decisions accordingly.

Sustainable distribution systems usually cannot operate in their regular topologies during restoration. With widespread renewable DERs, on-outage sustainable distribution systems can be sectionalized into self-adequate and networked microgrids by controlling switches and relays. The highest priority of on-outage systems is to maintain a reliable power supply. Thus, when sectionalizing the system, the DSO needs to ensure that the renewable DERs in each microgrid can be redispatched to match the load level in real time, considering the uncertainty of renewable generation and loads. As discussed in the previous sections, using BDA technologies, DSOs can forecast renewable generation and load levels with point estimates or interval estimates. With these forecasts, the DSO can optimize the sectionalization of the system. Subsequently, the dispatch of renewable DERs in each microgrid and the restoration of a sustainable distribution system can be optimized using AI tools.

AI-Aided Blackstart Restoration Using Renewable DERs

When an outage happens, customers in certain areas of the sustainable distribution system lose access to electricity. With renewable DERs assigned to each area, DSOs can reenergize the blackout areas temporarily. Then, the energized partitions are synchronized and interconnected when the faults are cleared. This process is also known as the *blackstart restoration of sustainable distribution systems*. During this process, the sequence of actuating renewable DERs and loads must be carefully designed according to grid conditions. Generally, renewable DERs with grid-forming inverters are activated first to establish the voltage and frequency for those with grid-following inverters to track. Further considering the reconnection of sectionalized microgrids, the blackstart restoration problem of sustainable distribution systems is usually modeled as a sequential decision-making process with integer variables and subject to renewable DER uncertainties. As the scale of the distribution system increases, the number of renewable DERs and switches also increases, resulting in a large-scale mixed-integer programming problem, which is inherently difficult to solve promptly and accurately.

Instead of solving the blackstart restoration problem with mixed-integer solvers, DSOs leverage advanced AI technologies to improve the decision-making process. One predominant challenge in sequential decision making, for example, optimizing the blackstart sequence, is anticipating the impact of current decisions in future scenarios. Deep reinforcement learning (DRL) is a transformative AI tool designed for complex sequential decision-making tasks that are computationally expensive to solve through optimization. The key idea behind DRL is called *trial and error*. As shown in Figure 4, during the training process, every time that the DRL agent comes up with a decision, it evaluates the decision performance with the digital twin environment, which is built on historical data and physical models. The DRL agent learns to optimize its decision-making logic based on the environment's feedback. The main challenge of applying DRL methods to the blackstart restoration is the curse of dimensionality. The dimension and volume of the action space grow as the scale of the system increases, making the DRL training process time consuming and hard to converge. Multiagent DRL can be applied to speed up the training, where the action space is decomposed into several subspaces and explored by multiple DRL agents. Furthermore, graph learning techniques can be embedded into the multiagent DRL framework such that the topology information is considered in the decision-making process. With this feature, the blackstart restoration plan becomes more reasonable and trustworthy, allowing DSOs to fully exploit renewable DERs in improving the reliability of sustainable distribution systems.

Conclusion and Path Forward

Prompted by supportive policies and technological advancements, renewable power capacity across the globe continues to surge. Renewable DERs play an important role in enhancing the sustainability of distribution systems, bringing

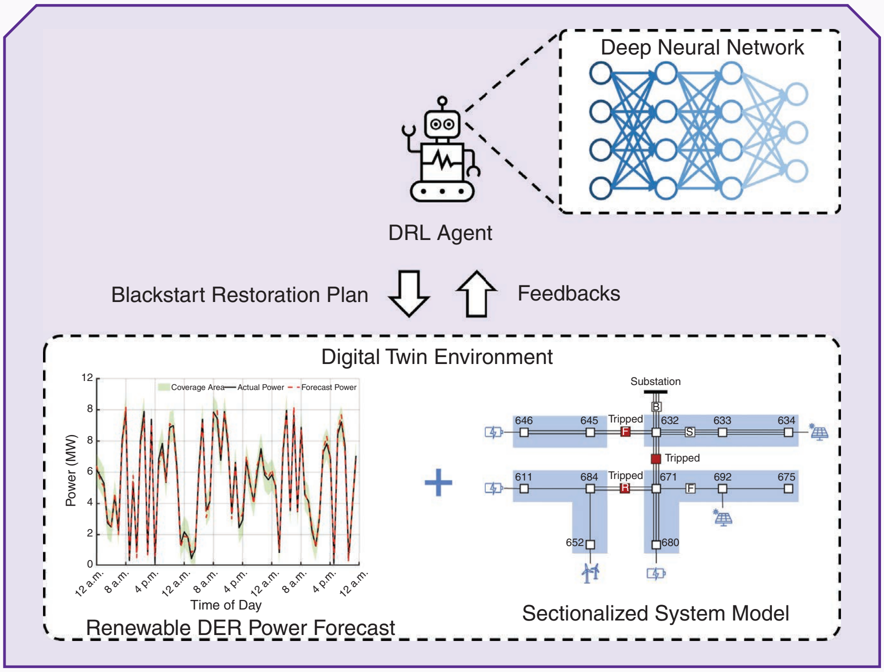

figure 4. AI-aided blackstart restoration of sustainable distribution system using renewable DERs.

both opportunities and challenges. Although the decarbonized and decentralized nature of renewable DERs promotes the sustainability of distribution systems, their uncertainty and intermittency urge DSOs to explore novel decision-making solutions for low-carbon distribution systems. The increasing amounts of sensing, metering, and communication devices lay the foundation for applying advanced AI and BDA technologies in sustainable distribution system problems. In this article, we discussed how to exploit the carbon-free benefits of renewable DERs in planning, operating, and restoring sustainable distribution systems. To tackle the challenges of renewable DER uncertainty and intermittency, AI and BDA technologies are widely adopted, revolutionizing the decision-making processes in the era of sustainability.

Although vast research efforts have been dedicated to these areas, there are still some unaddressed challenges in the sustainable transition of distribution systems. First, data integrity is predominant in AI and BDA technologies in forecasting the power of renewable DERs and modeling their impact on sustainable distribution systems. However, a lack of holistic frameworks that collect and store renewable DER data and other distribution system measurements with unified time frames could deteriorate the performance of AI and BDA algorithms. The second challenge originates from not every sustainable distribution system having sufficient historical renewable DER data to support their low-carbon planning, operation, and restoration. As the underlying physics laws and optimization theories are identical, it is intuitively possible for sustainable distribution systems with fewer or no data to benefit from the AI and BDA models that are trained for data-rich systems. However, how to modularize and transfer AI and BDA models from one system to another without leaking private data is still an open question. Moreover, as an emerging technology, renewable DERs are participating in evermore electricity markets. DSOs need novel AI and BDA technologies to incorporate renewable DERs' market behaviors in the system's operation model. With these challenges resolved, the potential of renewable DERs will be further unleashed, paving the way for a more sustainable, intelligent, and resilient future in the energy sector.

For Further Reading

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