

Advancements in Smart Grid Technology: Opportunities and Challenges with AI and Digital Twins (智能电网技术革新：人工智能和数字 孪生的新机遇与挑战)



Paris Climate Agreement and Carbon-neutrality (巴黎气候协议和碳中和)



Introduction (引言)

- Smart Grid (智能电网)
- AI and Digital Twin (AI和数字孪生)

AI in Smart Grids (AI在智能电网中的应用)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)



World leaders rejoicing at the adoption of the Paris Agreement on 12 December 2015 (From UNFCCC)
(世界领导人在2015年12月12日庆祝采纳巴黎协议 (来自联合国气候变化框架公约))

- First universal climate agreement.
(第一个全球性的气候协议)
- Limiting temperature rise well below 2 °C.
(将温度上升限制在远低于2° C)
- Publishing greenhouse gas reduction targets.
(公布温室气体减排目标)
- Helping poorer nations.
(帮助较贫穷的国家)
- Carbon neutral by 2050
(到2050年实现碳中和)

Power System Decarbonization (电力系统脱碳)

Energy Efficiency
(能源效率)

Renewable Energy
(可再生能源)

Economy-Wide Electrification
(全经济范围的电气化)

Zero-Carbon Fuels
(零碳燃料)

Carbon Capture and Removal
(碳捕获与移除)

Problems of Traditional Power Systems (传统电力系统的问题)



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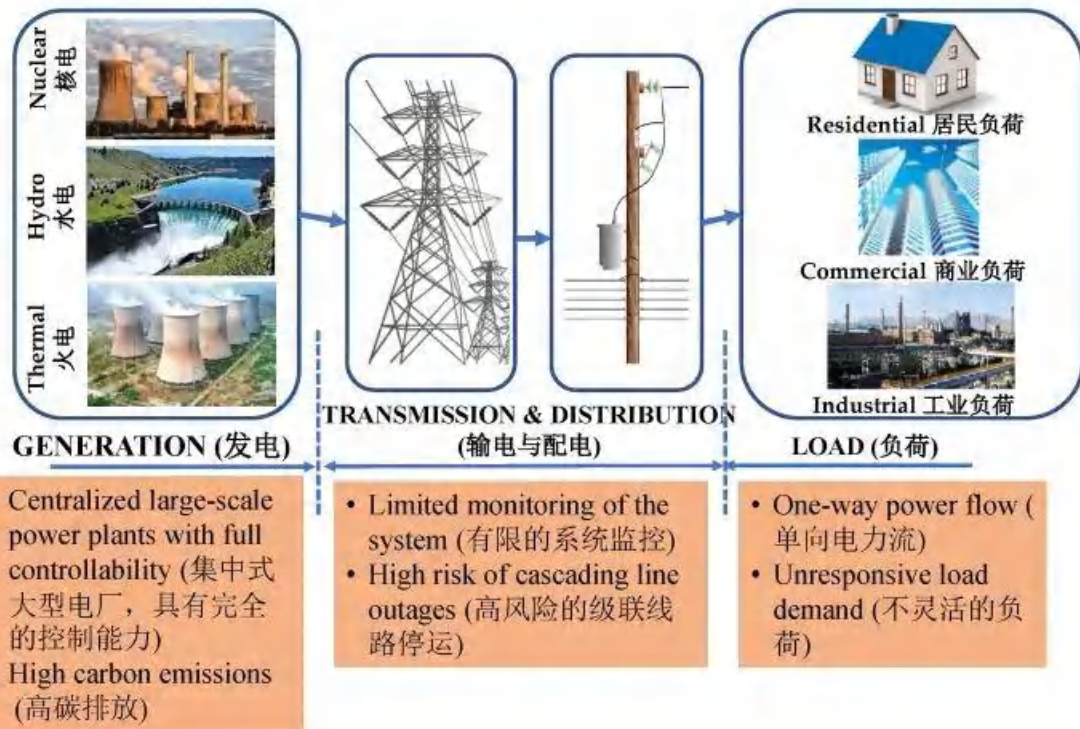
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IEEE definition for Smart Grid (IEEE对智能电网的定义):

“The smart grid is a revolutionary undertaking-entailing new communications-and control capabilities, energy sources, generation models and adherence to cross jurisdictional regulatory structures.” (“智能电网是一项革命性的工程——涉及新的通信和控制能力、能源来源、发电模型以及遵守跨司法管辖区的监管结构。”)

AI in Smart Grids

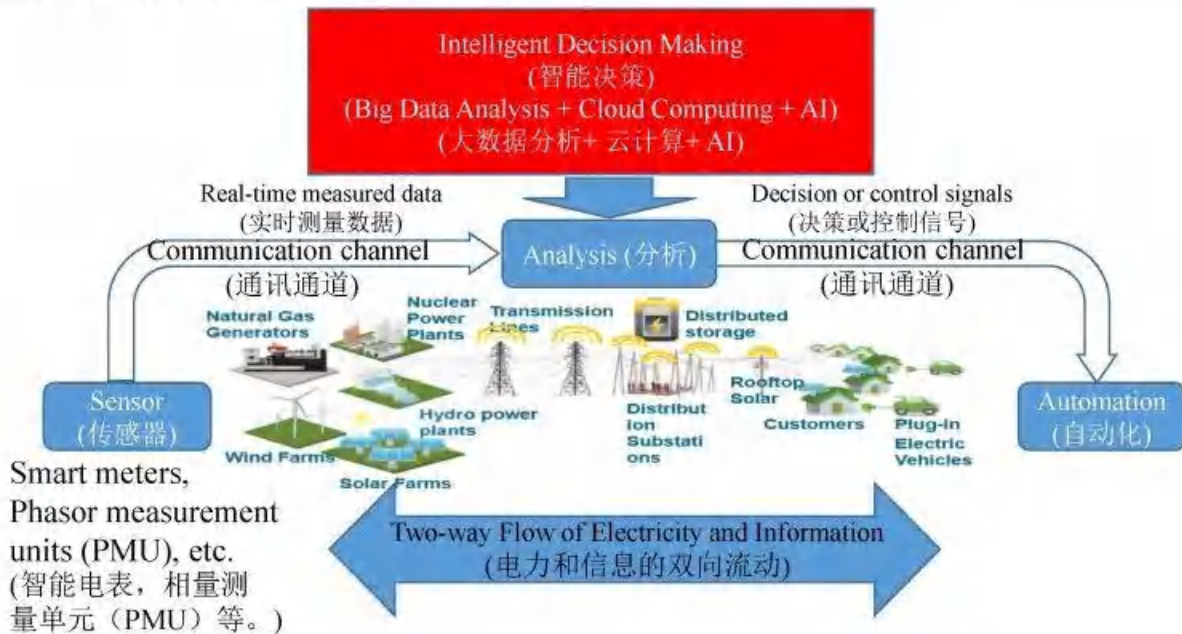
(AI 在智能电网中的应用)

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(挑战与展望)



Smart Grid Concept and the Challenges (智能电网概念及其挑战)



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Introduction (引言)

➤ Smart Grid (智能电网)

➤ AI and Digital Twin (AI和数字孪生)

- Extreme weather and climate change. (极端天气和气候变化)
- Technological challenges: Sensors; ICTs (5G & Cybersecurity), IOTs; Big data analytics; Data mining; AI; Advanced optimization; Automation and Robotics. (技术挑战: 传感器; ICT (5G和网络安全)、物联网; 大数据分析; 数据挖掘; 人工智能; 高级优化; 自动化和机器人技术)
- Three major trends: Electrification; Decentralization; Digitalization. (三大趋势: 电气化; 去中心化; 数字化)
- Application of diverse and grid edge technologies: EV, Energy Storage, Distribution Generation, Energy Efficiency, Demand Response. (应用多样化和电网边缘技术: 电动车、能源存储、分布式发电、能源效率、需求响应)
- Other key technologies such as Carbon Capture, Hydrogen, Battery (其他关键技术如碳捕获、氢能、电池)
- Increasing penetration of various energy sources and PE-based devices. (各种能源源和基于PE的设备的渗透率不断增加)
- Interaction with other infrastructure components in integrated energy systems, and smart cities. (与综合能源系统和智慧城市中其他基础设施组件的互动)
-

AI in Smart Grids

(AI 在智能电网中的应用)

Digital Twin Applications

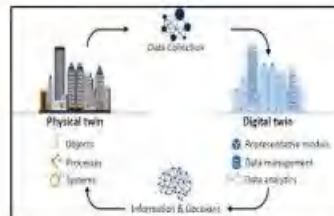
(数字孪生的应用)

Challenges & Prospects

(挑战与展望)

Advanced techniques for smart grids (智能电网的先进技术)

Artificial Intelligence
(AI) (人工智能)



Digital Twin
(数字孪生)

History of Artificial Intelligence (人工智能技术(AI)的发展历史)



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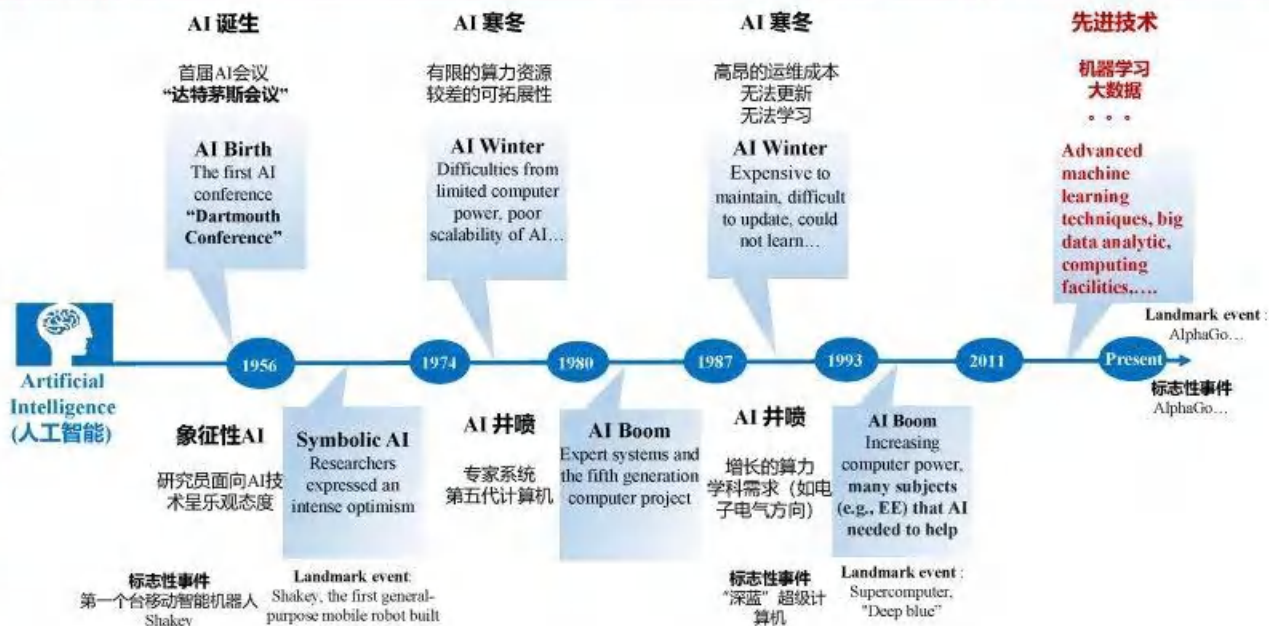
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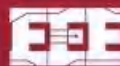
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What is AI? (什么是AI?)



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Challenges & Prospects (挑战与展望)

- **Simulation of human intelligence processes by machines, especially computer systems.** (由机器模拟人类智能过程，尤其是计算机系统)
- Focuses on cognitive skills: **Learning; Reasoning; Self-correction; Creativity.** (重点在于认知技能: 学习; 推理; 自我修正; 创造力)
- **Examples:** rules-based systems, neural networks, statistical methods and other AI techniques to generate new images, new text, new music and new ideas. (示例: 基于规则的系统、神经网络、统计方法及其他人工智能技术, 用于生成新图像、新文本、新音乐和新创意)
- **Strong AI vs. Weak AI (强人工智能 VS 弱人工智能)**
- **Central processing units (CPUs); Graphics processing units (GPUs); Tensor processing units (TPUs)** (中央处理器 (CPUs); 图形处理器 (GPUs); 张量处理器 (TPUs))

Components of AI



Applications

- Image recognition
- Speech recognition
- Chatbots
- Natural language generation
- Sentiment analysis

Types of models

- Deep learning
- Machine learning
- Neural networks

Software/hardware for training and running models

- GPUs
- Parallel processing tools (like Spark)
- Cloud data storage and compute platforms

Programming languages for building models

- Python
- TensorFlow
- Java
- C



- **Types of Machine Learning Algorithms: (机器学习算法的类型:)**
 - Supervised learning; (监督学习)
 - Unsupervised learning; and (无监督学习)
 - Reinforcement learning (强化学习)

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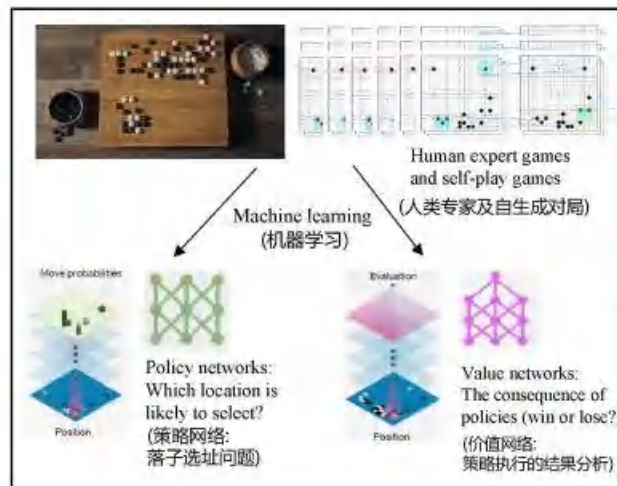
- Advanced machine learning techniques (e.g. convolutional neural networks, supervised learning, reinforcement learning) are combined with tree search techniques. (先进的机器学习技术(如卷积神经网络、监督学习、强化学习等)与树搜索算法相结合)
- The world's best Go player (e.g. Lee Sedol (9p), Fan Hui (2p)) were beaten by AlphaGo. (人类选手(如李世石(9段)、范辉(2段))被击败)



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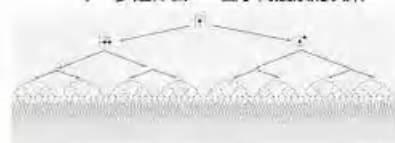
Aid decision-making for the current situation



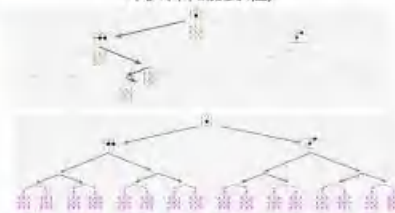
(针对当前形势的辅助决策)

What is the next step? — Tree search-based decisions

下一步是什么? — 基于树搜索的决策



Machine learning-based reduced complexity by cutting off numerous leaves of the tree (基于机器学习, 通过削减搜索树上的大量叶子来降低复杂性)



Fantastic News: ChatGPT and Sora

(突破性应用: AlphaGo)



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- A language model released by OpenAI in 2022, capable of **interacting** with users on various topics (于2022年发布的语言模型，能够与用户就各种主题进行交互)

- Answer questions (e.g., factual question) (问题答复 (例如, 现实问题))
- Write and debug computer programs (编写和调试计算机程序)
- Generate texts (e.g., student essays) (文档生产 (例如, 学生课题))
- Emulate systems (e.g., a Linux system....) (系统模拟 (例如, Linux系统,...))
-



- A text-to-video model released by OpenAI in 2024, capable of **generating videos** up to a minute long while maintaining visual quality and adherence to the user's prompt (于2024年发布的一种文本转视频模型，能够生成最长一分钟的视频，同时保持视觉质量和对用户提示的遵循)

- Understanding of language and simulation of the physical world (理解语言和模拟物理世界)
- Multiple characters (多个角色)
- Specific types of motion (特定类型的运动)
- Accurate details of the subject and background (主题和背景的准确细节)
- Create multiple **shots** within a single generated video (在单个生成的视频中创建多个镜头)
-



AI in Smart Grids

(AI 在智能电网中的应用)

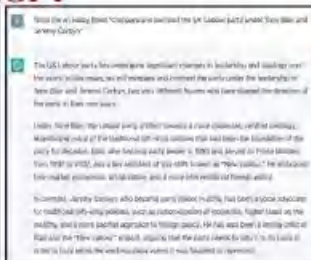
Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

ChatGPT



A paragraph of codes



An essay



A stylish woman walks down a Tokyo street

Sora



Historical footage of California

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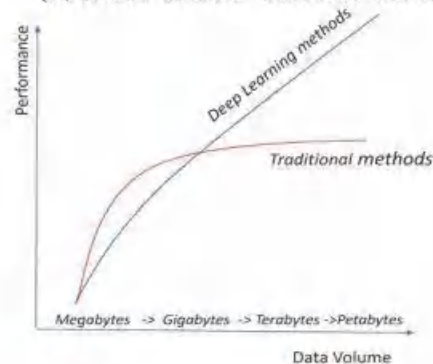
The success of ChatGPT/Sora comes from AI techniques (e.g., deep neural networks and reinforcement learning) (ChatGPT来源于AI技术，例如深度神经网络和强化学习)

Deep Learning Methods (深度学习方法)

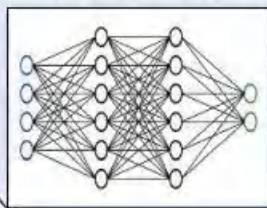
Advantages(优势):

- ❑ Excellently handle complex data structures (能处理复杂数据结构)
- ❑ Capable of learning feature hierarchies automatically (能自动学习特征层次)
- ❑ Improve performance as more data becomes available (随着更多数据的可用性提高性能)

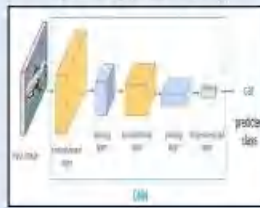
Performance comparison of traditional methods versus deep-learning methods (传统方法与深度学习方法的性能比较)



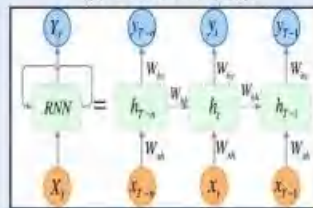
Deep neural network (深度神经网络)



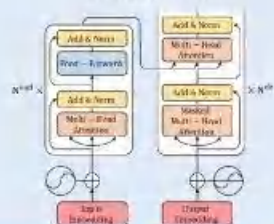
Convolutional neural network (卷积神经网络)



Recurrent neural network (循环神经网络)



Transformer



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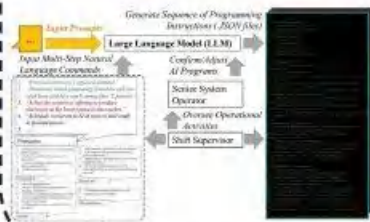
Challenges & Prospects (挑战与展望)

Domain Specific Generative AI (领域特定生成式AI)

Power & Energy
(电力与能源)

Economics & Finance
(经济与金融)

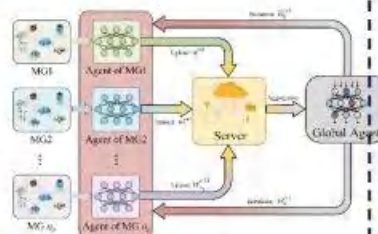
Health Care
(医疗保健)



Privacy Preserving AI (隐私保护AI)

Federated Learning
(联邦学习)

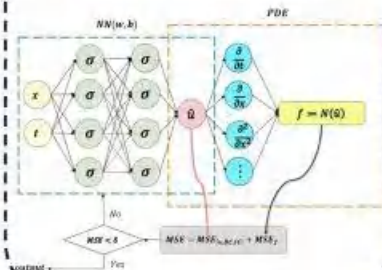
Edge Computing
(边缘计算)



Physical-Informed AI (物理信息AI)

Physical-Informed
Neural Network
(物理信息神经网络)

Fastly-Solving
Differential Equation
(快速求解微分方程)



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In 2021, Google announced Supply Chain Twin, a new Google Cloud solution that lets companies build a digital twin.
(2021年, 谷歌宣布推出供应链孪生, 这是一个新的谷歌云解决方案, 构建数字孪生)

- A **representation of their physical** supply chain. (物理供应链的表示)
- By organizing data to get a more complete view of suppliers, inventories, and events like weather. (通过数据, 更全面地了解供应商、库存和天气等事件)



Key Characteristics (关键特征):

1) Real-time Replication (实时复现):

A digital twin is **connected to its real-world counterpart** through sensors and data exchange. This connection allows the digital twin to update in real time as changes occur in the physical world.

(数字孪生通过传感器和数据交换与其现实世界的对应物连接。这种连接使得数字孪生能够随着物理世界的变化而实时更新)



2) Simulation and Analysis (模拟和分析):

Digital twins are used to simulate different scenarios and **predict outcomes without the risks** associated with testing in the real world. This capability is **invaluable for smart grids** where real-world experimentation can be costly or dangerous. (数字孪生用于模拟不同的场景并预测结果, 而无需承担在现实世界中测试的风险。这种能力对于智能电网非常宝贵, 因为现实世界的实验可能成本高昂或危险)



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Digital Twin Applications in Power Systems (电力系统中的数字孪生应用)



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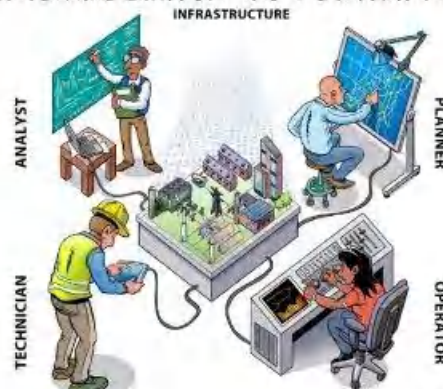
Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

The digital twin could expand beyond the local facilities, integrating and providing the cloud-based services (数字孪生可以扩展到本地设施之外, 集成并提供基于云的服务)



Many uses of digital twin including analytics, maintenance, real-time operations and planning (数字孪生的许多用途包括分析、维护、实时操作和规划)



Examples of applications (应用示例)

Functions	Traditional power system	Twin-enabled power system
Model validation	Offline with system models updated in span of few years	Online, models updated on the fly
Dispatch optimization	Offline	Online
Outage planning	Offline	Online
Phasor Measurement Unit (PMU) based wide area system	Monitoring, islanding	Predictive control

Introduction (引言)

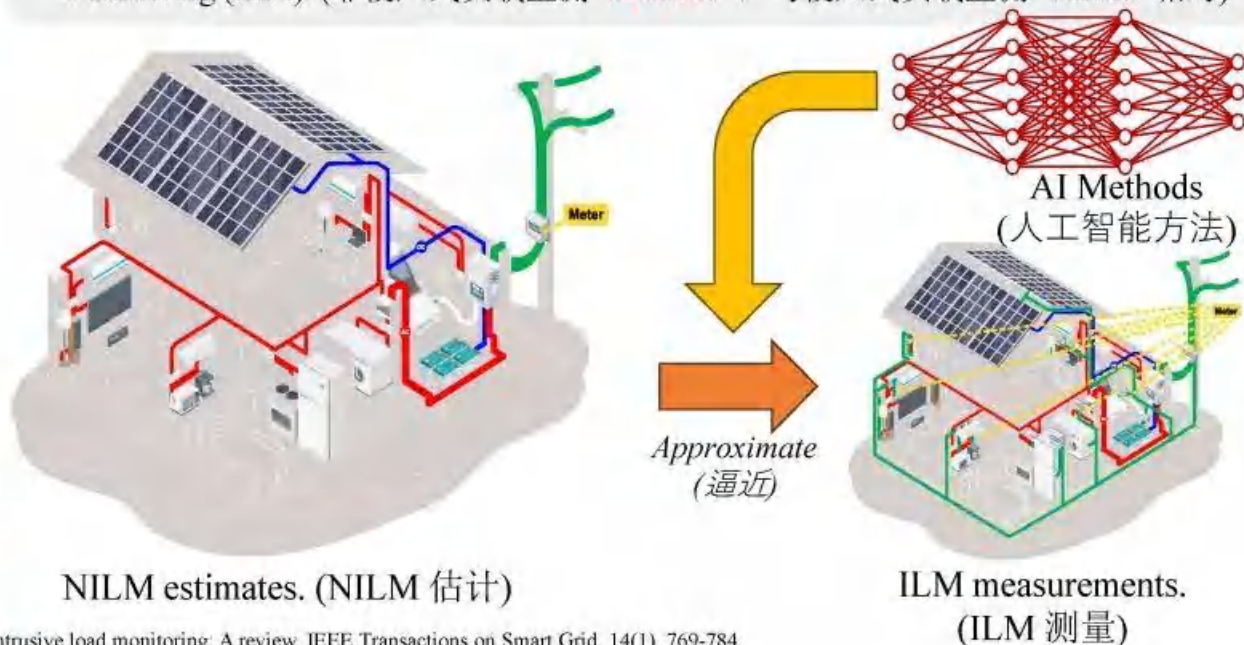
AI in Smart Grids (AI 在智能电网中的应用)

- Power Prediction (功率预测)
- Equipment Monitoring (设备监测)
- System State Estimation (系统状态估计)
- System Operation (系统运行)
- Stability Analysis (稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

- Extracting power disaggregation of appliances and their onsets and offsets based on measurement data and AI methods. (基于测量数据和人工智能方法提取设备的功率分解及其开启和关闭时间)
- Referred to as Non-Intrusive Load Monitoring (NILM), in contrast to Intrusive Load Monitoring (ILM). (非侵入式负载监测 (NILM)，与侵入式负载监测 (ILM) 相对)



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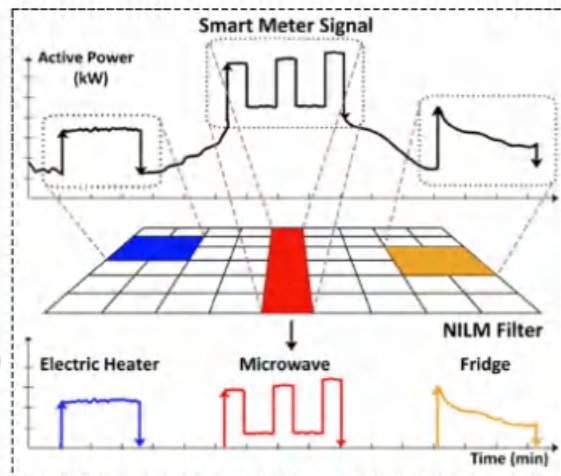
Challenges & Prospects (挑战与展望)

Current NILM Methods (当前非侵入式监测方法)

- | | |
|--|--|
| ✓ High sampling frequency
高采样频率 | ✗ Low sampling frequency
低采样频率 |
| ✓ Time independence of residents' behaviors (居民行为的时间相关性) | ✗ Time correlation of residents' behaviors (居民行为的时间相关性) |
| ✓ Increase of sampling frequency (增加采样频率) | ✗ The suitable sampling frequency (high storage requirement) (合适的采样频率 (高存储需求)) |

Current NILM Datasets (当前非侵入式数据集)

- | | |
|--|---|
| ✓ Most of datasets are from US, Australia or Europe (Total 29 datasets) (大多数数据集来自美国、澳大利亚或欧洲 (共29个数据集)) | ✗ The model trained by these datasets may not perform well in Hong Kong or Asia (由这些数据集训练的模型在香港或亚洲可能表现不佳) |
|--|---|



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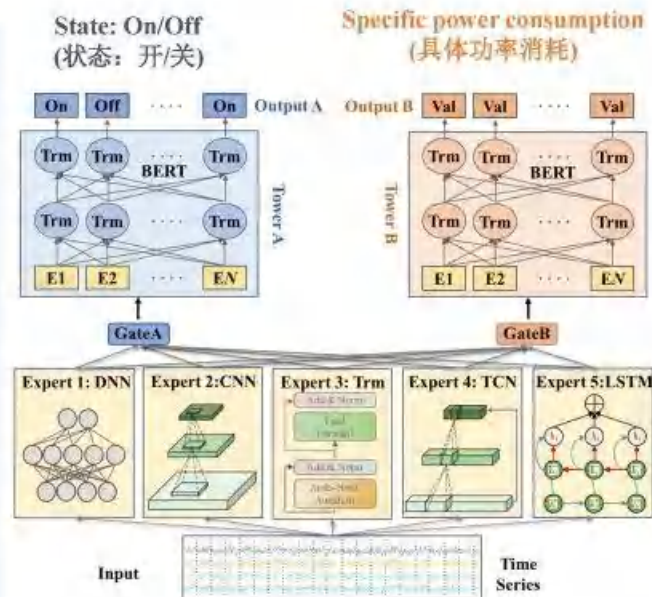
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Multi-Task Learning Framework with Multi-gate Mixture-of-Experts (基于混合专家的多任务学习框架)

➤ Advantages (优势):

- **Synergy Effect:** The synergy among tasks can help a **jointly trained model** better capture **shared patterns** that would otherwise be missed by independent training (协同效应: 任务之间的协同作用可以帮助联合训练的模型更好地捕捉独立训练可能遗漏的共享模式)
- **Diversity:** the experts are **different AI networks**, which can provide the source of diversity (多样性: 专家是**不同的AI网络**, 可以提供多样性来源)
- **Easy to upgrade:** tends to **upgrade better than other models** because it leverages several shared bottoms (independent experts) instead of using a single architecture (易于升级: **比其他模型更容易升级**, 因为它利用了多个共享底层(独立专家), 而不是使用单一架构)



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(功率预测)
- **Equipment Monitoring**
(设备监测)
- **System State Estimation**
(系统状态估计)
- **System Operation**
(系统运行)
- **Stability Analysis**
(稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

Testing Cases (测试算例)

➤ Publicly Available Dataset (公开可用的数据集)

UK-DALE (UK Domestic Appliance-Level Electricity): Five rooms
(UK-DALE (英国家庭电器级电力):五个房间)

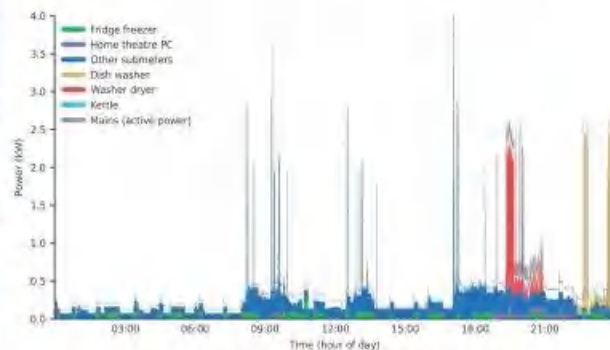
Training data set (训练集)

- **Rooms:** #1,3,4,5 rooms (房间: #1,3,4,5)
- **Appliances:** kettle, refrigerator, washer dryer, microwave,... (用电设备: 电热水壶、冰箱、洗衣干衣机、微波炉.....)
- **Sampling frequency:** 6s for both aggregated and appliance signals (采样频率: 总采样频率和设备采样频率均为6秒)

Test data set (测试集)

- **Rooms:** #2 room (房间: #2)
- **Appliances:** kettle, refrigerator, washer dryer, microwave,... (用电设备: 电热水壶、冰箱、洗衣干衣机、微波炉.....)
- **Sampling frequency:** 6s for both aggregated and appliance signals (采样频率: 总采样频率和设备采样频率均为6秒)

An example of energy consumption over the course of a day
for one of the houses in UK-DALE
(UK-DALE 中一个房屋一天中的能耗示例)



- **Measure features:** active power
(测量特征: 有功功率)

Introduction (引言)

AI in Smart Grids (AI 在智能电网中的应用)

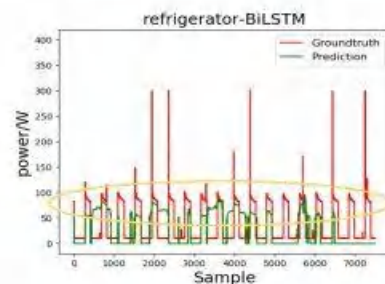
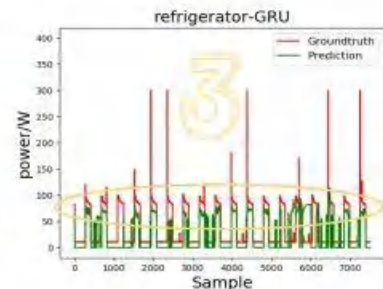
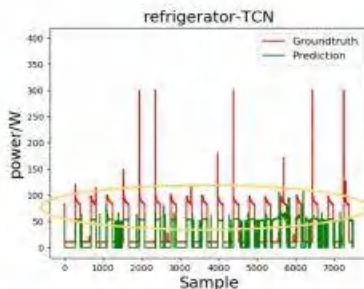
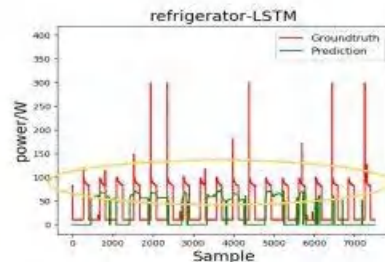
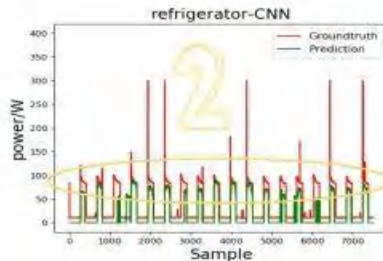
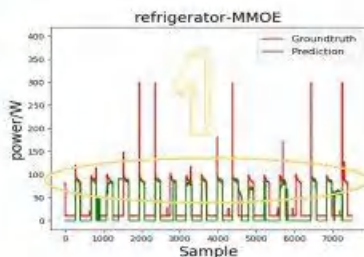
- Power Prediction (功率预测)
- Equipment Monitoring (设备监测)
- System State Estimation (系统状态估计)
- System Operation (系统运行)
- Stability Analysis (稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

Key Findings (主要结果)

UK-DALE



Introduction (引言)

- Predicting **load demand** based on their historical data and influential factors.
(根据历史数据和影响因素预测负荷需求)
- Classified according to microgrids, distribution systems, and transmission systems.
(根据微电网、配电系统和输电系统分类)

AI in Smart Grids

(AI 在智能电网中的应用)

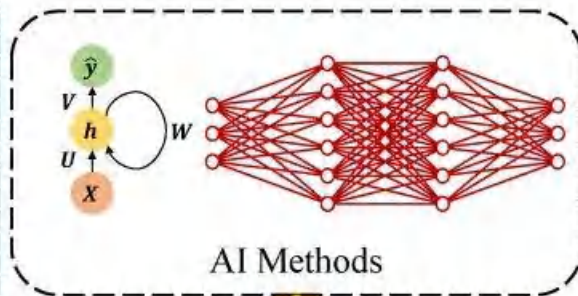
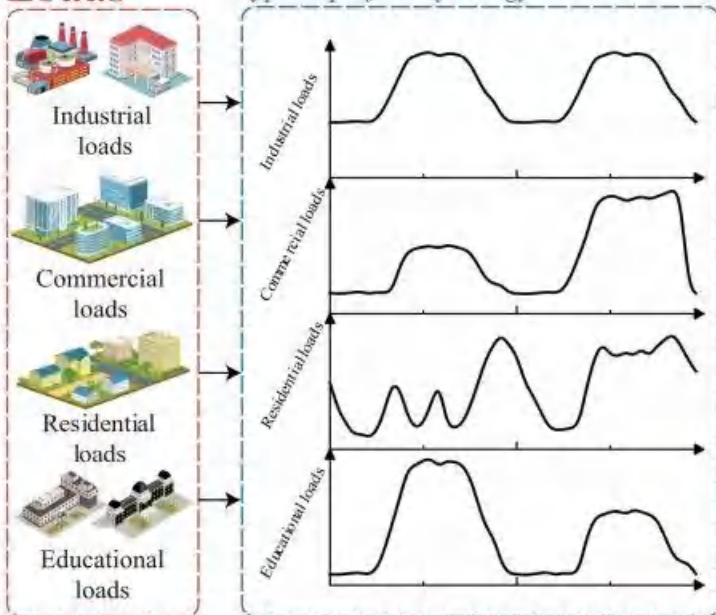
- **Power Prediction**
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(设备监测)
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(系统状态估计)
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(系统运行)
- **Stability Analysis**
(稳定性分析)

Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Loads

Typical profiles of energy demand



AI Methods

- ✓ Multi-step predictions.
(多步预测)
- ✓ Hierarchical predictions.
(分层预测)
- ✓ Probabilistic predictions.
(概率预测)

Introduction (引言)

AI in Smart Grids

(AI 在智能电网中的应用)

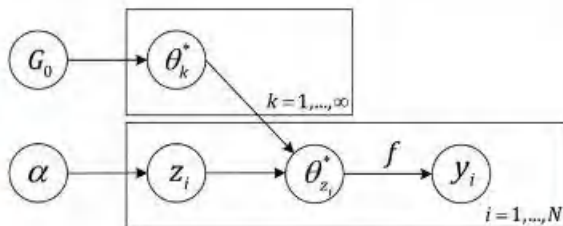
- Power Prediction (功率预测)
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Digital Twin Applications
(数字孪生的应用)

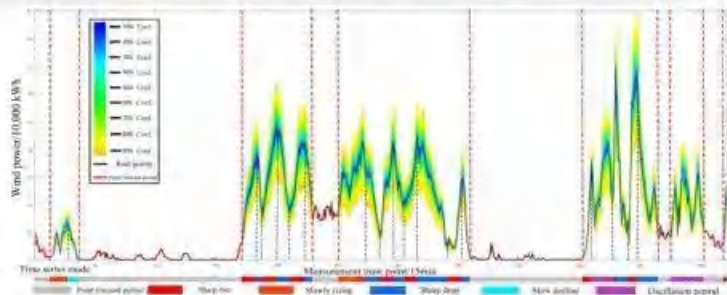
Challenges & Prospects
(挑战与展望)

➤ Opportunity 1: Bayesian learning for the uncertainty associated with prediction (机遇 1: 用于处理预测不确定性的贝叶斯学习)

- The loads and renewables fluctuate violently in a short period of time, particularly due to frequent **extreme weather**. (负荷和可再生能源在短时间内剧烈波动, 特别是由于频繁的**极端天气**)
- The Bayesian learning strategy can be used to **handle the uncertainty of load patterns** and improve the probabilistic predictions. (贝叶斯学习策略可用于**处理负荷模式的不确定性**并改进概率预测)



The Dirichlet process mixture model.



Probabilistic results with load patterns.

Introduction (引言)

AI in Smart Grids

(AI 在智能电网中的应用)

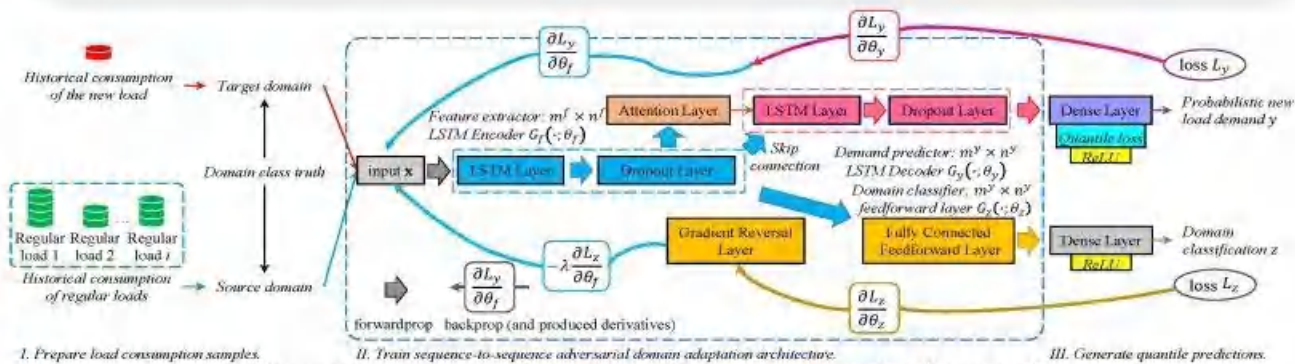
- Power Prediction (功率预测)
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Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

➤ Opportunity 2: Transfer learning for new loads and renewables (机遇 2: 用于新负荷和可再生能源的迁移学习)

- Insufficient data makes it hard to accurately predict the new loads and renewables. (数据不足使得难以准确预测新负荷和可再生能源)
- The transfer learning strategy can be used to align the distributions of sufficient data of lasting loads and renewables and the limited data of new ones. (迁移学习策略可以用来对齐持久负荷和可再生能源的充足数据与新负荷和可再生能源的有限数据的分布)



The sequence-to-sequence adversarial domain adaptation framework.

EV Charging Load Forecasting (电动汽车充电负荷预测)



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Introduction (引言)

- Predicting energy demand of electric vehicles (EVs) based on their charging records through **chargers in stations**. (基于电动汽车 (EV) 的充电记录, 通过充电站的充电头预测需求)
- Derived from individual EVs and their aggregation. (来源于单个电动汽车及其聚合)

AI in Smart Grids

(AI 在智能电网中的应用)

- Power Prediction (功率预测)
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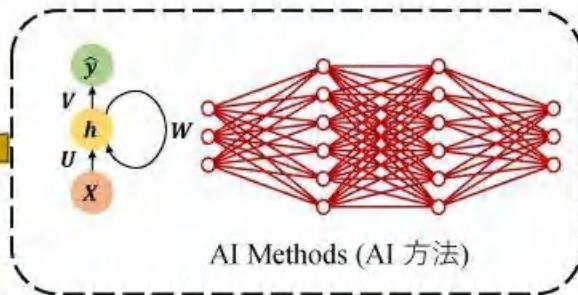
Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

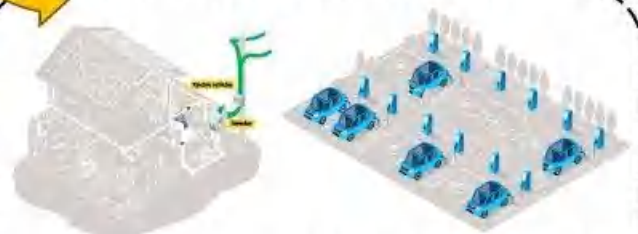


Spatial-temporal EV charging demand
(电动汽车时空充电需求)

- ✓ **Spatial** energy demand of individual EVs with trip chains. (具有行程链的单个电动汽车的空间能量需求)
- ✓ **Temporal** demand of EV aggregation (e.g., charging stations). (电动汽车聚合的时间需求)

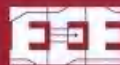


AI Methods (AI 方法)



Private EV chargers. Public EV charging stations.
(私人电动汽车充电器) (公共电动汽车充电站)

Renewable Power Generation Forecasting (可再生能源发电预测)



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Introduction (引言)

- Predicting **renewable power generation** (e.g., wind and solar) based on their historical data and weather conditions (or physical processes). (基于历史数据和天气条件（或物理过程）预测可再生能源发电（例如，风能和太阳能）)
- Classified according to its capacity. (根据其容量分类)

AI in Smart Grids

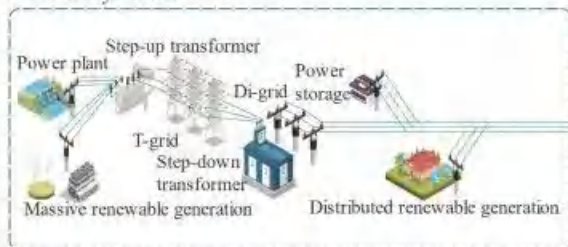
(AI 在智能电网中的应用)

- **Power Prediction**
(功率预测)
- **Equipment Monitoring**
(设备监测)
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- **System Operation**
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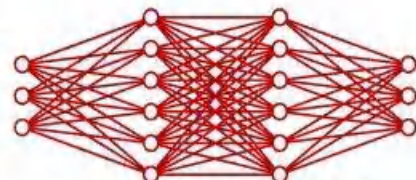
Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

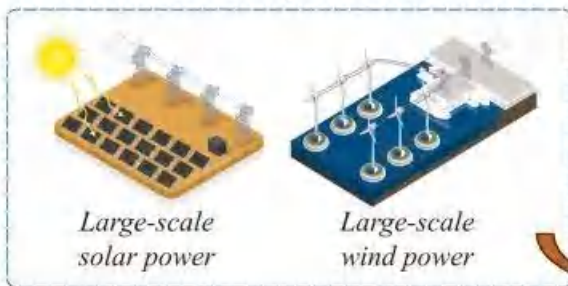
Power systems



Prosumers



AI Methods (AI 方法)



- ✓ Numerical weather predictions. (数值天气预测)
- ✓ Power generation predictions. (发电预测)

Introduction

(引言)

AI in Smart Grids

(AI 在智能电网中的应用)

- Power Prediction (功率预测)
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- System State Estimation (系统状态估计)
- System Operation (系统运行)
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Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Science Park, 198kW
(科学园: 198千瓦)



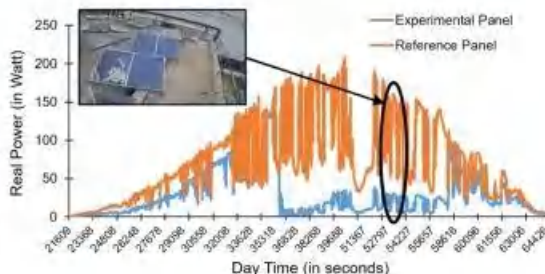
EMSD Headquarters, 350kW
(机电工程署总部: 350千瓦)



Disneyland Resort, 3050kW
(迪士尼乐园度假区: 3050千瓦)



Dusts can significantly reduce solar panel efficiency.
(灰尘会显著降低太阳能电池板的效率)



Expect to generate over 4,300,000 kWh annually.
(预计每年发电超过4,300,000千瓦时)

Introduction (引言)

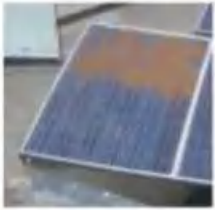
AI in Smart Grids

(AI 在智能电网中的应用)

- Power Prediction
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- Stability Analysis
(稳定性分析)

Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

	Dust Brown	Dust Red	Dust White	Splattered Dust
Large				
Medium				
Mild				

Soiling Power Loss Estimation at the Edge (边缘计算中的污垢功率损失估计)



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Introduction (引言)

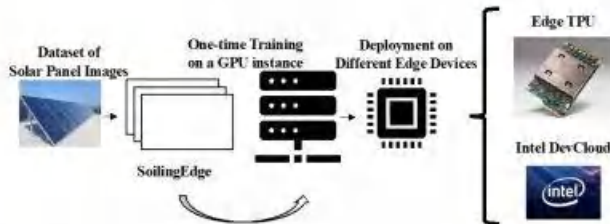
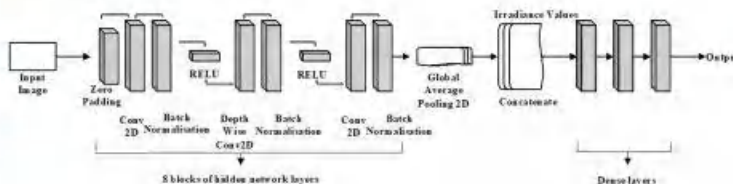
AI in Smart Grids

(AI 在智能电网中的应用)

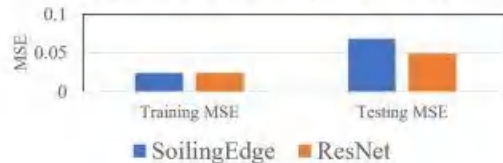
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Digital Twin Applications (数字孪生的应用)

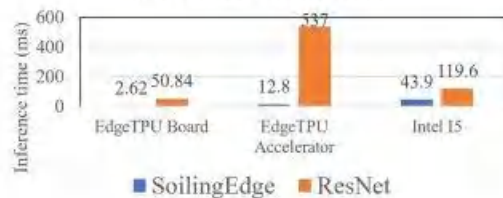
Challenges & Prospects (挑战与展望)



The mean square error (MSE) comparison of training and testing



Inference Time Comparison



Contributions (我们的工作):

- ❑ New deployment: Extend the model to the edge-computing (新部署: 将模型扩展到边缘计算)
- ❑ Informative reference: Provide references for engineers to deploy models at the edge (重要参考: 为工程师在边缘部署模型提供参考)

Introduction (引言)

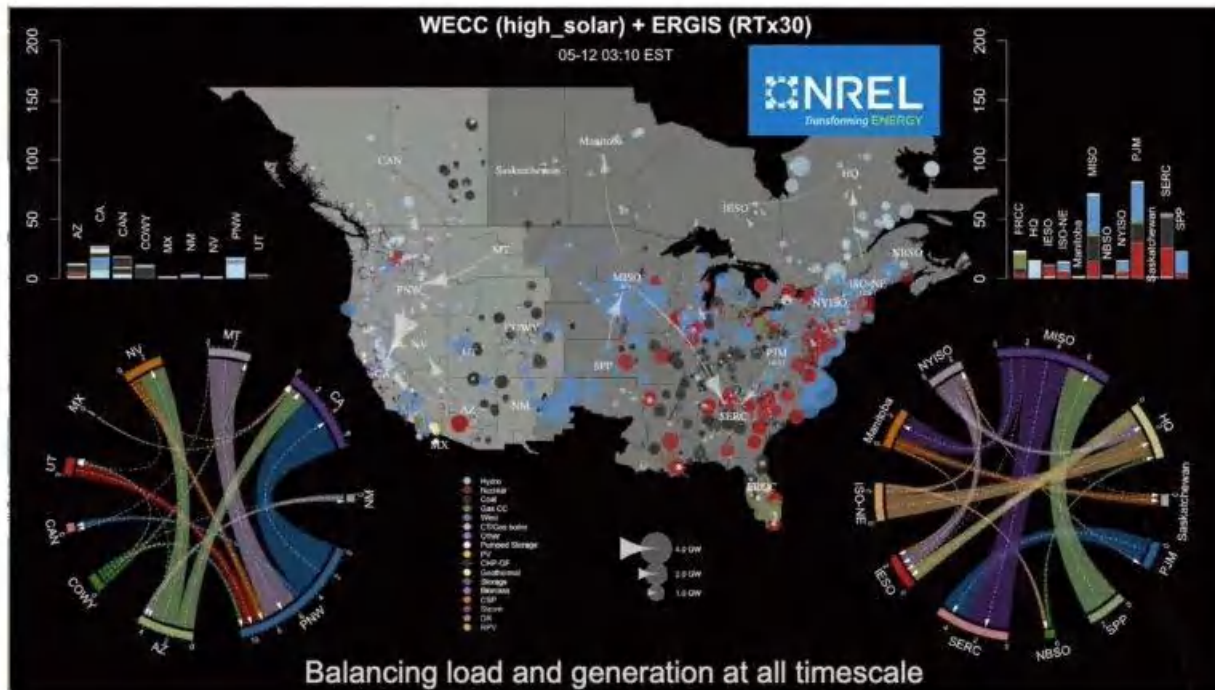
AI in Smart Grids

(AI 在智能电网中的应用)

- **Power Prediction**
(功率预测)
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(稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)



Introduction (引言)

- Various types of devices are being used in the smart grid.
(智能电网中使用了各种类型的设备)
- Their performance needs timely and accurate monitoring.
(它们的性能需要及时准确的监测)

AI in Smart Grids

(AI 在智能电网中的应用)

- Power Prediction
(功率预测)
- Equipment Monitoring
(设备监测)
- System State Estimation
(系统状态估计)
- System Operation
(系统运行)
- Stability Analysis
(稳定性分析)

Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)



Energy storage devices (Batteries, fuel cells,
supercapacitors, etc.)
(储能设备 (电池、燃料电池、超级电容器等))



Power electronics
(电力电子设备)



Solar panels
(太阳能电池板)



Wind turbines
(风力涡轮机)

Introduction (引言)

- Learning from historical data, AI models can predict the remaining useful life (RUL) of power electronics. (从历史数据中学习, AI 模型可以预测电力电子的剩余使用寿命 (RUL))

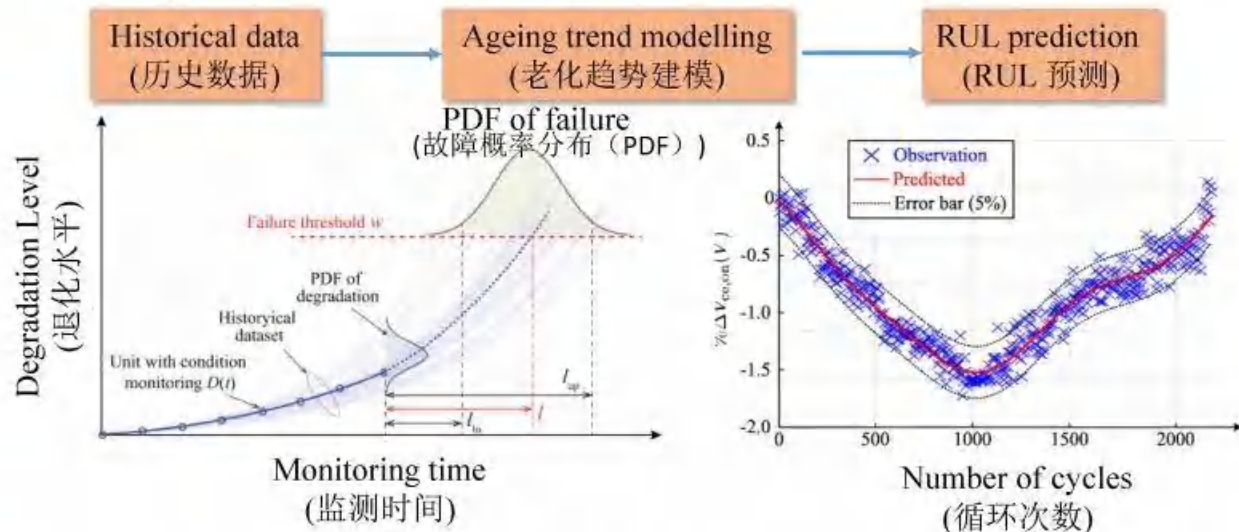
AI in Smart Grids

(AI 在智能电网中的应用)

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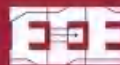
Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)



AI models can be used to monitor the life degradation of power electronics
(AI 模型可用于监测电力电子的寿命退化)

Anomaly Detection of Photovoltaic Panels



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Introduction (引言)

- AI can be combined with advanced sensors to analyze multi-dimensional signals for photovoltaic panel anomaly detection. (AI 可以与先进的传感器结合，分析多维信号以进行光伏电池板的异常检测)

Current sensor Voltage sensor Irradiance sensor
(电流传感器) (电压传感器) (辐照度传感器)



AI in Smart Grids

(AI 在智能电网中的应用)

➤ Power Prediction

(功率预测)

➤ Equipment Monitoring

(设备监测)

➤ System State Estimation (稳态电压 Steady voltage
稳态温度 Steady temperature
稳态湿度 Steady humidity)

➤ System Operation
(系统运行)

➤ Stability Analysis
(稳定性分析)

Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Introduction (引言)

- We developed EV battery fault detection models with a charging station company using realistic EV charging data. (我们与一家充电站公司合作，使用真实的电动汽车充电数据开发了电动汽车电池故障检测模型。)

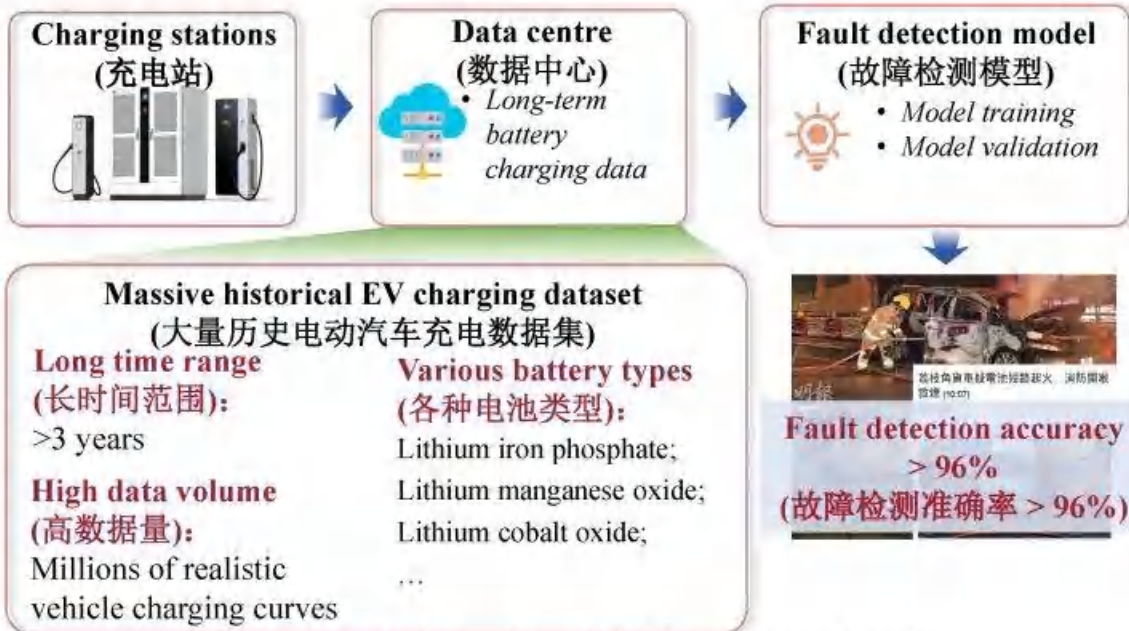
AI in Smart Grids

(AI 在智能电网中的应用)

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Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)



Accurate fault detection of EV batteries using AI.

(使用 AI 准确检测电动汽车电池故障)

Introduction (引言)

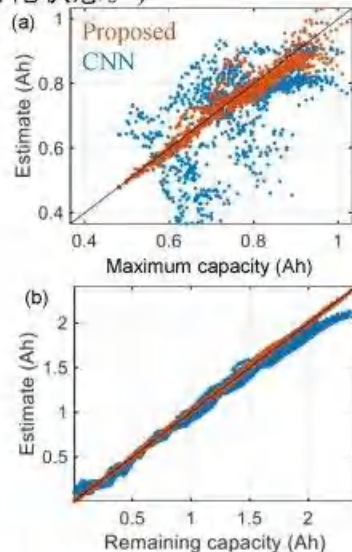
AI in Smart Grids (AI 在智能电网中的应用)

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Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

- AI learns from massive synthetic degradation data and few realistic degradation data. Battery ageing states are accurately estimated while testing efforts are sharply reduced. (AI 从大量的合成退化数据和少量的真实退化数据中学习。在测试工作量显著减少的同时，准确估计电池老化状态。)

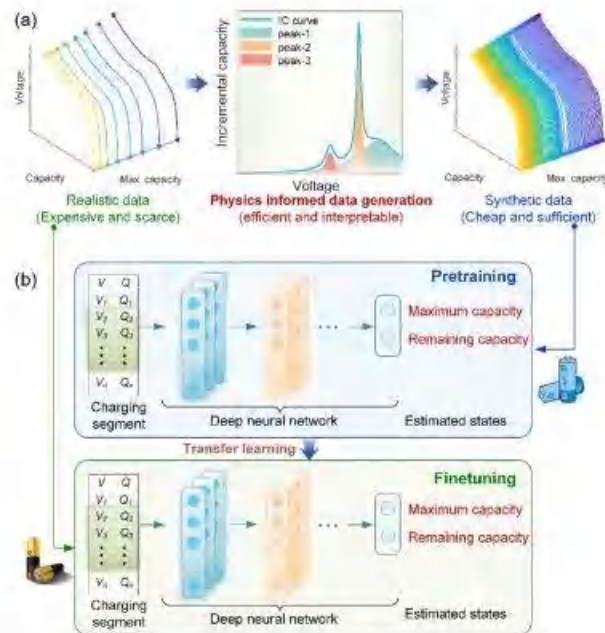


Accurate estimation of battery states using fewer testing data:

(a) maximum capacity and (b) remaining capacity estimation

(使用更少的测试数据准确估计电池状态:

(a) 最大容量估计和 (b) 剩余容量估计)



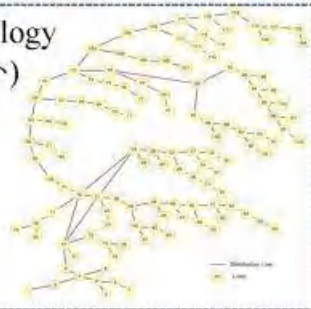
Introduction (引言)

➤ Measurement Data Calibration for PMU/SCADA (PMU/SCADA 测量数据校准)

- Erroneous data detection (错误数据检测)
- Missing data recovery (缺失数据恢复)
- Measurement noise cleaning (测量噪声清除)

➤ Topology Identification (拓扑识别)

Topology (拓扑)



Correlation analysis (相关性分析)

$$-A^{-1} = \begin{bmatrix} 1 & & & & & & \\ & 1 & & & & & \\ & 1 & 1 & & & & \\ & 1 & 1 & 1 & & & \\ & 1 & & & 1 & & \\ & 1 & & & 1 & 1 & \\ & 1 & & & 1 & 1 & 1 \end{bmatrix} \quad R = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 2 & 2 & 1 & 1 & 1 & 1 \\ 1 & 2 & 3 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 2 & 2 & 2 & 2 \\ 1 & 1 & 1 & 2 & 3 & 2 & 2 \\ 1 & 1 & 1 & 2 & 2 & 3 & 3 \\ 1 & 1 & 1 & 2 & 2 & 3 & 4 \end{bmatrix}$$



Connection matrix (连接矩阵)

$$\bar{A} = \begin{bmatrix} 1 & & & & & & \\ -1 & & & & & & \\ +1 & -1 & & & & & \\ & +1 & -1 & & & & \\ +1 & & & -1 & & & \\ & & & +1 & -1 & & \\ & & & +1 & & -1 & \\ & & & & & +1 & -1 \end{bmatrix}$$

➤ Cyber Attacks Detection (网络攻击检测)

AI in Smart Grids

(AI 在智能电网中的应用)

- Power Prediction (功率预测)
- Equipment Monitoring (设备监测)
- System State Estimation (系统状态估计)
- System Operation (系统运行)
- Stability Analysis (稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

Introduction (引言)

Classification of System Operation (系统运行分类):

Based on whether the system operates under **extreme weather**. (基于系统是否在极端天气下运行)

Routine System Operation (常规系统运行):

- **Focus on economic performance:** i.e., minimize total operation costs (关注经济性能: 即最小化总运营成本)
- **Uncertain factors:** RES uncertainty (不确定因素: 可再生能源的不确定性)
- **Environmental impact:** tracking and reducing greenhouse gas emissions from grid operations (环境影响: 追踪并减少电网运作中的温室气体排放)



Emergency System Operation (紧急系统运行):

- Extreme weather conditions (极端天气条件)
- Enhancing resilience (增强韧性)
- **Pre-disaster** vulnerability assessment (灾前脆弱性评估)
- Emergency resource allocation **during disaster** (灾中紧急资源分配)
- **Post-disaster** resilience recovery (灾后恢复韧性)



AI in Smart Grids

(AI 在智能电网中的应用)

- **Power Prediction** (功率预测)
- **Equipment Monitoring** (设备监测)
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- **System Operation** (系统运行)
- **Stability Analysis** (稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

Introduction (引言)

Motivations (动机):

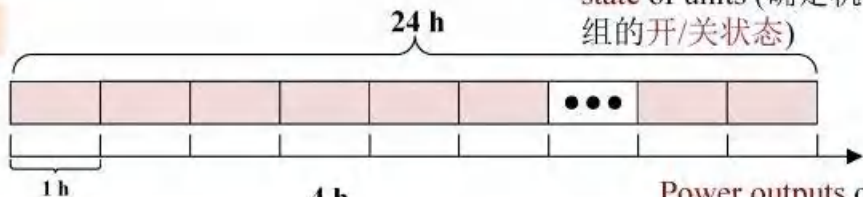
Substantial integration of complex and emerging components, such as power electronic devices, EVs and so on. (大量集成复杂且新兴的组件，如电力电子设备、电动车等)

Determine on/off state of units (确定机组的开/关状态)

Time Scale (时间尺度):

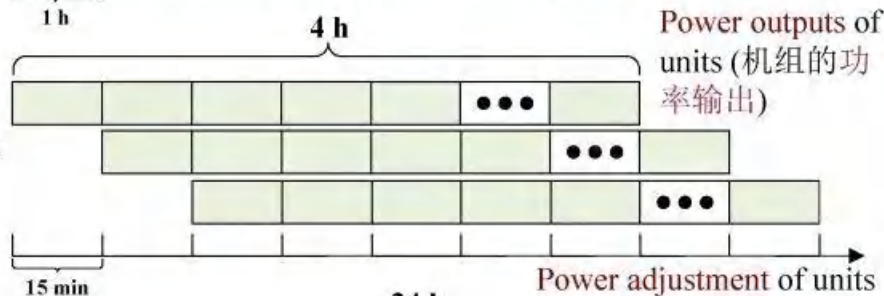
Day-ahead:

Unit commitment
(日前机组组合)



Intra-day:

Economic dispatch
(日内经济调度)

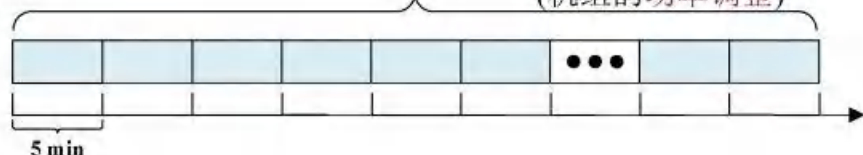


Power outputs of units (机组的功率输出)

Power adjustment of units
(机组的功率调整)

Real-time:

Adjustment
(实时调整)



AI



AI in Smart Grids

(AI 在智能电网中的应用)

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 - Routine Operation (常规运行)
 - Emergency Operation (紧急运行)
- Stability Analysis (稳定性分析)

Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Classification of AI in Smart Grid Routine Operation

(智能电网常规操作中AI的分类)



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Introduction (引言)

AI in Smart Grids (AI 在智能电网中的应用)

- Power Prediction (功率预测)
- Equipment Monitoring (设备监测)
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- Stability Analysis (稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

AI in Smart Grid Routine Operation (智能电网常规操作中的AI应用):

The application of AI in this domain can be broadly categorized into two main approaches:
(此领域中AI的应用可以大致分为两种主要方法:)

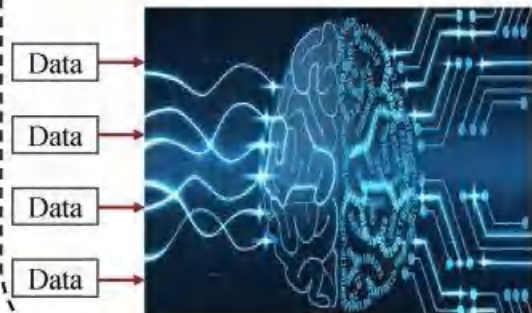
Reinforcement Learning (RL) (强化学习):

- ❑ Self learning (自我学习)
- ❑ Does not require data (不需要数据)
- ❑ But computationally intensive (计算量大)



Deep Learning (DL) (深度学习):

- ❑ Based on data (基于海量数据)
- ❑ Handle complex patterns (处理复杂模式)
- ❑ Less computational burden (计算负担较小)
- ❑ Adaptable to various tasks (适应各种任务)



Introduction (引言)

AI in Smart Grids (AI 在智能电网中的应用)

- Power Prediction (功率预测)
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Digital Twin Applications (数字孪生的应用)

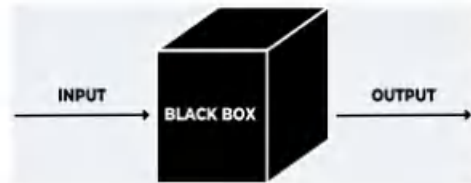
Challenges & Prospects (挑战与展望)

Deep Learning (DL) (深度学习)

Data based End-to-End Learning

(基于数据的端到端学习):

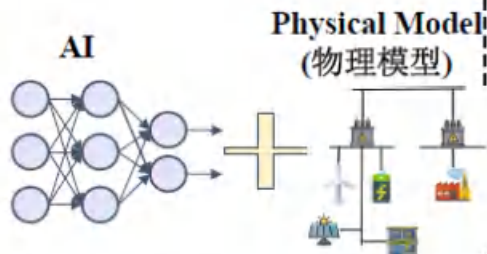
- Purely on historical and real-time data (完全依赖历史和实时数据)
- Without explicit programming of physical grid models (无需显式编程物理电网模型)
- Black-box nature (黑箱)



Physics-informed neural networks (PINN)

(物理信息神经网络 (PINN)):

- Incorporate physical knowledge and laws (结合物理知识和法则)
- Predictions and decisions adhere to physical constraints (预测和决策符合物理约束)
- Enhance interpretability (增强可解释性)
- Improve generalization (提升泛化能力)



Introduction (引言)

AI in Smart Grids

(AI 在智能电网中的应用)

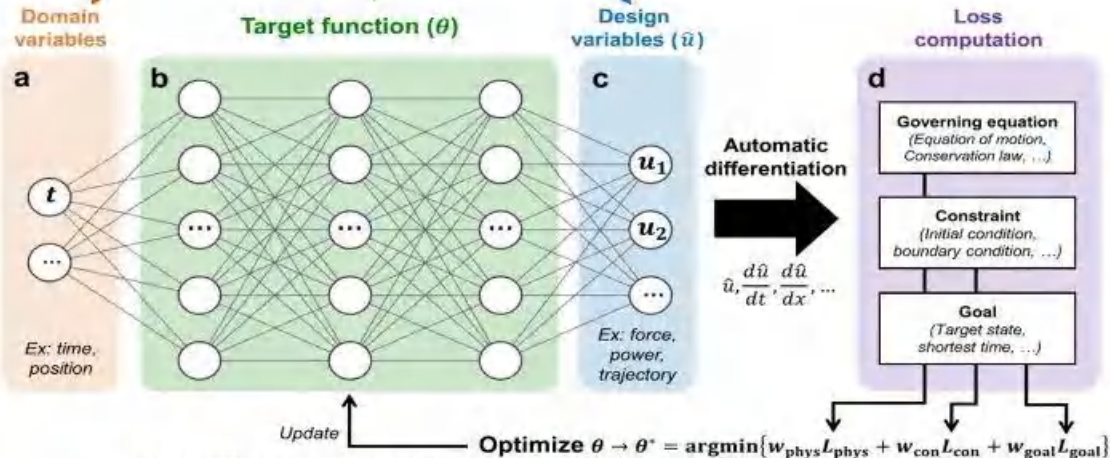
- Power Prediction (功率预测)
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- Stability Analysis (稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

Four types of paradigms of implementing the PINN (PINN的四种范式):

- Physics-Informed Target Function (物理信息目标函数)
- Physics-Informed Domain Variables (Initialization) (物理信息域变量(初始化))
- Physics-Informed Design of Network Architecture (物理信息网络架构设计)
- Hybrid Physics-DL Models (混合物理-DL模型)



Introduction (引言)

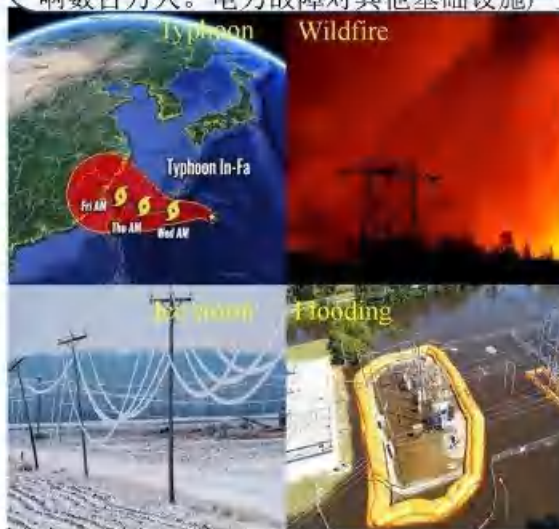
AI in Smart Grids (AI 在智能电网中的应用)

- Power Prediction
(功率预测)
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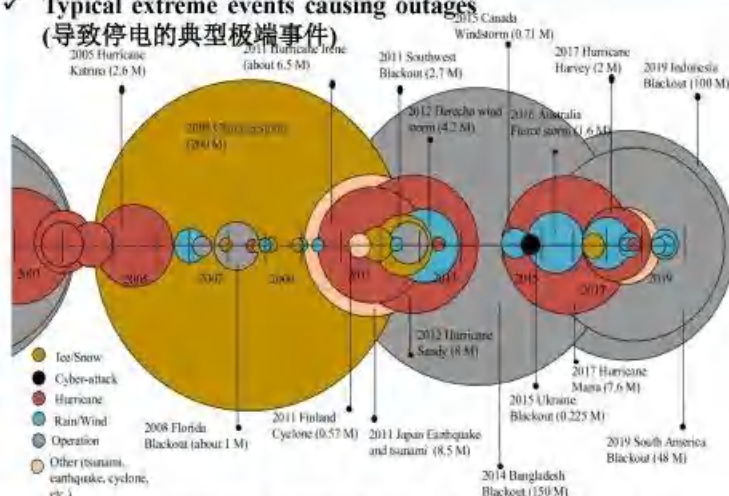
Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

The electric grid is essential but vulnerable, and the aging electrical infrastructure is increasingly strained by extreme weather events like hurricanes, wildfires, ice storms, flooding, and heat waves. Weather-related power outages affect millions of people each year. Power failures have cascading effects on other infrastructure and cost billions of dollars annually. (电网是必不可少但又极其脆弱的, 老化的电力基础设施因飓风、野火、冰雹、洪水和热浪等极端天气事件的影响越来越大。与天气相关的停电每年影响数百万人。电力故障对其他基础设施产生连锁反应, 并每年造成数十亿美元的损失)



✓ Typical extreme events causing outages (导致停电的典型极端事件)



Gonçalves A. C. R., et al. (2024). Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures. Sustainable Energy Research, 11(4), 1-28.

Bhusal N., Abdelmalak M., Kamruzzaman M. & Benidris M. (2020). Power system resilience: current practices, challenges, and future directions. IEEE Access, 8, 18064-18086.

<https://www.climatecentral.org/climate-matters/weather-related-power-outages-rising>

Four Phases of Emergency Management

(紧急管理的四个阶段)



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Introduction (引言)

Emergency response of electric grids encompasses four main phases: disaster forecast and power outage prediction, hardening and resilience investment, corrective actions and emergency response as well as electric damage assessment and restoration. AI can be applied across all the emergency management phases to automate and improve operational efficiency. (电网的紧急响应包括四个主要阶段：灾害预测和停电预测、加固和韧性投资、纠正措施和紧急响应以及电力损害评估和恢复。AI可以应用于所有紧急管理阶段，以自动化并提高运营效率)

AI in Smart Grids

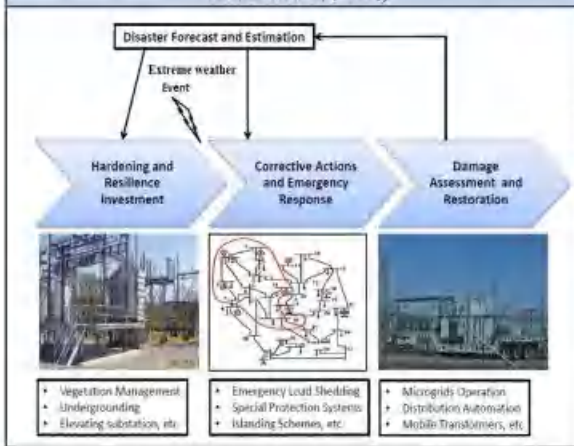
(AI在智能电网中的应用)

- Power Prediction (功率预测)
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- Routine Operation
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- Stability Analysis (稳定性分析)

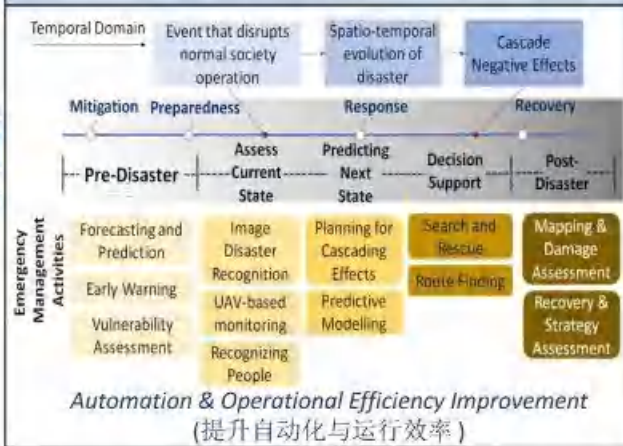
Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Timeline of the Emergency Response in Electric Grids under Extreme Weather Events (极端天气事件下电网紧急响应的时间线)



Emergency Management Phases and Operations where AI can be Utilized (AI-赋能的紧急管理和运行)



Wang Y., Chen C., Wang J. & Baldick R. (2016). Research on resilience of power systems under natural disasters—A review. IEEE Transactions on Power Systems, 31(2), 1604-1613.

Kyrkou C., Kolios P., Theocharides T. & Polycarpou M. (2023). Machine learning for emergency management: a survey and future outlook. Proceedings of the IEEE, 111(1), 19-41.

Necessity for AI application in Stability Analysis (稳定性分析中应用AI的必要性)



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Introduction (引言)

The **physical mechanism** usually also shows the **external characteristics** of the data correlation mechanically. To mine the data correlation in **transient problems** using AI is to reveal the physical properties of power system transient issues from the data perspective. (物理机制通常也机械地显示数据相关性的外部特征。使用AI挖掘暂态问题中的数据相关性，是从数据角度揭示电力系统暂态问题的物理属性)

AI in Smart Grids

(AI 在智能电网中的应用)

- Power Prediction (功率预测)
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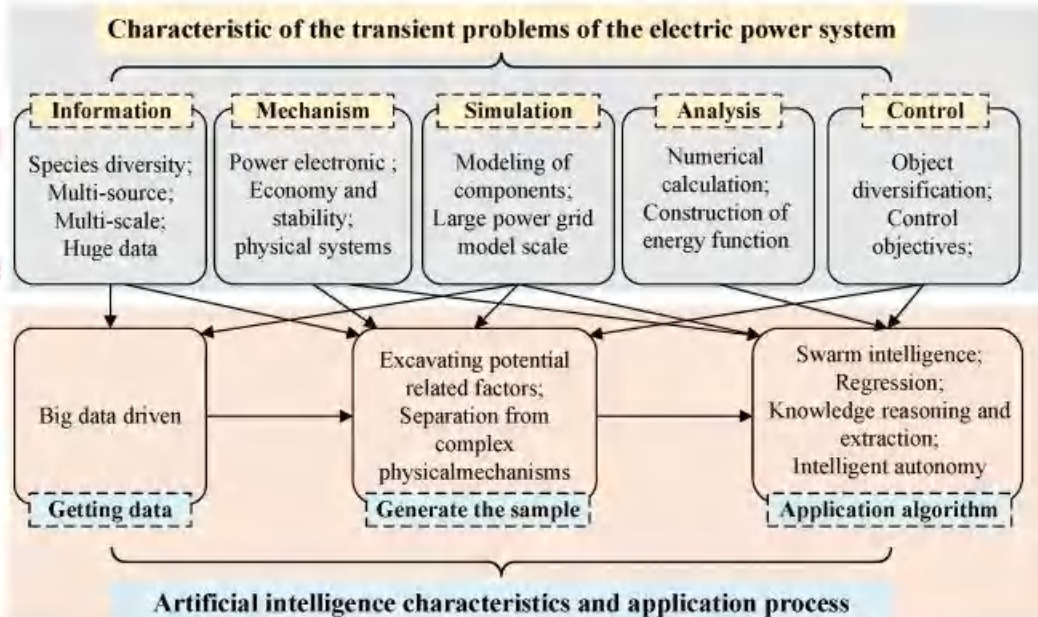
Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Physical
mechanism
(物理机制)

Simplified
(简化)

AI process
(AI过程)



Transient problem matches the process of AI (内嵌AI的暂态问题)

Comparisons of Transient Stability Analysis Methods (暂态稳定性分析方法比较)



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Introduction (引言)

AI-driven approaches have better performance in balancing efficiency, accuracy and adaptability.
(AI驱动的方法在平衡效率、准确性和适应性方面表现更好)

AI in Smart Grids (AI 在智能电网中的应用)

- Power Prediction
(功率预测)
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(设备监测)
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(系统状态估计)
- System Operation
(系统运行)
- Stability Analysis
(稳定性分析)

Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

Method (方法)	Information (相关信息)	Application (应用)	Challenges (挑战)
AI ANN-based, SVM, EL, DL...	Huge sample data, multi-scenes, multi-parameters, multi-agents (大样本数据, 多场景, 多参数, 多代理)	Reduce the negative impact of the analysis accuracy when the actual data is inconsistent with the preset data (减少实际数据与 预设数据不一致时分析精度的 负面影响)	Pre-processing and post processing of the data, proper environment modeling for obtaining data (数据预处理和 后处理, 为获取数据提供适当 的环境建模)
Direct method (直接 方法)	Initial conditions, system models and disturbance information (初 始条件、系统模型和干扰信息)	Fast stability estimate, online transient stability analysis, optimal control strategy (快速稳 定性估计, 在线暂态稳定性分 析, 最优控制策略)	Suitable calculation methods such as Lyapunov functions design (需要适合的计算方法 如李雅普诺夫函数设计)
Time-domain simulation (时间域 仿真)	System response based on numerical and differential equations (系统响应基于数值和 微分方程)	Main methods in the industry, accuracy standard for other methods (主流方法, 其他方法的 准确性标准)	Simulation accuracy, speed and transient instability criterion (模拟精度、速度和 暂态不稳定性标准)
Inverse trajectory and semi-tensor product (逆轨迹和 半张量积)	Estimate of domain of attraction for initial stability condition (域 的初步稳定性条件估计)	System stability assessment, improve control strategy, stability boundary (系统稳定性 评估, 改进控制策略, 稳定性 边界)	Non-linear system modeling, data vacancy and inaccuracy, calculation burden (非线性系 统建模, 数据空缺和不准确, 计算负担)
...			

Transient Stability Prediction (暂态稳定预测)



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Introduction (引言)

AI in Smart Grids

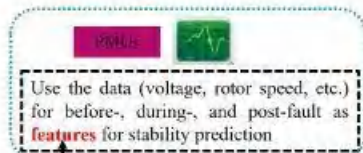
(AI 在智能电网中的应用)

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Digital Twin Applications (数字孪生的应用)

Challenges & Prospects (挑战与展望)

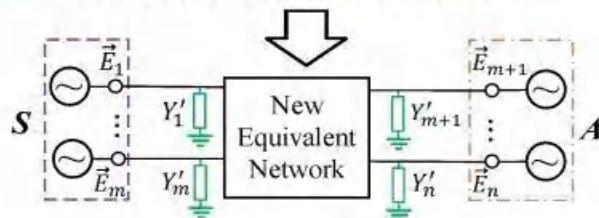
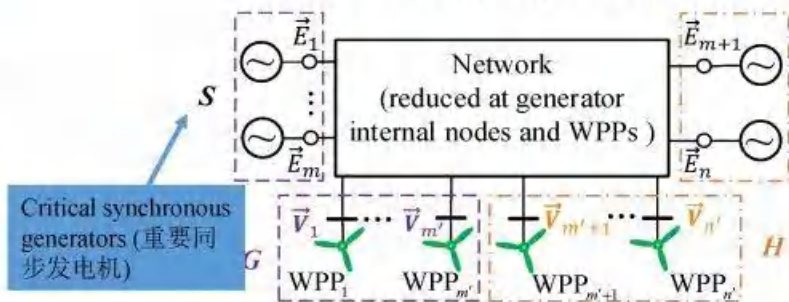
REAL-TIME DATA



INSTANTANEOUS PREDICTION



These features may no longer be so useful:



Equivalent Circuit of WPPs (WPPs的等效电路)

$$Y'_i = \sum_{g \in G} \left[\left(1 - \frac{\bar{V}_g}{\bar{E}_i} \right) Y_{ig} \right] + \sum_{h \in H} \left[\left(1 - \frac{\bar{V}_h}{\bar{E}_i} \right) Y_{ih} \right]$$

Y. Chen, M. Mazhari, C.Y. Chung, and B. Pal, "Rotor Angle Stability Prediction of Power Systems with High Wind Power Penetration Using a Stability Index Vector," *IEEE Trans. on Power Systems*.

Transient Stability Prediction Case Studies (暂态稳定预测的算例研究)



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Introduction (引言)

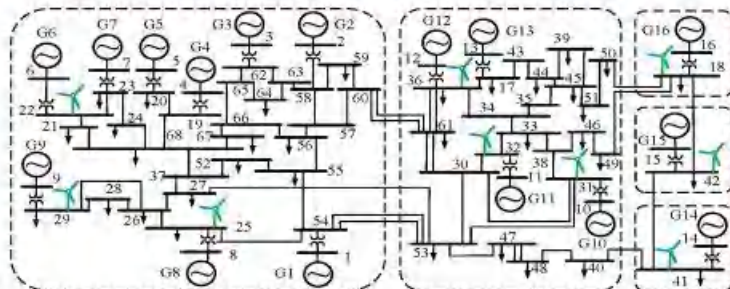
AI in Smart Grids

(AI 在智能电网中的应用)

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Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)



The modified 16-machine network with 9 wind power plants (WPPs)
Comparisons of the accuracy of different features (不同特征准确性的对比)

	Features			
WIC*	Rotor angles (δ)	Rotor speeds (ω)	Terminal voltages (V_G)	Proposed (SI vector)
10%	93.61%	97.05%	96.88%	98.98%
20%	92.59%	95.38%	95.79%	98.59%
30%	92.18%	94.82%	94.42%	98.46%
40%	91.14%	92.06%	92.29%	98.17%
50%	89.56%	91.24%	91.35%	97.96%

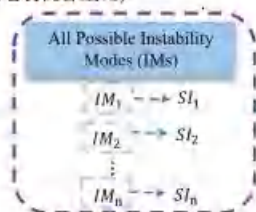
*WIC: Wind power Installed Capacity ratio (*WIC: 风电装机容量比)

Details of Simulation Analyses (详细信息)

- Fault is applied on each line randomly (故障随机加到每条线路上). Fault duration is select between 6-15 cycles randomly (故障持续时间在6到15个周期之间随机选择)
- Load level and WPP generation is sampled from historical data for each simulation (负载水平和WPP发电量根据每次模拟的历史数据抽样)
- All WPPs use DFIG wind turbines (所有WPPs使用双馈感应发电机 (DFIG) 风力涡轮机)
- **7000 cases** are simulated for each penetration (每个渗透率模拟7000个案例)

Calculate the stability index (SI) utilizing Extended Equal Area Criterion (EEAC) considering the dynamic admittances (利用扩展等面积准则 (EEAC) 计算稳定性指数 (SI))

$$SI = \frac{A_{dec} - A_{acc}}{A_{acc}}$$



(SI vector)

$$\begin{bmatrix} SI_1 \\ SI_2 \\ \vdots \\ SI_n \end{bmatrix}$$

Introduction (引言)

AI in Smart Grids (AI 在智能电网中的应用)

Digital Twin Applications (数字孪生的应用)

- AI-driven Digital Twin
- Digital Twin for AI

Challenges & Prospects (挑战与展望)

Achieve various applications: monitoring, control, predictions, state estimation, operation, etc.
实现各种应用：监控、控制、预测、状态估计、运行调度等

Various twin models:
不同的孪生模型:

Twin tower
孪生塔

Twin turbine
孪生风机

Twin substation
孪生电站

Twin Model
孪生模型

- ❑ AI tools AI工具
- ❑ Hardware devices 硬件设备
- ❑ Software platforms 软件平台

Real-world Model
真实模型

Data fusion from various
sources for specific tasks or
elements
用于特定任务或组件的来
自各种来源的数据融合



Introduction (引言)

AI in Smart Grids (AI 在智能电网中的应用)

Digital Twin Applications (数字孪生的应用)

- AI-driven Digital Twin
- Digital Twin for AI

Challenges & Prospects (挑战与展望)



Twin models 孪生模型

- Rich datasets for in **normal** scenarios 提供正常运行状况下的数据集
- Data in **rare or dangerous** scenarios 提供危险运行状况数据集

Data 数据

Corrections 校正

- Update and optimize twin models based on real operational data 根据实际数据更新孪生模型



AI model training
AI模型训练

Applications 应用

- Decision-making or analysis with **high accuracy** 高准确度的决策或分析



Real-world model
真实模型

Introduction (引言)

AI in Smart Grids
(AI 在智能电网中的应用)

Digital Twin Applications
(数字孪生的应用)

Challenges & Prospects
(挑战与展望)

Data (数据)

Quality and quantity
(质量和数量)

Privacy
(隐私)

Data should not only be voluminous but also of high quality, while respecting privacy regulations to support accurate performance. (数据不仅要量大, 还要高质量, 同时要尊重隐私法规以支持准确的性能)

Foundation (基础)

AI Method (AI 方法)

Interpretability and reliability
(可解释性和可靠性)

Multimodal inputs
(多模态输入)

AI method should be interpretable to foster trust and reliability, while also need to handle multimodal data in power system. (AI 方法应具有可解释性以促进信任和可靠性, 同时还需要处理电力系统中的多模态数据)

Enabler (赋能者)

Application (应用)

Gap between model and reality
(模型与现实之间的差距)

Scalability
(可扩展性)

Scaling AI across grid and tasks is challenge, and bridging the gap between models and reality requires further innovation. (跨电网和任务扩展 AI 是一项挑战, 弥合模型与现实之间的差距需要进一步创新)

Transformer (转化)

➤ Potential Challenges
(潜在挑战)

➤ Future Perspective

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- Potential Challenges
- Future Perspective
(未来展望)

Revolutionizing Data Utilization (革新数据利用)

Addressing the data issue by promoting **few-shot** or **zero-shot learning** to maximize the use of current data. Implementing **privacy-preserving methods** to enhance data security and privacy protection. (通过推动少样本学习或零样本学习来最大化当前数据的使用，从而解决数据问题。实施隐私保护方法以增强数据安全性和隐私保护)

Powering Up with Large Model (LM) (大型模型的增强)

Developing large models for power system, capable of handling **multi-modal data inputs** and achieving **scalability** when meeting a new grid or new task. (开发用于电力系统的大型模型，能够处理多模态数据输入，并在面对新电网或新任务时实现可扩展性)

Bridging Model and Reality (模型与现实的桥梁)

Creating **explainable AI models** to ensure interpretability and reliability of the model to realize **digital-twin**, thereby minimizing the gap between models and the real world through data. (创建可解释的人工智能模型，以确保模型的可解释性和可靠性，实现数字孪生，从而通过数据最小化模型与现实世界之间的差距)



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