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USING DIGITAL TWINS TO ENHANCE ENERGY GRID SUSTAINABILITY

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ABSTRACT

In the contemporary energy landscape, power generation is derived from both fossil fuels and renewable sources such as solar, wind, and hydropower[1]. While fossil fuels constitute a significant contributor to global energy supply, they also emit substantial quantities of greenhouse gases, thereby driving climate change. In contrast, increasing the utilization of renewable energy offers a potential means to mitigate these emissions. Renewable energy generation is highly dependent on meteorological patterns[2], rendering accurate prediction of energy production challenging and occasionally necessitating the overproduction of fossil fuel-based electricity as a contingency measure. This paper investigates the application of Digital Twins—virtual models of physical systems[3]—to simulate meteorological and geographical factors in order to enhance renewable energy forecasts and address this challenge.

Keywords: digital twins, renewable energy forecasting, meteorological modelling, energy production prediction, greenhouse gas emissions

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[1] Chibuike Peter Ohanu, Salihu Ahmed Rufai, and Ugbe Christiana Oluchi, "A comprehensive review of recent developments in smart grid through renewable energy resources integration" (2024) 10(3) Heliyon e25705 ⟨https://www.sciencedirect.com/science/article/pii/S2405844024017365⟩.
[2] Tudor Cioara and others, An Overview of Digital Twins Application Domains in Smart Energy Grid (2021) ⟨https://arxiv.org/abs/2104.07904⟩.
[3] Azad M Madni, Carla C Madni, and Scott D Lucero, "Leveraging Digital Twin Technology in Model-Based Systems Engineering" (2019) 7(1) Systems 7 ⟨https://www.mdpi.com/2079-8954/7/1/7⟩.

INTRODUCTION

In an electricity grid, the total energy supply comes from both fossil-fuel based production and renewable sources such as solar, hydropower and wind. Fossil-fuel based electricity production methods emit vast amounts of greenhouse gases to the atmosphere. To minimise greenhouse gas emissions, it is beneficial to increase electricity production from renewable sources and reduce electricity production from fossil-fuels. However, renewable energy generation relies on favourable weather conditions, which makes forecasting energy production from renewable sources difficult. As a result, an excess of fossil-fuel based electricity must be generated to meet the demand. Our research investigates the use of Digital Twins to forecast electricity generation from renewable energy sources. Such Digital Twins can simulate weather conditions such as rainfall, snow, wind velocity, cloud coverage, sunshine, humidity, and temperature as well as geographical factors such as latitude, longitude, altitude and topographical features. Collective usage of these simulated features and renewable energy powerplant models can mimic real-world scenarios, which can be used to forecast near-accurate electricity production that contributes to the total electricity grid. Such accurate forecasts will lead to the reduction of excess fossil-fuel based electricity generation, enhancing energy grid sustainability.

The remainder of this paper is structured as follows. Section “background” provides background on the energy grid’s continued reliance on fossil fuels and the inherent variability of renewable energy sources. Section “Greenhouse Gas Emissions in Energy Production” examines greenhouse gas emissions associated with energy production, emphasizing the need for more efficient integration of renewables. Section “Challenges in Renewable Energy Forecasting” discusses the key challenges in short-term renewable energy forecasting, including weather unpredictability and the limited availability of real-time data. Section “Proposed Solution” introduces Digital Twins as a proposed solution to enhance forecasting accuracy, while Section “Digital Twins” elaborates on their functionality and application within energy systems. Section “Role of Digital Twins in Energy Forecasting” explores the transformative role of Digital Twins in energy forecasting, particularly in enabling real-time data integration and predictive maintenance. Section “Experiment and Outputs” presents an experimental study involving a photovoltaic solar panel Digital Twin and its corresponding outputs. Section Legal and “Regulatory Implications of Digital Twins in Energy Systems” outlines future work, focusing on extending Digital Twin applications to other energy sources. Finally, the conclusion summarizes the potential of Digital Twins in supporting the development of a sustainable, low-carbon energy grid.

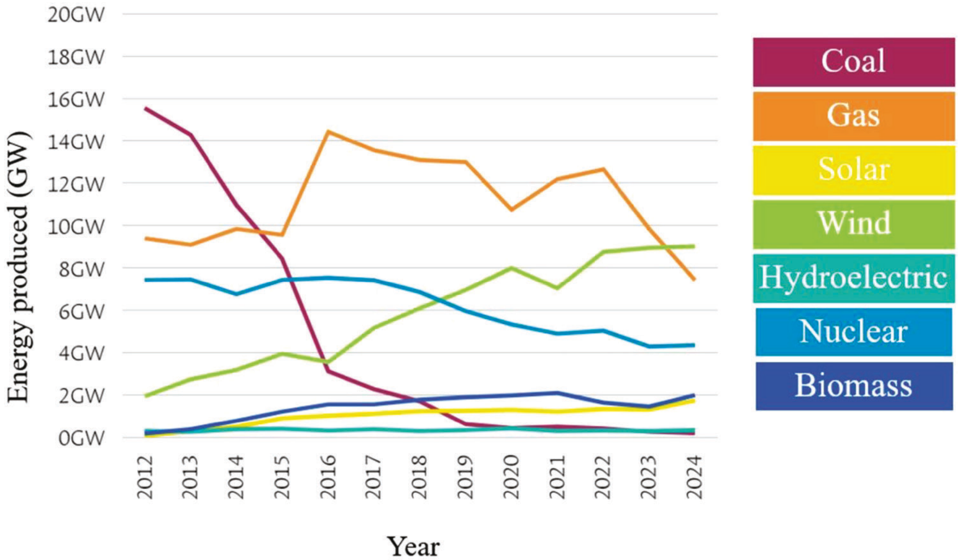

Figure 1. Energy production in UK from 2012 to 2024
source: https://grid.iamkate.com/

BACKGROUND

Accurately predicting the short-term contributions of renewable energy to the electricity grid presents significant challenges due to the variability of weather conditions. This unpredictability frequently results in the grid relying heavily on fossil fuel-based energy sources, such as coal and gas, to ensure a stable power supply. This reliance on fossil fuels increases greenhouse gas emissions, thereby undermining efforts to mitigate the environmental impact of energy production. The energy grid is a complex system powered by a diverse mix of sources, including coal, gas, nuclear, and renewable options such as solar, wind, hydroelectric, and biomass[4]. While renewable energy sources emit substantially fewer greenhouse gases compared to fossil fuels, the challenge lies in integrating them efficiently due to their dependence on weather conditions. Nuclear energy, although non-renewable, remains a stable and reliable source, given its capacity to produce large amounts of electricity with minimal emissions. The sustainability of the energy grid depends not only on the mix of energy sources but also on

[4] Ohanu, Rufai, and Oluchi (n 1).

Table 1. Energy production in the UK from 2012 to 2024 (Source: https://grid. iamkate. com/)

Energy Source	**Energy Produced (GW)**	**Percentage**
Coal	4.70	14.2%
Gas	11.31	34.2%
Solar	1.07	3.2%
Wind	5.78	17.5%
Hydroelectric	0.40	1.2%
Nuclear	6.33	19.2%
Biomass	1.48	4.5%
Total	**31.1**	**94%**

technological advancements, efficiency improvements, policy frameworks, and socio-economic factors that influence grid operations. However, inaccuracies in forecasting renewable energy contributions exacerbate the reliance on fossil fuels, resulting in higher emissions and rendering grid sustainability more difficult to achieve.

GREENHOUSE GAS EMISSIONS IN ENERGY PRODUCTION

Over the last 12 years, the average greenhouse gas emissions from energy production have been approximately 271 grams per kilowatt hour (g/kWh)[5]. Although this figure may seem small in isolation, its cumulative impact is significant, especially when considering the scale of global energy consumption and its role in climate change. Although there has been a reduction in emissions per kilowatt hour over the years, largely driven by the adoption of net-zero strategies and an increased share of renewable energy, several challenges remain. Fossil fuels account for approximately 90% of global CO_2 emissions from energy production, with renewables and nuclear energy contributing approximately only 5% each[6],[7]. Drilled down ranges of grammes of CO_2 emitted by each renewable source can be found in Table 2. Without the efficient use of renewable energy sources, continued reliance on fossil fuels and inefficient practices could hinder progress toward

[5] K Morley, National Grid - Live (2024).

[6] S Evans and V Viisainen, Analysis: UK electricity from fossil fuels drops to lowest level since 1957 (January 2024).

[7] govuk, Measuring UK greenhouse gas emissions (2024).

reducing emissions and meeting critical climate goals. To truly make an impact, both the adoption and efficient use of low-emission energy sources must be prioritised to achieve meaningful emission reduction.

CHALLENGES IN RENEWABLE ENERGY FORECASTING

Short-term forecasting of renewable energy faces numerous challenges due to the unpredictable and rapidly changing nature of weather conditions. Factors like cloud cover, wind speed, and rainfall directly affect energy generation from solar, wind, and hydropower, making it difficult to predict their output with precision. The irregular and fluctuating nature of these energy sources means that their contribution to the grid can vary significantly over short periods. Geographic factors such as altitude, topography, and location also play a crucial role, as they influence the energy production rates of renewables like wind and solar. Accurate forecasting is further complicated by the lack of up-to-date weather and grid data, which is crucial for short-term predictions. Traditional forecasting methods often rely on long-term averages, making them less effective in addressing the high variability seen in real-time energy production. Integrating forecasts from multiple renewable sources into a unified grid model adds another layer of complexity, as each energy source behaves differently and requires separate considerations. Additionally, extreme weather events, such as storms or heatwaves, can severely disrupt renewable energy generation, amplifying the forecasting challenge. Fluctuating energy demand patterns make it even more difficult to match renewable energy supply with grid requirements in real time, further complicating the task of ensuring a stable and efficient energy grid.

PROPOSED SOLUTION

This project aims to enhance the sustainability of the electricity grid by improving the accuracy of short-term renewable energy forecasts through the application of Digital Twin technology. Accurate predictions of renewable energy contributions are critical for reducing the grid's reliance on fossil fuels, which are responsible for the majority of greenhouse gas emissions in energy production. By simulating real-world systems and conditions, Digital Twins[8] can provide more precise forecasts of energy output from variable renewable sources such as wind, solar, and hydropower. This improvement in forecasting can lead to more efficient grid management, minimising the need for overproduction from fossil fuel-based sources and, in turn, lowering overall emissions. Ultimately, the integration of

[8] Michael Grieves, *Origins of the Digital Twin Concept* (2016).

Digital Twin technology into the energy forecasting process holds the potential to significantly reduce the environmental impact of energy production and support global efforts toward achieving a more sustainable and low-carbon energy system.

DIGITAL TWINS

This leads to the proposed solution: the use of Digital Twins. A Digital Twin is a virtual model that replicates a real-world object, system, or process, designed to mimic its physical counterpart in nearly every aspect[9]. In the context of energy systems, the physical counterpart is often referred to as the "physical twin", which collects data through sensors, is maintained manually, and encompasses various types of data and system complexities[10]. Physical twins, however, are non-automated, requiring manual oversight and lacking advanced data integration capabilities. Once a Digital Twin is created representing a physical twin, it mirrors the physical system, automating its functionality, and incorporating machine learning and simulation capabilities for real-time analysis and optimisation[11]. In the energy sector, a Digital Twin must be capable of monitoring several critical factors, including historical energy production, weather patterns, solar irradiance, geographical data, and wind velocity and direction. This real-time monitoring and predictive analysis allow for more efficient and accurate forecasting of renewable energy contributions, ultimately improving grid sustainability and reducing reliance on fossil fuels.

Digital Twins combine physical systems, data, and software models, raising key intellectual property (IP) issues. Copyright typically protects simulation code and interfaces, patents can cover novel optimisation or forecasting methods, and trade secrets safeguard proprietary datasets and calibration strategies World Intellectual Property Organization, *Intellectual Property Considerations for AI and Digital Twins* (2021) ⟨https://www. wipo.int/publications/en/details.jsp?id=4627⟩; United States Patent and Trademark Office, *Patent Eligibility Guidance for Software and Algorithms* (2020) ⟨https://www. uspto.gov/about-us/news-updates/uspto-issues-ai-subject-matter-eligibility-guidance⟩; European Parliament, *Data Governance and Digital Twin Implications* (2019) ⟨https:

//www.europarl.europa.eu/legislative-train/carriage/data-governance-act/report?sid= 10001⟩. Data ownership and licensing also require careful attention,

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[9] ibid.

[10] Wei Yu and others, "Energy digital twin technology for industrial energy management: Classification, challenges and future" (2022) 161 Renewable and Sustainable Energy Reviews 112407 ⟨https://www.sciencedirect.com/science/article/pii/S136403212200315X⟩.

[11] Net Zero by 2050 - A Roadmap for the Global Energy Sector (2021).

particularly under regulations like the EU GDPR European Commission, *Digital Europe Programme and EU AI Act* (2021) ⟨https://eur-lex.europa.eu/EN/legal-content/summary/digital-europeprogramme-2021-2027.html⟩. Emerging policies, including innovation incentives, standardisation frameworks (e.g., ISO 23247), and cybersecurity guidelines, provide guidance for safe deployment and interoperability of Digital Twins in energy systems International Organization for Standardization, *ISO 23247: Digital Twin Framework for Manufacturing* (2022) ⟨https://www.iso.org/standard/75066.html⟩; European Union Agency for Cybersecurity (ENISA), *Cybersecurity Guidelines for Digital Twins in Critical Infrastructure* (2020) ⟨https://www.enisa.europa.eu/topics/cybersecurity-of-critical-sectors⟩. Clear IP and policy frameworks enable reliable data use, protect innovation, and support Net-Zero energy transition goals.

ROLE OF DIGITAL TWINS IN ENERGY FORECASTING

Digital Twins play a transformative role in energy forecasting by facilitating real-time data integration, simulating environmental factors, and enhancing predictive accuracy[12]. By continuously collecting and integrating data from a multitude of sources, such as weather conditions, energy production metrics, and grid performance, Digital Twins create a dynamic model that reflects the current state of energy systems[13]. This real-time data integration allows for immediate adjustments and optimisations in forecasting renewable energy contributions. Additionally, Digital Twins can simulate various environmental factors, such as fluctuations in solar irradiance or wind patterns, enabling a deeper understanding of how these variables impact energy generation. This capability enhances the accuracy of forecasts, as it allows for the incorporation of real-world conditions into predictive models. Furthermore, Digital Twins enables scenario analysis by testing different operational strategies or environmental conditions, thereby informing decision-making processes and allowing stakeholders to explore the potential impacts of various interventions. Predictive maintenance is another critical function of Digital Twins. By analysing operational data, Digital Twins can identify potential issues before they escalate, thereby minimising downtime and ensuring optimal performance of energy systems.

Ultimately, capabilities of Digital Twins provide robust decision support for grid operators and energy planners, facilitating more effective management of

[12] Abiodun E Onile and others, "Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review" (2021) 7 Energy Reports 997 ⟨https://www.sciencedirect.com/science/article/pii/S2352484721000913⟩. 13ibid.

renewable energy sources and helping to achieve sustainability goals in the transition to a low-carbon energy landscape.

EXPERIMENT AND OUTPUTS

Building on the aforementioned context, an experiment was conducted to evaluate the effectiveness of a Digital Twin in estimating solar energy generation using forecasted weather data. The study centres on the development of a Digital Twin model for a photovoltaic solar panel, specifically based on a 60-cell configuration. The model is designed with sufficient flexibility to accommodate and represent a wide range of photovoltaic system configurations according to user-defined specifications. The developed Digital Twin incorporates several key components designed to enhance its functionality and user experience. Firstly, the location setter allows users to specify the solar panel's geographical placement, either by entering a location name or providing latitude and longitude coordinates. This capability is essential for accurately simulating solar energy production, as solar irradiance varies significantly based on geographic location. Secondly, the data request setter enables users to choose between retrieving historical energy production data or generating forecasts for future performance, facilitating a comprehensive analysis of the panel's efficiency over time.

To enhance the simulation process, a Fast Forward capability has been integrated, allowing the simulation to run at an accelerated pace, thereby providing

Figure 2. A snapshot of the Photovoltaic Digital Twin simulation.

quicker insights into performance outcomes under various scenarios. Users can select their preferred source of solar irradiance data through a set of options, choosing either a computational model or real-world data, which helps tailor the simulation to specific conditions and requirements. The Digital Twin also includes the ability to customise the solar panel based on the physical specifications of the panel, allowing for adjustments in parameters such as efficiency ratings and output characteristics. This comprehensive approach ensures that the Digital Twin not only reflects the physical characteristics of the solar panel but also provides a robust platform for optimising energy production and enhancing forecasting accuracy.

LEGAL AND REGULATORY IMPLICATIONS OF DIGITAL TWINS IN ENERGY SYSTEMS

Digital Twins are increasingly being adopted as key tools for monitoring, simulating, and optimising energy systems, enabling real-time data integration across electricity grids, industrial facilities, and renewable energy infrastructures. Their adoption, however, brings significant legal and regulatory considerations, particularly in the context of achieving Net-Zero targets outlined by major economies.

From a regulatory perspective, the European Union's interventionist approach under the *Fit for 55* package and the *EU Emissions Trading System (ETS)* provides a framework that could govern Digital Twin applications in energy management by ensuring compliance with sectoral emission targets and energy efficiency standards[13]. Similarly, the United Kingdom's Net Zero Strategy and carbon budgeting framework highlight the importance of accurate monitoring and reporting, which Digital Twins can facilitate, but also underline the need for enforcement mechanisms to ensure data integrity and regulatory compliance[14,15].

In the United States, federal policies such as the *Federal Sustainability Plan*, the *Inflation Reduction Act*, and sector-specific mandates for emissions disclosures

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[13] European Commission, *EU Energy Transition Outlook 2023* (2023) ⟨https://ec.europa.eu/eurostat/ web/interactive-publications/energy-2023⟩; European Climate Foundation, *European Green Deal and Fit for 55* (2022) ⟨https://europeanclimate.org/our-work/european-green-deal/⟩.

[14] Department for Energy Security and Net Zero, UK, *Energy Emissions Projections Report 2023 to*

[15] (2024) ⟨https://www.gov.uk/government/publications/energy-emissions-projections-2023-to2050⟩; Committee on Climate Change, *UK Climate Change Committee Report* (2023) ⟨https://www. theccc.org.uk/publication/reducing-uk-emissions-2023-progress-report-to-parliament/⟩.

present both opportunities and challenges for Digital Twin integration. Specifically, DTs can support compliance with science-based reduction targets and energy efficiency mandates, yet they must also navigate complex regulatory landscapes including environmental justice considerations under initiatives like *Justice40*[16].

In China and India, market-oriented approaches to decarbonisation, combined with state-led investments and voluntary industry commitments, suggest that Digital Twins could play a pivotal role in optimising energy usage and integrating renewable sources, provided legal frameworks evolve to address data governance, intellectual property rights, and cybersecurity concerns[17].

Overall, the regulatory implications of Digital Twin deployment in energy systems revolve around data transparency, interoperability, and compliance with existing carbon reduction mandates. Policymakers need to establish clear legal standards that ensure Digital Twin-generated data can be trusted for regulatory reporting, while also incentivising innovation in harder-to-abate sectors such as heavy industry and transport[18]. Harmonising Digital Twin governance with national and international climate targets will be critical to leveraging their full potential in the Net-Zero transition.

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[16] The White House, *Federal Sustainability Plan* (2021) ⟨https://www.whitehouse.gov/wp-content/ uploads/2021/12/Federal-Sustainability-Plan.pdf⟩; The White House, *Justice40 Initiative: Climate Investment Equity* (2021) ⟨https://www.whitehouse.gov/environmentaljustice/justice40/⟩; US Department of Energy, *U.S. Department of Energy: Emissions Data and Trends* (2021) ⟨https://www.energy. gov/eere/analysis/emissions-data-and-trends⟩.

[17] Ministry of Ecology and Environment, China, *China Dual Carbon Goals and Policy Framework* (2021) ⟨http://english.mee.gov.cn/Resources/Reports/202110/t20211026913152.shtml⟩; The Energy and Resources Institute, India, *India's Journey to Net Zero* (2024) ⟨https://www.teriin.org/publications/ indias-journey-net-zero⟩; National Development and Reform Commission, China, *China Energy Transition Outlook 2023* (2021) ⟨https://www.cet.energy/2023/12/14/china-energy-transformation-outlook2023/⟩.

[18] M Lockwood, "Comparative analysis of UK net-zero scenarios: The role of energy demand reduction" (2023) 179 Energy Policy 113620 ⟨https://www.sciencedirect.com/science/article/pii/ S0301421523002057⟩; F Alderson, S Fankhauser, and M Nachmany, "Policy Gaps in UK Industrial CCS
Deployment" [2022] Climate Policy ⟨https://netzeroclimate.org/wp-content/uploads/2025/01/MarketsMandates-2025.pdf⟩; International Energy Agency, *Global Energy Transition Outlook* (2023) ⟨https: //www.iea.org/reports/world-energy-outlook-2023⟩.

FUTURE WORK

The development of the Photovoltaic solar panel Digital Twin lays a foundational framework for expanding this technology to other renewable energy sources, such as wind, hydroelectric, and biomass systems. Future work will involve creating and integrating Digital Twins for these additional energy sources, allowing for a comprehensive and cohesive approach to renewable energy forecasting and management. Each Digital Twin will be tailored to reflect the unique operational characteristics and environmental factors pertinent to its respective energy source, enhancing the accuracy of performance predictions and optimising energy generation strategies. In addition to the development of these Digital Twins, there is a significant opportunity to leverage the integrated data from multiple renewable sources for informed decision-making. By consolidating insights from solar, wind, hydroelectric, and other renewable energy Digital Twins, stakeholders will be equipped with a holistic view of energy production capabilities and interdependencies within the grid. This integrated approach will enable more effective scenario analysis, risk assessment, and strategic planning, ultimately supporting efforts to enhance grid stability and sustainability. Future research will focus on refining the algorithms used for real-time data integration and forecasting, incorporating advanced machine learning techniques to improve predictive accuracy. By utilising historical performance data and real-time environmental inputs, the integrated Digital Twin system can provide actionable insights for grid operators, policymakers, and energy managers, facilitating the transition to a more resilient and low-carbon energy landscape. Overall, the goal is to create a robust ecosystem of Digital Twins that not only optimises individual renewable energy sources but also fosters collaboration among various systems to achieve collective sustainability objectives.

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