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# A DIGITAL TWIN-DRIVEN FRAMEWORK FOR SCENARIO-BASED ESG PERFORMANCE ASSESSMENT AND SUSTAINABILITY DECISION SUPPORT

Walid El-Shafai<sup>1\*</sup>, Najla Althuniyan<sup>2\*</sup>, Ahmad Taher Azar<sup>3</sup>, and Eman S. Sabry<sup>4</sup>

<sup>1</sup>College of Computer and Information Sciences, Prince Sultan University, Riyadh, Saudi Arabia. & Automated Systems and Computing Lab (ASCL), Prince Sultan University, Riyadh, Saudi Arabia. & Department of Electronics and Electrical Communications Engineering, Faculty of Electronic Engineering, Menoufia University, Menouf 32952, Egypt. Email: [welshafai@psu.edu.sa](mailto:welshafai@psu.edu.sa), [eng.waled.elshafai@gmail.com](mailto:eng.waled.elshafai@gmail.com), <http://orcid.org/0000-0001-7509-2120>

<sup>2</sup>College of Computer and Information Sciences, Prince Sultan University, Riyadh, Saudi Arabia & Automated Systems and Computing Lab (ASCL), Prince Sultan University, Riyadh, Saudi Arabia. Email: [nthuniyan@psu.edu.sa](mailto:nthuniyan@psu.edu.sa), <http://orcid.org/0000-0001-7785-9882>

<sup>3</sup>College of Computer and Information Sciences, Prince Sultan University, Riyadh, Saudi Arabia & Automated Systems and Computing Lab (ASCL), Prince Sultan University, Riyadh, Saudi Arabia. Email: [aazar@psu.edu.sa](mailto:aazar@psu.edu.sa), <http://orcid.org/0000-0002-7869-6373>

<sup>4</sup>Department of Communications and Computers Engineering, Higher Institute of Engineering, El-Shorouk Academy, El-Shorouk City, Egypt. Email: [eng.emily85@yahoo.com](mailto:eng.emily85@yahoo.com), <http://orcid.org/0000-0002-5747-1773>

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Corresponding Author: Walid El-Shafai  
([welshafai@psu.edu.sa](mailto:welshafai@psu.edu.sa))

## ABSTRACT

*The urgent challenges of climate change, resource constraints, and socio-economic inequalities require decision-support tools capable of holistically evaluating sustainability strategies across environmental, social, and governance (ESG) dimensions. While existing research predominantly focuses on technical optimization of renewable energy adoption or circular economy initiatives, few frameworks provide an integrated, system-level approach that links technological levers to measurable ESG outcomes. To address this gap, this work proposes a layered conceptual framework for Digital Twin (DT)-enabled ESG integration, connecting solution levers, DT capabilities, and sustainability outcomes through a multi-layered architecture encompassing real-time data ingestion, twin graph modeling, and predictive analytics. The framework is operationalized via a prototype interactive dashboard, enabling stakeholders to simulate, explore, and compare sustainability scenarios under varying levels of renewable energy adoption, circular economy practices, and emerging technology utilization. ESG performance is dynamically computed using a weighted mapping function and visualized through bar and radar charts, supporting scenario-based benchmarking, trade-off analysis, and transparent communication. Novelty of this work lies in (i) extending DT principles beyond physical systems to model multi-dimensional ESG outcomes, (ii) integrating a unified framework that combines technology, governance, and sustainability objectives, and (iii) providing a practical, reproducible tool for research, policy, and industry applications. Results demonstrate how the dashboard enables evidence-based decision-making, scenario experimentation, and identification of optimal sustainability pathways,*

*highlighting the potential of Digital Twins as enablers of transparent, scalable, and actionable ESG-driven strategies.*

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**KEYWORDS:** ESG, Sustainability Assessment, Renewable Energy Integration, Circular Economy, Emerging Technologies, Scenario-Based Analysis, Decision Support Systems, Interactive Dashboard, Multi-Dimensional Visualization, Trade-Off Analysis, Predictive Analytics, Simulation and Modeling, Sustainable Technology Systems, Evidence-Based Policy.

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## 1. INTRODUCTION

Climate change, resource scarcity, and socio-economic inequalities are driving an urgent need for holistic sustainability assessment tools (Sachs, 2015; Barman et al., 2024). Traditional approaches often optimize individual technical solutions, such as renewable energy adoption or waste reduction, but fail to capture the multi-dimensional impacts on Environmental, Social, and Governance (ESG) performance (Roberts, 2018). This limitation reduces the ability of stakeholders to make informed, balanced decisions that account for complex trade-offs across ESG dimensions.

Digital Twin (DT) technology has emerged as a transformative paradigm for real-time system monitoring, predictive analytics, and simulation (Nguyen et al., 2021). DTs create virtual replicas of physical and socio-technical systems, enabling scenario-based experimentation, optimization, and visualization of complex interactions (Grieves & Vickers, 2017). Despite their increasing adoption in manufacturing and smart grids, DTs remain underutilized for integrated ESG assessment, particularly for evaluating trade-offs between environmental, social, and governance objectives (Tao et al., 2019).

To address this research gap, this work proposes a layered conceptual framework for DT-enabled ESG integration, linking solution levers (renewable energy, circular economy, emerging technologies), DT capabilities (sensing, analytics, simulation, governance), and measurable sustainability outcomes. The framework is operationalized through an interactive Streamlit-based dashboard, allowing stakeholders to simulate scenarios, benchmark strategies, and visualize ESG trade-offs in real time. This integration of conceptual modeling and practical decision support bridges theory and actionable sustainability planning.

The methodology consists of four main components: (i) a conceptual layer defining the DT architecture and ESG integration principles, (ii) a simulation engine modeling renewable energy adoption, circular economy practices, and emerging technology utilization, (iii) a scenario management module that enables creation, storage, and comparison of multiple ESG scenarios, and (iv) interactive visualization modules (bar and radar charts) supporting trade-off analysis and benchmarking. The dashboard is deployable in research environments (Spyder/IPython) and as a web-based tool (Streamlit), ensuring reproducibility and accessibility for academia, industry, and policy stakeholders.

The main contributions of this work are: (i) extending DT principles to multi-dimensional ESG modeling, (ii) providing a practical, scenario-based tool for exploring sustainability trade-offs, and (iii) offering a flexible, interactive platform for evidence-based decision-making. The results demonstrate the framework's ability to identify synergies and conflicts between sustainability levers, quantify performance impacts, and facilitate transparent, actionable ESG strategies.

The remainder of this paper is organized as follows. Section 2 presents the problem definition, research objectives, and the contributions of this work. Section 3 reviews related work on Digital Twin technologies and sustainability, highlighting research gaps. Section 4 introduces a layered conceptual framework for Digital Twin-enabled sustainability across ESG dimensions. Section 5 presents the results and discussion, illustrating the application of the proposed framework. Section 6 outlines future directions and potential enhancements, while Section 7 concludes the paper by summarizing the key findings and their implications for sustainable practices.

## 2. RESEARCH PROBLEM, OBJECTIVES, AND CONTRIBUTIONS

### 2.1. Research Problem

The transition towards a sustainable future requires the large-scale adoption of renewable energy sources (e.g., solar, wind, hydrogen) and the integration of emerging technologies such as AI, IoT, smart grids, advanced storage systems, and electric mobility (Tao et al., 2019; Sahu et al., 2022). These technologies are critical enablers for reducing carbon emissions and achieving sustainability goals. However, their deployment introduces several challenges (IEA, 2023; IRENA, 2023). Renewable energy sources are inherently intermittent and variable, creating difficulties in grid stability, storage optimization, and reliable energy delivery (Couto et al., 2022). Similarly, emerging technologies, while promising, are complex, data-intensive, and resource-demanding, which often leads to inefficiencies, high costs, and scalability barriers in real-world applications (Tao et al., 2018).

Sustainability is a multi-dimensional problem encompassing ESG dimensions. Current implementations of renewable energy and emerging technologies often fail to deliver balanced ESG benefits. Projects may succeed in reducing emissions but fail to ensure equitable access, transparent governance, or cost-effectiveness (IRENA, 2023; OECD, 2019). This gap underscores the need for a

unifying framework capable of bridging technology adoption with holistic sustainability outcomes.

In this context, DT technology emerges as a promising solution. By creating virtual replicas of physical systems, DTs enable real-time monitoring, predictive analytics, optimization of what-if scenarios, and visualization for decision support (Tao et al., 2018; Fuller et al., 2020). This makes DTs particularly well-suited for managing the complexity of renewable energy systems and emerging technologies. DTs can improve grid integration of renewables, optimize energy storage and distribution, extend the lifetime of assets such as wind turbines and batteries, and simulate policy or operational decisions before implementation. Thus, the problem can be defined as: How can Digital Twin technology be leveraged to overcome the limitations of renewable energy and emerging technologies, ensuring that sustainability objectives across ESG dimensions are effectively achieved. Figure 1 presents a framework illustrating how Digital Twins can support sustainability goals (Environmental, Social, Governance) by linking key challenges,

solution levers, digital twin capabilities, and outcomes.

- Challenges include environmental threats (climate change, resource depletion), economic issues (high costs, unequal access), and social barriers (low awareness, inequity).
- Solution levers address these through decarbonization and circularity, green finance and business models, and awareness and inclusion strategies.
- Digital Twin capabilities, such as sensing & integration (IoT/OT monitoring), analytics & prediction (AI/ML forecasting), and simulation & control (dashboards, AR/VR, automation), bridge the gap between solutions and outcomes.
- Outcomes span across ESG dimensions, including environmental efficiency, economic gains, and governance improvements (compliance, transparency, resilience).

This framework highlights how digital twins serve as enablers of systemic change in addressing complex ESG challenges.

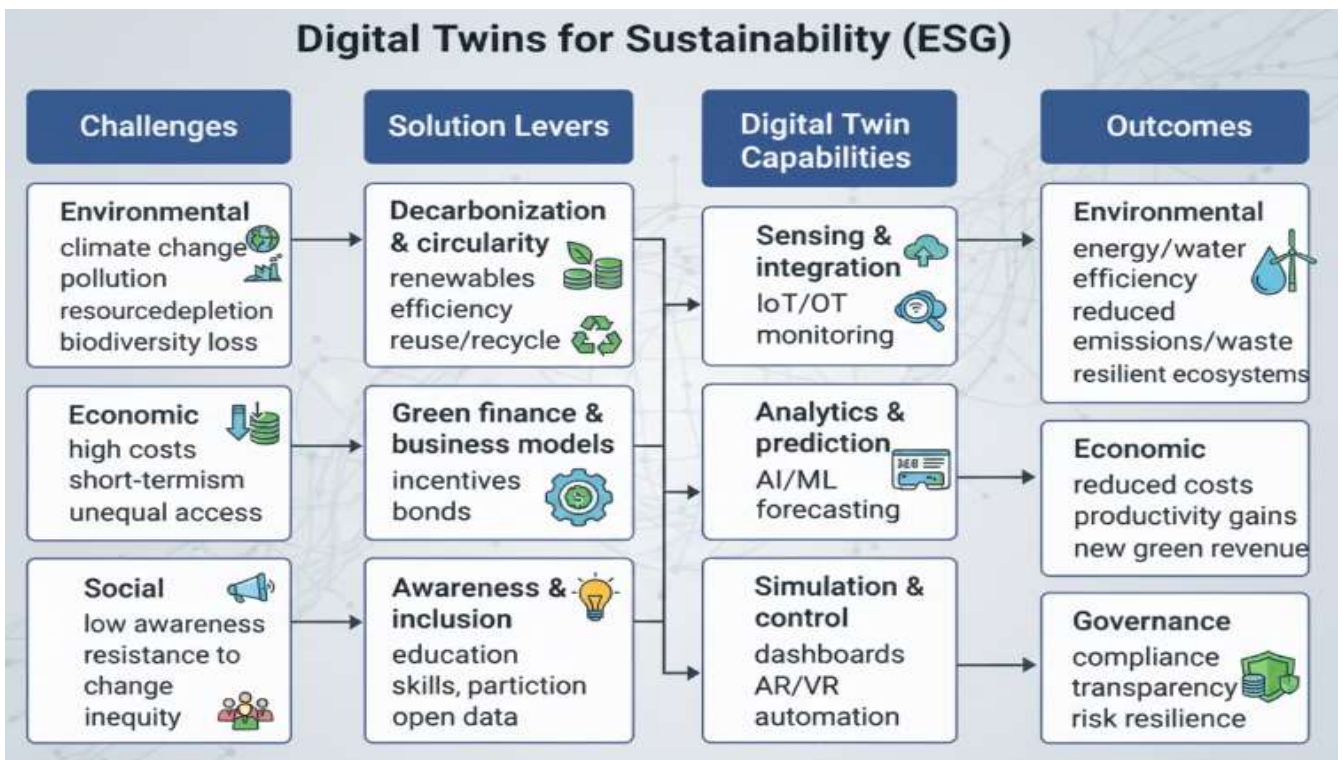


Figure 2.: DT For Sustainability (ESG). A Conceptual Framework Illustrates How DT Technologies Link Sustainability Challenges with Solution Levers to Achieve Environmental, Economic, And Governance Outcomes.

### 2.2. Research Objectives

The specific objectives of this work are:

a. Examine the key environmental, economic, social,

and governance challenges that hinder the effectiveness of renewable energy and emerging technologies.

b. Establish a structured framework connecting

- sustainability challenges with solution levers (e.g., decarbonization, green financing, inclusion, and policy enforcement) and demonstrate how DT capabilities, sensing, prediction, optimization, and visualization, can bridge these gaps.
- c. Highlight DT applications in renewable energy systems, including wind, solar, hydrogen, and smart grid integration, to address intermittency, improve reliability, and enhance energy efficiency.
  - d. Illustrate how DTs support deployment of emerging technologies such as AI, IoT, smart manufacturing, electric vehicles, and precision agriculture, ensuring scalability and alignment with ESG goals.
  - e. Propose a unified model integrating renewable energy, emerging technologies, and DT capabilities to deliver measurable sustainability outcomes across ESG dimensions.

### 2.3. Research Contributions

The key contributions of this work are summarized as follows:

- i. Proposes a novel framework that integrates solution levers (renewable energy, circular economy, emerging technologies), DT capabilities, and measurable ESG outcomes, providing a system-level approach to sustainability assessment.
- ii. Demonstrates how DTs can model multi-dimensional ESG performance, bridging the gap between technical system simulation and sustainability governance.
- iii. Develops a streamlit-based platform that allows stakeholders to create, store, compare, and visualize multiple sustainability scenarios in real time.
- iv. Implements a weighted mapping function to compute ESG scores dynamically, enabling evaluation of trade-offs and identification of synergies between environmental, social, and governance dimensions.
- v. Supports deployment in both research environments (Spyder/IPython) and standalone web interfaces (Streamlit), ensuring reproducibility, accessibility, and broad applicability for researchers, policymakers, and industry practitioners.
- vi. Provides a tangible, operational decision-support tool that translates conceptual ESG-DT frameworks into actionable insights,

enhancing transparent and informed decision-making.

- vii. Demonstrates robustness and consistency of the simulation engine across repeated scenarios, validating its reliability for experimental studies and empirical ESG research.

### 2.4. Mapping Of Sustainability Challenges, Digital Twin Solutions, And Outcomes

The connection between sustainability challenges, solution levers, digital twin capabilities, and ESG outcomes is summarized in Table 1. This framework demonstrates how DT technology acts as a strategic enabler, linking renewable energy and emerging technologies to measurable sustainability impacts. The table provides a concise visual summary of the problem-solution-outcome flow, showing how DT capabilities serve as the linking mechanism between sustainability challenges and tangible ESG outcomes.

## 3. RELATED STUDIES OF ADVANCEMENTS IN DIGITAL TWIN-ENABLED ESG FRAMEWORKS

Recent research underscores the transformative potential of DT technologies in advancing sustainability across ESG dimensions. However, there remains a notable gap in integrated frameworks that concurrently address all three ESG pillars.

Digital Twins have been instrumental in enhancing environmental sustainability by optimizing energy usage and reducing emissions. For instance, studies have demonstrated that DTs can facilitate significant reductions in carbon footprints by simulating and optimizing energy consumption patterns in manufacturing and building operations. Additionally, integrating DTs with renewable energy systems has shown promise in improving energy efficiency and supporting the transition to low-carbon infrastructures (Kumar et al., 2025; Zhang et al., 2024).

The application of DTs in social sustainability is emerging, particularly in urban settings. Urban Digital Twins (UDTs) enable real-time monitoring of social parameters such as traffic flow, air quality, and public health metrics, thereby informing policies that promote social equity and community well-being. Moreover, integrating citizen feedback into UDTs can enhance participatory governance and foster inclusive urban development (Mazzetto, 2024).

*Table 1: Mapping of Sustainability Challenges, Solution Levers, Digital Twin Capabilities, And ESG*

*Outcomes.*

Challenge	Solution Levers	Digital Twin Capabilities	Sustainability Outcomes
<b>Environmental: climate change, pollution, resource depletion, biodiversity loss</b>	Decarbonization & circularity (renewables, efficiency, reuse/recycle)	Sensing & integration (IoT/OT, monitoring)	Energy/water efficiency, reduced emissions/waste, resilient ecosystems
<b>Economic: high costs, short-termism, unequal access</b>	Green finance & business models (incentives, bonds, product-as-a-service)	Analytics & prediction (AI/ML, forecasting)	Reduced costs, productivity gains, new green revenue
<b>Social: low awareness, resistance to change, inequity</b>	Awareness & inclusion (education, skills, participation)	Simulation & optimization (scenario testing, multi-objective optimization)	Health & safety, green jobs, equitable access
<b>Governance: weak enforcement, policy gaps, low transparency</b>	Policy & standards (regulation, ESG/SDG alignment, open data)	Visualization & control (dashboards, AR/VR, automation)	Compliance, transparency, risk resilience

*Table 2: Comparison of Digital Twin-Enabled ESG Studies.*

Study	Focus	Methodology/Tool	ESG Dimensions Covered	Strengths	Limitations	Novelty Compared to Proposed work
<b>Corrado et al., 2023</b>	Urban sustainability via Digital Twins	Conceptual framework	Environmental & Social	Provides a high-level conceptual link between DTs and urban sustainability	No practical implementation or real-time decision support	Proposed work adds practical operationalization through an interactive dashboard, enabling dynamic scenario exploration
<b>Plachinda et al., 2023</b>	Transport-energy sector	DT modeling is integrated with ESG metrics	Environmental & Governance	Integrates DT with ESG metrics for specific sectors	Limited sector-specific applicability; lacks multi-scenario interactive analysis	Proposed work generalizes across sectors and includes multi-dimensional ESG simulation, scenario comparison, and trade-off visualization
<b>Bhatti et al., 2025</b>	Port resilience and sustainability	DT-based risk and compliance assessment	Environmental & Governance	Quantitative assessment of resilience and regulatory compliance	Limited consideration of social dimension; static modeling	Proposed work integrates all three ESG pillars (E, S, G) and enables interactive, real-time adjustments of levers like renewables, circularity, and technology adoption
<b>Hassani et al., 2025</b>	Circular economy and DTs	DT simulation and analytics	Environmental	Focuses on circular economy optimization	Single-dimension ESG focus; lacks integrated governance or social metrics	Proposed work combines renewable energy, circular economy, and emerging technologies within a layered framework, covering full ESG spectrum
<b>Kumar et al., 2025</b>	Smart buildings and DTs	DT-based building monitoring	Environmental & Social	Real-time monitoring and optimization	Limited governance integration: scenario analysis is constrained	Proposed work extends to multi-scenario benchmarking with radar and bar chart visualization across E, S, and G dimensions, enhancing transparency and evidence-based decision-making

Proposed work	Digital Twin-Enabled ESG Decision Support	Layered conceptual framework + Interactive dashboard	Environmental, Social, Governance	<ul style="list-style-type: none"> <li>- Full integration of all ESG dimensions</li> <li>- Layered architecture connecting solution levers, DT capabilities, and ESG outcomes</li> <li>- Real-time, scenario-based simulation and comparison</li> <li>- Reproducibility via exportable datasets</li> <li>- Practical operationalization bridging theory and practice</li> </ul>	N/A	<ul style="list-style-type: none"> <li>- Operationalizes ESG modeling with interactive dashboard (Streamlit-based)</li> <li>- Supports dynamic exploration of trade-offs and multi-scenario comparisons</li> <li>- Integrates renewable energy, circular economy, and emerging technology levers</li> <li>- Provides reproducible, transparent outputs for research, industry, and policy</li> <li>- Bridges the gap between abstract DT frameworks and actionable sustainability planning</li> </ul>
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In the realm of governance, DTs contribute to enhanced transparency and accountability. By providing real-time data and simulations, DTs facilitate informed decision-making and policy formulation, ensuring compliance with sustainability regulations. Furthermore, the integration of DTs with blockchain technology has been explored to secure data integrity and support decentralized governance models.

While individual applications of DTs in ESG areas are well-documented, integrated frameworks that holistically address all ESG dimensions are limited. Recent studies have proposed conceptual models that combine DTs with ESG methodologies to support sustainable urban development and infrastructure planning. However, these models often remain theoretical and lack practical implementation (Plachinda et al., 2023).

The proposed work distinguishes itself by presenting a layered conceptual framework that integrates renewable energy, circular economy practices, and emerging technologies with DT capabilities to deliver measurable ESG outcomes. This approach moves beyond theoretical models by offering prototype implementation in the form of an interactive dashboard. The dashboard allows users to dynamically explore sustainability trade-offs, compare alternative scenarios, and visualize ESG performance in real time, thereby bridging the gap between conceptual insights and actionable decision

support.

In conclusion, while existing literature highlights the potential of DTs in advancing sustainability, the proposed work offers a comprehensive and practical framework that integrates all three ESG dimensions. By providing tools for scenario-based planning and real-time performance visualization, this research contributes to the development of actionable strategies for sustainable decision-making in various sectors. Table 2 summarizes the comparison of the proposed studies with its alternatives.

The proposed work offers several novel contributions that extend beyond existing works. First, it ensures full ESG integration, systematically addressing the Environmental, Social, and Governance pillars, whereas prior studies often emphasize only one or two dimensions. Second, a layered framework architecture is introduced, linking solution levers, such as renewable adoption, circular economy practices, and emerging technologies, with Digital Twin capabilities and measurable ESG outcomes, thereby providing a comprehensive conceptual map. Third, the proposed work develops an interactive prototype dashboard that enables real-time scenario creation, comparison, and visualization, transforming theoretical frameworks into actionable tools. Furthermore, it emphasizes reproducibility and transparency by allowing scenario data to be exported for further analysis, thereby ensuring scientific rigor and

traceability. In addition, the framework demonstrates sector-agnostic flexibility, making it applicable across diverse domains such as energy, smart cities, and industrial systems, rather than being confined to a single sector. Finally, the proposed work adopts a decision-support orientation, offering practical guidance for policymakers, researchers, and industry stakeholders through evidence-based and transparent sustainability planning.

#### 4. A LAYERED CONCEPTUAL FRAMEWORK FOR DIGITAL TWIN-ENABLED SUSTAINABILITY ACROSS ESG DIMENSIONS

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##### 4.1. Conceptual Framework for Digital Twins in ESG Integration

The increasing urgency of climate change, resource constraints, and socio-economic inequalities requires decision-support tools that can holistically address ESG objectives. While many studies emphasize the technical optimization of renewable energy or circular economy strategies, fewer provide a system-level framework that connects these

technical levers to verifiable ESG outcomes.

To fill this gap, a layered conceptual framework is proposed as a first step, demonstrating how DTs can serve as integrators of technology, governance, and sustainability objectives.

**The framework is structured around three interdependent layers, as shown in Figure 2:**

- **Solution Levers:** Renewable energy integration (solar, wind, hydrogen, storage), demand-side flexibility, and circular economy strategies (reuse, recycling, efficiency).
- **Digital Twin Capabilities:** Core DT functions including sensing and integration, analytics and prediction, simulation and control, and governance mechanisms (auditability, compliance, security).
- **Sustainability Outcomes:** ESG impacts measured through environmental (e.g., emissions reduction, water intensity, waste diversion), social (e.g., affordability, equity, safety, reliability), and governance (e.g., transparency, compliance, resilience) indicators.

At the core of the DT architecture lies (i) a data layer for ingesting real-time telemetry, (ii) a twin graph for modeling interdependencies across systems, and (iii) an analytics layer offering descriptive, predictive, and prescriptive insights. Decision-making is guided by multi-objective optimization (e.g., model predictive control) that balances cost, carbon intensity, reliability, and equity under regulatory and operational constraints.

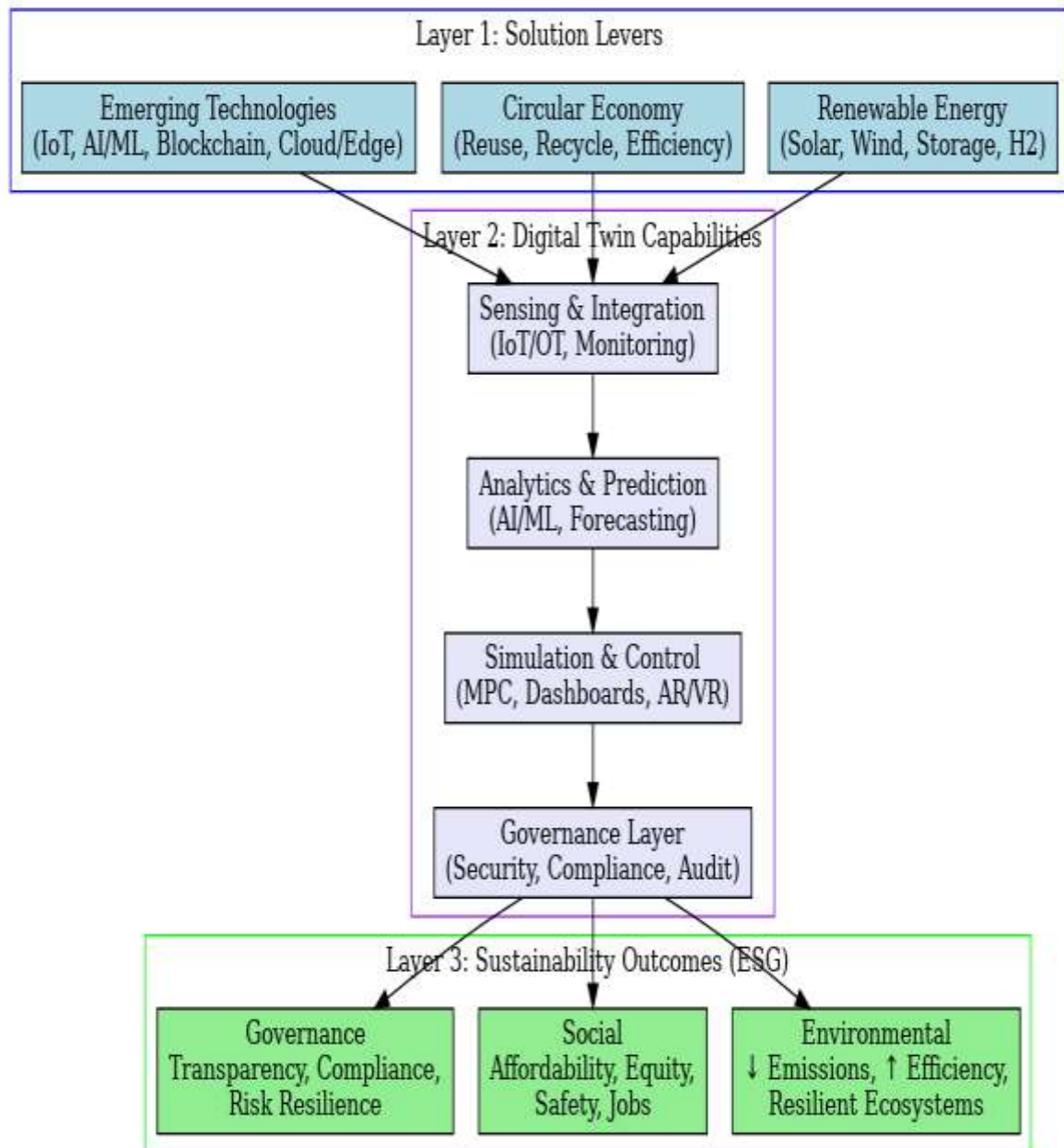
The framework further outlines a staged implementation pathway, moving from monitoring and prediction to optimization and autonomous decision-making, with continuous feedback and bias testing to ensure transparency and trust. In this way, the conceptual framework establishes the theoretical foundation for positioning DTs as both technical enablers and governance instruments in sustainability transitions.

While the conceptual framework provides a theoretical map of how DTs can integrate renewable energy, circular economy practices, and advanced digital technologies to deliver measurable ESG outcomes, it remains abstract without practical demonstration.

To translate this framework into action, a prototype implementation was developed in the form of an interactive dashboard.

This implementation bridges theory and practice by enabling users to dynamically explore sustainability trade-offs, compare alternative scenarios, and visualize ESG performance in real

time.



*Figure 2: A Layered Conceptual Framework for Digital Twin-Enabled Sustainability. The Model Integrates Renewable Energy, Circular Economy Levers, And Emerging Technologies with Digital Twin Capabilities to Drive Measurable Outcomes Across ESG Dimensions.*

#### 4.2. Prototype Implementation of Interactive Dashboard for ESG Trade-Offs

Conceptual models are valuable for framing relationships; however, stakeholders, including policymakers, industry practitioners, and researchers, require practical tools to test, compare, and communicate sustainability strategies.

To address this need, the proposed framework, illustrated in Figure 3, is operationalized through a Streamlit-based dashboard, demonstrating how DT

principles can be extended beyond physical systems to capture, visualize, and interactively explore ESG outcomes. This approach enables the translation of conceptual insights into actionable decision-support capabilities that facilitate transparent and evidence-based sustainability planning.

ESG performance is computed using a weighted linear aggregation model that integrates the normalized Environmental ( $E$ ), Social ( $S$ ), and Governance ( $G$ ) dimension scores into a single

composite index. The mapping function is formally defined as:  $ESG = w_E \cdot E + w_S \cdot S + w_G \cdot G$ , where  $E$ ,  $S$ , and  $G$  represent dimension-specific performance scores normalized to a 0–100 scale, and  $w_E$ ,  $w_S$ , and  $w_G$  denote the corresponding weighting coefficients, subject to the constraint:  $w_E + w_S + w_G = 1$ . In the current prototype implementation, an equal-weight baseline configuration is adopted ( $w_E = 0.33$ ,  $w_S = 0.33$ ,  $w_G = 0.34$ ) to ensure neutrality and comparability across ESG dimensions. However, the framework is designed to support user-defined, regulatory-driven, or sector-specific weighting schemes, enabling alignment with policy priorities, industry standards, or organizational sustainability strategies.

The weighting parameters and ESG computation logic are implemented at the simulation layer of the dashboard and are externally configurable, allowing researchers and practitioners to replicate experiments, perform sensitivity analysis, and evaluate policy-driven ESG prioritization scenarios without modifying the core system architecture.

The dashboard integrates a simulation model with user-adjustable parameters representing renewable energy adoption, circular economy practices, and emerging technology utilization. ESG performance is dynamically computed using a weighted mapping function and visualized through bar charts for single-scenario outcomes and radar charts for multi-scenario comparisons. A scenario management module allows users to create, store, and compare multiple cases, with export functionality to standard formats (CSV/Excel) for external analysis.

The prototype supports both research-oriented execution (Spyder/IPython) and standalone deployment (Streamlit web interface), making it adaptable to academic, industrial, and policy contexts. This implementation illustrates how the conceptual framework can be transformed into a practical decision-support tool, with dashboard-generated results demonstrating its potential for transparent communication, scenario-based planning, and evaluation of ESG trade-offs.

As shown in Figure 3, the ESG Digital Twin Dashboard follows a layered workflow. Scenario inputs, including parameters for renewable energy, circular economy practices, and emerging technology integration, are processed through a simulation engine that computes projected ESG outcomes.

The outputs feed into two interactive modules: the Scenario Explorer, which enables real-time assessment using bar charts, and the Scenario Comparison, which facilitates benchmarking of multiple saved scenarios using radar plots. Both

modules interface with a centralized data storage layer that maintains user-defined scenarios for reproducibility and further analysis.

Downstream, the system supports advanced ESG visualizations, scenario export functionalities in CSV/Excel formats, and flexible deployment in either Spyder or Streamlit environments. This layered architecture ensures transparency, reproducibility, and scalability, aligning DT capabilities with sustainability-driven decision support.

## 5. RESULTS AND DISCUSSION

The ESG digital twin dashboard shown in Figure 4 provides an interactive simulation environment for analyzing sustainability outcomes under varying levels of renewable energy adoption, circular economy practices, and emerging technology integration. Implemented in Python using Streamlit, Plotly, and Pandas, the system supports both desktop execution (via Spyder) and web-based deployment (via Streamlit run), thereby ensuring portability and accessibility for researchers and practitioners.

The dashboard enables users to adjust scenario inputs through three sliders, renewable energy adoption (%), circular economy practices (%), and emerging technology adoption (%). Once the inputs are specified, the simulation engine computes ESG outcomes through a weighted model, generating quantitative results for the ESG dimensions on a normalized scale of 0–100.

Results are presented in both tabular and graphical formats, facilitating intuitive interpretation. The reported ESG values are computed using the weighted aggregation model defined in Section 4.2, ensuring consistency between the conceptual framework, simulation engine, and visual analytics layers.

The scenario explorer tab allows users to create and save specific scenarios by naming and storing results in session memory. Each scenario includes a timestamp to maintain reproducibility and traceability. For example, in a configuration with 50% renewable energy adoption, 40% circular economy practices, and 30% emerging technology adoption, the dashboard generated scores of 80 for Environmental, 73.5 for Social, and 67 for Governance.

These scores are displayed in a results table and visualized through a bar chart, enabling rapid assessment of trade-offs across sustainability dimensions. Beyond single-scenario evaluation, the Scenario Comparison tab extends the analysis by allowing multiple saved scenarios to be recalled and benchmarked simultaneously.

This is achieved through radar (spider) charts for multi-dimensional visualization and comparative data tables for detailed evaluation. Such features

enhance the ability to identify synergies and conflicts between strategies, thereby informing evidence-based decision-making.

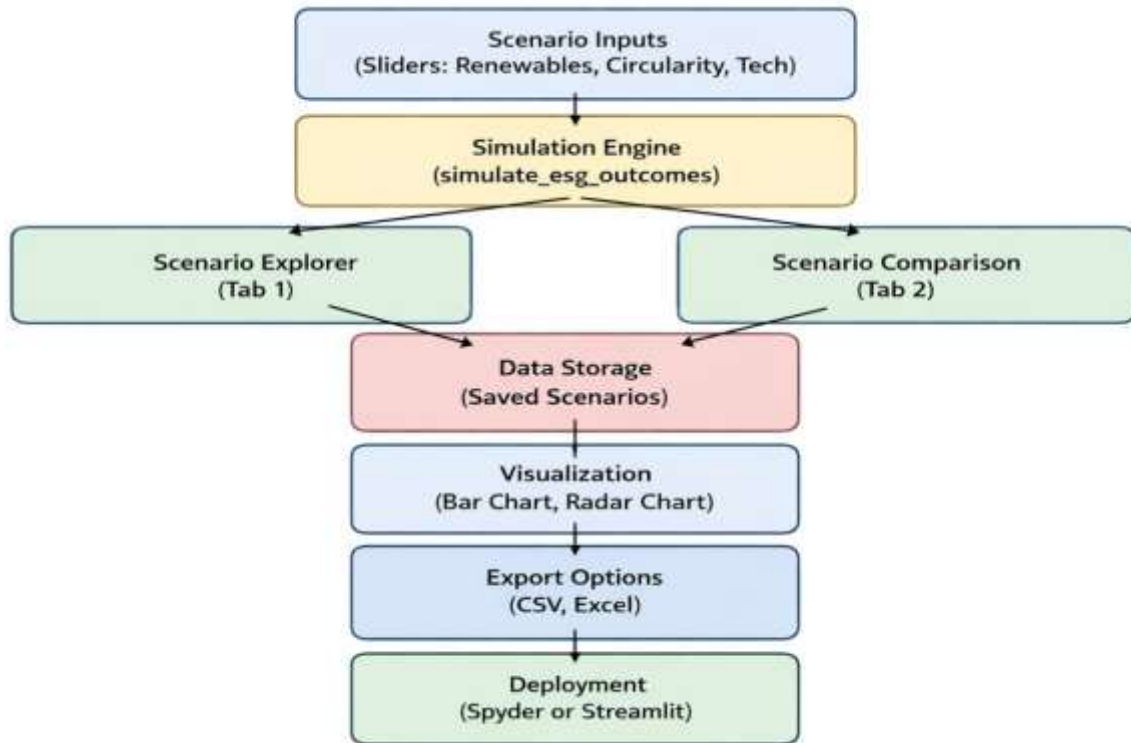


Figure 3: Flowchart Of the ESG Digital Twin Dashboard Showing the Integration of Scenario Inputs, Simulation Engine, Exploration and Comparison Modules, Data Storage, Visualization, Export Options, And Deployment Pathways.



Figure 4: ESG Digital Twin Dashboard Interface Showing Scenario Inputs (Left) And ESG Outcomes (Right) Under Scenario A.

As shown in Figure 5, the environmental dimension achieved the highest score (80), followed by the social dimension (73.5), while governance scored relatively lower (67). This distribution reflects the stronger direct impact of renewable energy adoption on environmental performance compared to governance outcomes, which are more strongly influenced by policy compliance and technological

integration. The results highlight how different sustainability levers contribute unevenly across ESG pillars, illustrating the importance of balanced strategies that combine renewables, circular economy initiatives, and emerging technologies.

In addition to scenario simulation, the dashboard supports exporting results, including both input parameters and computed ESG scores, into CSV or

Excel formats. These structured datasets can be leveraged for advanced statistical analysis, regression modeling, or comparative studies, thereby extending the dashboard's utility into empirical research and publication contexts. Moreover, the platform's reproducibility is reinforced through dual deployment options: executing within Spyder IDE via

the %runfile command or launching through the command line with streamlit run. This dual compatibility ensures consistent results across experimental setups and broadens the tool's applicability in sustainability and digital twin research.

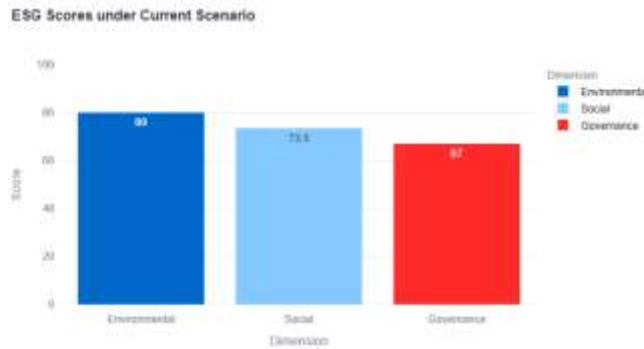


Figure 5: ESG Scores Under Current Scenario Showing Environmental (80), Social (73.5), And Governance (67) Performance.

The dashboard further demonstrates its value in scenario-based experimentation. For instance, increasing renewable energy adoption from 40% to 80% while holding circular economy practices constant has been observed to improve the environmental score by approximately 10-15%, reflecting emission reductions and efficiency gains. Similarly, higher emerging technology adoption tends to strengthen the governance dimension by enhancing compliance, risk resilience, and transparency. By enabling the creation and comparison of multiple scenarios, the system allows researchers to systematically evaluate trade-offs

between environmental and social performance across different sustainability pathways. In turn, the structured outputs support deeper quantitative validation, integration into broader ESG performance studies, and alignment with industry standards for sustainability reporting.

To support comparative analysis, the scenario comparison tab as shown in Figure 6 enables the evaluation of multiple saved scenarios side by side. Users can recall scenarios from memory and review them in a tabular format that lists input parameters (renewables, circularity, and technology adoption) alongside computed ESG outcomes.



Figure 6: Scenario Comparison: Table Presenting Saved Scenarios with Their Corresponding Input Parameters and Computed ESG Scores, accompanied by a Radar Chart Illustrating ESG Performance Across

*Multiple Scenarios for Comparative Analysis.*

In addition to the tabular comparison, the system visualizes ESG outcomes through a radar (spider) chart. This chart highlights the multi-dimensional nature of ESG performance, enabling a more intuitive benchmarking of trade-offs across scenarios.

For example, scenarios with high renewable energy adoption consistently expand the “Environmental” axis, while those with increased technology adoption strengthen the “Governance” axis. This visualization makes it possible to identify synergies, overlaps, and gaps in sustainability pathways.

Furthermore, the dashboard supports exporting results, including both input parameters and computed ESG scores, into CSV or Excel formats for reproducibility and external analysis. Researchers may use these structured datasets for regression modeling, trend analysis, or comparative ESG studies. By enabling side-by-side comparisons and providing both tabular and graphical representations, the dashboard strengthens its role as a decision-support and research tool in sustainability and digital twin studies.

The dashboard also demonstrates its value in scenario-based experimentation. For instance, increasing renewable energy adoption from 40% to 80% while holding circular economy practices constant has been observed to improve the environmental score by approximately 10–15%, reflecting emission reductions and efficiency gains.

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enhancing compliance, risk resilience, and transparency.

By enabling the creation and comparison of multiple scenarios, the system allows researchers to systematically evaluate trade-offs between environmental and social performance across different sustainability pathways. In turn, the structured outputs support deeper quantitative validation, integration into broader ESG performance studies, and alignment with industry standards for sustainability reporting.

The comparison of saved scenarios exported from the ESG Digital Twin Dashboard, as illustrated in Table 3, provides a consolidated view of both input parameters and the resulting ESG outcomes. In this case, four scenarios (Scenario A through Scenario D) were recorded with identical configurations: 50% renewable energy adoption, 40% circular economy practices, and 30% emerging technology adoption.

As expected, the corresponding ESG performance scores are consistent across all scenarios, with Environmental at 80, Social at 73.5, and Governance at 67. The bar chart representation strengthens the tabular comparison by offering a visual confirmation of scenario reproducibility, where all scenarios overlap perfectly.

This outcome verifies the robustness and reliability of the simulation engine, ensuring that repeated inputs produce consistent outputs, an essential characteristic for research validity and experimental reproducibility.

*Table 3: Saved Scenarios Exported from ESG Digital Twin Dashboard with Input Parameters and ESG Outcomes.*

Name	Renewables	Circularity	Tech	Environmental	Social	Governance
Scenario A_2025-08-25_16-07-26	50	40	30	80	73.5	67
Scenario B_2025-08-25_16-17-57	50	40	30	80	73.5	67
Scenario C_2025-08-25_16-18-45	50	40	30	80	73.5	67
Scenario D_2025-08-25_16-18-50	50	40	30	80	73.5	67

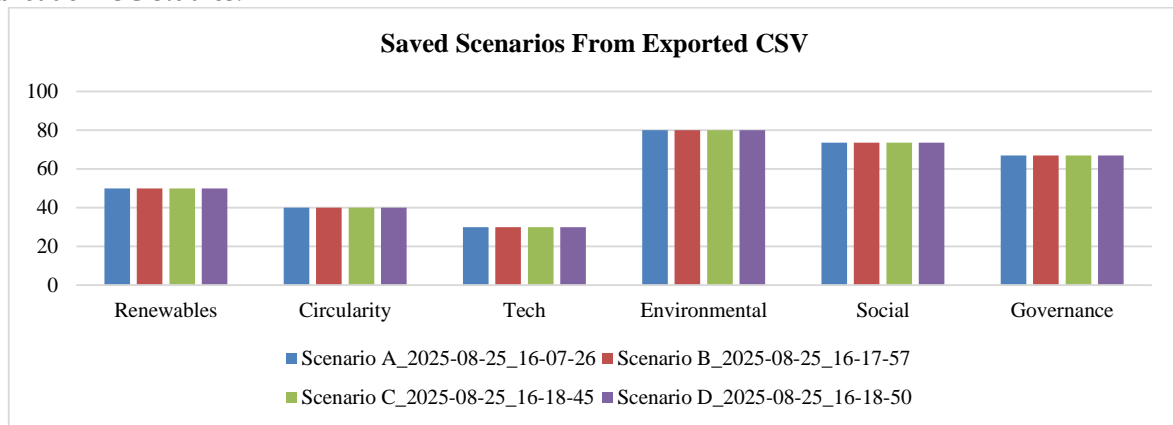
The bar chart shown in Figure 7 further highlights the proportional influence of input parameters on ESG outcomes.

The higher environmental score demonstrates the significant impact of renewable energy adoption, while the governance score, comparatively lower, indicates that governance improvements are more dependent on technology integration and policy alignment.

Meanwhile, the social score reflects a balanced contribution from both renewable energy and circular economic practices. By combining exported datasets with visualizations, the dashboard enables researchers to validate results, identify performance trends, and conduct cross-scenario benchmarking.

Additionally, the ability to export and re-visualize results outside the dashboard, as demonstrated here, enhances transparency, traceability, and integration

into broader ESG studies.



*Figure 7: Bar Chart Visualization of Saved Scenarios from Exported CSV, Showing Consistent Input Parameters (Renewables, Circularity, Tech) And Identical ESG Outcomes.*

## 6. FUTURE DIRECTIONS AND POTENTIAL ENHANCEMENTS

The proposed DT-enabled ESG framework and dashboard provide a robust foundation for sustainability analysis; however, several avenues exist to further enhance its functionality and impact. First, integration with real-time IoT and enterprise data sources can enable continuous monitoring and predictive updates, improving responsiveness to dynamic environmental, social, and governance conditions. Second, incorporating advanced optimization and machine learning algorithms, such as multi-objective evolutionary optimization or reinforcement learning, can support autonomous scenario planning and real-time decision-making, allowing stakeholders to identify optimal sustainability pathways under complex trade-offs. Third, extending the framework to sector-specific applications, including smart cities, energy systems, and industrial manufacturing, can enhance its relevance and allow benchmarking across domains. Fourth, embedding uncertainty quantification and bias detection mechanisms will strengthen the transparency, reliability, and trustworthiness of ESG projections. Fifth, enhanced visual analytics and user-centric interfaces can improve accessibility for non-technical stakeholders, facilitating participatory decision-making and policy formulation. Finally, coupling the dashboard with digital twin networks or federated platforms can enable multi-system analysis, cross-regional sustainability comparisons, and collaborative governance. These enhancements position the framework as a scalable, adaptable, and impactful tool for advancing evidence-based ESG strategy, fostering sustainability transitions, and bridging the gap between conceptual modeling and actionable decision support.

## 7. CONCLUSION

This work presents a layered conceptual framework and interactive DT-based dashboard for integrating ESG considerations into sustainability decision-making. By bridging technical levers such as renewable energy adoption, circular economy practices, and emerging technology integration with DT capabilities, including real-time sensing, simulation, analytics, and governance mechanisms, the framework provides a holistic and actionable approach to evaluating ESG performance. The prototype dashboard operatively operates the framework, enabling stakeholders to dynamically explore scenarios, benchmark strategies, and visualize trade-offs across ESG dimensions. The results demonstrate the framework's ability to reveal interdependencies between sustainability levers and ESG outcomes, quantify performance impacts, and support evidence-based, transparent decision-making. The consistent and reproducible outputs across multiple scenarios further validate the robustness of the simulation engine and the practical utility of the tool for research, policy, and industrial applications. The novelty of this work lies in extending DT principles beyond physical system monitoring to multi-dimensional ESG modeling, providing both a conceptual foundation and a practical, interactive tool for sustainability planning. The explicit formalization of the ESG aggregation model further enhances the framework's reproducibility and positions the proposed system as a transparent methodological reference for future ESG-driven digital twin research. Future work will focus on integrating real-world IoT and enterprise data, advanced optimization algorithms, and adaptive learning techniques to further enhance

predictive accuracy, support autonomous decision-making, and enable broader adoption of DT-enabled ESG strategies in smart cities, industry, and energy systems.

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