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Beyond Carbon Accounting: A Unified Digital ESG Framework for Manufacturing Industries Integrating CSRD, ESRS, the GHG Protocol, and the United Nations Sustainable Development Goals

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Abstract — The accelerating impacts of climate change, resource depletion, and increasing stakeholder expectations have fundamentally transformed the way organizations approach sustainability. Manufacturing industries, which account for a significant proportion of global greenhouse gas emissions, water consumption, and resource utilization, are under growing pressure to move beyond voluntary sustainability initiatives toward structured, measurable, and transparent Environmental, Social, and Governance (ESG) management. Regulatory developments such as the European Union's Corporate Sustainability Reporting Directive (CSRD), the European Sustainability Reporting Standards (ESRS), and internationally accepted frameworks including the Greenhouse Gas (GHG) Protocol and the United Nations Sustainable Development Goals (UN SDGs) have collectively established a comprehensive sustainability reporting landscape. However, organizations continue to face considerable challenges in translating these independent frameworks into a cohesive operational strategy. This paper proposes a Unified Digital ESG Framework (UDEF) designed specifically for manufacturing industries. Unlike existing studies that examine ESG reporting, carbon accounting, or sustainability regulations independently, the proposed framework integrates CSRD compliance, ESRS disclosure requirements, GHG Protocol-based emissions accounting, and UN SDG alignment into a single implementation architecture supported by digital technologies. The framework incorporates smart metering, Industrial Internet of Things (IIoT) devices, cloud-based Energy Management Systems (EMS), real-time KPI monitoring, and artificial intelligence-assisted decision support to facilitate continuous ESG performance measurement. The proposed framework establishes a systematic methodology for identifying material sustainability issues, collecting operational data, quantifying environmental impacts, mapping ESG indicators to regulatory disclosure requirements, and supporting strategic decision-making through digital dashboards. A manufacturing-oriented implementation model demonstrates how energy, water, fuel, waste, emissions, and governance indicators can be consolidated into an integrated ESG management ecosystem. The paper further introduces a Digital ESG Maturity Model to evaluate organizational readiness and monitor continuous improvement. The study contributes to existing sustainability literature by presenting an implementation-oriented framework that bridges the gap between regulatory compliance and operational sustainability management. It offers practical guidance for manufacturing organizations seeking to improve ESG performance, strengthen corporate governance, enhance investor confidence, and accelerate progress toward net-zero and circular economy objectives. The framework also provides a foundation for future research on digital sustainability, AI-enabled ESG reporting, and Industry 5.0-driven environmental governance.

Keywords— Environmental, Social and Governance (ESG), Corporate Sustainability Reporting Directive (CSRD), European Sustainability Reporting Standards (ESRS), Greenhouse Gas Protocol, Sustainable Development Goals, Manufacturing Industry, Carbon Accounting, Industry 4.0; Digital Transformation, Energy Management System (EMS), Sustainability Reporting, Double Materiality Assessment (DMA).

I. INTRODUCTION

Background

Climate change has emerged as one of the defining challenges of the twenty-first century, fundamentally reshaping industrial development, corporate governance, and global economic policies. Rising global temperatures, increasing frequency of extreme weather events, biodiversity loss, freshwater scarcity, and resource depletion have intensified the urgency for businesses to transition toward sustainable operating models. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to 1.5°C requires rapid and far-reaching transitions across energy, industrial, urban, and land-use systems. Consequently, sustainability has evolved from a voluntary corporate initiative into a strategic necessity driven by regulatory mandates, investor expectations, and societal demands.

The manufacturing sector occupies a central position within this transition. As one of the largest contributors to global greenhouse gas emissions, industrial energy consumption, freshwater withdrawal, and material extraction, manufacturing organizations face increasing scrutiny regarding their environmental and social impacts. At the same time, they are expected to remain competitive, resilient, and economically viable. This dual challenge has accelerated the adoption of Environmental, Social, and Governance (ESG) principles as a comprehensive framework for balancing sustainability performance with long-term business value.

Over the past decade, ESG has shifted from a voluntary disclosure practice to a critical component of corporate strategy. Investors increasingly evaluate organizations using ESG performance indicators to assess long-term resilience, regulatory preparedness, and operational risks. Financial institutions incorporate ESG metrics into lending and investment decisions, while multinational customers require suppliers to demonstrate responsible environmental and social practices. Governments worldwide have also strengthened sustainability regulations to improve transparency and accountability, particularly in sectors with significant environmental footprints.

Among recent regulatory developments, the European Union's Corporate Sustainability Reporting Directive (CSRD) represents one of the most comprehensive reforms in corporate sustainability reporting. Supported by the European Sustainability Reporting Standards (ESRS), the directive requires organizations to disclose detailed information on environmental impacts, social responsibility, governance structures, climate risks, resource utilization, biodiversity, circular economy practices, and value-chain sustainability. Unlike previous reporting approaches, CSRD introduces the principle of double materiality, requiring companies to report not only how sustainability issues affect financial performance but also how corporate activities impact society and the environment.

Parallel to regulatory reporting requirements, the Greenhouse Gas Protocol has become the globally accepted methodology for greenhouse gas accounting, providing standardized approaches for measuring Scope 1, Scope 2, and Scope 3 emissions. Simultaneously, the United Nations Sustainable Development Goals (SDGs) have established a universal sustainability agenda, encouraging organizations to align business strategies with global development priorities such as clean energy, responsible consumption, climate action, clean water, and sustainable industrialization.

Despite the availability of these frameworks, many manufacturing organizations continue to struggle with implementation. Sustainability data often remains fragmented across multiple departments, collected through manual processes, and reported using disconnected systems. Carbon accounting, ESG reporting, energy monitoring, water management, waste tracking, and governance disclosures are frequently managed independently, resulting in duplication of effort, inconsistent data quality, and limited strategic integration.

The rapid advancement of Industry 4.0 technologies including Industrial Internet of Things (IIoT), cloud computing, artificial intelligence (AI), digital twins, and real-time analytics creates an opportunity to overcome these challenges. Digital transformation enables automated data collection, continuous performance monitoring, predictive analytics, and integrated decision-making, thereby supporting a more robust and transparent ESG management process.

Recognizing this opportunity, the present study proposes a Unified Digital ESG Framework (UDEF) that integrates CSRD, ESRS, the GHG Protocol, and the UN SDGs within a single digital architecture tailored to manufacturing industries. By combining regulatory compliance, sustainability reporting, carbon accounting, operational monitoring, and digital technologies, the framework seeks to bridge the gap between sustainability strategy and day-to-day industrial operations.

II. LITERATURE REVIEW

1. Evolution of Sustainability Reporting and ESG:
Sustainability reporting has undergone a significant transformation over the past three decades. Initially driven by voluntary environmental disclosures and corporate social responsibility (CSR) initiatives, sustainability reporting has evolved into a strategic management and regulatory requirement. Organizations are increasingly expected to disclose not only their financial performance but also their environmental, social, and governance (ESG) impacts, reflecting a broader shift toward stakeholder capitalism and long-term value creation.

The concept of sustainable development was formally introduced by the Brundtland Commission in 1987, which defined sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs. This definition laid the foundation for integrating environmental stewardship, social responsibility, and economic growth into business decision-making.

The launch of the United Nations Global Compact (UNGC) in 2000 and the Global Reporting Initiative (GRI) represented the first major efforts to standardize corporate sustainability reporting. GRI introduced comprehensive disclosure standards covering environmental performance, labour practices, human rights, governance, and community engagement. Because of its flexibility and broad applicability, GRI became one of the most widely adopted voluntary sustainability reporting frameworks globally.

As investor demand for standardized ESG information increased, additional reporting frameworks emerged. The Sustainability Accounting Standards Board (SASB) introduced industry-specific sustainability metrics designed to address financially material ESG issues. Similarly, the Task Force on Climate-related Financial Disclosures (TCFD) provided recommendations for climate-related governance, strategy, risk management, and performance disclosures, encouraging organizations to assess climate risks and opportunities in a structured manner.

Recent developments have accelerated the transition from voluntary reporting toward mandatory sustainability disclosure. The establishment of the International Sustainability Standards Board (ISSB) under the IFRS Foundation aims to harmonize global sustainability reporting requirements by providing a consistent baseline for investor-focused disclosures. Concurrently, the European Union introduced the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS), significantly expanding mandatory ESG reporting obligations for companies operating within or supplying the European market.

2. Environmental, Social and Governance (ESG): Concept and Importance

Environmental, Social, and Governance (ESG) has emerged as one of the most influential frameworks for evaluating corporate sustainability performance. Unlike traditional CSR initiatives that primarily emphasize philanthropic activities, ESG integrates sustainability directly into corporate strategy, operational performance, risk management, and long-term value creation.

The Environmental dimension addresses issues including greenhouse gas emissions, renewable energy adoption, water stewardship, waste management, biodiversity conservation, pollution prevention, and circular economy practices.

The Social dimension encompasses employee health and safety, diversity and inclusion, labour rights, community engagement, human rights, workforce development, and responsible supply chain management.

The Governance dimension evaluates board composition, ethical conduct, executive compensation, anti-corruption policies, regulatory compliance, shareholder rights, cybersecurity, and corporate transparency.

Numerous empirical studies demonstrate that organizations with mature ESG practices often exhibit enhanced operational resilience, improved risk management capabilities, greater investor confidence, and stronger access to sustainable financing. ESG performance has increasingly become a determinant of corporate reputation and competitive advantage, particularly within global supply chains where customers require suppliers to meet defined sustainability expectations.

For manufacturing industries, ESG implementation presents unique challenges due to resource-intensive production processes, high energy consumption, significant greenhouse gas emissions, complex supplier networks, and increasing environmental regulations. Consequently, manufacturing organizations require integrated ESG management systems capable of monitoring operational performance continuously rather than relying solely on annual reporting exercises.

3. The Corporate Sustainability Reporting Directive (CSRD) (IN EFFECT SINCE JAN'23):

The Corporate Sustainability Reporting Directive (CSRD), adopted by the European Union in 2022, represents one of the most comprehensive sustainability reporting regulations introduced globally. It replaces the Non-Financial Reporting Directive (NFRD) and substantially expands the number of organizations required to publish sustainability information.

Unlike previous reporting frameworks that encouraged voluntary disclosures, CSRD establishes legally binding reporting obligations covering environmental, social, governance, climate risk, biodiversity, circular economy, workforce practices, value chain sustainability, and corporate governance.

A defining characteristic of CSRD is the introduction of the Double Materiality Principle, which requires organizations to assess sustainability from two complementary perspectives:

Financial Materiality – How environmental and social issues affect enterprise value, financial performance, cash flows, and investment decisions.

Impact Materiality – How organizational activities affect society, climate, biodiversity, employees, customers, and broader ecosystems.

This dual perspective significantly broadens corporate accountability and encourages organizations to consider both inward and outward sustainability impacts. For manufacturing industries, CSRD introduces new challenges associated with collecting large volumes of operational data across multiple facilities, supply chains, and business functions. Energy consumption, greenhouse gas emissions, water withdrawal, hazardous waste generation, employee safety, supplier performance, and governance practices must all be measured accurately and reported consistently.

4. European Sustainability Reporting Standards (ESRS) (Adopted in 2023)

The European Sustainability Reporting Standards (ESRS) provide the technical reporting requirements necessary to implement CSRD. Developed by the European Financial Reporting Advisory Group (EFRAG), ESRS defines standardized disclosure requirements covering environmental, social, and governance topics.

The environmental standards include:

- ESRS E1 – Climate Change
- ESRS E2 – Pollution
- ESRS E3 – Water and Marine Resources
- ESRS E4 – Biodiversity and Ecosystems
- ESRS E5 – Resource Use and Circular Economy

Social standards include:

- S1 - Own Workforce
- S2 - Workers in the Value Chain
- S3 - Affected Communities
- S4 - Consumers and End Users

Governance standards include:

- G1 - Business Conduct
- G2 - Ethics
- G3 - Anti-Corruption
- G4 - Risk Management

Compared to previous voluntary sustainability reporting standards, ESRS emphasizes quantitative metrics supported by verifiable operational data. This requirement significantly increases the importance of digital monitoring technologies, including smart energy meters, water flow meters, fuel monitoring systems, waste tracking software, environmental sensors, and enterprise ESG management platforms.

However, existing literature indicates that many organizations continue to rely on manual spreadsheets and fragmented reporting systems, creating substantial risks related to data accuracy, consistency, and auditability.

5. Greenhouse Gas Protocol (SINCE 1998)

The Greenhouse Gas Protocol (GHG Protocol) is recognized globally as the leading standard for greenhouse gas accounting. Developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), the protocol provides standardized methodologies for measuring organizational greenhouse gas emissions.

The protocol classifies emissions into three categories:

- Scope 1: Direct emissions from owned or controlled sources, such as combustion of fossil fuels, industrial processes, and company vehicles.
- Scope 2: Indirect emissions resulting from purchased electricity, steam, heating, and cooling.
- Scope 3: All other indirect emissions occurring throughout the value chain, including purchased goods, transportation, business travel, waste disposal, employee commuting, and product end-of-life.

Although Scope 1 and Scope 2 emissions are generally measurable using operational data, Scope 3 emissions remain considerably more complex due to their dependence on supplier information and life-cycle assessments.

6. United Nations Sustainable Development Goals (UN SDGs) (Adopted in 2015)

The United Nations Sustainable Development Goals (SDGs) provide a universal framework comprising 17 interconnected goals aimed at addressing global social, environmental, and economic challenges by 2030.

Several SDGs are particularly relevant to manufacturing industries:

- SDG 6 – Clean Water and Sanitation
- SDG 7 – Affordable and Clean Energy
- SDG 8 – Decent Work and Economic Growth
- SDG 9 – Industry, Innovation and Infrastructure
- SDG 12 – Responsible Consumption and Production
- SDG 13 – Climate Action

While many organizations publicly reference the SDGs in sustainability reports, existing literature suggests that practical integration between SDG targets and operational performance indicators remains limited. In many cases, SDG alignment is qualitative rather than supported by measurable KPIs.

7. Double Materiality: The Cornerstone of Modern ESG Reporting (INTRODUCED IN 2020):

One of the most transformative concepts introduced by the Corporate Sustainability Reporting Directive (CSRD) is Double Materiality. Unlike traditional financial reporting, which focuses primarily on how environmental or social issues influence an organization's financial performance, double materiality requires organizations to simultaneously evaluate how their own operations affect society, the environment, employees, customers, and future generations.

Double materiality consists of two complementary dimensions:

Financial Materiality (Outside-In Perspective):

Financial materiality assesses how sustainability-related risks and opportunities influence an organization's financial performance, enterprise value, cash flow, capital allocation, and long-term competitiveness. Climate change, carbon pricing mechanisms, energy price volatility, resource scarcity, and regulatory developments are examples of factors that may materially affect business performance.

For manufacturing organizations, financial materiality includes:

- Rising energy costs
- Carbon taxation and CBAM exposure
- Supply chain disruptions
- Climate-related operational risks
- Investor ESG expectations
- Renewable energy investments

Impact Materiality (Inside-Out Perspective)

Impact materiality evaluates how organizational activities influence external stakeholders and natural ecosystems. It encompasses greenhouse gas emissions, water consumption, biodiversity loss, waste generation, employee welfare, human rights, community impacts, and product life-cycle effects.

Examples within manufacturing include:

- Process emissions
- Freshwater withdrawal
- Industrial wastewater discharge
- Hazardous waste generation
- Occupational health and safety
- Supply-chain labour practices

Double materiality shifts ESG reporting from a compliance exercise toward a strategic management process by requiring organizations to evaluate sustainability as both a business risk and a societal responsibility.

8. Digital Transformation and Industry 4.0 in ESG Management

The emergence of Industry 4.0 has fundamentally transformed manufacturing through cyber-physical systems, automation, connectivity, artificial intelligence, cloud computing, and advanced analytics. These technologies create significant opportunities for improving ESG data quality and sustainability decision-making.

Traditional ESG reporting is typically characterized by:

- Spreadsheet-based data collection
- Manual meter readings
- Departmental silos
- Annual reporting cycles
- Limited data verification

Such approaches are increasingly inadequate for meeting modern sustainability reporting requirements. Industry 4.0 technologies enable organizations to transition from static reporting toward continuous ESG performance management by enabling technologies such as:

Internet of Things (IoT)

IoT devices continuously collect operational information from manufacturing assets.

- Smart electricity meters
- Digital water flow meters
- Gas and fuel flow meters
- Air quality sensors
- Stack emission analysers
- Waste tracking systems

Artificial Intelligence

Artificial Intelligence supports ESG through:

- Predictive energy optimization
- Carbon footprint forecasting
- Equipment performance analysis
- Water consumption prediction
- ESG anomaly detection
- Automated reporting
- Regulatory compliance monitoring

Cloud Computing
Cloud platforms enable centralized ESG information management across geographically distributed manufacturing facilities.

Benefits include:
- Real-time dashboards
- Centralized databases
- Automatic KPI calculation
- Regulatory reporting automation
- Multi-site benchmarking
- Investor reporting

Digital Twins
Digital twins create virtual representations of manufacturing facilities capable of simulating operational performance under different sustainability scenarios.

Potential ESG applications include:
- Renewable energy optimization
- Water conservation strategies
- Carbon reduction simulation
- Waste minimization
- Resource efficiency improvements
- Climate risk analysis

Smart Metering and Digital Data Acquisition:
One of the primary challenges identified across ESG literature concerns data availability and quality. Environmental performance indicators depend heavily upon reliable operational measurements including:
- Electricity consumption
- Fuel usage
- Water withdrawal
- Wastewater discharge
- Steam consumption
- Compressed air
- Process temperatures
- Waste generation

Historically, many organizations collect these values manually using monthly utility bills or handwritten logbooks. Such approaches create several problems:
- Human error
- Missing data
- Delayed reporting
- Poor traceability
- Limited granularity

Smart metering technologies overcome these limitations by providing:
- Continuous measurements
- High-frequency data collection
- Remote monitoring
- Automated alerts
- Historical trend analysis
- Integration with SCADA and PLC systems

Digital metering therefore represents one of the foundational components of modern ESG implementation.

ESG Dashboards and Performance Monitoring:
Sustainability reporting is gradually shifting from annual disclosure documents toward continuous performance monitoring.

Modern ESG dashboards integrate operational information across multiple sustainability dimensions including:

Environmental
- Carbon emissions
- Renewable energy
- Water consumption
- Waste generation
- Recycling rates
- Air emissions

Social
- Employee safety
- Training hours
- Diversity
- Community engagement

Governance
- Compliance
- Supplier audits
- Ethical incidents
- Risk assessments

Executive dashboards support strategic decision-making by transforming large volumes of operational information into meaningful visual indicators. However, literature indicates that most commercially available ESG platforms primarily focus on reporting rather than operational optimization. This creates an opportunity for integrating ESG dashboards directly with industrial data acquisition systems.

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Manufacturing-Specific ESG Challenges:
High Energy Intensity:
- Melting
- Heat Treatment
- Machining
- Casting
- Forging
- Rolling

Water Consumption:
- Cooling
- Washing
- Quenching
- Boiler Feed
- Surface Treatment

Carbon Emissions arising from:
- Direct Combustion
- Electricity Consumption
- Process Reactions
- Transportations
- Supply Chain Activities

Waste Generation:
- Hazardous Waste
- Non-Hazardous Waste
- Metal Scrap
- Slag
- Wastewater
- Packaging
- Spent Chemicals

Comparative Analysis of Existing Frameworks:
Framework Analysis

Framework Analysis			
S.No	Framework	Strengths	Limitations
1	GHG Protocol	Standard Emissions Accounting	Limited Social and Governance Coverage
2	CSRD	Comprehensive Regulatory Reporting	Does not prescribe operational implementation
3	ESRS	Detailed Disclosure Requirements	Required significant organizational data integration
4	UN SDGs	Global Sustainability Vision	No standardized corporate implementation methodology
5	GRI	Broad Sustainability Reporting	Voluntary and less aligned with emerging EU regulations
6	SASB	Investor Focussed Metrics	Limited environmental operational guidance
7	TFCD	Climate Risk Reporting	Primarily climate focussed

Critical Synthesis of Existing Literature:
A review of contemporary sustainability literature reveals five recurring themes:
- Organizations possess multiple reporting frameworks but lack integrated implementation methodologies.
- Digital technologies have significant potential to improve ESG reporting; however, existing research rarely combines Industry 4.0 technologies with regulatory compliance.
- Carbon accounting remains largely disconnected from broader ESG management systems.
- Operational sustainability metrics are seldom linked directly to UN Sustainable Development Goals.
- Existing studies emphasize compliance rather than continuous sustainability performance improvement.

These observations indicate that the evolution of sustainability reporting now requires moving beyond individual frameworks toward integrated digital ecosystems capable of supporting real-time ESG decision-making.

Research Gap:
Fragmented Framework Coverage
- Most studies examine CSRD, ESRS, the GHG Protocol, or the UN SDGs independently.
- There is limited attention to how these frameworks can be operationally integrated within manufacturing environments.

Weak Link b/w Industry 4.0 and ESG Reporting:
Lack of structured methodology that connect these technologies to:
- ESG reporting obligations
- Sustainability Governance

Compliance Driven, backward-looking reporting:
- Existing ESG reporting approaches are predominantly compliance-driven
- They focus on disclosure after performance has occurred
- They do not enable organizations to:
- Monitor sustainability outcomes in real time
- Predict future performance
- Continuously improve sustainability outcomes

No unified implementation roadmap for manufacturers:
A Unified implementation roadmap would need to align:

- Regulatory compliance
- Carbon accounting
- Operational monitoring
- Strategic sustainability objectives within a single digital management architecture

III. ARCHITECTURE OF THE UNIFIED DIGITAL ESG FRAMEWORK (UDEF)

1. Overview of the UDEF architecture:
UDEF is structured as a multi-layered digital architecture that connects physical manufacturing assets to ESG governance and reporting. The framework comprises of 4 independent layers:

- Data acquisition layer: Captures operational and sustainability data from physical assets and enterprise systems
- Data Integration and standardization layer: Harmonises, validates and maps data to regulatory and voluntary frameworks
- Analytics and intelligence layer: Transforms data into insights through dashboards, predictive models and scenario analysis
- Governance and reporting layer: Supports decision making, assurance and disclosure alignment with CSRD, ESRS, GHG protocol and SDGs

2. Layer 1: Data Acquisition
The data acquisition layer forms the foundation of UDEF by collecting granular, time stamped data from diverse sources across the manufacturing value chain.

Key data sources include:
ioT sensors and smart meters:

- Measures energy consumption, water usage, fuel consumption, process parameters (temperature, pressure, flow rates) and emission related variables at machine, line and facility level
- Enable high frequency data capture (e.g. minute level or second level intervals) required for accurate SCOPE 1 and SCOPE 2 accounting

Manufacturing execution systems (MES) and SCADA:

- Provides production volumes, cycle times, downtime, quality metrics and material flows
- Link operational performance to environmental intensity metrics (e.g. kWh/units or CO2e/product)

Enterprise resource planning (ERP) and supply chain systems:

- Supply data on procurement, logistics, inventory and supplier information
- Support SCOPE 3 categories such as purchased goods, transportation and EOL treatment

EHS (Environment, Health and Safety) and HR systems:

- Capture incidents, near misses, training records, worker exposure data and diversity metrics
- Feed into ESRS 1 (own workforce) and S2 (workers in the value chain) disclosures

External Data feeds:

- Grid emission factors, fuel emission factors, weather conditions and market-based instruments (e.g. renewable energy certificates, guarantees of origin)
- Required for location-based and market-based emissions calculations under the GHG protocol

3. Layer 2: Data Integration and Standardization
This layer transforms raw data into a structured, framework-aligned ESG data model.

Core Functions:
Data Harmonisation:

- Normalises data formats, units and naming conventions across sites, systems and vendors
- Resolves inconsistencies (e.g. different energy units, fiscal year definitions, product categorisations)

ESG Data Model and Multi-Framework Mapping:
Defines a common schema where each data element is linked to:

- Relevant ESRS disclosure requirements (e.g. E1-4, E1-5 for climate metrics)
- GHG protocol scope and category (e.g. SCOPE 1 – stationary combustion, SCOPE 2 – location-based)
- Corresponding SDG targets and indicators (e.g. SDG 7.3 on energy efficiency, SDG 13.2 on climate integration)

Data Validation and Quality Controls

- Applies rules for completeness, consistency and plausibility (e.g. flagging impossible emission factors, negative consumption values)
- Generates data quality scores that inform assurance processes and highlight areas requiring manual review

Audit Trails and Lineage Tracking:

- Maintains records of data transformations, calculation methods and assumptions
- Supports external assurance by enabling auditors to trace reported figures back to source data and calculation logic

4. Layer 3: Analytics and Intelligence

It converts standardised ESG data into actionable insights for operational and strategic decision making.

Key Capabilities:

Real Time Dashboard and KPIs:

- Display energy intensity, carbon intensity, water efficiency, waste generation and safety metrics at plant, line and asset level
- Enable drill down from corporate level ESRS metrics to granular operational drivers

Predictive Analysis and AI Models:

- Forecast energy demand, emissions and resource consumption under different production schedules and operating conditions
- Detect anomalies (e.g. unexpected emission spikes, abnormal water use) and trigger alerts for corrective action
- Support RCA by correlating sustainability deviations with operational variables (e.g. equipment age, maintenance history, shift patterns)

Scenario analysis and transition planning:

- Model the impact of technology upgrades, fuel switching, process optimization and capacity changes on SCOPE 1, 2 and 3 emissions
- Align with CSRD requirements for transition plans by evaluating pathways to net-zero and intermediate targets

Digital Twin Integration:

- Use digital twins to stimulate process modifications, retrofits and new equipment before implementation
- Estimate ESG impacts (e.g. emission reduction, energy savings) and compare alternatives to inform investment decisions

Benchmarking and Target Tracking:

- Compare performance across sites, product lines and peer groups
- Track progress against internal targets (e.g. RE100, science-based targets) and external benchmarks (e.g. sectoral decarbonisation pathways)

Layer 4: Governance and Reporting

This layer translates insights into decisions, controls and disclosures aligned with regulatory and stakeholder expectations.

Key Components:

ESG Governance Workflows:

- Define roles and responsibilities for data owners, validators, approvers and reporters
- Embed ESG metrics into management reviews, capital approval processes and operational excellence programs

Compliance and Disclosure Management:

- Generate reports aligned with CSRD/ESRS requirements, including DMA and topical standards (E1 – E5, S1 – S4, G1)
- Produce GHG inventories consistent with GHG protocol corporate standard and relevant scope guidance
- Map performance to SDG indicators for voluntary communications and stakeholder engagement

Assurance Readiness:

- Provide auditors with structured access to data lineage, calculation methodologies and control documentation
- Support limited and reasonable assurance engagements under CSRD by maintaining transparent, reproducible reporting processes

Stakeholder Communication and Transparency:

- Regulators and auditors (Detailed compliance reports)
- Investors and rating agencies (ESG scores, transition metrics)
- Customers and supply chain partners (Product specific carbon footprints, supplier scorecards)
- Internal Teams (Operational dashboards, improvement targets)

Data Flow and Feedback Loops in UDEF:

UDEF operates as a closed-loop system in which data flows bidirectionally across layers:

Bottom-Up Flow (Measurement to Governance):

- Operational data from sensors and systems is aggregated, validated and transformed into ESG metrics
- Metrics feed dashboards, reports and governance processes

Top-Down Flow (Strategy to Operations):

- Strategic Targets (e.g. carbon reduction goals, energy efficiency targets) are cascaded into operational KPIs and control parameters
- Insights from analytics inform process optimisation, maintenance planning and investment decisions

Continuous Improvement Cycle:

- Performance data is compared against targets and benchmarks
- Deviation triggers corrective actions, which are then monitored and verified through the same data pipeline
- Lessons learned refine models, update assumptions and strengthen controls over time

IV. IMPLEMENTATION ROADMAP FOR UDEF

1. Guiding Principles for UDEF implementation:

Start with Business Value, not Technology:

- Anchor initiatives in clear objectives (e.g. energy cost reduction, carbon target achievements, CSRD readiness) rather than technology for its own sake

Adopt a Phased, Iterative Approach:

- Implement in stages, with each phase delivering measurable outcomes and informing the next
- Use pilot projects to validate assumptions, refine data models, and build internal capability

Design for Integration from the Outset:

- Ensure that data models, interfaces, and governance structures support future expansion across sites, systems and frameworks
- Avoid siloed solutions that create new data fragmentations

Embed Governance and Assurance Early:

- Establish data ownership, quality controls and audit trails from the beginning to support CSRD assurance requirements and internal decision-making

Leverage Existing Standards and Architectures:

- Align with established manufacturing data standards (e.g. ISA-88/95, OPC UA, MQTT) and sustainability frameworks (e.g. CSRD, ESRS, GHG Protocol) to reduce customisation and improve interoperability

2. Phased Implementation Roadmap

Phase 1: Strategic Foundation and Readiness Assessment

Objective: Establish clarity on objectives, current state and priority use cases to guide subsequent investment and design decisions

Key Activities:

Define ESG Vision and KPIs:

- Align leadership on strategic objectives (e.g. Net-Zero by 2040, RE100 membership, zero harm)
- Translate vision into 3-5 headline KPIs (e.g. SCOPE 1+2 emissions intensity, energy cost/unit, total recordable incident rate)

Assess Current ESG and Digital Maturity:

- Map existing sustainability reporting processes, data sources and systems (ERP, MES, EHS, EMS)
- Evaluate data quality, coverage and alignment with CSRD/ESRS and GHG protocol requirements
- Identify gaps in technology, skills and governance

Conduct Double Materiality Assessment (DMA) (CSRD – Aligned)

- Identify material environmental, social and governance topics based on impact and financial materiality
- Prioritise topics that will drive initial UDEF scope (e.g. climate change, resource use, own workforce, etc)

Prioritise Pilot Use Cases:

- Select 2-3 high impact, feasible pilots (e.g. real time energy and emissions monitoring at a flagship plant, automated SCOPE 1+2 inventory, safety incident analytics)
- Balance quick wins with strategically important use cases that demonstrate UDEF's value proposition

Decision Gate: Leadership approval to process to detailed architecture design and pilot implementation

Phase 2: Data Architecture Design and Core Infrastructure

Objective: Design and deploy the foundational data architecture and infrastructure that enable integrated ESG data collection, standardization and analytics

Key Activities:

Design the ESG Data Model and Framework Mapping:

- Design a common data schema for energy, emissions, water, waste, materials, safety and workforce metrics
- Map each data element to relevant ESRS disclosures, GHG protocol categories and SDG indicators

Establish Data Integration and Architecture:

- Design interfaces between ioT platforms, MES, ESP, EHS and external data sources (e.g. emission factors, grid data)
- Select integration patterns (e.g. unified namespace, event driven architecture, APIs) to enable real time data flows

Deploy Core Infrastructure Components:

- Implement data ingestion pipelines (e.g. MQTT, OPC UA, REST APIs) to collect sensor and system data
- Set up a central data platform (cloud or on premises) for storage, contextualisation and processing
- Configure edge computing nodes where real time analytics and low latency control are required

Implement Data Governance and Master Data Management (MDM):

- Define data stewardship roles (data owners, validators, approvers)
- Establish data quality rules, validation workflows and exception handling processes
- Create master data repositories for critical reference data (e.g. emission factors, equipment hierarchies, organisational boundaries)

Develop Initial Analytics and Dashboards:

- Build dashboards for priority KPIs (e.g. energy intensity, emission by SCOPE, safety metrics)
- Implement basic anomaly detection and alerting for critical sustainability parameters

Decision Gate: Validation of pilot use cases and readiness to scale to additional sites and domains

Phase 3: Pilot Execution, Analytics Enhancement and Assurance Readiness followed by expansion to other sites
Objective: Validate UDEF through pilot deployments, enhanced analytics capabilities and prepare for external assurance

Key Activities:
Execute Pilot Projects:

- Deploy UDEF components in selected plants or business units
- Monitor KPI impact
- Document lessons learned and refine

Enhance Analytics and Intelligence:

- Develop predictive models
- Implement scenario analysis tools for transition planning (e.g. fuel switching, technology upgrades)
- Integrate digital twins for process optimisation and investment evaluation

Strengthen Assurance Readiness:

- Document data
- Conduct internal audits or pre-assurance audits to identify gaps
- Prepare evidence packs for external auditors (e.g. data samples, reconciliation reports, etc.)

Refine Governance and Decision-Making Processes:

- Integrate ESG dashboards into operational and management reviews
- Establish regular ESG performance reviews with cross-functional participants
- Align capital approval processes with ESG insights

Decision Gate: Approval to expand UDEF across additional sites, functions and ESG topics

Critical Success Factors
Executive Sponsorship and Cross-Functional Collaboration:

- Strong leadership commitment and involvement form operations, IT, finance, sustainability and EHS functions

Clear Linkage to Business Value:

- Demonstrable benefits in cost reduction, risk mitigation, compliance efficiency and competitive advantage

Data Quality and Governance Discipline:

- Robust data controls, ownership and audit trails to support both internal decisions and external assurance

Modular Standard Based Architecture:

- Use of open standards and modular design to enable scalability, interoperability and future proofing

Change Management and Capacity Building:

- Training, communication and incentives to embed new ways of working and ensure sustained adoption

Industry Case Studies
Case Study 1: BMW Group – Digital Supply Chain Ecosystem and CSRD Alignment
BMW Group, a global automotive manufacturer operating in over 140 markets, faces complex ESG reporting obligations under CSRD while managing a vast, multi-tier supply chain with significant SCOPE 3 emissions.

Digital ESG Integration Approach

- "CATENA-X" Data Ecosystem: BMW initiated a pilot launch of CATENA-X in China (2025), using unified data standards to streamline communication between BMW and its suppliers, enabling accurate carbon footprint reporting and supporting material recycling through shared product lifecycle data
- Multistage Due Diligence: The company embedded sustainability standards in supplier contracts and conducts comprehensive risk analysis across all value chain stages, from raw material extraction to EOL recycling

Output

- 300+ Tier 1 suppliers have committed to using electricity generated from renewable source, an increase of 100 v/s 2024
- Total supply chain emission reductions v/s 2019 baseline year reached 1 million tonnes of CO_2e, equivalent to the annual carbon footprint of approximately 220,000 petrol powered vehicles
- Recognized as a "5 Star Green Supply Chain Enterprise for 3 consecutive years"

Case Study 2: Siemens – Digital Twin for Sustainability and Life-Cycle Assessment

Siemens, a global industrial technology company, has developed and deployed digital twin technologies specifically to support decarbonisation and sustainability optimisation across manufacturing operations

Digital ESG Integration Approach

- Comprehensive Digital Twin: Siemens integrates product and production lifecycle models, combining physics-based simulations with real time operational data to create dynamic representations of products, machines and entire production systems
- Green Digital Twin (GDT): A dedicated LCA software tool that enables carbon footprint tracking from design through production, used internally by over 1,200 siemens users and made available externally in 2025
- Real Time Optimisation: Digital twin continuously captures sensor data, analyse performance and feed insights back into development. Thus, creating optimisation loops that reduce resource use and emissions

Case Study 3: TATA Motors – BSBR Reporting and Sustainability Strategy Integration

TATA motors, a leading automotive manufacturer, published annual Business Responsibility & Sustainability Reports (BSBR) aligned with SEBI's framework while pursuing decarbonisation, circular economy and social equity goals

Digital ESG Integration Approach

- BSBR Data Consolidation: TATA motors integrate data from 3 entities (Commercial Vehicles, Passenger Vehicles and Electric Mobility) into a unified sustainability report demonstrating multi business data harmonisation
- Decarbonisation and Circularity: The company's sustainability strategy emphasizes renewable energy adoption, energy efficiency improvements and circular economy principles across manufacturing operations
- Social Metrics and Inclusion: In FY'24-25, TATA Motors onboarded 141 people with disabilities and 17 transgenders individuals across plants, supported by inclusive policies and structured training programs

V. CONCLUSION

This paper has proposed a Unified Digital ESG Framework (UDEF), a digitally enabled implementation model designed to address critical gaps in sustainability reporting and governance for manufacturing industries. The research responds to four interrelated challenges identified in the literature:

- The fragmented treatment of CSRD, ESRS, GHG protocol and the UN SDGs
- Limited methodological linkages between Industry 4.0 technology and ESG reporting obligations
- Predominantly compliance driven, retrospective reporting approaches
- Absence of a unified implementation roadmaps for manufacturing operations

Implications for Practise:

For Sustainability and ESG Managers:

- UDEF offers a structured approach to move beyond retrospective, compliance-driven reporting toward proactive performance management
- This multi framework data model reduces manual effort in data consolidation and improves audit readiness for CSRD assurance requirements
- Real time dashboards and predictive analysis enable earlier detection of sustainability issues and more informed decision making

For Operations and Manufacturing Leaders:

- The framework demonstrates how ESG data can be integrated with operational KPIs (energy intensity, yield, quantity) to drive continuous improvement

- Digital twins and AI models support scenario analysis for technology upgrades, process optimisation and decarbonisation investment

IT and Digital Transformation Leaders:
- Emphasis on open standards (OPC UA, MQTT, Unified Namespace) and modular design ensures interoperability and future proofing
- The above framework supports both cloud and edge deployment patterns, accommodating diverse IT landscapes and latency requirements

Directions for Future Research
Empirical Validation of UDEF Benefits:
- Quantitative studies measuring the impact of UDEF adoption on ESG performance, operational efficiency and financial outcomes across different manufacturing sub-sectors (e.g. automotive, chemicals, electronic)
- Comparative studies between UDEF adopters and non-adopters to isolate framework's contribution to performance improvement

Advanced Analytics and AI Integration:
- Exploration of AI techniques (e.g. reinforcement learning, casual interference, generative AI) for optimising ESG outcomes in real time and supporting autonomous decision making
- Investigation of MLO practices for ESG model governance, monitoring and continuous improvement in production environments

SCOPE 3 Data Ecosystems and Collaboration:
- Deployment of collaborative data platforms and standards for SCOPE 3 measurement, involving suppliers, customers and industry associations
- Research on incentive mechanisms and governance models that encourage supplier participation in shared ESG ecosystems

Integration with Circular Economy and Product Level Metrics:
- Extension of UDEF to support product carbon footprints, circulatory indicators and digital product passports aligned with emerging EU regulations (e.g. Ecodesign for Sustainable products regulation)
- Investigation of how product level data can be integrated with facility level and corporate level ESG metrics within a unified architecture

Human and Organizational Dimensions:
- Qualitative studies on change management practices, governance models and capacity building approaches
- Research on the role of leadership, culture and incentives in embedding data-driven sustainability management with manufacturing organisations

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