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Integration of Real-time Carbon Accounting and Energy Management for Strategic Decarbonization in Electronics Manufacturing

Ying-Lun Mao,[1*] Huang-Chih Sung,[2] and Wei-Hsi Hung[1]

[1]Department of Management Information Systems, National Chengchi University, Taipei 11605, Taiwan
[2]Graduate Institute of Technology, Innovation & Intellectual Property Management, National Chengchi University, Taipei 11605, Taiwan

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The electronics manufacturing sector has significantly contributed to global greenhouse gas emissions, increasing the urgency for effective carbon footprint management. A traditional carbon accounting system (CAS) focuses primarily on compliance, relying on retrospective electricity billing data. However, CAS lacks equipment-level granularity, predictive capabilities, and real-time responsiveness. In this study, we integrated CAS with the energy management system (EMS) based on design science research methodology (DSRM). The CAS-EMS system addresses three key limitations: (1) insufficient granularity in ISO 14064-1 Category 2 emissions data, (2) the reactive nature of emission monitoring, and (3) data silos between CAS and EMS. The CAS-EMS system enables real-time, equipment-level carbon emission visibility and leverages advanced predictive analytics for proactive emission management. In electronics manufacturing, the system demonstrated a significant increase in data granularity by 91.7% and a reduction in anomaly response time by 93.8%. Such an enhanced decision support of the system enables targeted decarbonization strategies, leading to measurable economic and environmental benefits. The system underscores the transformative potential of integrated carbon and energy management as a scalable model for strategic decarbonization across various industries.

1. Introduction

The electronics manufacturing sector has significantly contributed to global greenhouse gas (GHG) emissions, accounting for more than 15% of total emissions from the Industrial Process and Product Use Sector in Taiwan.(1) The sector's environmental impact is amplified in the lifecycle of electronic devices from resource extraction and processing to high energy consumption. With growing global climate concerns, electronics manufacturers are under increasing pressure to minimize and manage their carbon footprint. This pressure extends to

*Corresponding author: e-mail: nhk4321@gmail.com
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stakeholders, including governments, investors, and customers, which drive demand for more sustainable practices and compliance with stricter regulatory frameworks.[2] This pressure to improve environmental performance comes from regulatory bodies as well as investors, customers, and other stakeholders who increasingly demand transparency and accountability.

Traditionally, carbon management in electronics manufacturing has been compliance-driven, with companies focused on meeting minimum regulatory requirements through periodic reporting cycles.[3] However, this method fails to account for the dynamic nature of manufacturing operations and overlooks opportunities for strategic emissions reduction. Transitioning from compliance-focused carbon accounting to strategic carbon management represents a fundamental paradigm shift from one that demands new methodologies, technologies, and organizational frameworks.[4]

A current carbon accounting system (CAS) in electronics manufacturing has limitations that hinder effective carbon management. First, CAS heavily relies on electricity billing to aggregate facility-level data, lacking granularity to identify specific emission sources and reduction opportunities at the equipment level.[5] This limitation creates a significant disconnection between carbon accounting and operational decision-making, preventing managers from directly linking emissions to specific production processes or equipment. Second, traditional CAS operates on the retrospective verification cycle, often monthly or quarterly, which is not real-time monitoring, so it does not immediately respond to emission anomalies. This approach delays the implementation of corrective actions and limits the ability to proactively control GHG emissions. The lag between emission generation and reporting presents a fundamental obstacle to effective carbon management. Third, this approach is isolated from other operational systems, particularly the energy management system (EMS), as it leads to data silos that impede comprehensive analysis and decision-making.[6] This leads to duplicated efforts, inconsistent data, and missed opportunities to optimize energy consumption and carbon emissions.

To overcome these limitations, we examined the following: (1) the integration of a carbon management system in electronics manufacturing, leveraging ISO 14064-1 Category 2 electricity consumption data at the production equipment level, (2) the expansion of CAS to incorporate EMS, enabling the proactive forecasting and management of carbon emissions, and (3) the fusion of carbon and energy management systems to facilitate the real-time tracking of carbon reduction targets and support the implementation of decarbonization measures. On the basis of the results, we have developed and validated an EMS integrated CAS system (CAS-EMS system) using data science research methodology (DSRM). The CAS-EMS system includes sensors and IoT devices to collect real-time data on carbon emissions in manufacturing processes.[4] The sensors used to measure carbon emissions and energy consumption include nondispersive infrared CO_2 sensors for accurate measurement and real-time monitoring, and current sensors, voltage sensors, pulse counters, and smart meters for the real-time monitoring of electricity consumption at various levels.[7,8]

The real-time data is used to identify specific areas or equipment that significantly contribute to carbon emissions. The system transforms the way that electronics manufacturers set decarbonization goals, from the broad, facility level to the specific equipment level, with the effective implementation of advanced technologies. The real-time nature of the system enables immediate feedback on carbon emission reduction, supporting continuously improved and adaptive management strategies.[4]

Integrating carbon accounting with energy management delivers environmental and economic benefits. By optimizing energy consumption based on carbon intensity, manufacturers can simultaneously lower emissions and reduce energy costs, strengthening their business and sustainability.[3]

2. Literature Review

2.1 ISO 14064-1 and GHG protocol

Carbon accounting requires standardized frameworks for measuring, reporting, and verifying GHG emissions. Two global frameworks, ISO 14064-1 and the GHG Protocol, set foundational principles and requirements for developing organizational GHG inventories.

ISO 14064-1 specifies principles and requirements for quantifying and reporting GHG emissions at the organizational level. In ISO 14064-1, emissions are classified into Categories 1–6: Category 1 represents direct emissions, Category 2 covers indirect emissions from imported energy, and Categories 3–6 encompass other indirect emissions. However, ISO 14064-1 provides limited guidance on implementation specifics within complex manufacturing environments. In the GHG Protocol, emissions are classified into Scopes 1–3, that is direct emissions, indirect emissions from purchased electricity, and other indirect emissions, respectively.[3] The GHG Protocol aligns well with financial accounting practices and has been widely used. Recent developments such as the Science-based Targets Initiative (SBTi) and the task force on climate-related financial disclosures (TCFD) emphasize structured target setting and enhanced integration between carbon and financial accounting.[4]

Despite these advancements, both frameworks primarily emphasize periodic reporting rather than real-time monitoring, limiting their applicability to dynamic manufacturing environments. Addressing this limitation requires integrating real-time operational functionality into existing methodologies.

2.2 Supervisory control and data acquisition (SCADA)

The SCADA system is widely used in the industrial control of carbon emissions, enabling supervisory management across manufacturing and infrastructure industries.[9] SCADA enables networked communications and provides graphical interfaces to manage the remote and real-time data collection and analysis from sensors and equipment for informed decision-making on carbon emission control (Fig. 1).[10] SCADA shows its effectiveness in real-time monitoring, enhancing the operational efficiency, predictive maintenance, and reliability of equipment.[11] SCADA with advanced technologies, such as IoT, significantly expands its capabilities, offering real-time data collection and presentation on web platforms.[12] The SCADA system integrates sensor data for the real-time management of carbon emission control in electronics manufacturing.

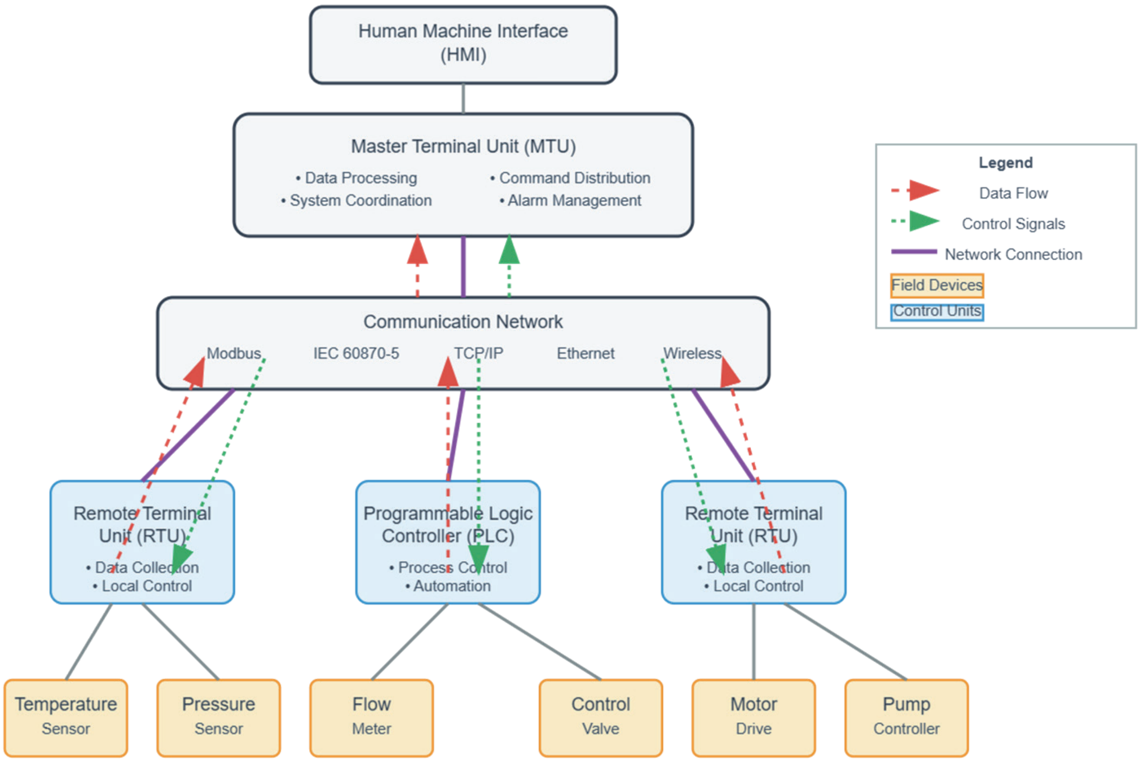

Fig. 1. (Color online) SCADA system architecture.

2.3 CAS and EMS in electronics manufacturing

CAS in electronics manufacturing has evolved from basic spreadsheets to sophisticated and automated platforms integrated with an enterprise resource planning (ERP) system. However, while CAS focuses on compliance rather than strategic carbon emission reduction, it suffers from a temporal disconnect between energy consumption data and emission reporting. EMS, on the other hand, optimizes energy consumption based on real-time sensor data, with machine learning (ML) algorithms for the prediction of energy consumption and carbon emissions.[6] EMS and CAS complement each other to enhance operational and carbon management effectiveness.[4] Recent studies have explored the integration of EMS and CAS, highlighting their benefits in enhancing decision-making to reduce energy consumption and carbon emissions. On the basis of the results, we developed a CAS-EMS system tailored to electronics manufacturing in this study.

2.4 Limitations of current method

Current systems lack equipment-level granularity in carbon emission tracking, as well as predictive capabilities and real-time management. With aggregated facility-level data, variations among equipment are not easy to identify, requiring targeted carbon emission reduction. The limited forecasting capabilities of the current systems also hinder proactive carbon emission management in dynamic operations. Additionally, the independent operation of CAS and EMS leads to data silos, restricting strategic decision-making and real-time corrective actions. Recent advancements, such as AI-driven forecasting and ML-powered real-time analytics, are promising solutions for overcoming these limitations through the effective integration of CAS and EMS. This enhances the operational effectiveness of carbon emission control systems.

3. Methodology

3.1 DSRM in system design and development

DSRM enables a structured approach to solving complex problems related to carbon emission control systems. Unlike traditional methods that focus on describing, explaining, or predicting, DSRM is used to create and evaluate systems designed to solve problems.(13) DSRM is particularly well suited for developing a system that integrates carbon accounting and energy management in electronics manufacturing. The DSRM employed in this study comprises six steps:(14) (1) problem identification and motivation, (2) definition of solution objectives, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. This iterative process enables the continuous refinement of the CAS-EMS system for carbon emission control based on evaluation results and stakeholder feedback. Figure 2 illustrates the DSRM integrated into the CAS-EMS system in this study.

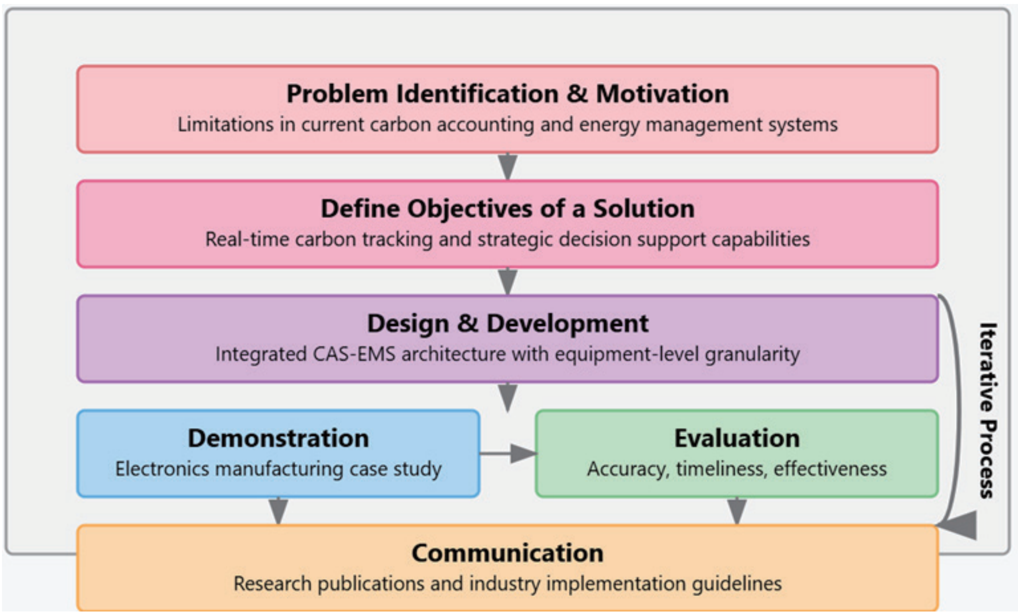

Fig. 2. (Color online) DSRM employed in CAS-EMS integration.

3.2 Problem identification

To identify key limitations and bottlenecks, current carbon accounting and energy management in electronics manufacturing methods were analyzed, and a literature review, sector benchmarking, and stakeholder interviews were conducted. The results revealed the following problems: (1) a lack of equipment-level granularity in carbon emission data, preventing targeted carbon emission reduction goals, (2) the reactive nature of carbon accounting, focusing on verification rather than proactive management, and (3) the limited integration between carbon accounting and energy management systems, leading to data silos and inefficiencies. These challenges in the electronics manufacturing sector stem from its energy-intensive nature, reliance on complex supply chains, and growing regulatory and market pressure.

3.3 Objectives of CAS-EMS system

Building on the identified limitations, the CAS-EMS system was designed with the following objectives: (1) enhancing equipment-level carbon emission control efficiency by disaggregating ISO 14064-1 Category 2 electricity consumption data to individual production equipment, (2) shifting from reactive verification to proactive management through real-time data integration and predictive analytics, and (3) supporting decarbonization strategies with advanced data collection, scenario modeling, and recommendation engines. These objectives were used for the system's design and development to address challenges and deliver tangible benefits to electronics manufacturers.

3.4 System module

The CAS-EMS system consists of modules that were developed according to the system objectives. The development process involved the following steps:

- Framework is designed by integrating CAS with EMS for data collection, modeling, calculation, and system architecture design.
- Data integration layer is developed by developing interfaces and protocols for collecting, validating, and integrating data from energy meters, production equipment, ERP systems, and supply chain partners.
- System module is developed by implementing the components of the CAS-EMS system, including the calculation engine, energy optimization algorithms, and data storage infrastructure.
- Analytics and visualization module is developed by developing advanced analytics for pattern recognition, anomaly detection, and predictive modeling on visualization interfaces for different stakeholder groups.
- Decision module is developed by implementing scenarios, optimization algorithms, and recommendation engines for strategic decarbonization decisions.

Throughout the process, stakeholder feedback was gathered iteratively to refine the system module design, which aligns with user requirements.

3.5 Validation method

The CAS-EMS system for electronics manufacturing was validated by evaluating its effectiveness in addressing identified limitations and achieving defined objectives. The validation was conducted from the perspectives described below.

3.5.1 Facilities

The validation of the CAS-EMS system was conducted in a medium-sized factory of electronics components. The facility operates 24 h seven days with multiple production lines. It has diverse equipment with different energy consumption patterns. The factory is a representative environment for testing the system.

3.5.2 Data collection and analysis

The validation was conducted in the following steps:

- Baseline assessment: The current carbon accounting and energy management practices are documented, using data collection methods, calculation methods, reporting frequencies, and decision-making processes.
- System implementation: The hardware components are implemented in the CAS-EMS system, including sensors (e.g., infrared CO_2 sensors, current sensors, voltage sensors, and pulse counters) and smart meters, or gateways (IoT or smart meter gateways), and software modules for data integration, carbon calculation, analytics, and visualization.
- Parallel operation: The CAS-EMS system is operated in existing systems for three months to compare their performance characteristics and results.
- Data collection: Quantitative and qualitative data are collected on system performance, user experiences, and outcomes throughout the validation period.
- Comparative analysis: the data are collected to compare the effectiveness of the CAS-EMS system in baseline practices and evaluating its contribution to achieving the defined objectives.

3.5.3 Metrics for evaluation

Various metrics were calculated to assess the system's performance.

- Accuracy for data collection, carbon emission calculation, equipment-level granularity, and forecasting was measured on the basis of the mean absolute percentage error (MAPE).
- Timeliness was evaluated for data refresh interval, anomaly detection time, decision response time, and compliance reporting time.
- Effectiveness in carbon emission reduction, energy cost savings, decision-making effectiveness for reducing carbon emissions, and user satisfaction were assessed. In particular, decision-making effectiveness was assessed by experts.

These metrics were used for a multidimensional assessment of the CAS-EMS system's performance and its contribution to addressing the identified problems in carbon accounting and energy management.

4. System Development and Integration

4.1 System architecture

The CAS-EMS system architecture was designed to enable seamless data flow from different energy consumption sources. The architecture consists of data source, integration, core system, and application layers (Fig. 3).

The CAS-EMS system employs a service-oriented architecture (SOA) with standardized application programming interfaces (APIs) to facilitate data exchange between modules.(6) The system comprises the following components:

- A unified data structure was used to harmonize energy consumption data, emission factors, production metrics, and contextual information from diverse sources.
- Middleware components were employed to handle data transformation, validation, and routing between CAS and EMS modules.
- A real-time event processing system detected significant patterns or anomalies in energy consumption or carbon emissions and triggers appropriate responses.

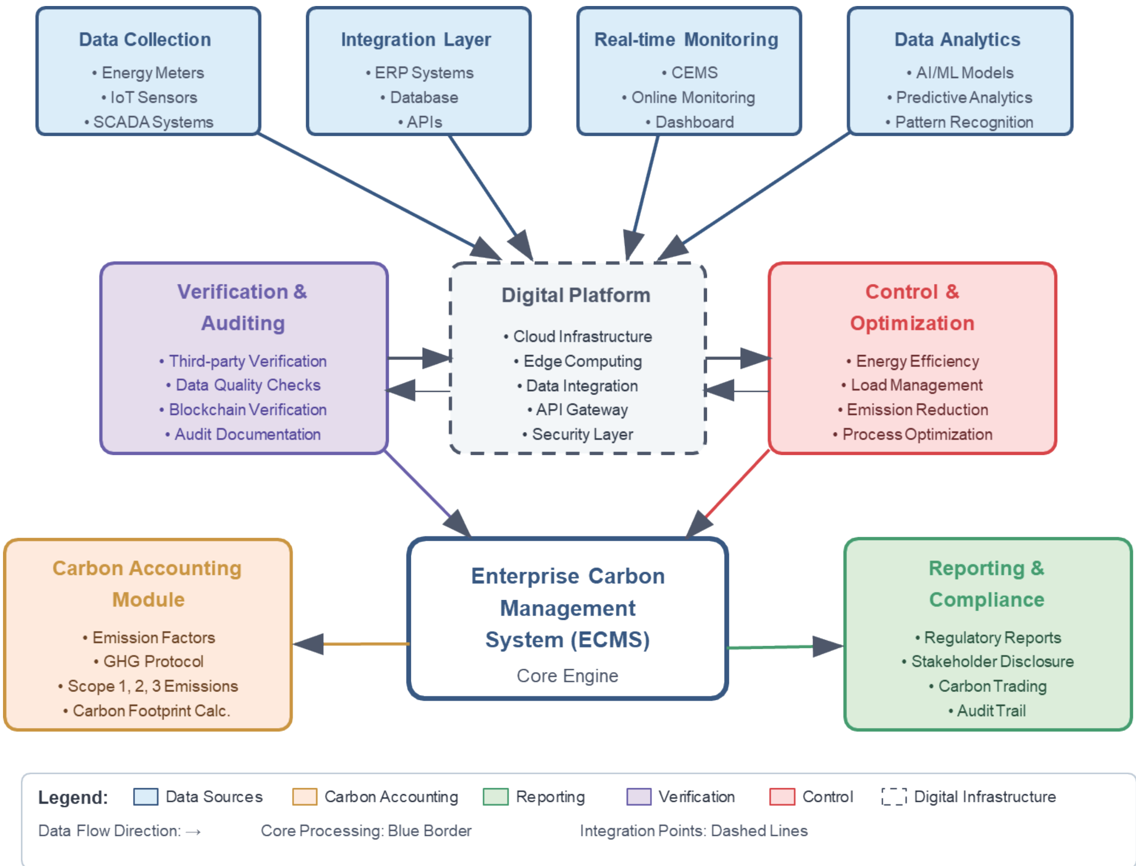

Fig. 3. (Color online) Architecture of CAS-EMS system.

- A centralized repository was employed for managing reference data, carbon emission factors, equipment specifications, and organizational hierarchies.

The system enables bidirectional data flow between CAS and EMS modules, enabling decisions on energy optimization considering carbon emission reduction and energy efficiency.

4.1.2 Energy consumption

The CAS-EMS system disaggregates facility-level energy consumption to individual equipment following ISO 14064-1 Category 2. It employs both top-down and bottom-up methods to ensure accuracy and completeness.

- Top-down method: With the facility-level electricity consumption estimated with utility bills, the system allocates energy consumption to systems, such as the heating, ventilation, air conditioning (HVAC) control, and lighting systems, based on meter data and historical patterns.
- Bottom-up method: Energy consumption for production equipment is measured using meters or power monitoring devices to collect granular, real-time data.
- Reconciliation algorithm: An advanced algorithm reconciles top-down allocation with bottom-up measurements, detecting and distributing discrepancies to ensure that the sum of equipment-level energy consumption aligns with the total energy consumption.
- Dynamic profiling: Equipment-specific energy consumption profiles are created on the basis of operational status, production volumes, and environmental conditions for the accurate estimation of the energy consumption of equipment without direct measurement.

The method to estimate energy consumption enables the visualization of equipment-level carbon emissions to identify carbon emission hotspots to implement targeted reduction measures.

4.1.3 Real-time data collection and processing

The real-time data collection and processing module is the backbone of the CAS-EMS system for periodic reporting and continuous monitoring and the management of energy consumption and carbon emission reduction. The developed module consists of the following components:

- IoT network: At the gateways in a distributed network, data are collected from energy meters, equipment sensors, and production systems at intervals of 1–5 min.
- Data validation engine: A developed automated module examines incoming data for completeness, accuracy, consistency, and anomalies for further analysis.
- Real-time processing engine: A data processing engine converts energy consumption data to carbon emissions on the basis of emission factors.
- Temporal database: A time-series database is constructed for the efficient storage, retrieval, and analysis of historical energy and carbon emission data.

These components enable the prompt detection of emission anomalies, the rapid response to changing conditions, and the continuous tracking of carbon emissions and reduction.

4.2 Modules

The CAS-EMS system comprises interconnected modules for carbon emission monitoring and energy management. The CAS-EMS system's effectiveness stems from this synergistic combination: physical sensors and meters provide the foundational data, gateways ensure efficient data flow, specialized software processes and analyzes this data for predictive insights, and an intuitive dashboard makes these insights actionable for decision-makers.

4.2.1 Energy consumption-tracking module

The equipment-specific energy consumption tracking module is used to analyze energy consumption patterns at an individual equipment level. It performs the following functions: The module consists of diverse sensors and smart meters, including electricity, gas, water, thermal, and steam meters, complemented by current transformers and various environmental sensors (temperature, humidity, flow, pressure, occupancy, light, and fuel level sensors). These devices capture granular data from utility entry points to individual equipment. The data collected is aggregated and transmitted by data loggers and gateways, which are responsible for protocol conversion and initial data processing. Software, such as Apache Kafka, is used to process real-time data. This module functions as follows.[15]

- Equipment registration in a database, including all energy-consuming equipment, specifications, operational parameters, and expected consumption patterns
- Real-time energy consumption monitoring through direct measurement or estimation based on operational status and dynamic profiles of equipment
- Correlation analysis of energy consumption among production volumes, equipment status, and environmental parameters to evaluate efficiency
- Automated identification of unusual energy consumption patterns related to equipment malfunction, inefficient operation, or data collection errors

This module converts generic energy consumption data of equipment to carbon emission data for the development of targeted and optimized carbon reduction measures.

4.2.2 Predictive analytics module

In this module, advanced software packages are used to forecast energy consumption and carbon emissions. ML libraries and frameworks, such as Scikit-learn, TensorFlow, and PyTorch, are used for statistical modeling and anomaly detection. Algorithms for time-series forecasting (e.g., ARIMA, and Prophet) and anomaly detection methods are adopted in the module to identify unusual patterns. Simulation and optimization engines are also employed to evaluate alternative energy strategies and identify optimal solutions for emission reduction. This module requires high-performance computing resources, either through dedicated on-premise servers or scalable cloud computing platforms, with edge computing for real-time predictions. This module performs the following functions:[16,17]

- Time series data forecasting: The ML algorithm analyzes historical patterns to predict future carbon emissions on multiple time scales (hourly, daily, and monthly).
- Multivariate analysis with multiple variables (e.g., production schedules, weather forecasts, and grid carbon intensity) is conducted to improve forecast accuracy.
- Modeling: Different scenarios are created to evaluate carbon emissions and identify optimal strategies.
- Uncertainty quantification: Reliability in the forecast is assessed using sensitivity analysis, and the result enables an understanding of potential results.

This module enables proactive carbon emission control by predicting carbon emission patterns and evaluating the potential impact of different carbon emission reduction strategies before implementation.

4.2.3 Dashboard module

The dashboard module provides an intuitive user interface (UI), presenting complex data in an easily digestible format. Front-end development frameworks, including React and Angular, are employed to create interactive web-based UIs. Powerful data visualization libraries (e.g., D3.js, Plotly, and Grafana) are integrated to render dynamic charts, graphs, and customized dashboards to gather data on energy consumption, carbon emissions, and reduction target achievements. The module's backend is supported by web server software and APIs that connect the module to the underlying databases and analytics engines. Servers are used to run the application. The dashboard module enables the intuitive visualization and decision-making of different stakeholder groups. This module functions as follows.[17]

- Real-time monitoring of current energy consumption, carbon emissions, and performance metrics at facility and equipment levels.
- Visual representation of historical patterns, progress toward reduction targets, and performance comparison of equipment or facilities.
- Interactive decision support in different scenarios by evaluating carbon emission reduction measures and developing strategic decarbonization plans.
- Notification for emission anomalies, target deviations, or optimization opportunities, ensuring timely response to changing conditions.

The dashboard module processes complex data for informed decision-making at operational and strategic levels. Figure 4 illustrates the data flow in the CAS-EMS system.

5. Results

5.1 System validation

The CAS-EMS system was validated on the basis of its performance and capabilities across various scenarios, including normal operations, production variations, equipment maintenance incidents, and simulated anomalies. The validation results are summarized in Table 1.

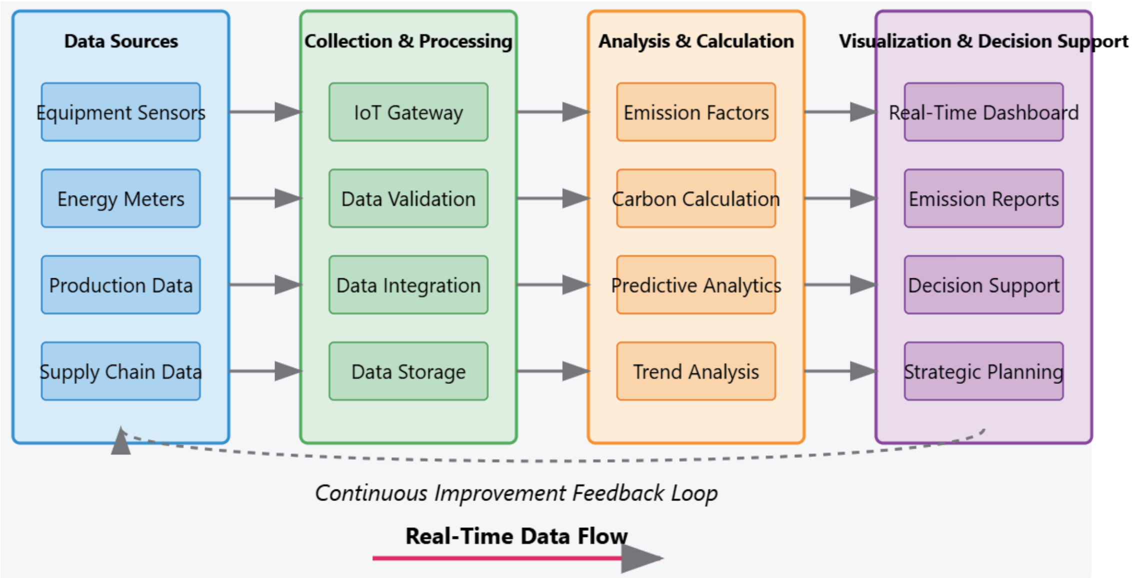

Fig. 4. (Color online) Real-time carbon emission data flow in CAS-EMS system for electronics manufacturing.

Table 1
Summary of validation results: baseline and post-implementation energy consumption and carbon emissions, and their improvement.

Performance metric	Measurement	Baseline performance	CAS-EMS system performance	Reduction (%)
Visualization of equipment energy consumption	System functions and operation interface	Non-available	Available	-
Visualization of achievement of reduction targets	System functions and operation interface	Non-available	Available	-
Equipment-level granularity	Average data refresh interval	1–24 h	5 min	> 91.7
Temporal resolution	Average data refresh interval	24 h	5 min	99.70
Decision response time	Average time from anomaly detection to corrective action	72 h	4.5 h	93.80
Reporting time	Person hours required for monthly compliance reporting	42.5 h	8.3 h	80.50

This table presents the validation results for the CAS-EMS system, comparing its performance with traditional methods. Reduction (%) presents the improvement achieved by the system. The reduction was calculated by determining the difference between the baseline performance and the CAS-EMS system performance, and then dividing that difference by the baseline performance, multiplied by 100 as a percentage.

5.1.1 Accuracy and granularity improvements in energy consumption at equipment level

The CAS-EMS system significantly enhanced accuracy and granularity compared with traditional carbon accounting methods. Such improvements were enabled by the direct measurement of equipment-level consumption, an advanced reconciliation algorithm, bottom-up measurements, and top-down allocation. The system improved the equipment-level granularity by 91.7% by identifying emission hotspots that were not detected in traditional methods. For example, a single-wave soldering machine accounted for 18.2% of total carbon emissions despite representing only 7.5% of production capacity, being identified as a key target for the optimization of energy consumption and carbon emissions.

5.1.2 Decision-making capability for carbon emission reduction

The system's real-time management capability was assessed through the scenario-based testing of decision-making processes. The average response time from anomaly detection to corrective action decreased from 72 h with traditional methods to 4.5 h, showing a 93.8% reduction. This rapid response enables immediate corrections of identified inefficiencies, preventing prolonged periods of carbon emissions. The system's decision support capability was effective in evaluating alternative carbon emission reduction measures. In a simulated scenario, it identified that upgrading the HVAC control system reduced carbon emissions by 4.2% in 14 months, while optimizing the compressed air system reduced carbon emissions by 3.8% in only seven months. This analysis result enabled investment prioritization considering environmental and financial factors.

5.2 Overall system capability

The validation results demonstrated that the combination of top-down allocation, bottom-up measurement, reconciliation algorithms, and dynamic profiling enabled an effective breakdown of facility-level energy consumption to individual equipment. A 91.7% faster equipment-level granularity showed the effectiveness of the CAS-EMS system. The system also bridges the gap between the compliance data of ISO 14064-1 Category 2 and real decision-making in operation at the equipment level. A 93.8% reduction in decision response time showed the system's capability of transforming reactive verification into proactive management. Integrating real-time energy consumption data with carbon emission calculations enables continuous monitoring and rapid responses to changing conditions (Table 2). The predictive analytics module provides accurate forecasts and supports proactive planning and optimization, considering the temporal carbon emission dynamics. The validation results also indicated the real-time tracking of the goal achievement of carbon emission reduction and data-driven decisions for decarbonization measures. The system's ability to identify emission hotspots, evaluate alternative reduction measures, and provide immediate feedback on changes in carbon emissions leads to a continuous improvement cycle that accelerates decarbonization efforts.

Table 2
Comparison of performance characteristics of traditional carbon accounting methods and CAS-EMS system.

Feature	Traditional method	CAS-EMS system	Improvement
Data granularity	Facility-level aggregation based on utility bills	Equipment-level monitoring with real-time sensor data	Enhanced precision in identifying emission sources and reduction opportunities
Temporal resolution	Monthly or quarterly reporting cycles	Real-time or near real-time monitoring	Immediate detection of anomalies and rapid response capability
Emission calculation	Retrospective calculation using emission factors	Dynamic calculation with real-time energy consumption data	More accurate emissions quantification reflecting operational variations
Decision support	Reactive analysis based on historical data	Proactive forecasting and scenario modeling	Strategic decision-making with predictive capabilities
Compliance management	Manual verification and reporting processes	Automated data collection and verification	Reduced compliance risks and reporting errors
Integration with operations	Siloed from operational systems	Fully integrated with production and energy systems	Holistic view of carbon-energy-production relationships
Data validation	Limited cross-verification capabilities	Multi-source data validation and anomaly detection	Higher data quality and reliability
Stakeholder engagement	Periodic disclosure through sustainability reports	Continuous visibility through dashboards and alerts	Enhanced transparency and stakeholder trust

The validation results confirmed that the CAS-EMS system successfully addressed the limitations of traditional carbon accounting methods by providing unprecedented capabilities of real-time carbon emission monitoring and strategic decarbonization decision-supporting in the electronics manufacturing sector.

6. Discussion

6.1 CAS-EMS system

The integration of CAS and EMS has enhanced carbon emission control in the electronics manufacturing sector, transforming a compliance-driven method into one that incorporates strategic methods into daily operations. The CAS-EMS system enables effective carbon emission control in electronics manufacturing by breaking down facility-level energy consumption into individual equipment consumption, enhancing granularity in carbon emission control. The system combines top-down allocation with bottom-up measurement to ensure accuracy and completeness.

The architecture of the system was designed to avoid data silos and functional disconnects that limit the effectiveness of traditional methods. The system adopts advanced predictive analytics of carbon emissions and energy consumption for proactive planning. These capabilities empower manufacturers to predict emission patterns, evaluate alternative strategies, and minimize their carbon emissions. The decision support module in the system processes complex carbon emission and energy consumption data in an easily understandable form. This significantly enhances the quality and timeliness of decarbonization decisions, thereby accelerating progress to achieve emission reduction targets. The CAS-EMS system addresses limitations in current carbon management systems, including limited granularity, reactive verification, and insufficient decision support. The validation results indicated that the system demonstrated significant improvements across all three areas.

The CAS-EMS system contributes to socio-technical sustainability by integrating traditionally separate domains. The application of DSRM in the system enables the integration of different systems for ensuring sustainability. By adopting real-time analytics for continuous carbon emission control, manufacturers can enhance their carbon emission control ability in existing energy management systems. The modular architecture and phased implementation of the CAS-EMS system are affordable at varying levels of technical and organizational maturity. The improvements of the system in accuracy, timeliness, and effectiveness encourage companies to invest in the integrated carbon and energy management system.

6.2 New approach to carbon emission control

The CAS-EMS system enables the identification of operational metrics that affect daily decisions on equipment operation, considering energy consumption and carbon emission reduction. The metrics used in the system can be used with other operational metrics, including quality, productivity, and costs, in formulating a manufacturing strategy. This integration redefines how to control carbon emissions. Carbon emission reduction efficiency is influenced by daily decisions and controlled by other operational metrics such as quality, productivity, and costs. The real-time feedback of the system enhances the equipment-level granularity and targeted optimization strategies in carbon emission control, which was previously impossible with aggregated data and traditional methods.

The CAS-EMS system allows managers to intervene on the bases of emission impact, implementation cost, and operational constraints, maximizing the return on investments in decarbonization. The system also pinpoints emission hotspots in the manufacturing facility, enabling timely interventions. The system optimized energy consumption and carbon emissions. Traditional methods treat them separately, leading to conflicting strategies. The CAS-EMS system allows for holistic optimization as it identifies solutions that simultaneously reduce both energy costs and carbon emissions. This approach strengthens sustainable development by delivering environmental and economic benefits. The CAS-EMS system offers the following advantages beyond carbon emission reductions:

- Enhanced decision-making capability: Real-time data, predictive analytics, and scenario modeling tools empower informed and timely decisions regarding production scheduling, equipment maintenance, energy procurement, and capital investments. These improved capabilities enhance the speed and quality of carbon-related decisions, providing a competitive edge in dynamic regulatory and market environments.
- Streamlined compliance processes: Automated data collection, validation, and reporting functions significantly reduce the time and resources needed for compliance activities. An 80.5% reduction in compliance reporting time contributes to substantial cost savings and

reduced compliance risks. Improved data accuracy also ensures the credibility of carbon emission data, increasing stakeholder trust.

- Operational efficiency improvement: Data on equipment-level energy consumption and operational inefficiencies are provided to improve equipment reliability, product quality, and production throughput. Integrating a carbon emission control strategy with operational systems facilitates continuous improvements of sustainability and efficiency.
- Strategic response to regulations: As regulations on carbon emissions become more stringent and comprehensive, companies with advanced carbon emission control capabilities better adapt to new requirements, employing the CAS-EMS system. The system provides data infrastructure, analytical capabilities, and organizational processes to respond effectively to evolving regulations.

These advantages enable companies to adopt integrated carbon and energy management systems, beyond mere regulatory compliance or market-driven pressures.

6.3 Applicability and challenges

The CAS-EMS system has applicability across various industrial sectors with similar characteristics to the electronics manufacturing sector. Automotive, chemical, pharmaceutical, and food processing sectors share common characteristics with electronics manufacturing in terms of complex production processes, diverse equipment types, and significant energy consumption. The ability of mapping facility-level energy consumption to the individual equipment of the CAS-EMS system can be applied to other sectors with minimal modifications. Industries that need continuous manufacturing processes, such as paper, cement, and steel industries, benefit from the real-time monitoring and predictive analytics capabilities of the system. Forecasting models need to be modified according to the processes; the architecture of the system in this study is applicable. The principles of integrating energy management with carbon accounting extend beyond manufacturing to commercial buildings, where HVAC systems, lighting, and IT infrastructure are the major carbon emission sources. By modifying the modules, the CAS-EMS system can be adapted to the building management system with different operational patterns and control systems. The scalability of the system is enhanced by its modular architecture, which allows for the selective implementation of components based on needs, technical capabilities, and resource constraints. This modularity enables the implementation, starting with high-impact areas and gradually expanding to comprehensive coverage.

By integrating sophisticated AI techniques, such as deep learning and reinforcement learning, the system's predictive and optimization capabilities can be enhanced. These techniques enable the accurate forecasting of complex carbon emission patterns of different types of equipment, the autonomous optimization of operational parameters, and intelligent anomaly detection with reduced false positives. The current system focuses on Scope 2 emissions (indirect emissions from purchased electricity). The system needs to be enhanced to incorporate Scope 1 (direct emissions from owned sources) and Scope 3 (all other indirect emissions) emissions. This necessitates additional data sources from diverse supply chains and product management systems, and the development of additional calculation methods. Intuitive visualization techniques, such as augmented reality interfaces that overlay carbon data on physical equipment, need to be added to enhance user engagement and understanding. These advanced interfaces contribute to more tangible and accessible carbon emission analysis and prediction. Financial planning and accounting systems can be combined to strengthen carbon emission reduction initiatives with cost-benefit analyses and return on investment calculations. This integration enables the effect of carbon emissions and their control on capital planning, budgeting, and performance management processes. For the mentioned advancements, a sector-wide collaborative platform must be constructed to share anonymized carbon performance data, best practices, and reduction strategies, and accelerate learning and innovation. These platforms leverage the data generated by the CAS-EMS system to identify patterns and opportunities at the individual facility level.

Future research and development are necessary to improve the present CAS-EMS system. The system applied to existing operational systems enables the electronics manufacturing sector to transition to a low-carbon industry while maintaining competitiveness and operational excellence. To ensure successful modification and cross-sector application, the following needs should be enhanced:

- Data availability and quality: Different sectors and companies vary in data infrastructure, which might limit the immediate applicability of the CAS-EMS system. Data gaps require additional investments in metering, sensing, and data management.
- Process complexity: Industries with highly complex, interconnected processes require sophisticated modeling to accurately measure energy consumption and carbon emissions in manufacturing processes and equipment.
- Organizational readiness: The successful implementation of the integrated carbon and energy management system requires technical capabilities and organizational readiness in terms of skills, processes, and cultural alignment.

These challenges can be addressed by developing sector-specific implementation guidelines, reference architectures, and capability development programs through collaboration among technology providers, companies, research institutions, and regulatory bodies.

7. Conclusion

In this study, we demonstrated that the integration of CAS and EMS transforms carbon emission control in electronics manufacturing, which can be an essential strategic operational function. The developed CAS-EMS system enhances data and equipment granularity by breaking down facility-level energy consumption to individual equipment, ensuring high accuracy and completeness, and adopting a hybrid top-down and bottom-up measurement approach. Advanced sensors, meters, gateways, and software technology enable the granularity enhancement, which provides the foundational, high-resolution data inputs for the entire system.

The CAS-EMS system's robust architecture effectively overcomes the limitations of traditional approaches by providing advanced predictive analytics and comprehensive decision support. The system empowers manufacturers to proactively manage emissions, accelerate decarbonization efforts, and achieve reduction targets more efficiently. Beyond direct carbon reductions, the CAS-EMS system delivers advantages, including an improved decision-making capability through real-time data and scenario modeling, streamlined compliance processes (an 80.5% reduction in reporting time), enhanced operational efficiency, and a strengthened ability to respond strategically to evolving carbon regulations. By integrating carbon and energy management with operational metrics, such as quality, productivity, and cost, optimal solutions are provided to yield environmental and economic benefits.

The CAS-EMS system is applicable across diverse industrial sectors sharing similar operational characteristics, such as automotive, chemical, pharmaceutical, and food processing, and can even be adapted for commercial buildings. However, successful cross-sector adoption and further enhancement necessitate addressing challenges related to data availability and quality, process complexity, and organizational readiness. Therefore, future research and development are necessary to integrate advanced AI techniques, such as deep learning and reinforcement learning, to expand the system that incorporates Scope 1 and Scope 3 emissions, and enhance user engagement through intuitive visualization tools such as augmented reality. The continuous development and integration of the CAS-EMS system require sophisticated sensor technologies to capture finer details of energy consumption and environmental parameters. Financial planning and accounting systems must be linked to decarbonization efforts. By establishing sector-wide collaborative platforms, data, best practices, and innovation can be shared. Ongoing innovation in sensor technology contributes to the construction of a powerful framework for industries to maintain competitiveness and operational excellence with low-carbon policies.

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