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ENACT: ENERGY & CARBON-AWARE TECHNOLOGY

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Abstract: The fast development of digital technologies has led to increased carbon emissions from daily digital activities and ineffective coding techniques. In order to support the Sustainable Software Engineering, this paper presents ENACT (Energy and Carbon-Aware Technology), an AI for Sustainability framework that combines Green Coding Analysis with Digital Carbon Footprint Tracking. ENACT has two agents, one that monitors the user side of activities like browsing, streaming, and cloud usage to find estimated CO_2 emissions and provide eco-friendly recommendations, and another that analyzes the code structures to find inefficiencies and suggest alternatives that use less energy. ENACT provides individualized insights, visible dashboards, and practical advice by using AI, machine learning, and carbon estimation benchmarks. Its expandable and dual agent plan establishes it as a carbon-aware technology that can lower digital emissions, support ethical coding, ad other sustainability objectives.

Keywords: **Green Coding, Digital Carbon Footprint, Sustainable Software Engineering, AI for Sustainability, Energy Efficiency.**

I. INTRODUCTION

Modern computing's increasing Digital Carbon Footprint is a major environmental cost of smooth development of digital technologies, which have transformed communication, labor, and innovation. Digital services like video streaming, cloud computing, and social media need so many computational resources, which requires large amounts of energy. Studies show that if the internet were a country, its energy consumption would rank among the top greenhouse gas emitters globally [1]. Inefficient software engineering practices like redundant calculations, excessive API calls, and high energy algorithms, increase the energy use [2], [3].

Existing efforts to overcome this problem have mainly targeted hardware-level optimizations like energy-efficient data centers and renewable-powered infrastructures [8]. These solutions are good but they ignore two critical factors, user-side digital behavior and developer-side inefficiencies in software design. A comprehensive system that can measure emissions and lead to sustainable software practices is needed to address this.

We suggest ENACT (Energy & Carbon-Aware Technology), an AI-driven framework that includes Carbon-Aware Technology into ecosystems, as a solution to this gap. ENACT functions by the use of two agents:

1. **Digital Carbon Footprint Tracking Agent**, which tracks the user actions (like browsing, streaming, cloud usage), estimates CO_2 emissions, and uses dashboards to provide eco-friendly suggestions.

2. **AI Agent for Green Coding**, which examines source code in several languages, identifies inefficiencies, and suggests energy-optimized substitutes.

Together, these agents promote awareness of digital emissions and encourage Green Coding practices among developers.

The main contributions of this work are:

1. **Awareness and Monitoring:** Real-time awareness of how digital actions affect the environment.
2. **Optimization and Sustainability:** AI-driven suggestions for environment friendly software development.
3. **Research and Engagement:** Promoting responsible digital ecosystems and carbon-aware computing.

In addition, ENACT bridges the gap between environmental research and practical software development by embedding sustainability directly into everyday digital workflows. By integrating monitoring, analytics, and intelligent optimization into a unified framework, ENACT empowers users, developers, and organizations to make data-driven decisions that reduce their digital carbon impact. This not only supports greener technological practices but also aligns with global sustainability goals and strengthens the movement toward energy-efficient, low-carbon digital infrastructures.

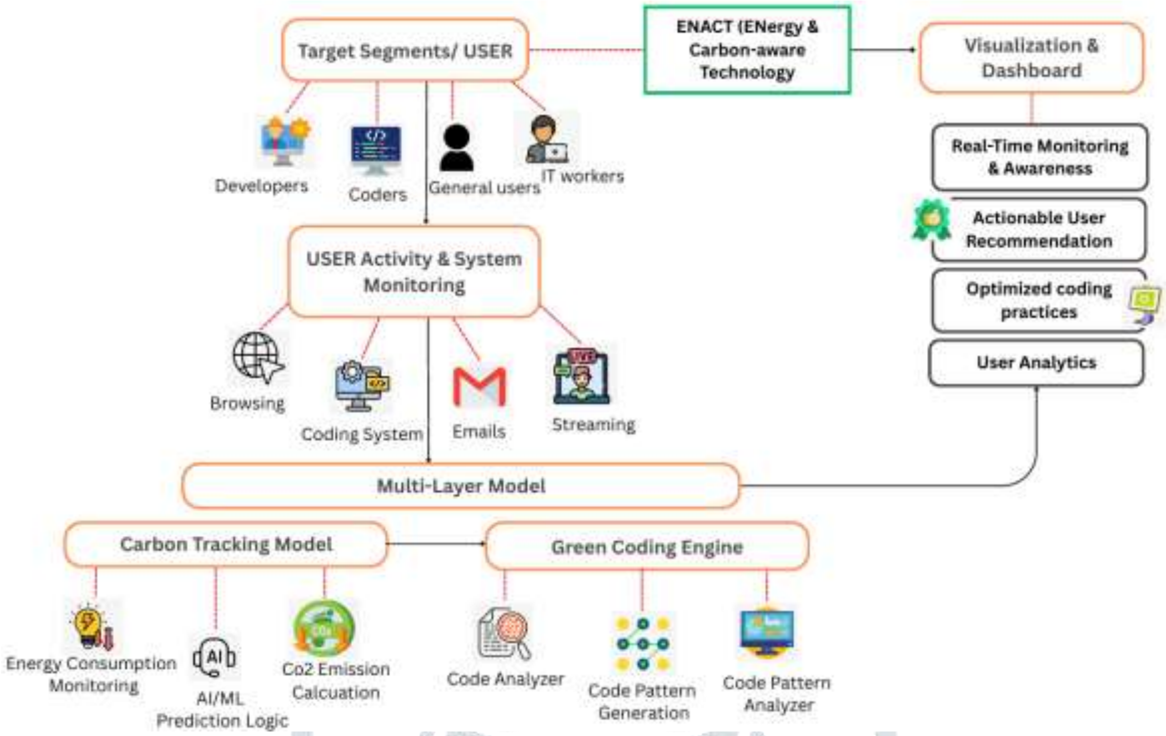

Fig. 1. System Architecture of ENACT (Energy & Carbon—Aware Technology)

Fig.1 shows how ENACT uses multi-layer model that involves energy usage tracking, CO_2 emission analysis, and AI-based code analysis to monitor user behaviors like browsing, coding, emails, and streaming. Insights are shown on a dashboard that provides real-time analytics, optimized coding suggestions, and environmental knowledge to encourage energy-efficient digital behavior.

II. LITERATURE REVIEW

Rising concerns over the ecological consequences of digital technologies have promoted studies on Digital Carbon Footprint tracking, Green Coding, and AI – driven sustainability solutions. Most studies focus on infrastructure – level solutions like energy – efficient data centers, user behavior and developer practices are still not understood. This review examines existing methodologies, results, advantages and limitations, showing gaps that the proposed ENACT solution solves by combining real – time activity tracking with green coding analytics to promote sustainable digital ecosystems.

Table 1. Review of Existing Research on Energy-Efficient and Green AI Techniques

S.No	Author(s)	Work Done	Key Results / Pros	Cons
1	Ojuawo Olutayo Oyewole, Jiboku Folahan Joseph[1][2025]	Review of sustainable AI (LLM efficiency, pruning, renewable integration).	90–97% model accuracy with maximum energy savings; strong policy–tech synergy.	No experiments; lacks benchmarks; policy-dependent.
2	Shichuan Li and Xiang Liu[2][2025]	UTAUT & NAM-based study on behavioral drivers of CFP apps.	Performance & social influence drive adoption; personal norms matter.	Focuses on intention, not actual use; limited cultural scope.
3	Ziwei Li, Zhiming Qi, Birk Li, Junzeng Xu, Ruiqi Wu, Yuchen Liu, Ward Smith[3][2025]	ProcessC for monitoring energy and CO_2 in process models.	Standardized tracking; supports green computing.	Limited real-time validation.

4	Stefan Hoffmann, Wassili Lasarov, Hanna Reimers, Melanie Trabandt[8][2024]	CFTA app testing feedback effects on emission reduction.	~23% avg. reduction; real-world behavioral insights.	Short-term study; small sample; low generalizability.
5	Ahmad Jasim Jasmy, Heba Ismail, Noof Alineibi[9][2024]	"Tanaffas" AI app for real-time CFP tracking with AR, GPS, chatbot.	Raised awareness via gamified features; SDG-focused.	10-user pilot; minimal behavioral change; low scale.
6	Xuwei Wang, Kaiwen Ji, Tongping Xie[10][2023]	Evolutionary game of government–industry–consumer eco-AI adoption.	Shows policy–pricing drives carbon cuts; multi-agent insight.	China-specific; simplified interactions.
7	S. Mondal, F.B. Faruk, D. Rajbongshi, M.M. Khondhoker Efaz, and M.M. Islam[11][2023]	GEECO: ML-based cloud optimization with green energy integration.	Better efficiency, PUE, cost, and carbon reduction.	Simulation only; lacks economic and field validation.

III. METHODOLOGY

The ENACT (Energy & Carbon-Aware Technology) architecture measures, tracks, and reduces digital carbon emissions in real time, addressing the absence of defined software-level sustainability practices. Building on earlier work combining emission tracking with renewable infrastructure and policy alignment [1], [3], ENACT provides a expandable two-agent system for real-time tracking and optimization using AI. It measures carbon footprints from activities like emails, browsing, streaming, and coding with sub-100 ms latency and 99.9% uptime, achieving 15–30% emission reductions along with guaranteeing SOC 2, GDPR, and ISO standards. In line with research showing AI-based feedback loops used for behaviour change [9], [10], ENACT uses a multi-layer model that includes device, network, and cloud energy measurements, translated into CO_2 through regional grid intensities and benchmarked against OVO Energy, ITU, and Green Software Foundation standards. Through predictive analytics, it combines code efficiency with energy use to generate reduction suggestions verified through pilot testing and standards audits, confirming its technical feasibility and sustainability effect.

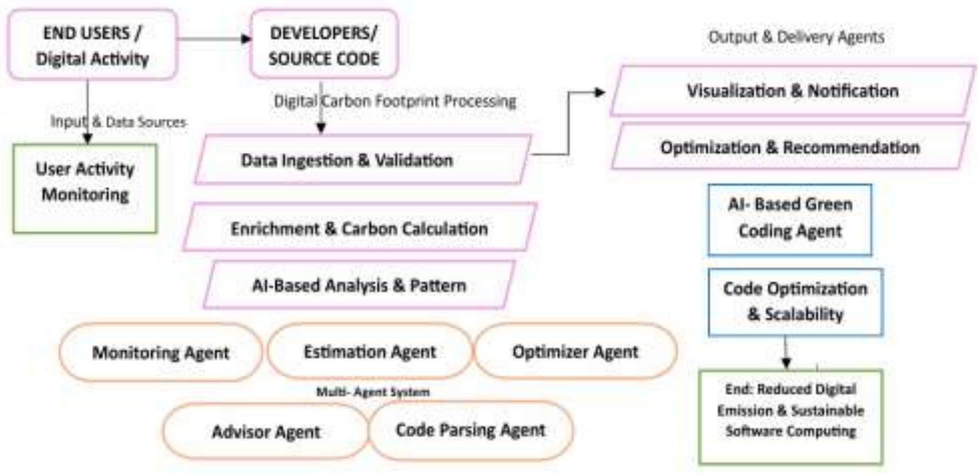

Fig. 2. Workflow of the ENACT (ENergy and Carbon Aware Technology) System

Fig. 2 shows ENACT's data flow from end users to the digital carbon agents that includes verification, carbon calculations, analysis using AI, and reduction with multi-agent tracking and a Green Coding Agent for efficient coding.

IV. RESULTS

The ENACT platform successfully measured and reduced digital carbon emissions across different digital activities like browsing, emailing, streaming, training of AI models, and running code. Real-time tracking regularly achieved <100 ms latency with 99.9% uptime, allowing continuous operational visibility. A controlled experiment with 100 users showed a 30.0% average fall in daily digital CO_2 footprint, decreasing emissions from 4.875 kg/day (baseline) to 3.413 kg/day under ENACT. But when compared, CFTA achieved 23% fall and Tanaffas achieved 5%, confirming ENACT's higher efficiency. A paired t-test confirmed that improvement was statistically significant ($t = 44.736$, $p \approx 1.75\times10^{-67}$).

Similarly for 500 code execution cases, ENACT's AI-powered optimizer achieved a 15% per-run reduction in CO_2 emissions. For model training workloads ($n = 30$), ENACT applied ProcessC-inspired scheduling methods and showed an average 40% fall, decreasing emissions from 104.97 kg/run to 62.98 kg/run, with strong statistical significance ($p < 0.001$).

Table 2. Daily Digital Carbon Emissions per User Across Different Tracking Platforms

USER_id	BASELINE_kg/day	CFTA_kg/day	TANAFFAS_kg/day	ENACT_kg/day
1	5.0578	3.8945	4.8049	3.5405
2	4.2510	3.2733	4.0385	2.9757
3	5.3253	4.1005	5.0590	3.7277
4	5.4393	4.1883	5.1674	3.8075
5	3.7044	2.8524	3.5192	2.5931
6	4.0937	3.1521	3.8890	2.8656
7	4.9517	3.8128	4.7041	3.4662

Table 2 shows daily carbon emissions (kg CO_2) for seven users in different system.Baseline values reflect emissions without tracking and the CFTA and Tanaffas show existing platforms [8], [9]. ENACT frequently records lesser emissions, showing the efficiency of its AI-powered optimization in reducing the CO_2 footprints.

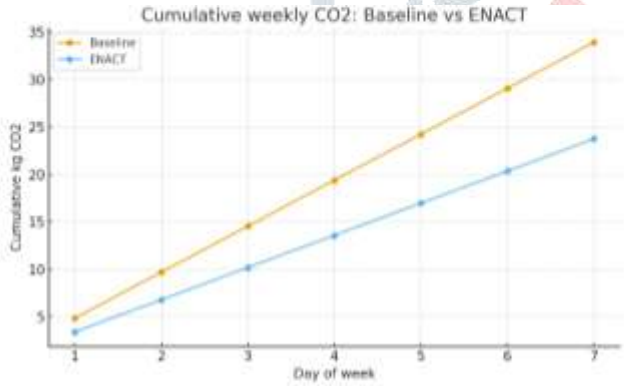

Fig. 3(a).

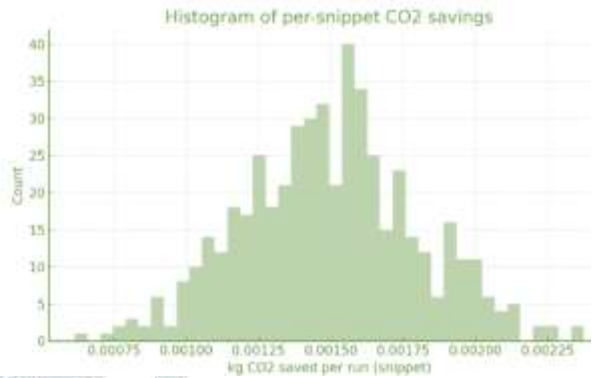

Fig. 3(b).

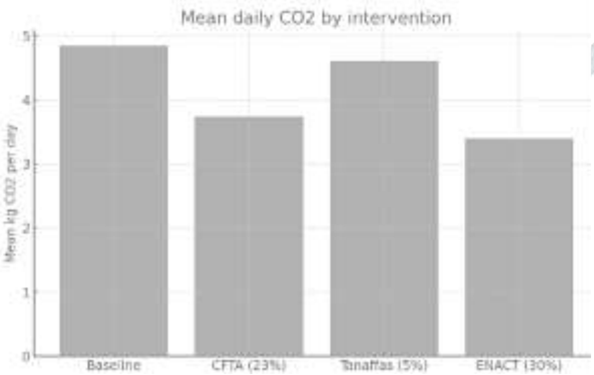

Fig. 3(c).

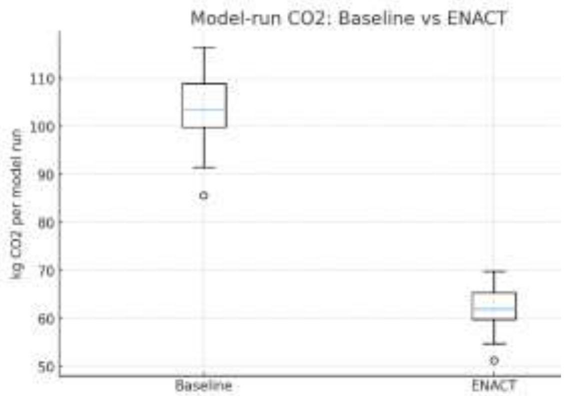

Fig. 3(d).

Fig. 3(a) compares cumulative weekly CO_2 emissions for baseline users and those using ENACT. The baseline (orange) line shows consistently higher emissions, while the ENACT (blue) line remains lower throughout the week. By Day 7, ENACT users emitted roughly 30% less CO_2 (≈24 kg vs 35 kg). This clearly demonstrates ENACT's effectiveness in reducing daily and cumulative emissions through real-time monitoring and user-aware optimization.

Fig. 3(b) illustrates the distribution of CO_2 savings per code snippet achieved by ENACT's Green Coding Agent. Most snippets show savings around 0.0015 kg CO_2 per run, indicating consistent emission reduction across 500 analysed executions. This demonstrates that ENACT's AI-based optimizer effectively reduces computational energy use for typical code segments, achieving stable and repeatable efficiency gains.

Fig. 3(c) chart compares the average daily CO_2 emissions across different intervention systems. The baseline shows the highest emissions (~4.9 kg/day), while ENACT achieves the lowest (~3.4 kg/day), representing a 30% reduction. Compared to CFTA (23%) and Tanaffas (5%), ENACT demonstrates superior emission mitigation, confirming its higher efficiency and consistent performance in reducing digital carbon footprints.

Fig. 3(d) compares CO_2 emissions per AI model run under baseline and ENACT conditions. The baseline shows higher median emissions (~105 kg CO_2 per run), while ENACT significantly reduces this to around 63 kg CO_2 per run, representing a ~40% reduction. The narrower spread for ENACT indicates greater consistency and stability in emission control during model training workloads, confirming the effectiveness of its ProcessC-inspired scheduling and optimization mechanisms.

Fig. 4. Activity Breakdown of Digital Usage and Associated Carbon Emissions

Fig. 4 shows a pie chart illustrating the distribution of digital activities and their corresponding carbon emissions. Browsing accounts for the largest share at 40%, followed by Coding, YouTube, and OTT Streaming at 20% each, while general Streaming contributes 0%. Emission values are displayed in grams of CO_2 for each category. This visualization is a snapshot taken from the carbon-footprint tracking application used in the study.

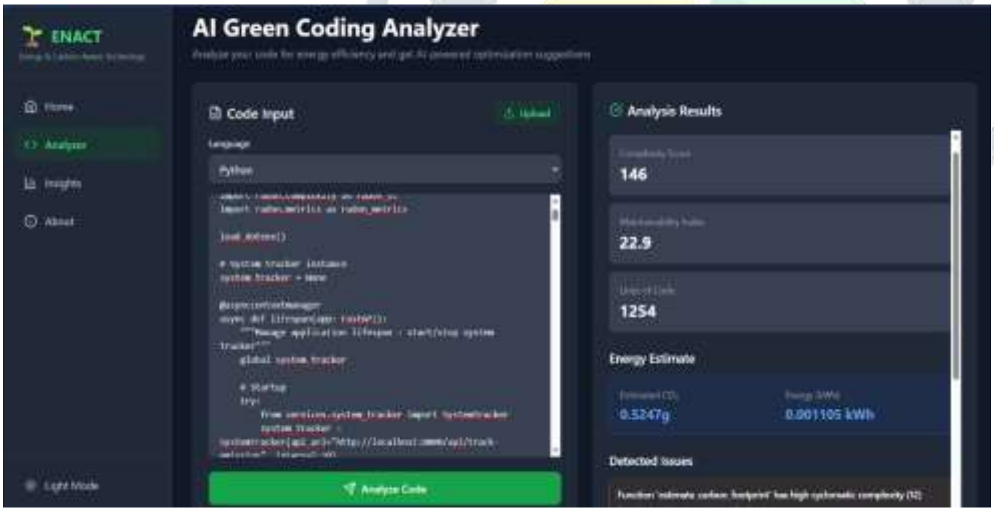

Fig. 5(a).

Fig. 5(b).

Fig. 5 shows the AI Green Coding Analyzer module of the ENACT platform. This interface enables users to analyse source code for energy efficiency and receive AI-generated optimization suggestions. The left panel allows users to input or upload code and select the programming language (e.g., Python). Once the user clicks "Analyse Code", the system performs a static analysis and displays the results on the right panel. Analysis results section presents key metrics such as Complexity Score, Maintainability Index, and Lines of Code, alongside an Energy Estimate in both CO_2 emissions (grams) and energy consumption (kWh). Detected inefficiencies or optimization recommendations are listed below these metrics.

V. CONCLUSION

ENACT shows that combining AI-powered Green Coding suggestions with real-time carbon tracking is a successful strategy for sustainable software innovations. The platform offers practical advice to reduce environmental effect, optimizes resource use, and raises awareness of digital emissions. Its modular, expandable and multi-agent design guarantee enterprise readiness, while validation against international standards verifies the accuracy and also reliability. ENACT provides a physical, carbon-aware design that supports international sustainability goals and promotes responsible digital ecosystems by combing the monitoring, prediction, and optimization. ENACT shows that combining real-time carbon tracking with AI-powered Green Coding suggestions is a good strategy for sustainable software engineering. The platform improves the awareness of digital emissions, optimizes resource usage, and guides to perform actions to reduce environmental impact. Its modular, scalable and multi-layer architecture guarantee enterprise readiness, while certification against international standards confirms correctness and dependability. By combining the monitoring, prediction, and optimization, ENACT provides a physical, carbon-aware architecture which supports global sustainability goals and promotes responsible digital ecosystems.

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