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The Unaccounted Carbon Cost of AI-Assisted Software Engineering: A Hidden Debt and Sustainability Challenge

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GREEN2025

The Tenth International Conference on Green Communications, Computing and Technologies

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Nelly Nicaise Nyeck Mbialeu obtained her Master's degree in Informatik at the Clausthal University of Technology, Germany in 2021. She is currently a doctoral student and a research assistant at the Institute of Software Systems Engineering in the same university.

Her research is in the research group Emerging Technologies for the Circular Economy, precisely in the domain of sustainability, artificial intelligence and circular economy.

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The ETCE research group conducts interdisciplinary research at the intersection of computer science and sustainability. Our research focus includes:

- ❖ Development and conceptual design of self-organizing software systems
- ❖ Digital identities
- ❖ Sustainable and resilient food production
- ❖ Digital technologies facilitating the circular economy and circular societies

Rationale

- Our motivation
  - The use of Artificial Intelligence (AI)-based tools like GitHub Copilot is causing a paradigm change in Software Engineering (SE).
  - Their long-term environmental costs via hidden emissions and code flaws are quite invisible.
- Our contribution
  - Introduce the concept of Carbon Debt in AI-assisted software engineering.
  - Propose a sustainability lens for developer practices and tool design.
  - Introduce a conceptual path towards a Sustainability Impact Factor.

Research Landscape

- Currently, the focus lies on
  - Sustainable SE
    - cloud optimization, hardware lifecycle, energy-efficient infrastructure
    - Limitation: software treated in isolation with no link to AI's carbon footprint
  - AI in SE
    - productivity boost, code quality, usability
    - Limitation: environmental costs overlooked due to "productivity at any cost" mindset
  - AI Carbon Footprint
    - training and inference emissions of large models
    - Limitation: too general and high-level (not applied to SE tools) while ignoring developer-side impact

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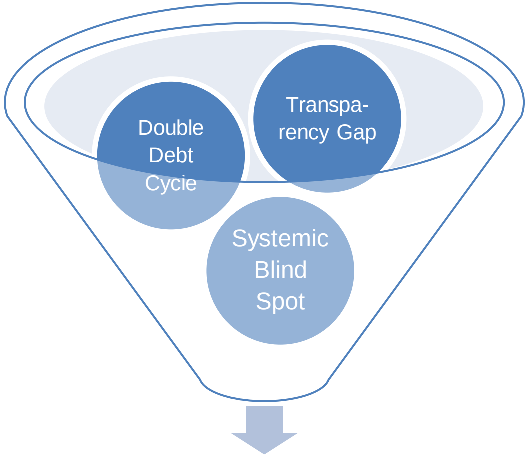
Problem Statement

- The usage-level inference emissions of AI DevTools are invisible, unmanaged, and unmeasured.
- Thereby creating a hidden impact that threatens long-term sustainability.

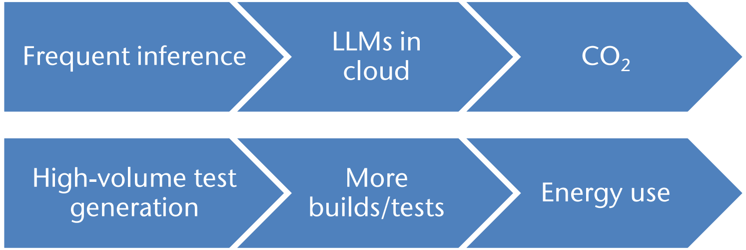


Hidden Carbon Debt

What is “Carbon Debt”?

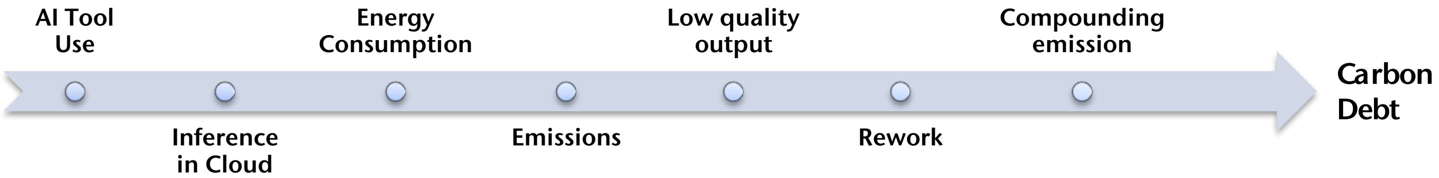
- The unacknowledged environmental footprint left by repeated use of energy-intensive AI tools.

- For example:
  - GitHub Copilot
  - AI Testing Tools



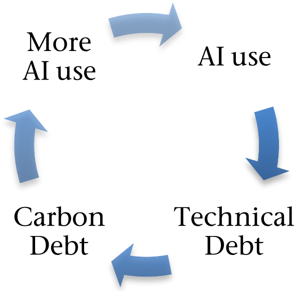
While Microsoft does not disclose precise figures, each suggestion is reported by community estimates to consume about 0.002kWh of energy, equivalent to roughly 1.2g CO2 per inference

- How does this invisible Carbon Debt build up?



Double Debt

- A vicious cycle
  - AI-generated code often inefficient → higher runtime energy use
  - More maintenance → more CI/CD pipeline emissions



- This is a double debt trap in which AI-assisted tools create Technical Debt that silently inflates Carbon Debt

- Carbon debt is not just a technical side effect but a behavioural and structural problem in the software lifecycle.

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Mitigation Strategies

Strategy	Actor	Summary	Examples
Carbon-Aware Tooling	Tool vendor	Show emissions per AI use	• Green mode in IDE • real-time contextual pop-ups
Selective Invocation	Developer	Use AI only when needed	• Green prompting • set CO_2 limits • turn off Copilot in tests
Education on Sustainability	Universities, Educators	Train students and developers to increase awareness	• Workshops and reflective exercises • integrate “Green AI-SE” in computer science programs
Policy Enforcement	Policymakers, Institutions	Encourage regulations on carbon accountability	• Carbon taxes for AI vendors

- Implementation challenges
  - Economic trade-offs: Productivity vs Sustainability
  - Technical barriers: Lack of emissions data from vendors

From Carbon Debt to Sustainability Impact

- Carbon Debt as a focused example within the broader conceptual framework of Sustainability Impact Factor (SIF) suggested by Lawrenz et al.
- SIF includes both fixed (e.g., training, hardware) and variable (inference) impacts.
- The focus is on the invisible, cumulative emissions from daily use of AI tools.

SIF Dimension	Metric Example	Why It Matters
Operational Efficiency	CO_2 per 1000 completions	Tracks operational footprint
Model training efficiency	Total CO_2e from training	Captures upstream cost
Usage intensity	AI calls per developer/day	Shows embeddedness of tool
Energy source	Renewable : fossil-powered energy	AI sustainability contrast
Hardware lifecycle	GPU replacement cycle/e-waste	Tracks material sustainability
Transparency	Availability of data on model size, energy use, emissions	Enables accountability

Proposed Preliminary SIF Criteria

Future Research

- The scope:
  - Discuss the Carbon Debt concept with focus on variable emissions during AI tool usage
  - Propose preliminary SIF criteria to make emissions in AI-SE visible and discussable

- What's next?

For us:

Formalisation and Evaluation

- Define carbon debt as a software quality attribute
- Operationalise SIF with standardized metrics
- Test these metrics

For the community:

Tooling and Measurement

- Develop Carbon-tracking plugins for IDEs
- Capture both direct (inference) and indirect (CI/CD) emissions
- Explore "green modes" that restrict high-carbon use

Ethics and Consideration

- Evaluate policy levers like emissions labelling for cloud-based AI
- Position sustainability as a core criterion in responsible innovation
- Develop ethical frameworks around AI minimalism and non-adoption

Ethical Reflection

- Just because we can use AI for everything, should we?
- Sustainability could mean non-adoption, not just mitigation.
- “Not every solution is progress. Some are just acceleration.” – Daniel Schmachtenberger, Consilience Project

Conclusion

- Carbon Debt is the next tech debt and should not be ignored.
- Collective actions are then required for the transition to a carbon-aware digital economy
  - Developers: Demand transparency from toolmakers
  - Researchers: Build emissions-tracking tools
  - Educators: Integrate sustainability into AI-SE courses
- The goal is to put sustainability at the center of responsible innovation debates.

References

- L. Hampton et al., “From mining to e-waste: The environmentaland climate justice implications of the electronics hardwarelife cycle”, MIT Schwarzman College of Computing, 2024,[Online]. Available: https://mit-serc.pubpub.org/pub/w9ht6hue/release/5.
- A. Zewe, “Explained: Generative ai’s environmental impact”,Published by MIT News on January 17, 2025, 2025, [Online].Available: https://news.mit.edu/2025/explained-generative-ai-environmental-impact-0117.
- A. A. Fawole, O. F. Orikpete, N. N. Ehiobu, and D. R. E. Ewim,“Climate change implications of electronic waste: Strategies forsustainable management”, Bulletin of the National ResearchCentre, vol. 47, no. 1, p. 147, 2023.
- Y. Yu et al., “Revisit the environmental impact of artificialintelligence: The overlooked carbon emission source?”, Fron-tiers of Environmental Science & Engineering, vol. 18, no. 12,pp. 1–5, 2024.
- J. Vaidya and H. Asif, “A critical look at ai-generate software:Coding with the new ai tools is both irresistible and dangerous”,Ieee Spectrum, vol. 60, no. 7, pp. 34–39, 2023.
- E. Strubell, A. Ganesh, and A. McCallum, “Energy andpolicy considerations for modern deep learning research”, inProceedings of the AAAI conference on artificial intelligence,vol. 34, 2020, pp. 13 693–13 696.
- D. Patterson et al., “Carbon emissions and large neural networktraining”, arXiv preprint arXiv:2104.10350, 2021.
- GitHub Community, How much co2/ghg does copilot emit?,https : / / github . com / orgs / community / discussions / 38168,[Retrieved: April 2025], 2025.
- F. Palomba, A. Panichella, A. Zaidman, R. Oliveto, and A. DeLucia, “Automatic test case generation: What if test code qualitymatters?”, in Proceedings of the 25th International Symposiumon Software Testing and Analysis, 2016, pp. 130–141.
- Microsoft Corporation, 2022 environmental sustainability re-port, https://news.microsoft.com/wp-content/uploads/prod/sites/42/2023/05/2022- Environmental-Sustainability- Report.pdf,[Retrieved: April 2025], 2023.
- H. Pearce, B. Ahmad, B. Tan, B. Dolan-Gavitt, and R. Karri,“Asleep at the keyboard? assessing the security of githubcopilot’s code contributions”, Communications of the ACM,vol. 68, no. 2, pp. 96–105, 2025.
- L. F. W. Anthony, B. Kanding, and R. Selvan, “Carbontracker:Tracking and predicting the carbon footprint of training deeplearning models”, arXiv preprint arXiv:2007.03051, 2020.
- N. Ding et al., “Enhancing chat language models by scal-ing high-quality instructional conversations”, arXiv preprintarXiv:2305.14233, 2023.[40] P. Becker, Sustainability science: Managing risk and resiliencefor sustainable development. Elsevier, 2023.
- B. Penzenstadler et al., “Everything is interrelated: Teachingsoftware engineering for sustainability”, in Proceedings ofthe 40th International Conference on Software Engineering:Software Engineering Education and Training, 2018, pp. 153–162.
- S. Lawrenz et al., “Implementing the circular economy bytracing the sustainable impact”, International journal of envi-ronmental research and public health, vol. 18, no. 21, p. 11 316,2021.
- Z. Stein, “Technology is not values neutral: Ending the reignof nihilistic design”, Consilience Project, 2022.