How Clean is Nuclear? An Investigation Into Public Awareness on the Topic of Nuclear Energy

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***Abstract*—Software carbon-accounting tools typically estimate emissions using geography-based electricity carbon-intensity factors, but this approach does not capture market-based accounting choices or the uncertainty associated with lifecycle emissions. This issue is particularly relevant for nuclear electricity, whose reported carbon intensity depends strongly on modeling assumptions and system boundaries. In this paper, we present NUCLEARMIX, an extension to CodeCarbon that supports user-specified electricity mixes, lifecycle-aware factor sets, uncertainty ranges, and factor provenance metadata. We also develop a scrollytelling website that explains nuclear lifecycle emissions and their relevance to software carbon accounting. We evaluate the website through a paired pre/post survey with 17 participants and evaluate NUCLEARMIX through controlled scenario analysis. The survey results show a statistically significant improvement in participant knowledge after interacting with the website. The technical analysis shows that reported emissions can vary substantially depending on the selected accounting perspective, nuclear share, and lifecycle factor set. These findings indicate the importance of transparency in electricity carbon accounting and suggest that explanatory artifacts can improve understanding of lifecycle-based emissions reporting. We provide the code and analysis accompanying this work in our replication package.**

***Index Terms*—Nuclear Energy, Carbon Emission Calculation, Code Carbon**

I. INTRODUCTION

The environmental impact of software and machine learning workloads has increased the use of tools that estimate energy consumption and associated carbon-dioxide equivalent (CO_2e) emissions [1], [2]. A common formulation models emissions as the product of consumed energy and an electricity carbon-intensity factor [3]. In CodeCarbon, for example, emissions are computed from tracked hardware energy use and carbon-intensity data associated with the region, cloud provider, or country in which the workload executes, with fallbacks to country energy mixes or global averages when more specific data are not available [3]. This design is practical and portable, but it is centered on geography-based electricity factors rather than on user-declared electricity procurement choices.

That distinction matters because greenhouse-gas accounting standards separate *location-based* and *market-based* Scope 2 accounting [4]. The location-based method reflects the average emissions intensity of the grid where electricity is consumed, whereas the market-based method reflects electricity attributes associated with contractual instruments and supplier choices [4]. For organizations that procure electricity through specific contracts, power-purchase agreements, or certified energy products, a purely geographic factor may therefore fail to represent the accounting perspective that the organization intends to report.

This limitation is particularly salient for nuclear electricity. Nuclear generation has very low direct operational combustion emissions, yet its full lifecycle footprint includes upstream and downstream stages such as uranium mining, conversion and enrichment, fuel fabrication, plant construction, waste management, and decommissioning [5], [6], [7]. Prior life cycle assessment (LCA) studies consistently place nuclear well below fossil electricity in lifecycle GHG intensity, but they also show substantial variability caused by differences in system boundaries, ore grade, enrichment technology, construction assumptions, plant lifetime, capacity factor, and end-of-life modeling [5], [6], [7]. As a result, describing electricity as simply "carbon-free" or reducing accounting to a single opaque factor can conceal modeling choices that materially affect the reported result.

This paper addresses the problem from two complementary directions. First, we develop NUCLEARMIX, an extension to CodeCarbon that supports user-specified electricity mixes, lifecycle-aware factor sets, optional uncertainty ranges, and explicit metadata about factor provenance. Second, we develop a scrollytelling website that explains the difference between operational and lifecycle emissions, walks users through the nuclear lifecycle, and connects these concepts to software carbon accounting. We then evaluate the website using a paired pre/post survey and evaluate the extension through controlled scenario analysis against baseline CodeCarbon calculations.

The study is guided by the following research questions:

- **RQ1.** To what extent does the website improve participants' understanding of nuclear lifecycle emissions and the distinction between grid-average and contract-based electricity accounting?
- **RQ2.** How much can estimated software emissions differ between baseline geography-based accounting and user-specified electricity-mix accounting?

The contribution of the paper is therefore threefold: (1) a lifecycle-aware electricity-mix extension for CodeCarbon, (2) a web-based explanatory artifact for communicating nuclear lifecycle accounting, and (3) an empirical evaluation that combines a paired survey with technical validation of the resulting calculations.

II. BACKGROUND

A. *Electricity Carbon Accounting in Software Tools*

Most software carbon-accounting tools estimate emissions by combining energy use with an electricity carbon-intensity signal [1], [3]. CodeCarbon formalizes this as the product of energy consumed and carbon intensity, where the latter is resolved from regional, provider, or country-level data and, when necessary, from fallback values [3]. This approach is appropriate for broad deployment because it avoids the need for users to manually specify energy-system details for every run.

However, the Scope 2 Guidance of the GHG Protocol distinguishes between two legitimate accounting perspectives [4]. The first is a location-based view that reflects the average emissions intensity of the grid on which electricity consumption occurs. The second is a market-based view that reflects electricity attributes associated with contractual instruments and supplier-specific procurement [4]. For software carbon accounting, this distinction implies that the same workload can produce different reported emissions depending on whether the calculation uses a grid-average factor or a contract-based electricity mix.

Related electricity-data systems have already made this semantic distinction more explicit. For example, Electricity Maps distinguishes direct operational emission factors from lifecycle emission factors and computes carbon intensity from the electricity mix available on a grid after accounting for power flows between interconnected regions [8]. This is relevant for software engineering because it shows that factor semantics, spatial assumptions, and lifecycle boundaries can be modeled explicitly rather than being hidden inside a single undifferentiated carbon-intensity value.

B. *Nuclear Lifecycle Emissions*

The LCA literature on nuclear electricity provides two findings that are central to this project. First, nuclear electricity is a low-carbon source when evaluated over its full lifecycle relative to fossil alternatives [5], [6], [7]. Second, the numerical estimate is not unique because it depends strongly on system boundaries and modeling assumptions [5], [6], [7].

Warner and Heath's systematic review and harmonization showed that published lifecycle estimates for light-water reactors vary widely and that harmonization substantially reduces, but does not eliminate, that variation [5]. They identify primary energy mix, uranium ore grade, and LCA method as major drivers of residual variability [5]. More recent work confirms this picture. Gibon and Menacho develop a parametric cradle-to-grave model and show that enrichment technique, ore grade, construction requirements, and other parameters can materially alter estimated lifecycle emissions [6]. Pomponi and Hart likewise demonstrate, for a European pressurized reactor, that different methodological choices and scenario assumptions produce a non-trivial spread of lifecycle values [7].

For the purposes of this paper, the implication is methodological rather than normative. A carbon-accounting tool that aims to represent nuclear electricity should not treat "nuclear" as a single context-free label. Instead, it should expose at least three dimensions: (i) the electricity mix being claimed, (ii) the factor set and lifecycle boundary being used, and (iii) the uncertainty or range associated with those factors. This motivates the design of NUCLEARMIX as a transparent factor-based extension rather than as a single replacement constant.

C. *Communication Need*

The second part of the project is motivated by the communication challenge around nuclear energy. The OECD Nuclear Energy Agency reports that perceptions of nuclear matters are closely connected to broader perceptions of science and risk [9]. This suggests that an explanatory intervention should not merely present a final number, but should make assumptions and boundaries legible. Accordingly, the website developed in this project is designed to explain where lifecycle emissions occur, why estimates are reported as ranges, and how these choices affect software carbon-accounting results.

III. METHODOLOGY

A. *Study Overview*

The study consists of two linked components. The first is the design and implementation of two artifacts: (i) a scrollytelling website on nuclear lifecycle emissions and electricity accounting, and (ii) the NUCLEARMIX extension for CodeCarbon. The second is the empirical evaluation of those artifacts through a paired survey study and a technical validation study.

The website is used as the educational intervention. The extension is used as the accounting artifact that operationalizes the concepts introduced by the website. Together, these two components allow the paper to address both the communication problem and the measurement problem.

B. *Artifact Design*

a) Website.: The website follows a scrollytelling format with pinned visuals and short explanatory text blocks. Its content is organized into five conceptual units: (1) baseline software carbon accounting, (2) the distinction between grid-average and contract-based electricity mixes, (3) operational versus lifecycle emissions, (4) the full nuclear lifecycle from mining to decommissioning, and (5) a practical demonstration of how electricity-mix assumptions affect CodeCarbon results. The website is intentionally descriptive rather than persuasive. Its purpose is to explain accounting assumptions and lifecycle stages in a way that supports measurable changes in conceptual understanding.

b) NUCLEARMIX.: The extension augments baseline CodeCarbon output with a user-specified electricity mix and a selectable factor set. For a workload that consumes E kWh, with technology shares $w_1, \ldots, w_n$ such that $\sum_i w_i = 1$, and technology specific emission factors $f_1, \ldots, f_n$, the estimated emissions are computed as

$$\widehat{\mathrm{CO_2e}} = E \cdot \sum_{i=1}^{n} w_i f_i. \tag{1}$$

When uncertainty ranges are available, the extension also reports lower and upper estimates by replacing each f_i with $f_i^{\min}$

and $f_i^{\max}$, respectively. In addition to the final estimate, each run stores metadata including the accounting mode, factor-set name, dataset version, mix breakdown, and factor sources. This design supports comparison with baseline CodeCarbon results while preserving traceability.

C. Website User Study

1) Participants and Recruitment: We recruited a convenience sample of adult participants through our personal network and social media channels. The target population is intentionally broad because the website is designed for non-specialist audiences interested in software sustainability, energy systems, or carbon accounting. Participants with prior expertise in nuclear engineering or LCA were not excluded, but prior familiarity was measured and used as a covariate in exploratory analyses.

2) Survey Instrument: The survey consists of three blocks.

1) **Pre-survey block.** This block records demographics (country of residence and current role), self-reported prior familiarity with nuclear energy and nuclear fuel cycle, and a knowledge test administered before website exposure.
2) **Website block.** Participants were asked to visit and read through our website which contained the information required for the knowledge test.
3) **Post-survey block.** After viewing the website, participants answer the knowledge test again, together with short items on perceived clarity, confidence, and usefulness. At the end, participants may provide open-ended feedback on which concepts were most or least clear.

The knowledge test is designed to measure conceptual understanding rather than attitude. Representative items cover: (i) the difference between operational and lifecycle emissions, (ii) identification of lifecycle stages in nuclear electricity, (iii) the reason lifecycle estimates are reported as ranges, (iv) the distinction between grid-average and contract-based electricity accounting, and (v) the interpretation of a carbon-intensity factor in $\mathrm{gCO_2e/kWh}$. The total knowledge score is the sum of correct answers across items.

Before deployment, the questionnaire was pilot-tested with a small number of participants to check wording clarity, completion time, and technical usability.

3) Procedure: Participants first read an information sheet and provide consent. They then complete the pre-survey block including the knowledge test. Next, they are directed to the website and asked to navigate it in full at their own pace. After the intervention, participants complete the post-survey block.

Responses were excluded if the participant did not complete both the pre- and post-survey. All data collection procedures were conducted subject to the applicable institutional ethics requirements.

4) Analysis: The primary outcome is the paired change in total knowledge score from pre-survey to post-survey. We computed mean, standard deviation (SD), and median for both blocks and for their difference. Because the score differences were *not* normally distributed, we used the Wilcoxon signed-rank test to evaluate the paired change in scores and report paired Cohen's d as an effect-size measure.

At the item level, we analyzed changes in correctness using McNemar's test. For Likert-type post-intervention items, we report medians and interquartile ranges. As an exploratory analysis, we examined whether prior familiarity with nuclear energy, sustainability, or carbon-accounting tools is associated with larger or smaller knowledge gains.

Open-ended responses were analyzed qualitatively using a lightweight thematic coding procedure. The purpose of this analysis is not theory generation, but the identification of recurring points of confusion that can inform future iterations of the website.

D. Technical Validation of NUCLEARMIX

The extension will be evaluated along three dimensions.

a) Correctness.: We will implement unit tests for mix normalization, factor retrieval, uncertainty propagation, and metadata generation. These tests verify that shares sum to one, that the selected factor set is applied consistently, and that output metadata exactly reflects the configuration used for the run.

b) Comparative behavior.: We will compare baseline CodeCarbon estimates against NUCLEARMIX estimates for controlled scenarios with identical energy use but different accounting assumptions. These scenarios will include fixed 1 kWh examples, synthetic workload traces, and sample `emissions.csv` files produced by CodeCarbon. For each case, we will report the baseline estimate, the NUCLEARMIX estimate, the absolute difference, and the relative difference.

c) Sensitivity.: Because lifecycle estimates depend on factor choice, we will run a sensitivity analysis over alternative factor sets and uncertainty ranges. This analysis will show how strongly the final emissions estimate changes when the nuclear share, lifecycle boundary, or source-specific factor values are varied. The goal is not to identify a universally correct nuclear factor, but to demonstrate that the extension makes these assumptions explicit and auditable.

IV. RESULTS

A. Questionnaire Results

We collected responses from 17 participants, all residing in the Netherlands. The sample consisted primarily of students (11), together with two engineers or technical specialists, two members of the general public, one teacher, and one data scientist. Participants reported higher baseline familiarity with nuclear energy (mean 3.06 out of 5, SD=0.90) than with the more specific concept of the nuclear fuel cycle (mean 1.71 out of 5, SD=0.99).

Table I presents the analysis of pre- and post-intervention scores. A Shapiro-Wilk test on the score differences indicated that the differences were not normally distributed ($W = 0.8448$, $p = 0.0089$). We therefore used a Wilcoxon signed-rank test, which showed a significant improvement in knowledge scores after the intervention ($p = 0.0004$). The mean score increased from 8.88 (SD=3.77) before the intervention to 12.35 (SD=3.26) after the intervention, corresponding to a mean paired difference of 3.47 points (SD=3.20). The paired Cohen's d was 1.0833, indicating a large effect size. The 95% confidence interval for the mean difference was [1.95, 4.99], which excludes zero.

	Mean	SD	Median
Pre-score	8.88	3.77	9.0
Post-score	12.35	3.26	13.0
Difference	3.47	3.20	3.0

TABLE I
Knowledge Test Analysis (N=17)

Item-level analysis (see Appendix A) showed that Q2 (lifecycle terminology) had the largest improvement (+58.8%, McNemar $p = 0.002$). Significant gains were also observed for Q11 (CO_2e meaning; +41.2%, $p = 0.0156$) and Q8 (+35.3%, $p = 0.0312$). Additional improvements were observed for Q5 (+29.4%), Q6 Conversion (+29.4%), and Q6 Fuel Fabrication (+29.4%), although these did not reach statistical significance. Performance remained unchanged for Q4 (carbon footprint) and Q6 Fuel Storage, while Q6 Recycling decreased slightly by 5.9 percentage points.

Spearman correlations were calculated to assess the relationship between prior familiarity and knowledge gain. All correlations were negative, suggesting that participants with greater prior familiarity tended to show smaller gains, but none of these relationships reached statistical significance. The correlation was (ρ=-0.4053, p=0.1065) for average familiarity, $\rho = -0.3753$ ($p = 0.1376$) for nuclear energy familiarity, and $\rho = -0.4105$ ($p = 0.1017$) for fuel-cycle familiarity.

Usability was assessed via the System Usability Scale (SUS), resulting in a median of 72.5, a mean of 66.38 and an IQR of [65.0, 75.0]. Detailed per-item metrics are available in Appendix B. Qualitative feedback from three participants indicated confusion regarding the "frequent use" survey question, difficulty matching the stages of the cycle diagram, and concerns that excessive graphics were distracting and make it difficult to navigate the website see Appendix C).

B. NuclearMix *Results*

We evaluated **NuclearMix** through controlled scenario analysis to assess how much estimated emissions can differ between baseline geography-based accounting (using codecarbon's sources) and user-specified electricity mix accounting. Following the technical validation plan as outlined in subsection III-D, we report results for three complementary analyses, namely, (1) country-level comparison, (2) fixed with 1 kWh scenario comparisons, and (3) sensitivity to nuclear share and factor choices.

1) Country-level Comparison: Figure 1 compares the stored country-level carbon intensity of CodeCarbon with recomputed values obtained from the same national electricity mix under alternative sets of lifecycle factors. Across several countries with non-trivial nuclear shares, the recomputed value depends materially on the selected factor set. As an example, we analyze France, for which 65.3% of its energy is sourced by nuclear energy. The baseline CodeCarbon value is 56.0 gCO$_2$eq/kWh, while the recomputed value is 92.0 gCO$_2$eq/kWh under the CodeCarbon default factor set, 63.1 gCO$_2$eq/kWh under the IPCC AR5 median factors, 55.3 gCO$_2$eq/kWh under UNECE 2020, 47.7 gCO$_2$eq/kWh under the IPCC low case, and 373.4 gCO$_2$eq/kWh under the IPCC high case. We see very similar trends in other nuclear-reliant countries such as Slovakia, Ukraine, Hungary, Belgium, and Sweden.

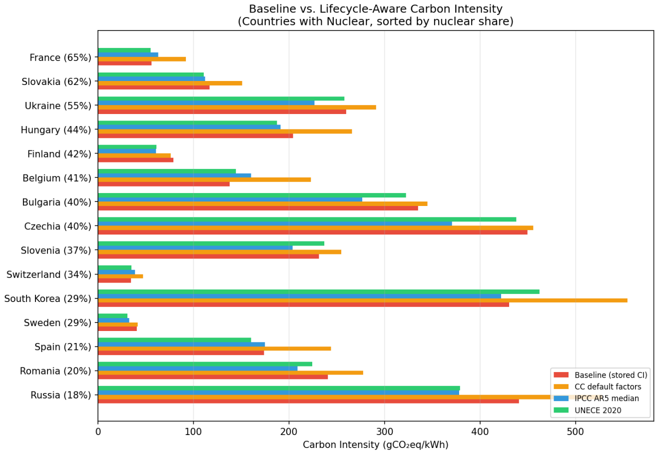

Fig. 1. Comparative plot of carbon intensity based on different accounting strategies for nuclear-reliant countries.

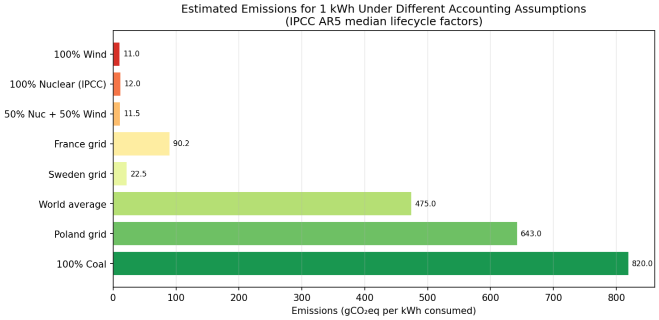

Fig. 2. An estimation of expected CO_2e emissions for different scenarios for a workload of 1 kWh.

Taken together, these are indicators that even when the underlying electricity mix is fixed, the reported carbon intensity is not uniquely determined; it depends heavily on the lifecycle factors set used for nuclear generation. This directly supports the design motivation of our tooling and further reinforces the need for such accounting software to expose factor provenance and uncertainty rather than collapsing all assumptions into a single opaque number.

2) Scenario Comparisons for Identical Energy Use: To isolate the effect of accounting assumptions, we next evaluated a set of fixed 1 kWh scenarios. The world-average fallback remains 475.0 gCO$_2$eq/kWh under all factor sets because no nuclear-specific reweighting is involved. In contrast, scenarios with nuclear electricity show substantial variation. A France grid scenario yields 90.2 gCO$_2$eq/kWh under the IPCC AR5 median factors, while a Sweden grid scenario yields 22.5 gCO$_2$eq/kWh. A 100% nuclear power-purchase

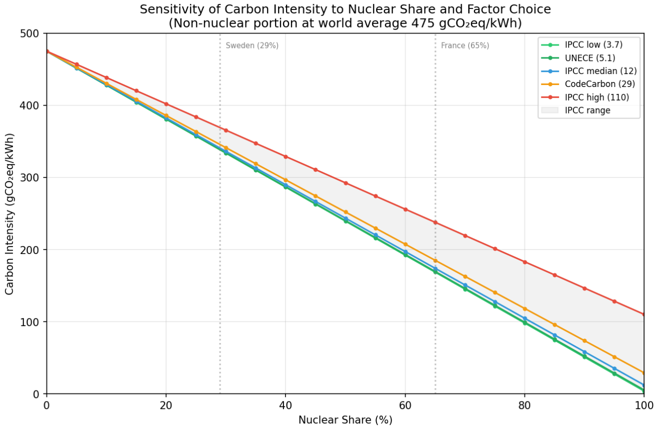

Fig. 3. A visualization of changes in carbon intensity as a function of nuclear shares based on factor choices.

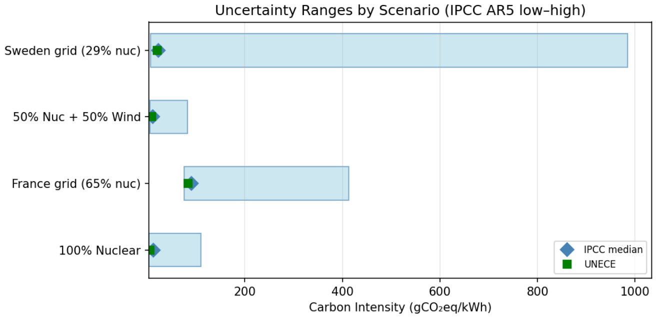

Fig. 4. Uncertainty ranges for carbon intensity per kWh based on different scenarios.

agreement (PPA) yields 12.0 gCO_2eq/kWh under the IPCC median factors, whereas a 50% nuclear and 50% wind PPA yields 11.5 gCO_2eq/kWh, and a 100% wind PPA yields 11.0 gCO_2eq/kWh. By comparison, a 100% coal scenario yields 820.0 gCO_2eq/kWh under the same factor basis. A more extensive visualization of these results can be found in Figure 2.

3) Sensitivity to Nuclear Share and Factor Choice: Figure 3 shows how estimated carbon intensity changes as the nuclear share increases from 0% to 100%, while the non-nuclear portion is fixed at the world-average intensity of 475.0 gCO_2eq/kWh. For all factor sets, the relationship is monotonic, meaning that higher nuclear shares lead to lower estimated carbon intensity. However, the magnitude of this decrease depends on the selected lifecycle factor. At 100% nuclear, the estimate ranges from 3.7 gCO_2eq/kWh under the IPCC low case to 110.0 gCO_2eq/kWh under the IPCC high case, with intermediate values of 5.1 for UNECE 2020, 12.0 for the IPCC median, and 29.0 for the default CodeCarbon factor. The uncertainty band therefore widens as the nuclear share increases, meaning it spans only 10.6 gCO_2eq/kWh at 10% nuclear, but 106.3 gCO_2eq/kWh at 100% nuclear, as also shown in Figure 4. These results indicate that both the share of nuclear electricity and the chosen lifecycle factor materially affect the final emissions estimate.

V. Discussion

A. *Questionnaire and Learning Outcomes*

The participant group was small and relatively homogeneous, which may limit the generalizability of these findings (see Section VI). Participants initially reported higher familiarity with the general concept of nuclear energy than with the specific "nuclear fuel cycle". This disparity likely comes from nuclear energy being a broad topic frequently mentioned in public, whereas the fuel cycle is a technical term rarely encountered outside specialized fields. Consequently, participants lacked exposure to these specific processes prior to the intervention.

Because the distribution of paired score differences was not normal, we used a Wilcoxon signed-rank test rather than a paired t-test. The results showed a statistically significant increase in post-intervention knowledge scores, with a large paired effect size. This indicates that the website improved conceptual understanding of the covered material for this sample.

At the item level, the largest gains were observed for lifecycle terminology (Q2), the meaning of CO_2e (Q11), and Q8. These results suggest that the website was particularly effective at improving understanding of core terminology and basic accounting concepts. Several other items, including Q5 and multiple sub-items of Q6, also improved, but the evidence for these changes is weaker at the current sample size.

In contrast to the earlier analysis, Q4 did not decline and Q6 Fuel Storage also remained unchanged. The only negative movement was a small decrease in Q6 Recycling. It might be that soe diagram-based or process-mapping questions remained difficult, while the strongest improvements were concentrated in terminology and conceptual interpretations.

The exploratory familiarity analysis showed negative correlations between prior familiarity and score gain, but none reached statistical significance. This means the data are compatible with the possibility that less familiar participants benefited more, but the current sample does not support a strong claim on that point.

Furthermore, the website was perceived as usable, with a SUS median of 72.5, which exceeds the industry average of 68, but the mean was 68.38, indicating acceptable usability with substantial variation between participants. Specifically, participants reported that the system was easy to use (SUS3), did not require technical support (SUS4), and was not unnecessarily complex (SUS2). The qualitative feedback highlighted specific areas for future refinement and possible causes of the aforementioned variation in the results. The confusion regarding the "frequent use" of the system (SUS1) likely comes from the tool's nature as an educational recourse. Users typically do not intend to use a single-topic learning platform frequently once the information is acquired. The difficulty matching cycle stages to the diagram could be addressed by providing more explicit visual cues or detailed descriptions for each stage. Finally, although only one participant found the website graphics and layout overwhelming, it suggests that the high density of visual and textual information may hinder navigation for some. To enhance accessibility for users who prefer less visual stimulation, a simplified "minimalist" version of the website could be developed as a future iteration.

B. NUCLEARMIX

The *NuclearMix* results show that reported software emissions are highly sensitive to the accounting perspective used to characterize electricity supply. When the same 1 kWh workload is evaluated under geography-based grid averages, reported emissions remain tied to the average composition of the local grid. When the same workload is evaluated under user-specified contractual mixes, the resulting estimates can be substantially lower, as shown by the comparison between the France grid scenario (90.2 gCO_2eq/kWh) and the 100% nuclear PPA scenario (12.0 gCO_2eq/kWh). At the same time, the sensitivity analysis shows that a low-carbon claim based on nuclear electricity still depends on the lifecycle factor set used. This is visible in the spread between the IPCClow and IPCC high nuclear values, which leads to a wide uncertainty interval at high nuclear shares. The implication is not that one single nuclear factor should replace all others, but that carbon-accounting tools should expose the factor source, lifecycle boundary, and uncertainty ranges used in the estimations. In this respect, *NuclearMix* improves interpretability over a single stored country-level factor by making these assumptions explicit in the output metadata.

VI. LIMITATIONS

While this study provides initial insights into the role of lifecycle-aware accounting tools and educational interventions, several limitations must be considered when interpreting the results. The main issue with the study is its small and similar group of participants. T he small sample size limits the statistical power of the findings and prevents generalisation to the broader software engineer or general public population. The sample lacks geographic diversity as all participants were residents of the Netherlands. Furthermore, participants were recruited through a convenience sample of personal networks and social media. This may have introduced a self-selection bias, attracting individuals already interested in sustainability or carbon accounting.

Furthermore, the educational intervention was not uniformly effective across all topics. While general terminology scores improved, participants demonstrated a decrease in correctness for questions regarding the stage with the largest carbon footprint (Q4) and the fuel storage stage (Q6). This indicates that specific sections of the website actively confused participants rather than clarifying the concepts.

Participants reported that the website's structure was difficult to follow, noting that the "start the journey" function caused users to skip vital chapters and that visual markers in the lifecycle diagrams were poorly placed.

Finally, although the *NuclearMix* implementation is included in the replication package, broader practical impact would require integration into the main *CodeCarbon* toolchain so that these accounting options are directly accessible to the wider developer community.

VII. FUTURE WORK

To improve the generalizability of the results, future iterations should move beyond the current convenience sample of 17 participants. Future studies should recruit participants from diverse geographical regions outside of the Netherlands to account for different cultural perceptions. Additionally, future studies should recruit participants from diverse professional backgrounds, including software engineers, business professionals, sustainability officers and more, to better understand the tool's applicability across different industries.

The educational intervention requires refinement to address specific points of confusion, particularly regarding the fuel storage stage and the identification of the largest carbon footprint stage, where participant scores actually decreased. Qualitative feedback suggests that the "scrollytelling" navigation must be restructured to prevent the "journey" feature from skipping vital chapters. Improving the visual clarity of lifecycle diagrams and the placement of process labels will further enhance the conceptual flow for the website's intended non-specialist audience.

VIII. CONCLUSION

This study successfully introduced NuclearMix, a lifecycle-aware extension for CodeCarbon, alongside an educational scrollytelling website aimed at improving understanding of nuclear electricity carbon accounting. The results indicate that the website significantly improved participants' conceptual understanding and proving particularly effective for non-specialists.

However, the findings also revealed specific areas of confusion particularly concerning fuel storage and the largest carbon footprint stages. Furthermore navigation issues with the website's "journey" feature were also identified. Due to the small and homogeneous sample size future research will focus on a more diverse professional and geographic population to ensure the findings' broad applicability in sustainable software engineering.

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APPENDIX

A. *Item-level Analysis Of Questionnaire*

TABLE II
QUESTIONNAIRE PERFORMANCE PER ITEM ($N = 17$)

Item	Pre (%)	Post (%)	Change	McNemar p
Q2: Lifecycle Term.	29.4%	88.2%	+58.8%	0.002*
Q11: CO2e Meaning	29.4%	70.6%	+41.2%	0.0156*
Q8: [Topic Name]	23.5%	58.8%	+35.3%	0.0312*
Q5: [Topic Name]	52.9%	82.4%	+29.4%	0.0625
Q6: Conversion Stage	11.8%	41.2%	+29.4%	0.0625
Q6: Fuel Fabrication	11.8%	41.2%	+29.4%	0.1250
Q3: [Topic Name]	52.9%	76.5%	+23.5%	0.1250
Q9: [Topic Name]	52.9%	76.5%	+23.5%	0.2188
Q6: Power Plant	41.2%	64.7%	+23.5%	0.2188
Q6: Waste Disposal	58.8%	76.5%	+17.6%	0.3750
Q1: [Topic Name]	70.6%	82.4%	+11.8%	0.5000
Q7: [Topic Name]	58.8%	70.6%	+11.8%	0.6250
Q10: [Topic Name]	88.2%	94.1%	+5.9%	1.0000
Q6: Mining and Milling	94.1%	100.0%	+5.9%	1.0000
Q6: Enrichment	29.4%	35.3%	+5.9%	1.0000
Q4: Carbon Footprint	64.7%	64.7%	+0.0%	1.0000
Q6: Fuel Storage	41.2%	41.2%	+0.0%	1.0000
Q6: Recycling	76.5%	70.6%	-5.9%	1.0000

*Significant at $p < 0.05$.

B. *SUS Per-Item Scores*

TABLE III
SUS INDIVIDUAL ITEM SCORES ($N = 17$)

Item	Median	Mean
SUS1	3.0	2.82
SUS2	2.0	2.29
SUS3	4.0	4.00
SUS4	2.0	1.71
SUS5	4.0	3.65
SUS6	2.0	2.06
SUS7	4.0	3.76
SUS8	2.0	2.35
SUS9	4.0	3.53
SUS10	2.0	2.00

C. *Qualitative Feedback*

TABLE IV
PARTICIPANT QUALITATIVE FEEDBACK

ID	**Qualitative Feedback**
P1	I don't understand the question of if I would regularly use this system. It is an informative site about 1 topic so why would somebody use this system on a frequent basis?
P2	I found the matching image part a bit confusing even after reading the website. Also to indicate process, I thought the number might better lie in the middle instead of the end point of the process
P3	It was very difficult to navigate. The amount of graphics, text, images etc made it difficult to easily find the right piece of information. I did not understand the structure of the website. For example "start the journey" brings me to these chapters (it took me a while to understand it was the chapters of the cycle, and then I don't understand the purpose of all the other sections which get skipped)

D. *Questionnaire*

You are invited to participate in a research study titled: **NuclearMix: an Investigation Into Public Awareness on NuclearEnergy Lifecycle Emissions**

PURPOSE OF THE STUDY

The purpose of this study is to investigate whether an educational website about nuclear lifecycle emissions improves people's understanding of nuclear energy accounting and its relevance for software carbon-footprint estimation.

WHAT PARTICIPATION INVOLVES

If you choose to participate, you will complete a short pre-survey, view the study website, and then complete a short post-survey. The full study will take approximately 10 to 15 minutes.

VOLUNTARY PARTICIPATION

Your participation is entirely voluntary. You may stop at any time before submitting the survey by closing your browser window. You may also skip any question you do not wish to answer. There are no negative consequences if you decide not to participate.

DATA COLLECTED

This survey is designed to be anonymous. We do not intend to collect your name, email address, student number, or other direct identifiers. The survey will be configured not to record IP addresses or similar online identifiers. Please do not enter personal information in any response field.

RISKS AND DISCOMFORT

This study presents minimal risk. Some participants may experience mild discomfort or uncertainty when answering knowledge questions. You are free to skip any question or stop participation at any time before submitting the survey. As with any online activity, a residual risk of data breach can never be fully eliminated, but we will take reasonable technical and organizational measures to minimize this risk. Confidentiality and storage Survey responses will be accessed only by the research team. Exported data will be stored on secure TU Delft systems with restricted access. Anonymous research data, analysis files, and study materials may be retained for up to 10 years for research verification and publication purposes.

USE OF THE DATA

The anonymous data collected in this study will be used for academic research, including scientific publications, presentations, and project reporting. Results will be reported only in aggregate form. No participant will be identified in any output.

WITHDRAWAL

Because the survey is anonymous, once you submit your responses we may not be able to identify your specific data and remove it from the dataset. If you do not wish your data to be used, please withdraw before submitting the survey.

BENEFITS AND COMPENSATION

There is no direct personal benefit from participation.

QUESTIONS OR COMPLAINTS

If you have any questions about the study, please contact: Roham Koohestani (rkoohestani@tudelft.nl)

Responsible Researcher: Dr. Luiz Miranda da Cruz (L.Cruz@tudelft.nl)

CONSENT

By clicking "I agree" and proceeding to the survey, you confirm that:

1) you are at least 18 years old;
2) you have read and understood the information above;
3) you voluntarily agree to participate in this study.

QI: What is your country of residence?

QII: Which of the following best describes your current primary role?

- Student (Graduate or Undergraduate)
- Engineer / Technical Specialist (Software, Nuclear, Energy, stc.)
- Policy maker / Decision Maker (Sustainability officer, Government, Management)
- Academic / Researcher
- General Public / Non-Specialist
- Other: ....

QIII: How familiar are you with Nuclear energy?

QIV: How familiar are you with Nuclear Fuel Cycle?

E. Knowledge test

Now, you are presented with 11 questions to help us measure your prior understanding of nuclear energy concepts. Each of the 10 multiple choice questions has a "I don't know" option. Please select this option if you are unsure about the answer rather than guessing the answer. There is one open ended question where you only need to answer with one word. You are not graded or scored on this section.

Q1: If an energy technology is described as having "zero-emissions" at the point of generation (the power plant), does this mean it has no impact on climate change?

1) Yes, because no CO_2 is released while generating electricity.
2) No, because CO_2 is released during the construction of the facility and the sourcing of its fuel. (correct)
3) Yes, as long as the fuel used is not a fossil fuel.
4) I don't know.

Q2: Which term refers to the sum of all greenhouse gas emissions from "cradle to grave" (extraction to disposal)?

1) Operational carbon.
2) Lifecycle Assessment Emissions. (correct)
3) Indirect Grid Emissions.
4) I don't know.

Q3: Is there a difference between lifecycle and operational emissions?

1) No, they represent the same concept but for different fuels.
2) Yes, they represent total carbon footprint and gases produced during daily use respectively. (correct)
3) I don't know.

Q4: For a typical nuclear power plant, which stage is responsible for largest portion of its lifecycle carbon footprint?

1) Daily plant operations and maintenance.
2) Uranium mining and centrifugal enrichment. (correct)
3) Steam release from cooling towers.
4) I don't know.

Q5: Which of these activities is not included in a standard lifecycle assessment (LCA) of nuclear energy?

1) Transporting nuclear fuel rods.
2) The CO_2 emitted by employees commuting to the plant. (correct)
3) The energy used to manufacture the steel and concrete for the containment building.
4) I don't know.

Q6: The picture shows a nuclear fuel cycle. Can you identify each stage?

1) Mining and Milling
2) Conversion
3) Enrichment
4) Fuel Fabrication
5) Power Plant
6) Recycling
7) Fuel Storage
8) Waste Disposal

Q7: Why do scientific reports often provide a range (e.g., a low and a high estimate) for nuclear carbon intensity instead of a single fixed number?

1) Because carbon footprint depends on the specific technology, the enrichement method, and the local electricity grid used during construction. (correct)
2) Because different countries use different units to measure carbon.
3) Because scientists cannot agree on whether nuclear is "green".
4) I don't know.

Q8: A data center is physically connected to a local power grid that is 80% coal. However, the data center buys "Green Certificates" from a distant wind farm. Which accounting method allows them to claim they are "100% renewable"?

1) Location-based (Grid-average) accounting.
2) Market-based (Contract-based) accounting. (correct)

3) Direct-source accounting.
4) I don't know.

Q9: If a software tool uses "Grid-average" accounting, it calculates emissions based on:

1) The specific energy contract the user signed.
2) The mix of all energy sources (solar, gas, nuclear, etc.) currently on the local power line. (correct)
3) The maximum possible emissions the computer could produce.
4) I don't know.

Q10: If a computer task has carbon intensity of $500gCO_2e/kWh$, what does the "kWh" represent:

1) The weight of the hardware.
2) The amount of energy consumed over time. (correct)
3) The speed of the internet connection.
4) I don't know.

Q11: What does the letter "e" stand for in the metric gCO_2e/kWh? answer: equivalent

The knowledge test questions repeat here.

In this part you are presented with 10 usability questions where we'd like you to give us feedback on your experience with our website you saw previously. In all questions we refer to the website as the "system". Answer the questions as accurately as possible.

1) I think that I would like to use this system frequently.
2) I found the system unnecessarily complex.
3) I thought the system was easy to use.
4) I think that I would need the support of a technical person to be able to use this system.
5) I found the various functions in this system were well integrated.
6) I thought there was too much inconsistency in this system.
7) I would imagine that most people would learn to use this system very quickly.
8) I found the system very cumbersome to use.
9) I felt very confident using the system.
10) I needed to learn a lot of things before I could get going with this system.

Below you can add any comments or feedback:

......

F. Visualization of Survey Results

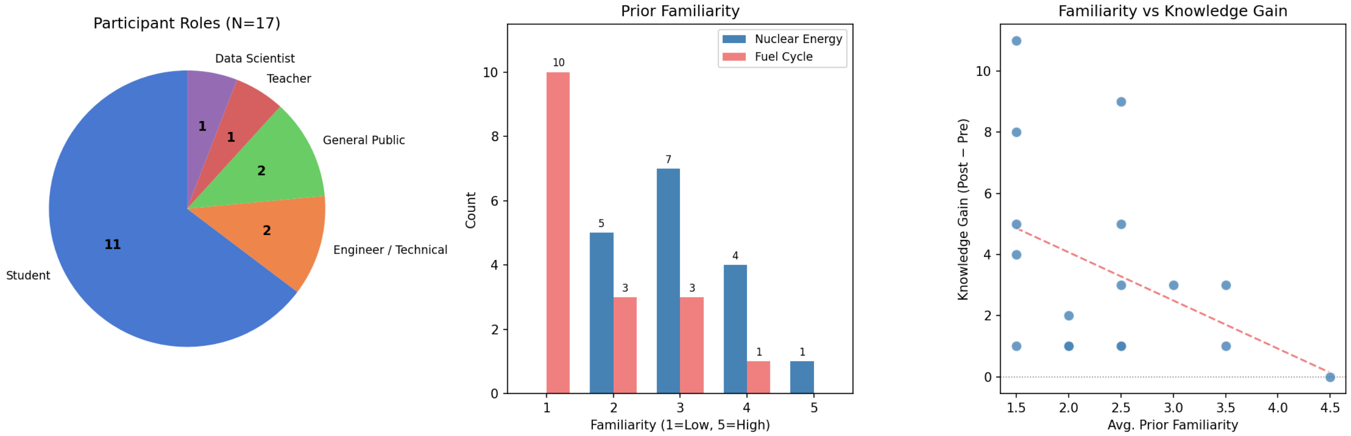

Fig. 5. A visualization of the distribution of the participants in the study.

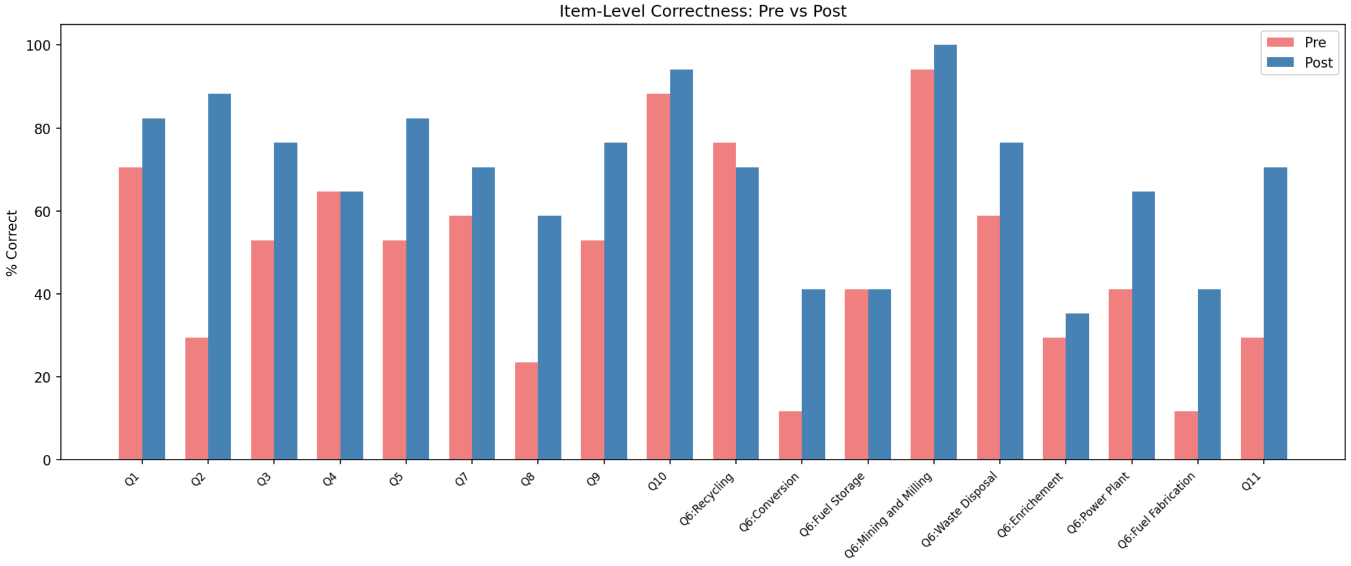

Fig. 6. Item-level corectness of questions pre and post intervention.

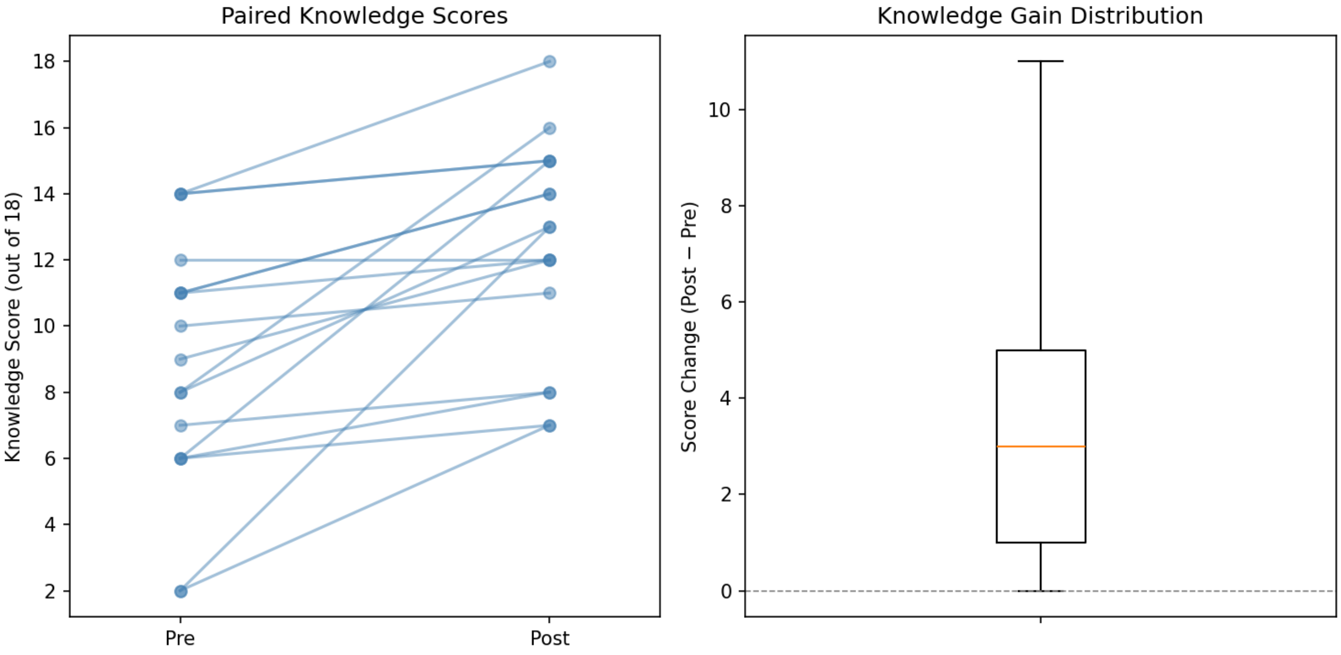

Fig. 7. Item-level knowledge gain pre- and post intervention.

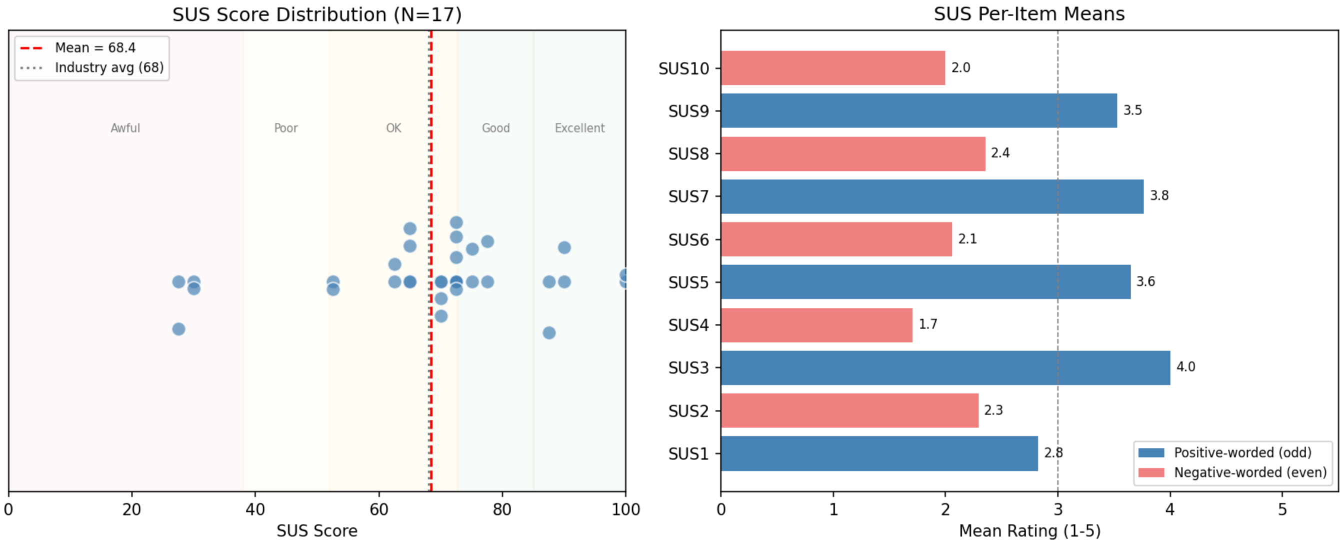

Fig. 8. A visualization of the SUS results from the sruvey.