Project Report

A Monte Carlo Analysis of Carbon Emissions from Household Showers

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1. Introduction:

The high emissions leading to the total lifecycle of carbon footprint, based on the use of products, is the aim of this project. However, this depends on the user behavior and the infrastructure of the region (locally or globally). In this study, we use Monte Carlo Simulations (MC) (N=1000) to quantify the distributions of CO_2 emissions from a single household shower. Three of the key variables were used in this study: Shower duration, Water source, and the Heat source.

2. Objective:

The primary objective is to answer the question:

What is the true range and nature of a shower's carbon footprint?

3. Methodology:

3.1. The Carbon Emission Model

The simulation is based on the equation given as:

Total CO_2 (kg)= ((Shower length * Flow Rate) * (EF for Water + (Heat Energy Per Liter * Emission Factor for Heat Energy))

3.2. Random and Fixed Parameters

1. Random Parameters

1. Shower Length:

This was drawn from the Lognormal Distribution to model the user behavior, which tends to have a right-skewed distribution which means it has more of the shorter showers and very few of the long showers.

2. Heat Source Emission Factor:

This was selected by using the Multinomial Distribution. However, the probability of choosing a given heat technology (which was Natural Gas, Heat Pump, etc).was based on the normalized proportion from the dataset provided.

3. Water Source Emission Factor:

This was also selected by the Multinomial Distribution, but also based on the normalized proportion.

2. Fixed Parameters

Fixed parameters included a standard flow rate of 2.5 gallons per minute (9.46 L/min) and a calculated heat energy requirement of 0.146 MJ per liter, assuming a water temperature with an increase of 35°C.

4. Results and Analysis:

The N=1000 simulation runs produced a distribution of CO_2 emission values, which are summarized below.

Statistic	**Value (kg CO2)**	**Interpretation**
Lowest	0.002	Represents a near-zero emission, best-case scenario
25th Percentile	0.454	Upper bound for the lowest impact
Median	**0.873**	**The central, most typical outcome of the simulation.**
Mean	0.896	Pulled above the median
75th Percentile	1.264	The lower bound for the highest-impact quarter of showers.
Highest	3.947	The worst-case emission scenario, ~4x the median.
IQR	0.810	The range contains the middle 50%.

The results show a right-skewed distribution, with a median of 0.873 kg CO_2 and a mean of 0.896 kg CO_2, indicating that a small number of high-emission showers pull the average above the central tendency. The middle 50 % of showers (IQR = 0.810 kg) fall between 0.45

kg and 1.26 kg CO_2. The maximum simulated emission was 3.95 kg, around 4.5 times the median, representing rare long-duration or high-carbon heating cases**.**

5. Descriptive Statistics:

The statistical summary reveals a spread and a right-skewed distribution. The distribution is right-skewed, as shown by the divergence between the **mean (0.896 kg)** and the **median (0.873 kg)**, indicating a long upper tail of high-emission cases.

5.1 Visual Analysis:

It is illustrated below in the box plot and histogram form:

A. Boxplot:

It is important to visualize the skewness and spread, and clearly illustrates:

- The **median** is the center line:

Specifically, **50% of all simulated showers emit less than the median value of 0.87 kg CO_2**

- The **Interquartile Range (IQR):**

It captures the middle 50% of the data.This dense cluster represents the CO_2 range for the most typical shower scenarios, showing where the majority of emission values fall.

- The **right-skewness** & the longer upper whisker:

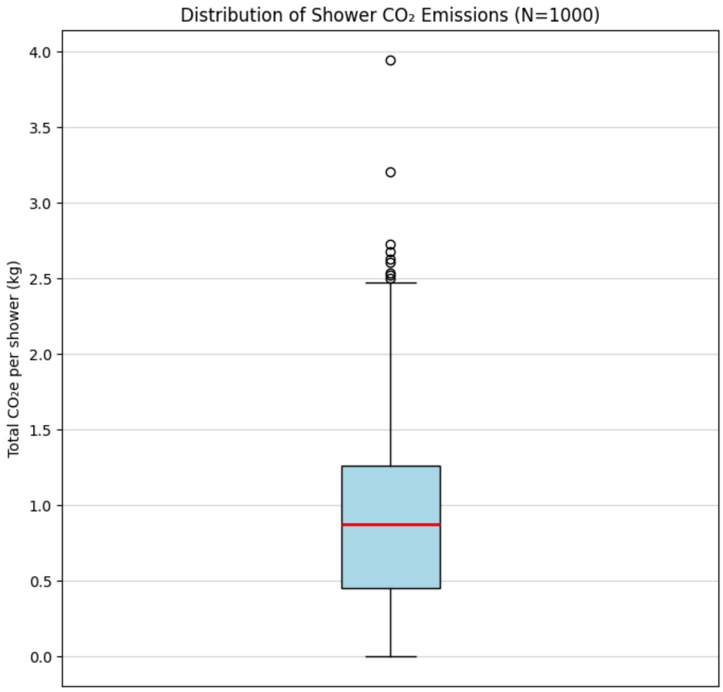
The mean being greater than the median.The **longer upper whisker** and the fact that the **"Mean (0.896 kg) is greater than Median (0.873 kg)"**. demonstrate that the average emission is pulled higher by a long tail of high-emission events.

- The presence of **high-emission outliers**:

The individual points beyond the upper whisker represent the **worst-case, maximum CO_2 scenarios**. These outliers are critical for identifying the upper limit of the carbon footprint risk caused by rare, high-consumption or high-carbon-factor combinations.

- **Highest value Interpretation: 3.947 kg CO_2:**

The **worst-case emission scenario**. This value is ≈ 4.5× the median (0.873 kg), demonstrating the **extreme range of carbon risk** when the longest duration, highest temperature, and highest emission factor are selected together.



B. Histogram:

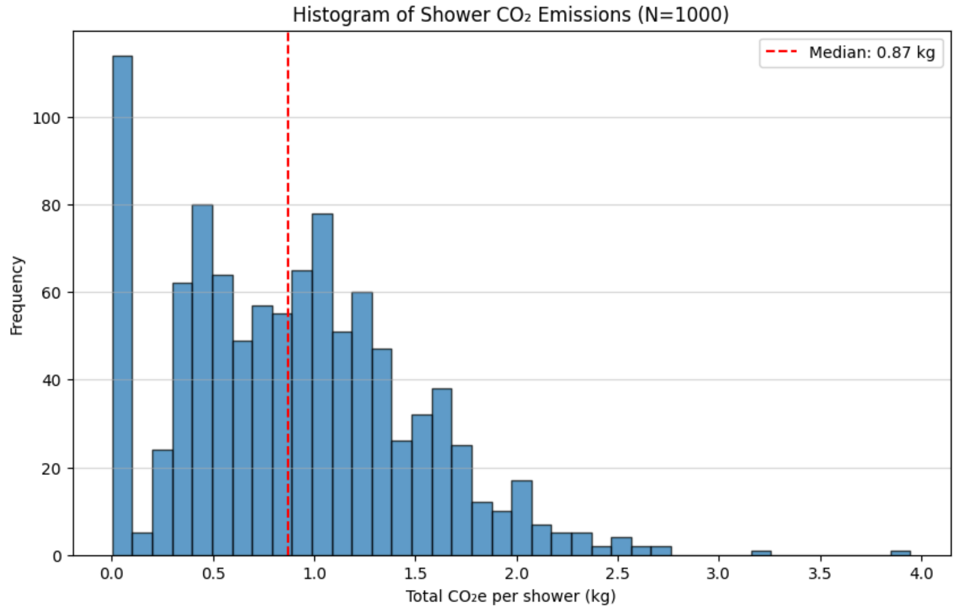
The histogram reveals the **frequency and structural nature** of the emissions distribution, confirming the simulation's most significant finding: a **bimodal** (two-peaked) shape.

- **The Low-Emission Mode (Peak near 0 kg CO2):**

  This extremely tall, thin bar on the far left confirms the presence of a distinct category of **ultra-low-carbon showers**. This is a **correct outcome** that results from the random selection of the Switzerland-based, low-emission factor heating source, which, despite its low probability, significantly impacts the overall frequency near zero.

- **The Primary Mode (Around 1.1 kg CO2):** This main cluster is the **most frequent outcome** of our simulation. It represents the **typical CO2 footprint** because it is created by combining the input factors that have the highest probability of being chosen: the most common **shower duration**, the most popular **temperature**, and the most frequent **heating system** (e.g., the Gas Boiler). It shows the range of emissions for the majority of all simulated showers.

Conclusion: The bimodal distribution is the **single most important finding**, revealing that the CO2 risk is divided into two fundamentally different populations: one representing the standard emission profile and one demonstrating the powerful, including infrequent, effect of the ultra-low-carbon heating technology.



6. Diagnosing the Low-Emission Mode:

The next step was to diagnose the cause of this low-emission cluster. However, to understand the reason for creating a low-emission shower with zero emissions. For this, the simulations that fall in the lowest 20% of all the CO2 results, this means that all the values fall below the value of 0.669kg CO2.

However, if we analyze these technologies installed, it reveals the most important pattern given below:

Top Heat Source Contributors in Low-Emission Showers:

Heat Source Name	**Geography**	**Share of Low-Emission Showers**
Heat, district, or industrial	Switzerland (CH)	47.3%
Electricity, Low voltage	Switzerland (CH)	46.8%

7. Interpretation:

The data shows that the low-emission mode is almost exclusively driven by **clean heating technologies available in the Swiss (CH) region**.

- **District Heating** and **Low-Voltage Electricity** from this region have near-zero
- emission factors. This points to a grid powered predominantly by renewables, nuclear, or other low-carbon sources.
- In contrast, an analysis of the **water source** in this low-emission group showed no clear pattern; choices were spread across all available options.

This shows that the choice of the heating technology is the dominant and best factor to produce an ultra-low carbon shower. However, the user behavior, which includes the shower length and also the source of water, is also relevant, but with a significant margin in comparison to the heating factor.

8. Discussion and Conclusion:

Through the Monte Carlo simulation, the most critical insight is the discovery of a **bimodal distribution**, which demonstrates that "average" emissions are a misleading concept. The existence of a distinct, near-zero emission cluster, driven entirely by access to low-carbon heating infrastructure, leads to a powerful conclusion:

The simulation with respect to this shower dataset (Low Carbon Emission) showed that if 1000 simulations are run, to account for the real-world randomness of a shower, the most typical result for carbon footprint was 0.873 kg of CO_2 (median).The corresponding mean emission across 1000 simulations was **0.896 kg CO_2**, confirming a modest right-skew in the distribution. These updated values are derived from the fixed-seed run (SEED = 42) for reproducibility.

However, to decarbonize or reduce carbon emissions, infrastructure plays a very critical role. This transformation from high carbon emission to low is driven by switching to cleaner energy sources for water heating.

This could, however, serve as a roadway for policymakers/companies by suggesting that efforts and investments should be focused on decarbonizing the regional energy grids, which would ultimately lead them to promote technologies like heat pumps and renewable energy – district heating systems.