

# A Data-Driven Comparative Assessment of Pollution from Ethanol Production and Refrigeration & Air-Conditioning Systems

*Global life-cycle emissions, pollutant screening, forecasting to 2050, and per-unit appliance comparison*

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## Abstract

This paper compares the environmental burden of fuel ethanol production with refrigeration and air-conditioning (RAC) systems, including household air conditioners and refrigerators. The analysis is global rather than country-specific and uses publicly available data from the International Energy Agency (IEA), United Nations Environment Programme (UNEP), Our World in Data, the International Institute of Refrigeration (IIR), the Renewable Fuels Association (RFA), and published peer-reviewed life-cycle studies on ethanol. The study treats carbon dioxide equivalent (CO<sub>2</sub>e) as the main climate metric, while SO<sub>2</sub>/SO<sub>x</sub>, NO<sub>x</sub>, VOC and particulate matter are modelled as screening indicators rather than regulatory inventories. Results show that AC and RAC systems are a much larger global climate problem than fuel ethanol production. In 2022, air conditioning alone was approximately 1.75 GtCO<sub>2</sub>e, while all cooling/RAC was roughly 3.6 GtCO<sub>2</sub>e. In comparison, global fuel ethanol production in 2025 was about 32 billion gallons, corresponding to roughly 0.13 GtCO<sub>2</sub>e/year using a 52.4 gCO<sub>2</sub>e/MJ ethanol life-cycle intensity. By 2050, AC-only emissions may approach 3.8 GtCO<sub>2</sub>e in a baseline scenario and all cooling/RAC may reach 7.2 GtCO<sub>2</sub>e under business-as-usual assumptions. A sustainable cooling pathway could reduce cooling emissions to around 2.6 GtCO<sub>2</sub>e by 2050. At the household functional-unit level, one 1.5-ton AC running continuously for 24 hours emits roughly 16.2 kgCO<sub>2</sub>e using a global-average electricity factor, while one refrigerator running for 24 hours emits roughly 0.67 kgCO<sub>2</sub>e. Producing one litre of ethanol is approximately 1.1 kgCO<sub>2</sub>e on a life-cycle basis, plus about 0.75 kg of physical biogenic fermentation CO<sub>2</sub> that should be reported separately. The conclusion is data-based: RAC is more dangerous globally for climate change because of scale, electricity demand and refrigerant leakage; ethanol plants are more dangerous locally where wastewater, vinasse, VOC and boiler emissions are poorly controlled.

## Keywords

CO<sub>2</sub> emissions; CO<sub>2</sub>e; ethanol production; bioethanol; RAC; air conditioning; refrigerators; refrigerant leakage; HFCs; global warming potential; SO<sub>x</sub>; NO<sub>x</sub>; VOC; life-cycle assessment; forecasting.

## 1. Introduction

Climate pollution is often discussed only through vehicles, industries and power plants, but a large share of modern environmental load comes from hidden systems: cooling appliances, cold chains, household refrigerators, air conditioners, and biofuel production plants. Ethanol is promoted as a renewable transport fuel because the carbon in its feedstock is biogenic; however, producing ethanol still requires feedstock cultivation, transport, fermentation, distillation, steam, electricity and effluent treatment. RAC systems appear clean at the point of use, but they produce indirect emissions through electricity consumption and direct emissions through refrigerant leakage. For a data and AI/ML-oriented research approach, the correct question is not simply whether ethanol or AC is more polluting, but how their emissions compare under a defined functional unit, boundary and forecasting scenario.

This paper therefore compares two types of pollution sources: (1) ethanol production plants, which are industrial point sources, and (2) distributed RAC systems, which exist across millions to billions of homes, shops, vehicles, food chains and commercial buildings. The same analytical logic used in machine learning applies here: define features, define labels or metrics, separate direct and indirect variables, document assumptions, and make the model reproducible.

## 2. Research Objectives

- To compare global greenhouse-gas impact of ethanol production and RAC systems using public data.
- To estimate per-unit pollution from running one AC for a day, running one refrigerator for a day, and producing one litre of ethanol.
- To forecast future global risk to 2050 using simple, transparent scenario modelling.
- To compare climate pollutants and air-pollution indicators, including CO<sub>2</sub>e, SO<sub>2</sub>/SO<sub>x</sub>, NO<sub>x</sub>, VOC and PM<sub>2.5</sub>.
- To identify which system is more dangerous under different definitions of harm: global warming, household emissions, industrial wastewater, and local air pollution.

## 3. Scope and System Boundary

The analysis uses a global boundary and does not focus on any single country. For RAC, the boundary includes electricity consumed during operation and refrigerant leakage during operation. Manufacturing, shipping, installation and end-of-life recycling are discussed but not numerically modelled in the main per-day test. For ethanol, the boundary includes life-cycle carbon intensity per megajoule, plant fermentation CO<sub>2</sub>, refining/process energy, and wastewater concern. Because global measured totals for SO<sub>2</sub>/SO<sub>x</sub>, NO<sub>x</sub> and VOC from every AC, refrigerator and ethanol plant do not exist in a single public dataset, those pollutants are modelled as screening estimates using transparent factors. They should be treated as directional, not regulatory.

## 4. Data Sources

Table 1. Public sources and how they are used

Dataset / source	Value used	Use in paper
IEA Space Cooling	Space cooling electricity-related CO <sub>2</sub> around 1 Gt in 2022; refrigerants add non-CO <sub>2</sub> GHG risk	AC baseline climate context
Our World in Data AC synthesis	AC emissions about 1.75 GtCO <sub>2</sub> e in 2022 when refrigerants are included	AC total GHG anchor
UNEP Global Cooling Watch 2025	Cooling emissions may reach 7.2 GtCO <sub>2</sub> e by 2050; sustainable pathway around 2.6 GtCO <sub>2</sub> e	RAC forecast
International Institute of Refrigeration	Refrigeration sector estimated at 4.14 GtCO <sub>2</sub> e and 7.8% of global GHG; AC model 77% indirect, 23% direct	RAC direct/indirect split
RFA Annual World Fuel Ethanol Production	World fuel ethanol production 32,000 million gallons in 2025	Ethanol global scale
Xu et al. 2022 ethanol LCA	Corn ethanol baseline 52.4 gCO <sub>2</sub> e/MJ; production/refining 25.6 gCO <sub>2</sub> e/MJ	Ethanol CO <sub>2</sub> e calculation

EPA AP-42 methodology	Public emission-factor framework for stationary combustion	SOx/NOx/VOC screening logic
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## 5. Methodology

### 5.1 Climate metric

The main climate metric is carbon dioxide equivalent (CO<sub>2</sub>e). CO<sub>2</sub>e converts different greenhouse gases into the warming effect of carbon dioxide over a selected time horizon, commonly 100 years. For RAC, CO<sub>2</sub>e has two major parts: electricity-based emissions and refrigerant leakage. For ethanol, CO<sub>2</sub>e is based on published life-cycle intensity per megajoule and is reported separately from physical fermentation CO<sub>2</sub> because fermentation CO<sub>2</sub> is generally biogenic.

RAC CO<sub>2</sub>e formula:

Total RAC CO<sub>2</sub>e = electricity use (kWh) x grid factor (kgCO<sub>2</sub>/kWh) + refrigerant leakage (kg) x refrigerant GWP

Ethanol CO<sub>2</sub>e formula:

Ethanol CO<sub>2</sub>e per litre = ethanol energy content (MJ/L) x ethanol carbon intensity (gCO<sub>2</sub>e/MJ) / 1000

### 5.2 Forecasting method

The forecast is intentionally simple and reproducible. It uses anchor points reported by public sources and applies compound annual growth or decline between the baseline and 2050 target values. This is not a deep climate integrated assessment model. It is a transparent screening forecast suitable for a research paper or data-science demonstration. For ethanol, the RFA 2021-2025 production trend is used to calculate observed growth, but a moderated 1.5% annual growth scenario is used as the main long-term forecast because the energy transition may reduce transport-fuel ethanol growth over time.

## 6. Global Data-Based Comparison

Table 2. Global emissions comparison and forecast anchors

sector	2022_GtCO <sub>2</sub> e	2050_GtCO <sub>2</sub> e_BAU_or_baseline	2050_sustainable_GtCO <sub>2</sub> e
Air conditioning only	1.750	3.800	nan
All cooling/RAC	3.600	7.200	2.600
Fuel ethanol production, LCA	0.116	0.194	nan

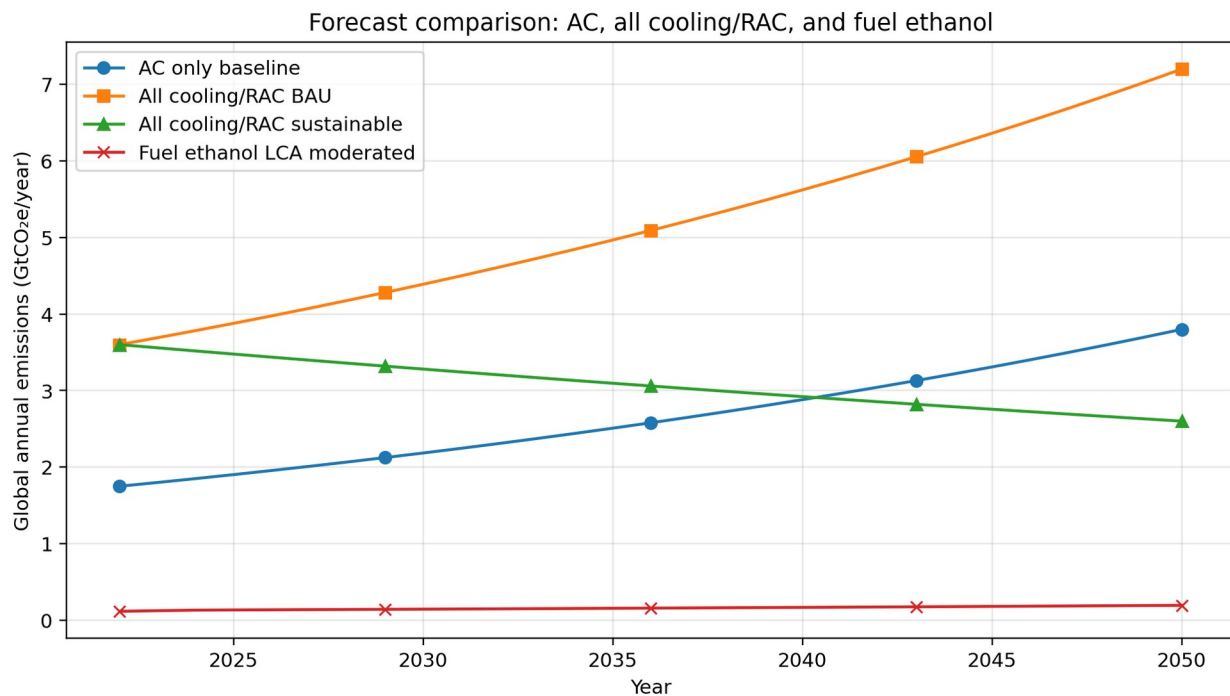


Figure 1. Forecast comparison of AC, all cooling/RAC and fuel ethanol emissions.

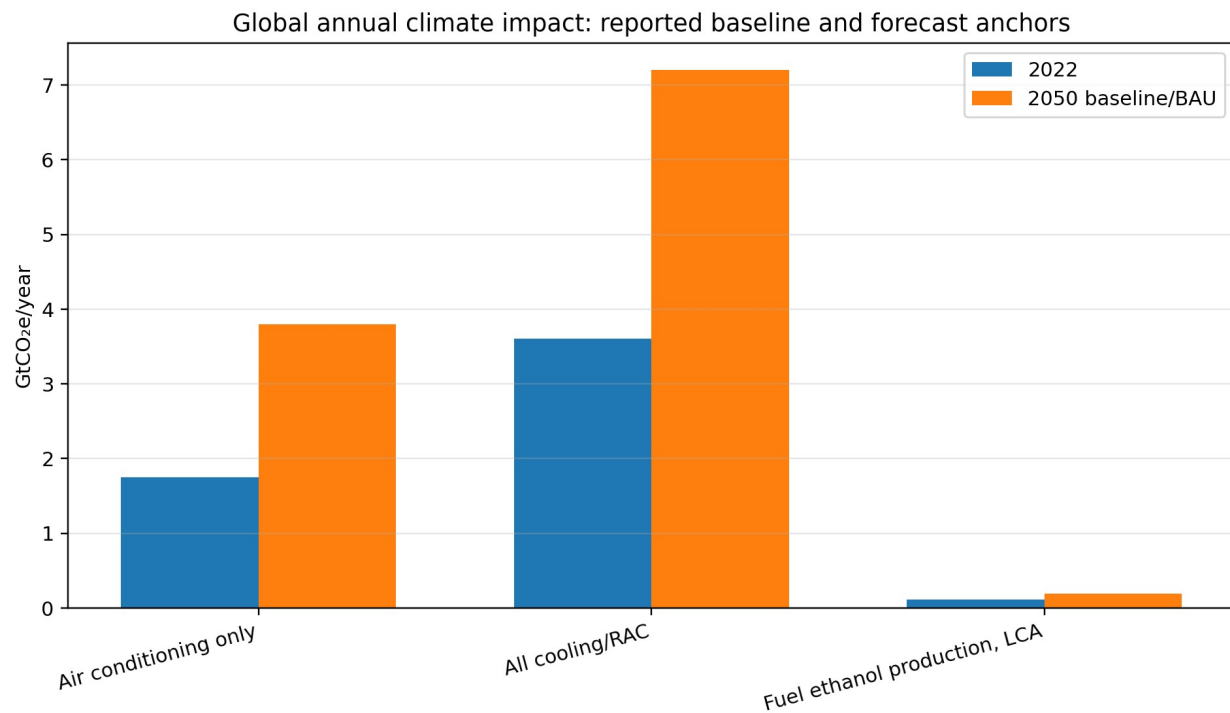


Figure 2. Global annual climate impact: baseline and 2050 anchors.

The global result is clear: RAC and cooling dominate ethanol production in total climate impact. In 2022, AC alone was approximately 1.75 GtCO<sub>2</sub>e and all cooling/RAC was approximately 3.6 GtCO<sub>2</sub>e. Using the 2025 world ethanol production value of 32 billion gallons and the published 52.4 gCO<sub>2</sub>e/MJ ethanol life-cycle intensity, fuel ethanol production corresponds to roughly 0.13 GtCO<sub>2</sub>e/year. Even if ethanol grows after 2025, its climate impact remains far below the forecasted climate load of AC and all cooling/RAC systems.

The reason is scale. One ethanol plant may be a visible industrial source, but RAC is a distributed global network of appliances. Every AC and refrigerator individually appears small, yet the total system creates electricity demand, peak load, fossil power generation and refrigerant leakage.

## 7. Per-Unit Comparison

Table 3. Per-unit climate comparison

case	energy_CO2e_kg	refrigerant_CO2e_kg	ethanol_or_biogenic_CO2_kg	total_CO2e_kg
1 AC, 24 h	16.02	0.137	0.000	16.16
1 AC, 8 h night	5.340	0.137	0.000	5.477
1 refrigerator, 24 h	0.668	0.004	0.000	0.671
1 L ethanol production	1.106	0.000	0.750	1.106

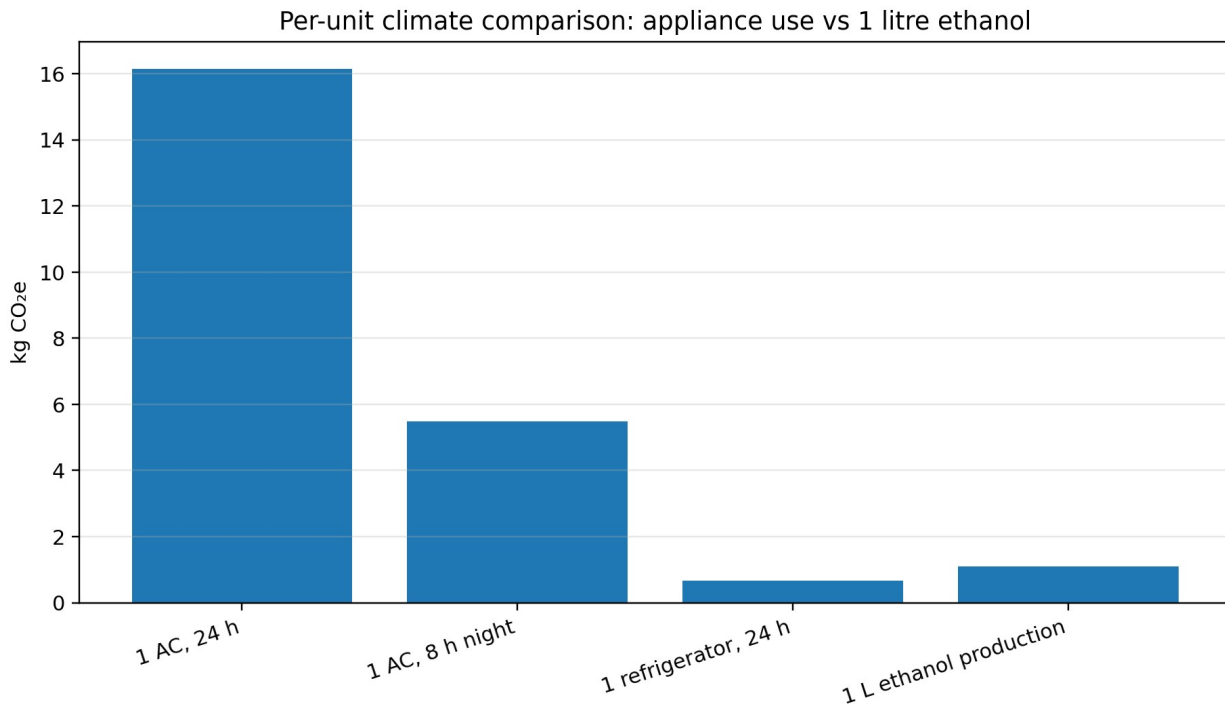


Figure 3. Per-unit climate comparison: appliance use versus 1 litre ethanol production.

A 1.5-ton AC running for 24 hours is estimated at roughly 16.2 kgCO<sub>2</sub>e using the global electricity factor of 445 gCO<sub>2</sub>/kWh plus a daily allocation of R-410A leakage. A refrigerator running for 24 hours is estimated at about 0.67 kgCO<sub>2</sub>e in an older HFC-134a leakage case. A modern hydrocarbon refrigerator would have even lower direct refrigerant climate impact. One litre of ethanol is about 1.1 kgCO<sub>2</sub>e using the 52.4 gCO<sub>2</sub>e/MJ life-cycle intensity and 21.1 MJ/L energy content. In addition, the plant physically releases about 0.75 kg of biogenic fermentation CO<sub>2</sub> per litre unless captured.

Therefore, for a simple functional-unit test, one AC running for a full day is much more climate-polluting than producing one litre of ethanol. A refrigerator running for one day is lower than one litre ethanol production in climate-accounting terms, but refrigerators run every day for many years, which makes their lifetime electricity demand important.

## 8. SOx, NOx, VOC and PM2.5 Screening Results

The following charts show screening estimates, not measured global emissions. For AC and refrigerator, the pollutants are not emitted by the appliance inside the room; they are mainly emitted at power plants supplying electricity. For ethanol, the values shown here are plant heat-stage screening estimates from natural-gas boiler-style factors and do not include farming, fertilizer, transport or uncontrolled process vents.

Table 4. Screening pollutant estimates per functional unit

pollutant	1 AC, 24 h_g	1 refrigerator, 24 h_g	1 L ethanol plant heat stage_g
SO2/SOx	16.20	0.675	0.002
NOx	19.80	0.825	0.360
VOC	1.080	0.045	0.020
PM2.5	1.440	0.060	0.028

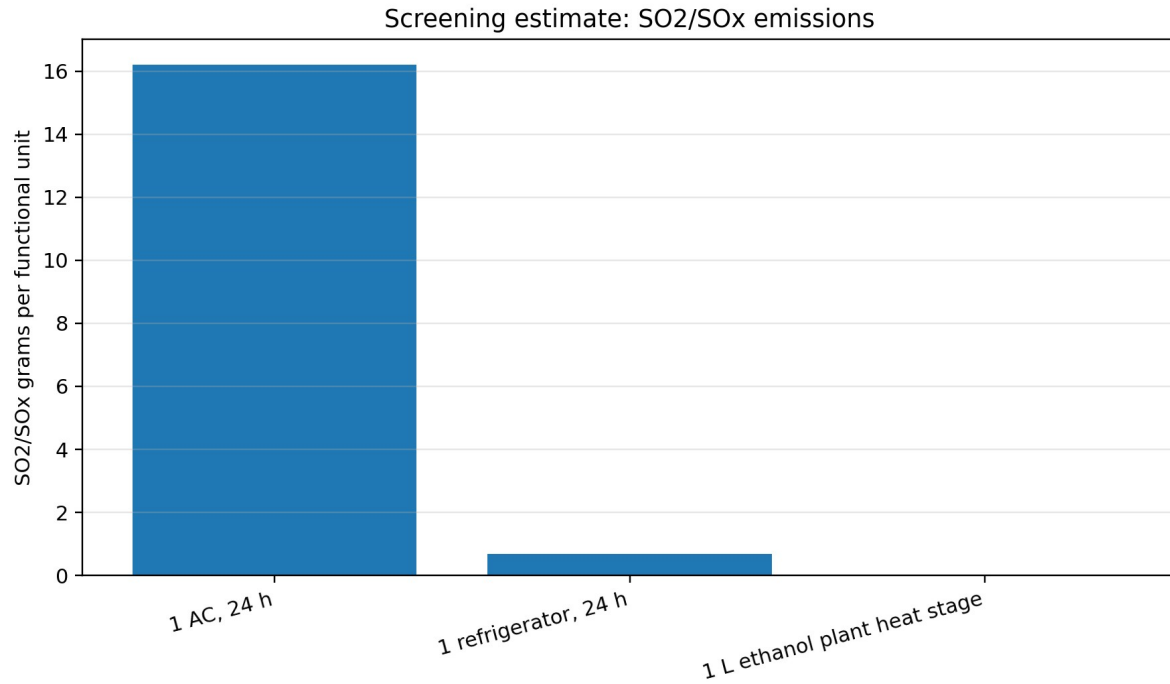


Figure 4. Screening estimate for SO2/SOx.

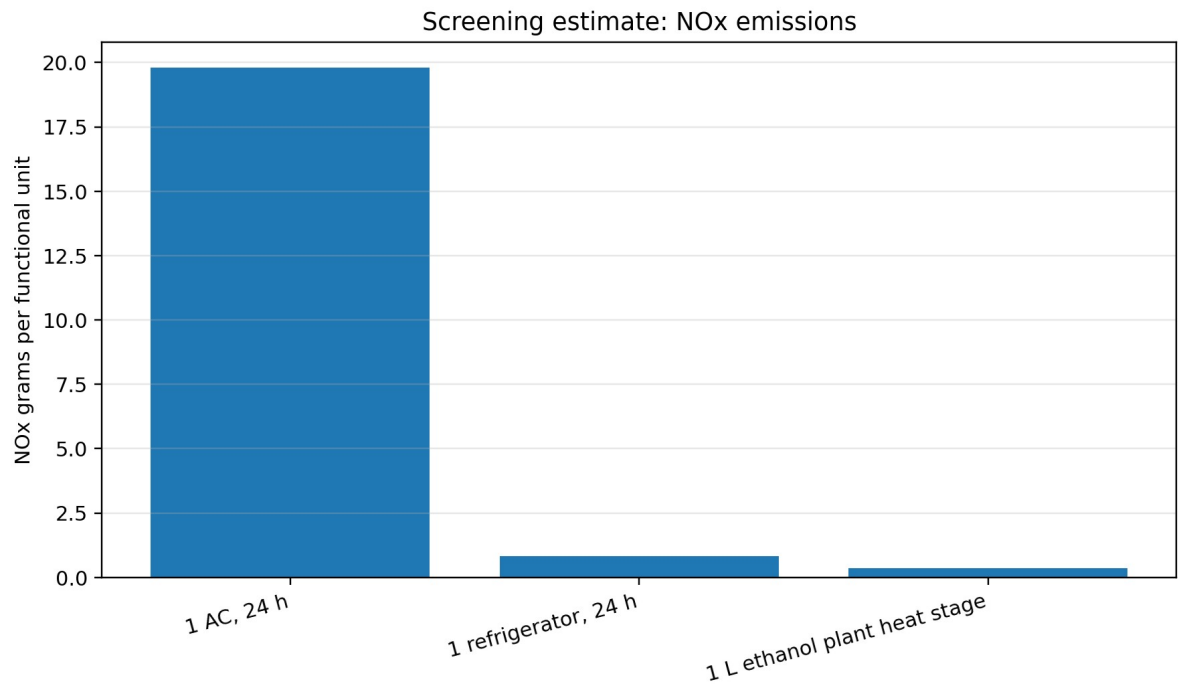


Figure 5. Screening estimate for NOx.

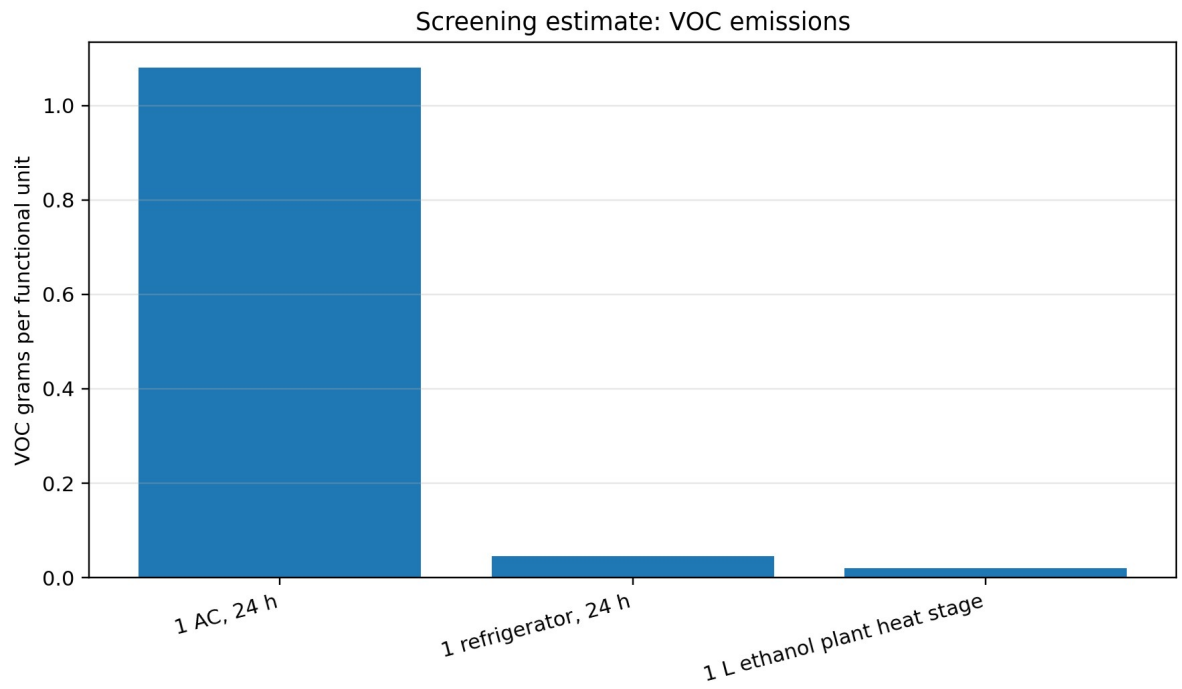


Figure 6. Screening estimate for VOC.

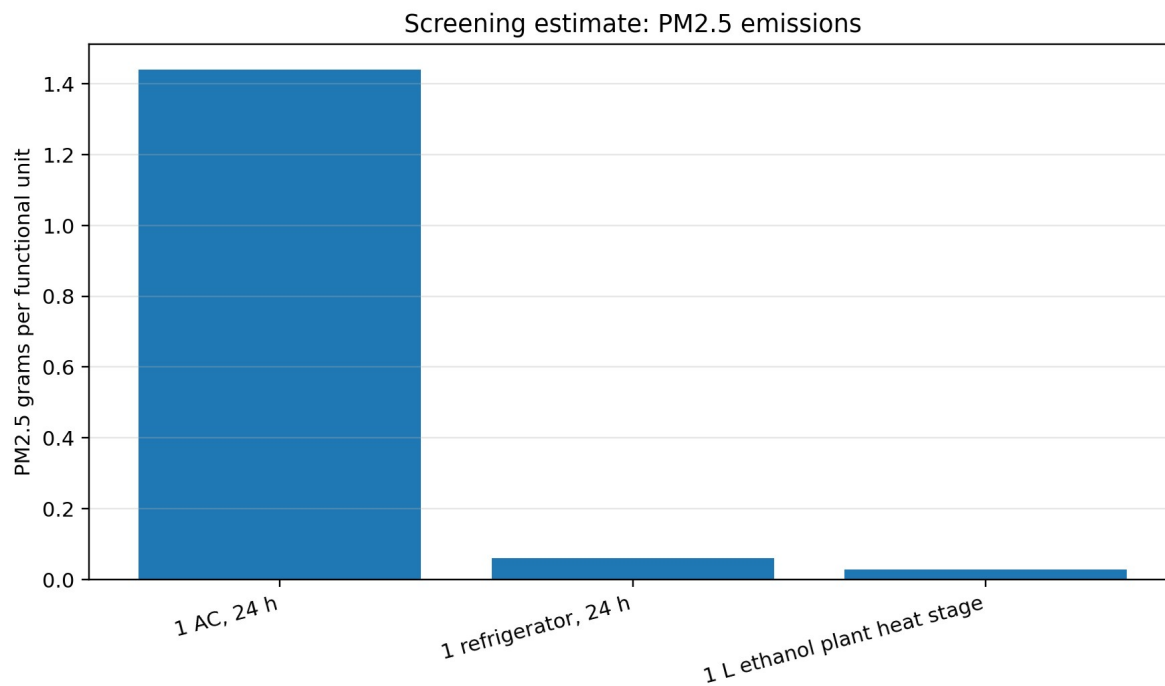


Figure 7. Screening estimate for PM2.5.

The screening model shows that the AC dominates power-sector SOx and NOx per day because it consumes much more electricity than a refrigerator. Ethanol plant heat-stage pollutant values per litre look smaller in this simplified chart, but this does not mean ethanol plants are harmless. The major local pollution danger of ethanol plants is wastewater, high-strength stillage/vinasse, odor, high biological and chemical oxygen demand, and process VOC release if control systems are weak.

## 9. Global Warming Potential of Refrigerants

Air-conditioning climate impact split (IIR model)

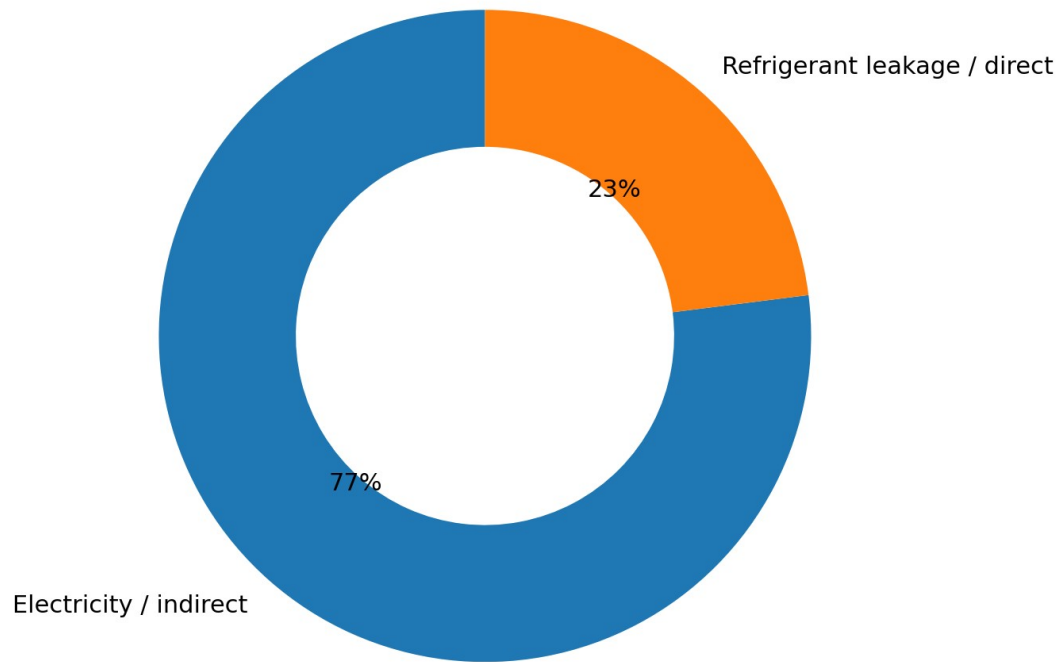


Figure 8. AC climate impact split: indirect electricity and direct refrigerant leakage.

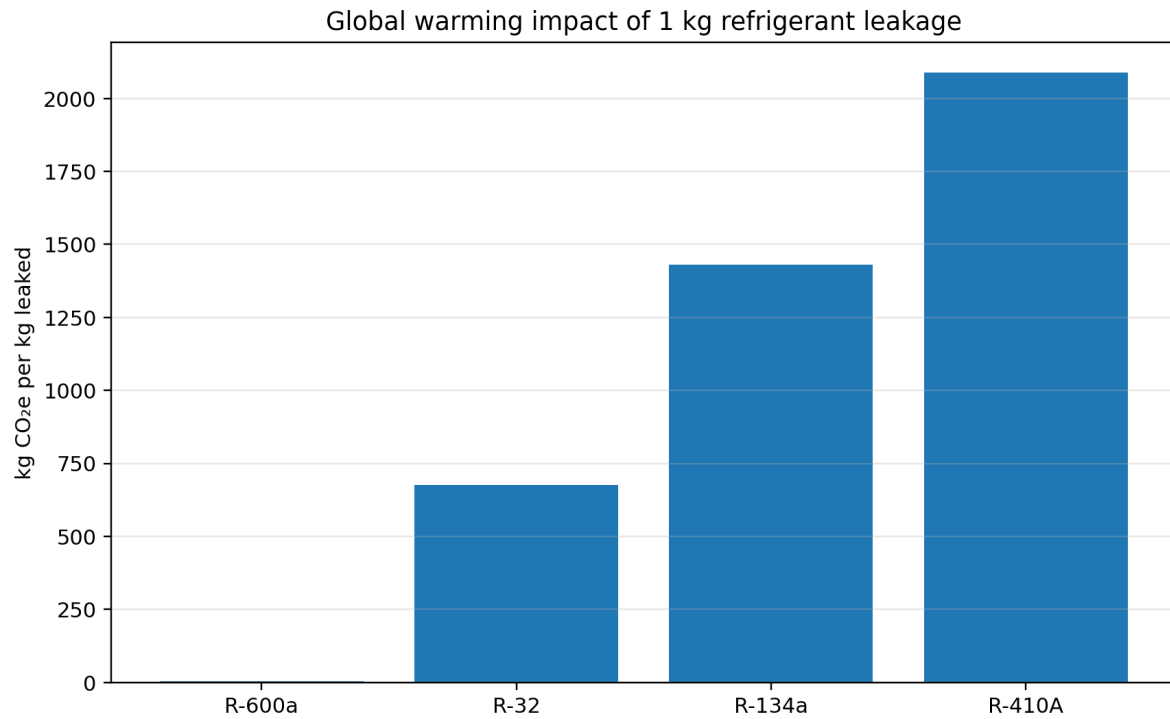


Figure 9. Global warming impact if 1 kg of refrigerant leaks.

Refrigerants make RAC dangerous because a small mass can create a large climate effect. For example, one kilogram of R-410A leakage is equivalent to roughly 2,088 kilograms of CO<sub>2</sub>e. R-134a is about 1,430 kgCO<sub>2</sub>e per kg leaked, while R-32 is lower but still high at about 675 kgCO<sub>2</sub>e per kg leaked. Modern hydrocarbons such as R-600a have much lower GWP, but safety and flammability requirements must be managed.

This is why ACs and refrigerators are not only electricity devices. They are also chemical-storage devices. Poor installation, bad servicing, informal gas refilling and improper disposal can convert a cooling appliance into a high-GWP leakage source.

## 10. Ethanol Production Pollution Beyond CO<sub>2</sub>

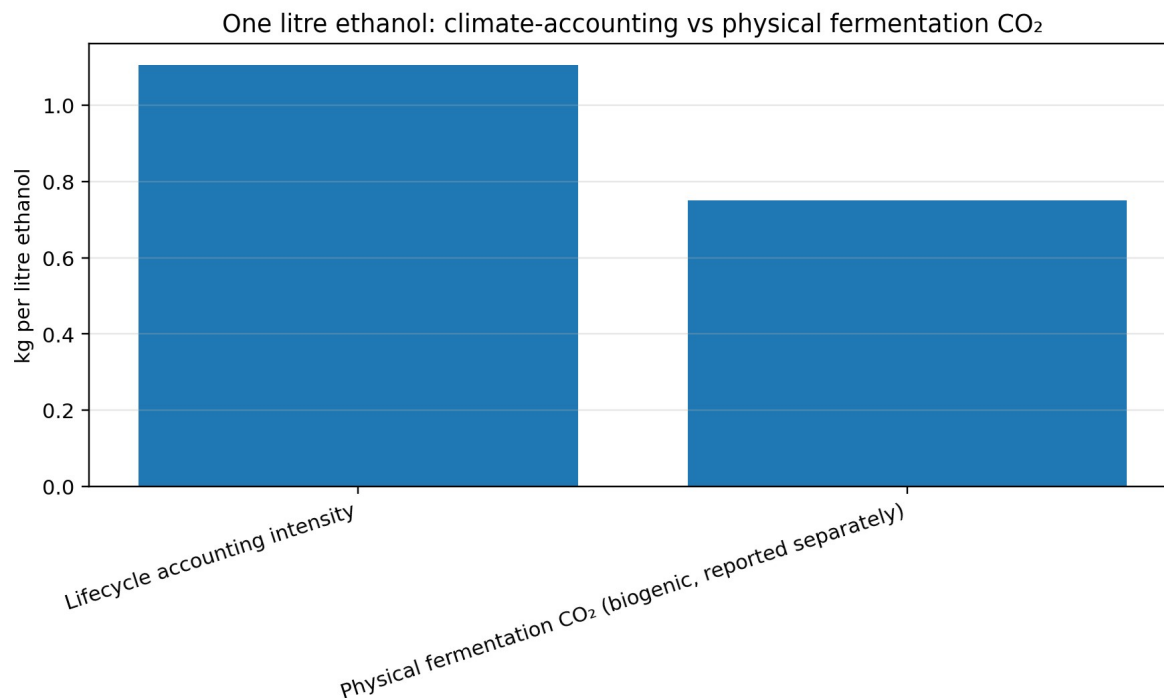


Figure 10. One litre ethanol: life-cycle CO<sub>2</sub>e and physical fermentation CO<sub>2</sub>.

Ethanol is different from RAC because its pollution is concentrated at production facilities and agricultural supply chains. The fermentation reaction converts sugar into ethanol and CO<sub>2</sub>, so a plant physically emits fermentation CO<sub>2</sub>. Because the carbon came from biomass, climate inventories usually treat this CO<sub>2</sub> differently from fossil CO<sub>2</sub>, but from a plant-stack perspective it is still a real gas stream. This makes ethanol plants attractive for carbon capture because the fermentation CO<sub>2</sub> stream can be relatively pure.

The more serious non-climate issue is wastewater. Distilleries are reported in the literature as among the more polluting industries because fermentation and distillation generate large volumes of high-strength liquid effluents. Vinasse/stillage can contain high organic load, color, odor, nutrients and salts. If untreated, it can reduce water quality, cause oxygen depletion and damage aquatic ecosystems. Therefore, ethanol is not automatically clean. It is only environmentally better when feedstock sourcing, energy, water use, effluent treatment and carbon capture are properly managed.

## 11. Final Test: 1 AC + 1 Refrigerator Running a Full Day

Using the global-average electricity factor and conservative high-GWP refrigerant assumptions, one 1.5-ton AC running for 24 hours plus one refrigerator running for 24 hours emits approximately 16.83 kgCO<sub>2</sub>e/day.

Breakdown: AC full-day operation is approximately 16.16 kgCO<sub>2</sub>e/day; refrigerator operation is approximately 0.67 kgCO<sub>2</sub>e/day. Together, this daily household cooling load equals roughly 15.2 litres of ethanol production on a life-cycle CO<sub>2</sub>e basis.

Danger interpretation: the AC is far more dangerous than the refrigerator on a daily climate basis because it consumes much more electricity and usually contains a larger refrigerant charge. The refrigerator is less intense per day, but it runs continuously throughout the year; old refrigerators with inefficient compressors or HFC refrigerants can become important lifetime pollution sources. The most dangerous part of both appliances is not visible smoke; it is indirect power-plant emissions and refrigerant leakage.

## 12. Discussion: Which Is More Harmful?

If the metric is global warming, RAC is more harmful globally than ethanol production because its annual emissions are already in the gigatonne range and are forecast to rise strongly without intervention. If the metric is local industrial pollution, ethanol plants can be more harmful near the production site, especially through wastewater, odor, VOC releases, high-COD effluent, boiler emissions and feedstock-related impacts. Thus, the correct conclusion is not one universal winner; the harmfulness depends on the pollution pathway.

From a policy and engineering perspective, the mitigation routes are different. RAC needs high-efficiency appliances, clean power, better building design, passive cooling, low-GWP refrigerants, skilled servicing, leak testing and safe end-of-life recovery. Ethanol needs low-carbon process heat, renewable electricity, efficient distillation, wastewater treatment, feedstock optimization, reduced fertilizer emissions and carbon capture of fermentation CO<sub>2</sub>.

## 13. Limitations

- The global RAC forecast uses public anchor points rather than a full integrated assessment model.
- SO<sub>x</sub>, NO<sub>x</sub>, VOC and PM<sub>2.5</sub> results are screening estimates and should not be treated as regulatory inventories.
- The ethanol LCA value is based mainly on corn ethanol literature; sugarcane, molasses and cellulosic ethanol can differ significantly.
- Manufacturing emissions and end-of-life appliance disposal are not included in the main daily appliance test.
- Local grid electricity factors can change results strongly; the code is designed so users can replace the global factor with a regional value.

## 14. Conclusion

The data-supported conclusion is that refrigeration and air-conditioning systems are the larger global climate concern, while ethanol plants are a concentrated industrial pollution concern. In 2022, AC alone was around 1.75 GtCO<sub>2</sub>e, and all cooling/RAC was roughly 3.6 GtCO<sub>2</sub>e. By 2050, cooling emissions could reach 7.2 GtCO<sub>2</sub>e under business-as-usual conditions, while a sustainable cooling pathway could reduce this to about 2.6 GtCO<sub>2</sub>e. Global fuel ethanol production, even at 32 billion gallons/year, is closer to the low hundreds of million tonnes CO<sub>2</sub>e/year when modelled with a 52.4 gCO<sub>2</sub>e/MJ life-cycle intensity.

At the household test level, one AC running for a full day emits about 16.2 kgCO<sub>2</sub>e, one refrigerator about 0.67 kgCO<sub>2</sub>e, and one litre of ethanol production about 1.1 kgCO<sub>2</sub>e on a life-cycle basis. Therefore, one full-day AC run is approximately fifteen times more climate-polluting than producing one litre of ethanol. However, ethanol production can be more dangerous locally if wastewater and VOCs are poorly controlled. The best final decision is: RAC is the bigger global warming risk; ethanol plants are the bigger local industrial water-pollution risk.

## 15. Declarations and Availability Statements

### 15.1 Author Information

Tarun is an independent researcher based in India with an interest in data-driven environmental analysis, AI/ML-assisted research workflows, and reproducible Python-based modelling. The author is not affiliated with any company for this work.

### 15.2 Data and Code Availability

The Python forecasting model, CSV data tables, generated chart files, and supplementary research package are available through a public GitHub repository and archived through Zenodo. GitHub repository: <https://github.com/krtarunsingh/ac-rac-ethanol-emissions-study>; Zenodo DOI: <https://doi.org/10.5281/zenodo.21021495>. The analytical files prepared for release include `forecast_and_pollution_model.py`, `forecast_timeseries.csv`, `global_forecast_comparison.csv`, `per_unit_co2e_comparison.csv`, `per_unit_screening_pollutants.csv`, and generated figure PNG files.

### 15.3 Funding Statement

This research received no external funding. The work was conducted independently using publicly available data and author-generated Python scripts.

### 15.4 Declaration of Competing Interest

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### 15.5 Ethics Statement

This study used publicly available aggregate data, published literature, and computational modelling only. It did not involve human participants, animal subjects, clinical data, private personal data, or field experiments. Therefore, formal ethics approval was not required.

### 15.6 AI-use Disclosure

AI tools were used for language editing, structure improvement, article correction, formatting support, and code-drafting assistance. The author reviewed the manuscript, sources, assumptions, calculations, code logic, and conclusions and remains responsible for the final content.

### 15.7 Supplementary Material

The supplementary material should include the GitHub/Zenodo release package containing the manuscript source file, reproducible Python code, requirements file, CSV outputs, and all generated charts. EarthArXiv should receive the manuscript as one PDF, while supplementary code and data should be linked externally through GitHub and/or Zenodo.

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## Appendix A: Reproducible Python model

The complete Python file is provided separately as `forecast_and_pollution_model.py`. It contains the data anchors, assumptions, forecast calculations and chart-generation code.