





Kigali Sim: Open source simulation toolkit for modeling substances and policies related to the Montreal Protocol

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DOI: [10.21105/joss.10104](https://doi.org/10.21105/joss.10104)

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Submitted: 04 November 2025

Published: 08 May 2026

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Summary

Kigali Sim offers stock and flow modeling of Montreal Protocol-controlled substances. This includes hydrofluorocarbons (HFCs) at the center of the Kigali Amendment. These potent substances contribute to climate change through warming potentials much greater than carbon dioxide. Supporting a diverse community with heterogeneous programming expertise, this parallelized toolkit democratizes advanced computational tools by interoperating visual no-code rapid model development and a domain-specific language (DSL). Either through WebAssembly (WASM) or Java Virtual Machine (JVM), Kigali Sim affords portable, private, and rigorous simulation in support of history's most successful international environmental treaty, aiding both atmospheric science and policy development.

Statement of Need

Signed by all UN member states, the Montreal Protocol phased out 99% of ozone-depleting substances ([World Meteorological Organization, 2022](#)). Already the most successful international environmental treaty ([Molina & Zaelke, 2018](#)), its ambitious 2016 Kigali Amendment extends this multilateral framework and related international funding to hydrofluorocarbons (HFCs), potent substances which contribute significantly to climate change ([Birmpili, 2018](#); [Velders et al., 2009](#)). However, research and policy analysis for these substances involves modeling complex economic, technological, energy, and policy interactions ([MLF Staff, 2024](#)).

State of field

On the current public market, only the proprietary HFC Outlook offers a reusable full lifecycle model for the Montreal Protocol ([Gluckman Consulting, 2023](#)). Otherwise, organizations typically build private ad-hoc models, a multi-dataset process incorporating treaty-specific conventions ([MLF Staff, 2024](#)).

Contribution

With broad applicability to modeling of halocarbons following treaty conventions, Kigali Sim provides the first open source reusable lifecycle modeling toolkit focused on Montreal Protocol-controlled substances. It emerged after the Multilateral Fund for the Implementation of the Montreal Protocol (MLF) met the University of California Schmidt Center for Data Science

and Environment (DSE) during a 2023 presentation of an interactive simulation tool developed by DSE and their partners for a global plastics pollution treaty (A. Samuel Pottinger et al., 2024). From that initial conversation, co-design sessions in 2024 sought to consider game design-inspired techniques for participatory data science similar to that prior project (A. Samuel Pottinger et al., 2025) but within the Montreal Protocol's science and policy context. Kigali Sim's design ultimately focuses on reducing barriers to entry in modeling emissions, energy, consumption, equipment populations, trade, and policy (Multilateral Fund Secretariat, 2025). Finally, Kigali Sim was implemented by DSE in collaboration with MLF as well as users from various governments and supporting organizations (Kigali Sim Community, 2026).

Research impact statement

Kigali Sim serves Article 5 nations (United Nations, 1987b), Implementing Agencies, analysts, researchers, and related organizations. This includes National Ozone Units (NOUs) with limited resources (UNEP OzonAction, n.d.) for whom developing ad-hoc models may be burdensome. Though usage remains anonymized, more than a dozen nations and supporting organizations co-designed Kigali Sim over more than a year. This effort spanned scientists, analysts, and policy-makers. Participating in many international meetings (Executive Committee of the Multilateral Fund, 2025; Natarajan et al., 2025; Pacific Island Countries Ozone Officers Network, 2025; South East Asia and the Pacific Ozone Officers Network, 2025), multiple governments publicly acknowledge contributing to this community project (Kigali Sim Community, 2026). This open source effort also received media coverage (Shaban, 2025).

Implementation

Migrated from an original JavaScript implementation for performance and portability, Kigali Sim runs via JVM or browser-based WASM through TeaVM (Konshin, 2024). Without transmitting simulations to external servers, both modalities enable privacy-preserving parallel local computation.

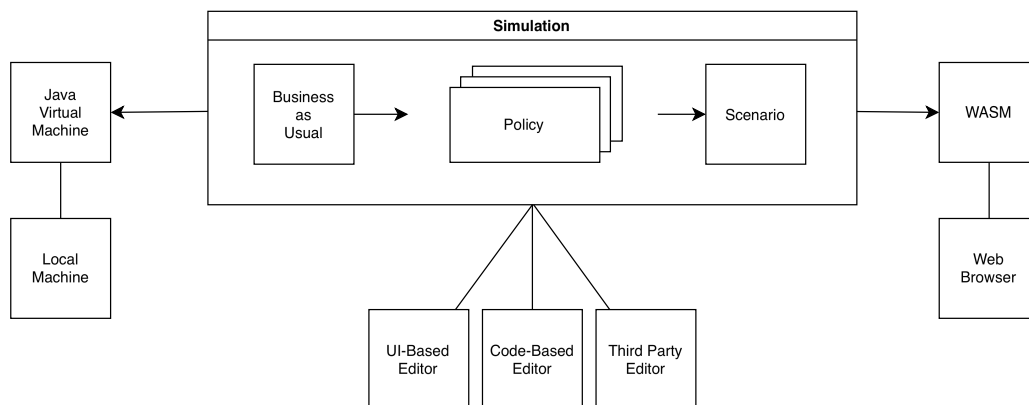


Figure 1: Diagram describing multi-modal execution in which simulations run across different platforms with simulation results displayed via a web browser.

Software Design

Kigali Sim's engine supports domain experts in atmospheric science and environmental policy with varied programming expertise through a dual-interface design.

Flexible engine

Countries and supporting organizations work with varied information from trade records to industry census data. Kigali Sim pushes information from known to unknown stocks, providing automated unit conversions dependent on equipment properties. As opposed to a unidirectional structure with a single entry-point, this propagates limited user-provided values through substance flows and lifecycles to estimate unmeasured quantities. It then layers complex policy interventions such as permitting and recycling on top of this “business as usual” scenario.

A graph structure depicted in Figure 2 achieves this flexibility. Equipment characteristics allow the engine to calculate between sales, population, consumption, and emissions. Given one of these values, the engine can calculate the value of the others through a traversal where equipment properties enable moving between edges connecting variables. Note that all values can be outputs except exports which, under treaty trade attribution rules, cannot be fully inferred by the other values from the same country ([First Meeting of the Parties to the Montreal Protocol, 1989](#); [United Nations, 1987a](#)).

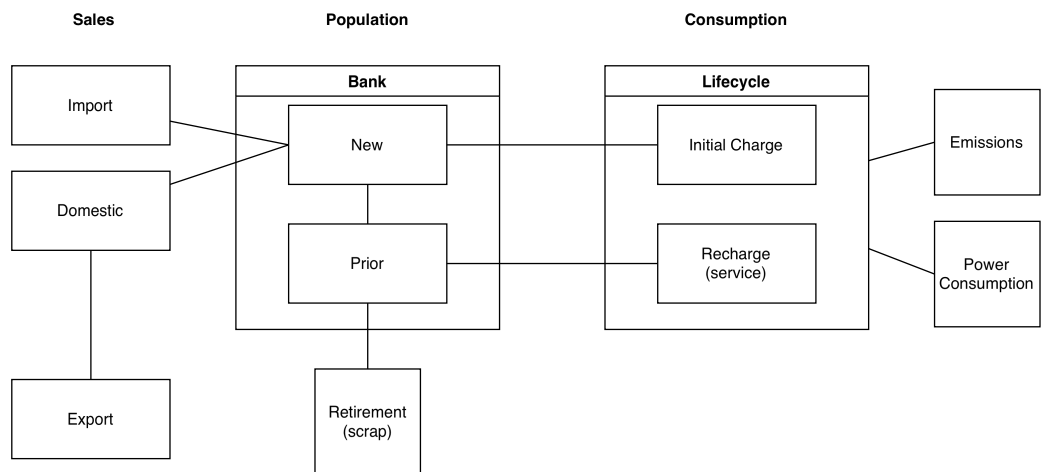


Figure 2: Bi-directional graph diagram for calculating between simulation variables using equipment properties.

Dual-interface design

Most simulations can be modified either with the UI-based editor or the code-based editor where changes in one reflect in the other. This may help bridge preferences and skill sets.

UI-based authoring

To support beginning programmers, the UI-based point-and-click editor acclimates users to Kigali Sim. This web interface exposes functionality through a 4-step Kishōtenketsu sequence ([Hayashida & Nutt, 2012](#)). This series of disclosures builds up the tool UI over time:

- **Introduction:** With vocabulary visible in the starting state for orientation but with controls disabled or hidden, the application specification button introduces the primary loop.
- **Development:** Specification of consumption offers first modeling decisions.
- **Twist:** The interface reveals that multiple scenarios can run with different policies, introducing the secondary loop.
- **Conclusion:** Specification of additional simulations for comparison continues using the mechanics first introduced in development.

Given the goal to introduce the user loops ([Guardiola, 2016](#)), this sequence only runs if the

user does not have a simulation loaded in the tool when opening the app like, for example, if they are visiting for the first time. GUI-based changes automatically translate to code run for immediate feedback and eventual transition to code-based authoring.

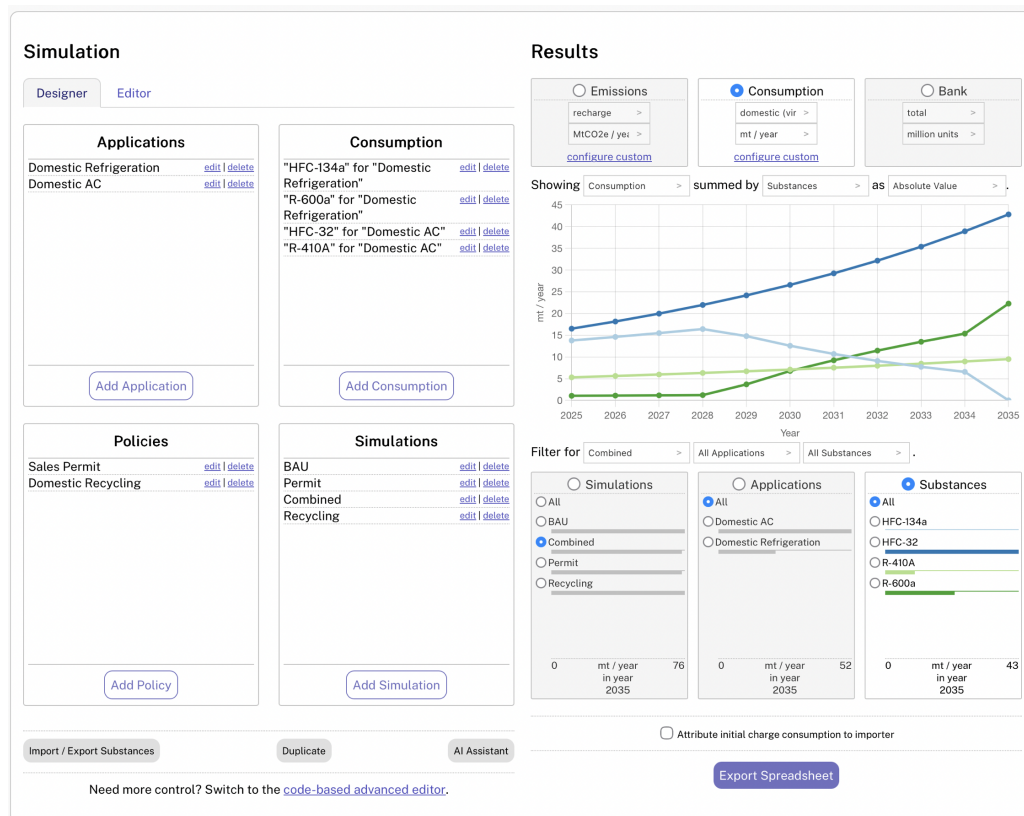


Figure 3: Screenshot of the UI-based editor modifying an example simulation.

Code-based authoring

Many Kigali Sim users do not identify as programmers. Prior empirical work suggests that domain experts with “limited programming knowledge” benefit from DSLs (Hoffmann et al., 2022). Therefore, we created the QubecTalk domain-specific language to facilitate expression of complex models in human-readable syntax. This DSL is inspired by HyperTalk (Wheeler, 2004). Mirrored by the UI-editor, QubecTalk speaks in treaty terminology, translating terms of art into simulations for improved usability (Rein et al., 2019). This also supports uncertainty quantification, conditional logic, and policy stacking. With optional AI assistant compatibility via the llms.txt specification (Howard, 2024), users may author scripts in a web-based programming portal (Appleton, 2022) or outside with direct JVM invocation.

Limitations and future work

Kigali Sim focuses only on the Montreal Protocol. First, it can model energy consumption but only estimates direct emissions. Users may use Kigali Sim to calculate indirect emissions by exporting consumption data from the tool to join with outside energy mix data (Ang & Su, 2016). Additionally, it embodies Montreal Protocol definitions such as trade attribution rules (First Meeting of the Parties to the Montreal Protocol, 1989; United Nations, 1987a) and it will receive updates as official guidance changes in the future (Multilateral Fund Secretariat, 2025). Therefore, substances not subject to Montreal Protocol conventions are out of scope.

Acknowledgments

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Thanks

Thank you to Amanda Anderson-You, Tina Birmibili, Matt Fisher, Ava Hu, Kevin Koy, Douglas McCauley, Alejandro Ramirez-Pabon, Frederico San Martini, Annie Snyder, Suzanne Spencer, and Elina Yuen. Thank you to runtime dependencies:

- Ace Editor ([Ajax.org, 2010](https://ace.c9.io/))
- ANTLR ([Parr et al., 2014](https://www.antlr.org/))
- Apache CSV ([Apache Software Foundation, 2024](https://commons.apache.org/proper/commons-csv/))
- Chart.js ([Chart.js Contributors, 2024](https://www.chartjs.org/))
- ColorBrewer ([Harrower & Brewer, 2013](https://colorbrewer2.org/))
- D3 ([Bostock et al., 2011](https://d3js.org/))
- Papa Parse ([Holt, 2024](https://papaparse.com/))
- Prism.js ([Verou, 2024](https://prismjs.com/))
- QUnit ([OpenJS Foundation, 2024](https://qunitjs.com/))
- Tabby ([Ferdinandi, 2024](https://github.com/teuchocloud/tabby))
- Webpack ([Webpack Contributors, 2024](https://webpack.js.org/))
- TeaVM ([Konshin, 2024](https://teavm.com/)).

Also, thank you to drawio ([JGraph & draw.io, 2023](https://draw.io/)) and valued community members ([Kigali Sim Community, 2026](https://kigali-sim.com/)).

Funding

Ongoing funding and maintenance provided by the Eric and Wendy Schmidt Center for Data Science and the Environment at UC Berkeley. We have no conflicts to disclose.

AI usage disclosure

As described in-repo, AI providers used with constrained tasks and strict human review:

- Claude ([Anthropic, 2025](https://www.anthropic.com/claude))
- Copilot ([GitHub et al., 2025](https://github.com))
- IntelliJ ([Sokolov, 2024](https://www.jetbrains.com/idea/))
- Replit ([Replit, 2025](https://replit.com)).

No substantial LLM use in original JavaScript implementation.

References

- Ajax.org. (2010). *Ace: The High Performance Code Editor for the Web*. <https://ace.c9.io/>
- Ang, B. W., & Su, B. (2016). Carbon emission intensity in electricity production: A global analysis. *Energy Policy*, 94, 56–63. <https://doi.org/10.1016/j.enpol.2016.03.038>
- Anthropic. (2025). *Claude*. <https://www.anthropic.com/claude>
- Apache Software Foundation. (2024). *Apache Commons CSV*. <https://commons.apache.org/proper/commons-csv/>
- Appleton, M. (2022). *Programming Portals*. <https://maggieappleton.com/programming-portals>

- Birmipili, T. (2018). Montreal Protocol at 30: The governance structure, the evolution, and the Kigali Amendment. *C. R. Geosci.*, 350(7), 425–431. <https://doi.org/10.1016/j.crte.2018.09.002>
- Bostock, M., Ogievetsky, V., & Heer, J. (2011). D³ Data-Driven Documents. *IEEE Transactions on Visualization and Computer Graphics*, 17(12), 2301–2309. <https://doi.org/10.1109/TVCG.2011.185>
- Chart.js Contributors. (2024). *Chart.js: Simple yet flexible JavaScript charting library*. <https://www.chartjs.org/>
- Executive Committee of the Multilateral Fund. (2025). *Report of the Ninety-Seventh Meeting of the Executive Committee*. United Nations Environment Programme. <https://www.multilateralfund.org/api/drupal-documents/download/file/8f132cb8-e84c-418e-88c2-e55d9798a33d?filename=9702.pdf>
- Ferdinandi, C. (2024). *Tabby: Lightweight, accessible vanilla JS toggle tabs*. <https://github.com/cferdinandi/tabby>
- First Meeting of the Parties to the Montreal Protocol. (1989). *Decision I/12A: Clarification of terms and definitions: Controlled substances (in bulk)* (Report of the First Meeting of the Parties No. UNEP/OzL.Pro.1/5). United Nations Environment Programme. <https://ozone.unep.org/treaties/montreal-protocol/meetings/first-meeting-parties/decisions/decision-i12a-clarification-terms-and-definitions-controlled-substances-bulk>
- GitHub, OpenAI, & Microsoft. (2025). *GitHub copilot*. <https://github.com/features/copilot>
- Gluckman Consulting. (2023). *HFC Outlook: Description and Specification*. <https://www.gluckmanconsulting.com/wp-content/uploads/2023/11/HFC-Outlook-Description-and-Specification.pdf>
- Guardiola, E. (2016). The Gameplay Loop: a Player Activity Model for Game Design and Analysis. *Proceedings of the 13th International Conference on Advances in Computer Entertainment Technology*. <https://doi.org/10.1145/3001773.3001791>
- Harrower, M., & Brewer, C. A. (2013). ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps. *The Cartographic Journal*, 40(1), 27–37. <https://doi.org/10.1179/000870403235002042>
- Hayashida, K., & Nutt, C. (2012). *The Structure of Fun: Learning from Super Mario 3D Land's Director*. <https://www.gamedeveloper.com/design/the-structure-of-fun-learning-from-i-super-mario-3d-land-i-s-director>
- Hoffmann, B., Urquhart, N., Chalmers, K., & Guckert, M. (2022). An empirical evaluation of a novel domain-specific language—modelling vehicle routing problems with Athos. *Empirical Software Engineering*, 27(7), 1–44. <https://doi.org/10.1007/s10664-022-10210-w>
- Holt, M. (2024). *Papa Parse*. <https://www.papaparse.com/>
- Howard, J. (2024). *The //lms.txt file*. Answer.AI. <https://llmstxt.org/>
- JGraph, & draw.io. (2023). Jgraph/Drawio: Draw.io is a JavaScript, client-side editor for general diagramming and whiteboarding. In *GitHub*. GitHub, Inc. <https://github.com/jgraph/drawio>
- Kigali Sim Community. (2026). *Kigali Sim Credits*. <https://kigalisim.org/guide/credits.html>
- Konshin, A. (2024). *TeaVM: Build Fast, Modern Web Apps in Java*. <https://teavm.org/>
- MLF Staff. (2024). *Preparation of Kigali HFC implementation plans*. Secretariat of the Multilateral Fund for the Implementation of the Montreal Protocol; Presentation at 46th Meeting of the Open-Ended Working Group of the Parties to the Montreal Protocol. <https://ozone.unep.org/system/files/documents/OEWG%20KIP%20Side%20Event%2046.pdf>

20MLFS_070824.pdf

- Molina, M., & Zaelke, D. (2018). Triumph by treaty. *Our Planet*, 2017(4), 18–19. <https://doi.org/10.18356/e300f295-en>
- Multilateral Fund Secretariat. (2025). *Multilateral Fund for the Implementation of the Montreal Protocol Policies, Procedures, Guidelines and Criteria*. https://www.multilateralfund.org/api/drupal-documents/download/file/4286a8ec-a765-493c-bc0a-2155717410b8?filename=policies_combined.pdf
- Natarajan, B., Pottinger, S., Bruyn, M. de, & Birmpili, T. (2025). *HFC consumption modelling tool: Consumption assessment and projections*. Multilateral Fund Secretariat. https://ozone.unep.org/system/files/documents/MLF_HFC_ModellingAgenda.pdf
- OpenJS Foundation. (2024). *QUnit*. <https://qunitjs.com/>
- Pacific Island Countries Ozone Officers Network. (2025). *Final Agenda: Network Meeting of Pacific Island Countries National Ozone Officers*. UNEP OzonAction. https://admin.ozonactionmeetings.org/system/files/2025-09/Final%20Agenda_Network%20Meeting%20Fiji%20Sep%2025.pdf?token=-4AgUCZDrrxpNhhPHCSk_yjRE3xPsrZkDHS6vQOPZo×tamp=1767648637
- Parr, T., Harwell, S., & Fisher, K. (2014). Adaptive LL(*) parsing: The power of dynamic analysis. *Proceedings of the 2014 ACM International Conference on Object Oriented Programming Systems Languages & Applications*, 579–598. <https://doi.org/10.1145/2660193.2660202>
- Pottinger, A. Samuel, Biyani, N., Geyer, R., McCauley, D. J., Bruyn, M. de, Morse, M. R., Nathan, N., Koy, K., & Martinez, C. (2025). *Using Game Design to Inform a Plastics Treaty: Fostering Collaboration between Science, Machine Learning, and Policymaking*. <https://doi.org/10.48550/arXiv.2312.11359>
- Pottinger, A. Samuel, Geyer, R., Biyani, N., Martinez, C. C., Nathan, N., Morse, M. R., Liu, C., Hu, S., Bruyn, M. de, Boettiger, C., Baker, E., & McCauley, D. J. (2024). Pathways to reduce global plastic waste mismanagement and greenhouse gas emissions by 2050. *Science*, 386(6726), 1168–1173. <https://doi.org/10.1126/science.adr3837>
- Rein, P., Taeumel, M., & Hirschfeld, R. (2019). Towards Empirical Evidence on the Comprehensibility of Natural Language Versus Programming Language. *Design Thinking Research*, 111–126. https://doi.org/10.1007/978-3-030-28960-7_7
- Replit. (2025). *Replit AI*. <https://replit.com/ai>
- Shaban, B. (2025). *UC Berkeley offers tech to United Nations to fight global pollution*. NBC Bay Area. <https://www.nbcbayarea.com/news/local/uc-berkeley-tech-united-nations-pollution/3994242/>
- Sokolov, A. (2024). AI Assistant in JetBrains IDE: Insights and Challenges. *Proceedings of the 1st ACM International Conference on AI-Powered Software*, 178. <https://doi.org/10.1145/3664646.3676273>
- South East Asia and the Pacific Ozone Officers Network. (2025). *List of Participants*. UNEP OzonAction. https://admin.ozonactionmeetings.org/system/files/2025-12/List%20of%20participants_0.pdf?token=EPR0bhi2ZJMA6r5XChspmPU174-eovkf7b6IKbdJHHg×tamp=1766625365
- UNEP OzonAction. (n.d.). *National Ozone Officers' Capacity Building*. United Nations Environment Programme; Web page. <https://www.unep.org/ozonaction/national-ozone-officers-capacity-building>
- United Nations. (1987a). *Montreal Protocol on Substances that Deplete the Ozone Layer, Article 3: Calculation of control levels*. <https://ozone.unep.org/treaties/montreal-protocol/>

[articles/article-3-calculation-control-levels](#)

United Nations. (1987b). *Montreal Protocol on Substances that Deplete the Ozone Layer, Article 5: Special situation of developing countries*. <https://ozone.unep.org/treaties/montreal-protocol/articles/article-5-special-situation-developing-countries>

Velders, G. J. M., Fahey, D. W., Daniel, J. S., McFarland, M., & Andersen, S. O. (2009). The large contribution of projected HFC emissions to future climate forcing. *Proc. Natl. Acad. Sci. U. S. A.*, *106*(27), 10949–10954. <https://doi.org/10.1073/pnas.0902817106>

Verou, L. (2024). *Prism*. <https://prismjs.com/>

Webpack Contributors. (2024). *Webpack*. <https://webpack.js.org/>

Wheeler, K. (2004). *HyperTalk: The Language for the Rest of Us*. <https://www.memoryhole.net/~kyle/papers/hypertalk.pdf>

World Meteorological Organization. (2022). *Scientific Assessment of Ozone Depletion 2022* (p. 509). GAW Report No. 278. ISBN: 978-9914-733-97-6