The energy module of FRIDA v2.1: endogenous investment and the timing of climate policy in the global energy system

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Model

Energy investment follows observed behaviour: supply–demand feedback and marginal costs, with no optimized or prescribed pathway.

Play with the model
frida.earth

Timing Matters

Early carbon tax and early subsidy together give the lowest warming: 2.16 °C median in 2100, against 3.16 °C without policy. All four policy medians stay above 2 °C. Negative emission technologies were not considered.

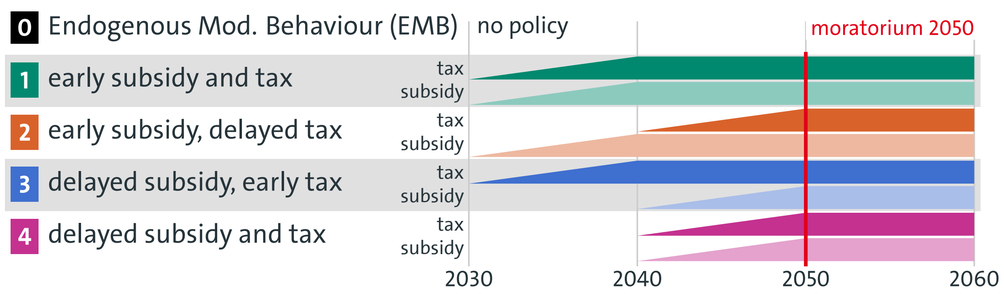
Harm and Opportunity

Abrupt policy can cause severe economic disruptions interacting with FRIDA's non-equilibrium economy. But successful climate policy can improve outcomes over the no policy baseline (EMB).

Motivation

- Optimizing IAMs prescribe rational planning, yet observed investment is often not optimal.
- FRIDA takes behaviour patterns as they are, in a fully coupled model of climate and humans.
- **Questions:** what do current behaviour patterns imply for future trajectories? How do timing and sequencing of carbon taxes and renewable subsidies change them?

Scenarios



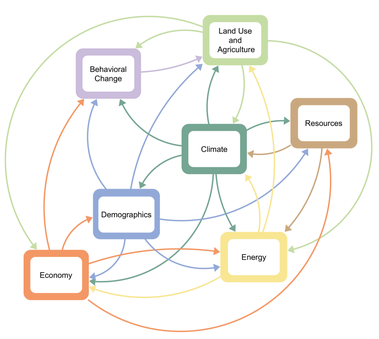
Carbon tax: ramps to 300 \$/t CO_2 over 10 years, starting 2030 or 2040.

Subsidy: solar, wind and hydropower installation, ramps to 75 % of installation cost over 10 years, starting 2030 or 2040, capped at 0.5 % of GDP each.

Moratorium: no new fossil investment from 2050.

EMB: endogenous model behaviour.

Endogenous investment



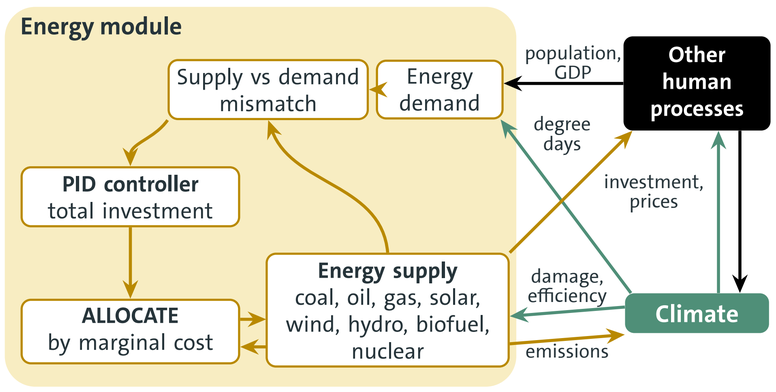
High-level modules of FRIDA. Schoenberg et al. (2025a), Fig. 2, CC BY 4.0.

FRIDA v2.1: global System Dynamics IAM, 1980–2150 (Schoenberg et al., 2025a).

Energy module: based on MIND (Edenhofer et al., 2005). New: investment, demand, nuclear, supply–demand balance.

Coupled to: economy (Grimeland et al., 2026), climate (Wells et al., 2026b), impacts (Wells et al., 2026a).

Behaviour: investors act only on information available at each time step, without foresight.

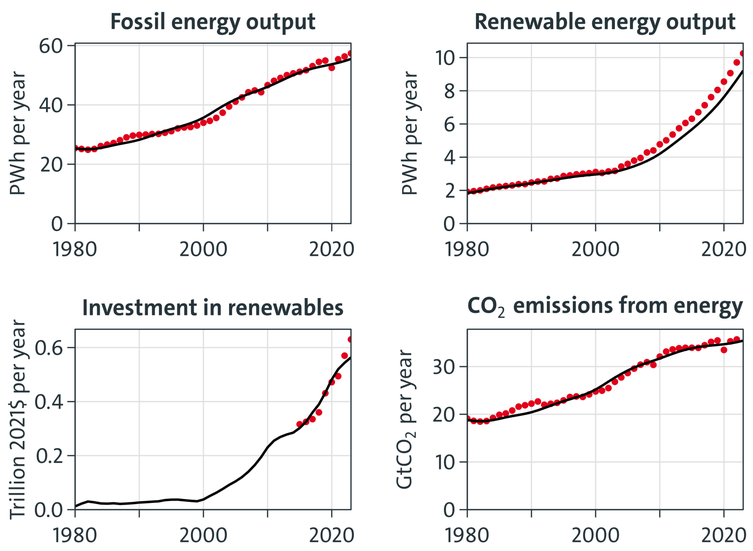


Feedbacks of the energy module, after Schoenberg et al. (2025a), Fig. 7.

- **Total investment:** PID control of supply–demand mismatch.
- **Allocation:** by marginal cost, with calibrated spread.
- **Marginal cost:** learning, stepping-on-toes, scarcity, integration, damage, policy.

Calibration and uncertainty

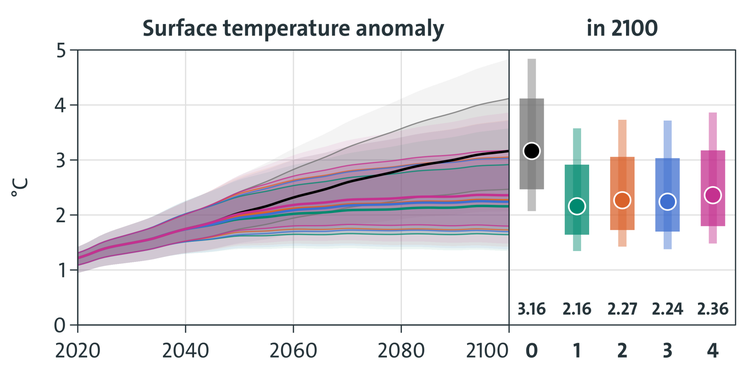
Calibrated to 53 time series, 1980–2023. Sobol sampling of uncertain parameters within calibration likelihood ranges: 100 000-member ensembles.



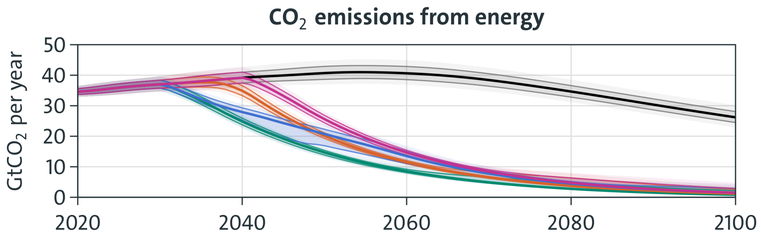
Observations (red dots) and calibrated default run (black line).

Climate

Without policy, median warming passes 3 °C by 2100. Early action on both instruments gives the lowest warming, but all policy medians stay above 2 °C.

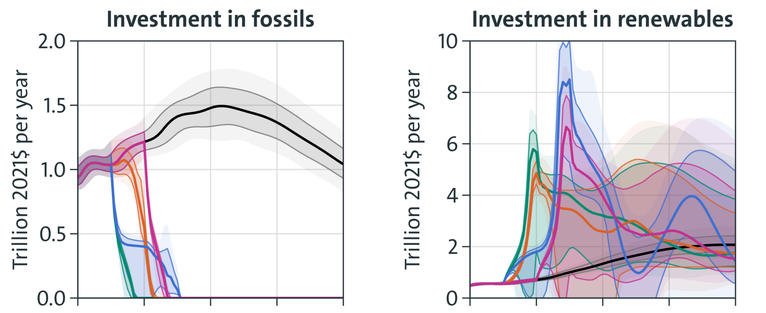


Medians (lines), 67 % and 95 % ensemble ranges (bands), in all scenario panels. Bars, numbered as in Scenarios: median (dot), 67 % (thick), 95 % (thin).



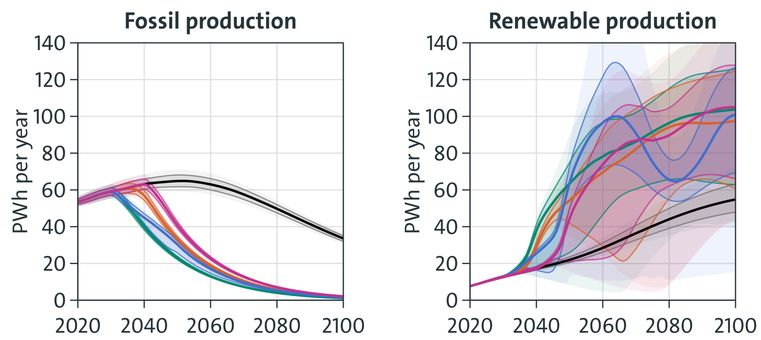
Investment sequencing

- **Subsidy first:** renewables grow before fossil shrinks.
- **Tax first:** fossil collapses, then renewables spike.



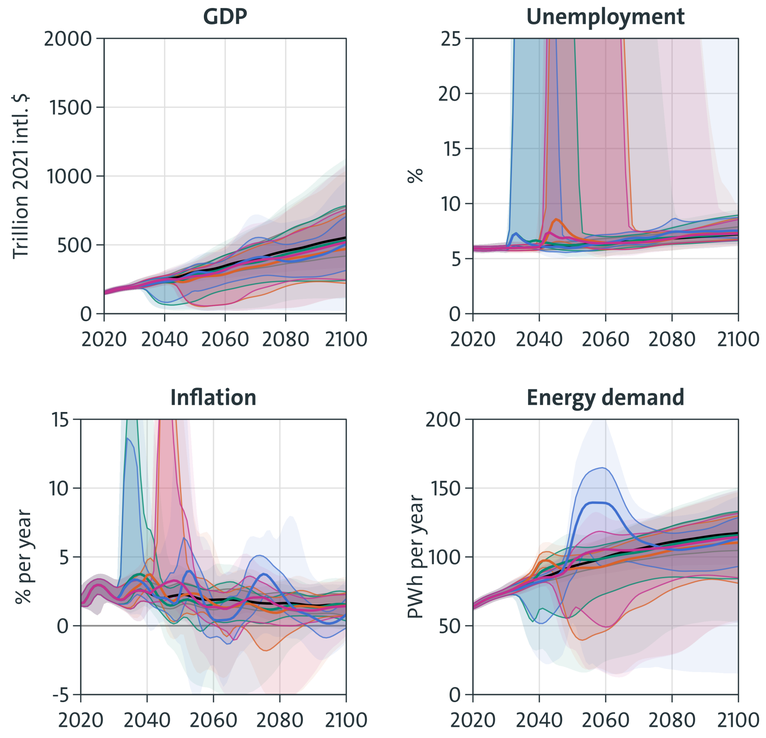
Energy production

Decarbonization is mainly substitution. Medians in 2100, policy vs EMB: fossil 1–2 vs 34 PWh, renewables 98–105 vs 55 PWh, demand 110–116 vs 117 PWh.



Macroeconomy and demand

- **Bad outcomes:** in each indicator's worst year, one in six members has GDP 64–81 % below EMB, unemployment 50–71 points or inflation 10–20 points above it.
- **Duration:** upper bound of the 67 % range of unemployment above 10 % for 15–25 years (EMB: 0).
- **Causes:** stranded assets, supply chains, subsidy-induced inflation, abrupt policy.
- **Better than EMB:** with strong climate damage, avoided warming pays off, a synergy of climate and economic policy. GDP in 2100 up to 5 % above EMB (97.5th percentile).
- **Medians:** GDP in 2100 4–15 % below EMB, peak unemployment 0.1–1.4 points above.



Limitations and next steps

- **Demand:** global GDP only; next, sectors and behaviour.
- **CCS:** prototype only in v2.1; included in v3.1.
- **Carriers:** no split into liquids and electricity.
- **Policy:** stylised here. An upcoming broad sensitivity study reverses the question: which policy bundles achieve a given outcome?

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