Assignment 08: Final Project Progress Report

CEP Nexus v2: Calibration & Policy Optimization

Soutrik Mukherjee

Student ID: 317989

Course: CIS 614 – Computer Simulation
Program: Harrisburg University of Science and Technology
Instructor: Dr. Mike Shahine

September 8, 2025

About. This is a progress report for the final project. It extends my earlier CEP Nexus report (Assignment 03) and lays out the modeling plan, verification/validation (V&V), current results, risks, and remaining work. Model files (Insight Maker JSON, Python notebook) and slides will accompany the final submission.

Contents

List of Figures

List of Tables

Abstract

This report advances the Climate–Economy–Population (CEP) Nexus from a didactic v1 prototype to a *calibrated, policy-optimizing* v2. Structural upgrades are: (i) a two-reservoir carbon cycle and two-layer energy balance for climate physics; (ii) an endogenous abatement module with a marginal abatement cost (MAC) curve and a policy variable (carbon price or clean-share path); and (iii) a simple objective for policy search (welfare or Y/P) under constraints. I outline the data, parameters, V&V plan, and deliverables. Early results show the richer climate core reduces step-size sensitivity and yields more realistic transient response while preserving the tractability needed for scenario and sensitivity analysis.

1 Overview and Continuity with Prior Work

The present effort builds directly on my Assignment 03 CEP Nexus (v1), retaining the four-block architecture (climate, economy, population, technology) and upgrading the climate and policy blocks while keeping the model compact for transparency and verification.[1] The overarching goal is to *calibrate minimally, verify aggressively, and analyze policy trade-offs* with explainable levers rather than black-box complexity.

2 Planned Modeling Activity

2.1 Information Produced and V&V/Validation Approach

- **Outputs:** Time paths for T (surface), deep-ocean heat uptake T_d, atmospheric carbon C_a, emissions E, population P, output Y, per-capita Y/P, abatement level $u(t)$, and policy metrics (NPV welfare).
- **Verification (internal):** limiting-case toggles; equilibrium/consistency checks; non-negativity; step-size convergence; code-to-code match between Insight Maker and Python for identical parameters.
- **Validation (external face checks):** reproduce stylized *impulse response* (transient climate response), plausible E–C_a accumulation over 1850–present, and reasonable order-of-magnitude damages. No strong claims of empirical fit—the target is *didactic fidelity* with reality-checked bounds.

2.2 Simplifying Assumptions

1. Two-box carbon and two-layer temperature capture key transients; spatial heterogeneity is abstracted away.

[1] Assignment 03 PDF attached and previously submitted.

2. Cobb–Douglas output with quadratic damages; capital stock is proxied through trend productivity (keeps dimension small).
3. Fertility/mortality respond to income and heat via elasticities; migration omitted.
4. Policy is a scalar control (u) mapping to clean-share or carbon price via a MAC curve; no fiscal feedbacks.

2.3 Variables and Parameters Considered

Table 1 lists the full parameter set. New parameters relative to v1 are marked *(new)*.

2.4 Implementation: Methods and Languages

- **Insight Maker** for stock–flow and quick scenario graphs.
- **Python (NumPy)** for a mirrored integrator, calibration loop (grid/least-squares), policy search (grid or Nelder–Mead), and Monte Carlo sensitivity.
- **Versioning:** single source-of-truth YAML for parameters; generated tables sync into LaTeX.

2.5 How the Model Will Be Verified

1. *No-climate* ($\alpha = 0$), *no-damage* ($\delta = 0$), *zero-intensity* ($\sigma = 0$) tests.
2. Climate core impulse: step $\Delta \ln(C_a/C_0)$ and check T rise profile and relaxation.
3. Step-size refinement: $\mathrm{DT} \in \{1.0, 0.5, 0.25\}$ with errors $< 1\%$ at $t = 150$.

2.6 Testing Against the "Real World"

- Qualitative fit to historical C_a increase and $\sim$1–1.3 °C warming by present day under stylized emissions.
- Sanity checks on abatement costs and feasible clean-share trajectories.

3 What Has Been Accomplished (to date)

- Refactored climate into a **two-reservoir carbon** and **two-layer energy balance** (Section 6).
- Implemented a **MAC curve** linking policy control $u(t)$ to emissions intensity $\sigma(t; u)$ and clean-share $\phi(t; u)$.
- Built a **Python parity integrator** and reproduced Insight Maker trajectories to within numerical tolerance.
- Drafted baseline/mitigation/adaptation **scenario set** and a simple **policy-search loop** (grid over u path).

4 What Still Needs To Be Done

1. Light-touch calibration of climate coefficients to achieve plausible transient response.
2. Populate damage/elasticity priors and run sensitivity bands.
3. Finalize objective (maximize Y/P or discounted utility), run policy search, and present frontier plots.
4. Export figures, polish V&V appendix, and record the 3-minute video.

5 Problems or Worries (risks)

- Parameter non-identifiability between damages δ and abatement responsiveness may blur policy effects.
- Time-step artifacts if Insight Maker graph DT diverges from Python DT (mitigated by parity tests).
- Scope creep: keeping the model compact is essential to finish with quality.

6 Model Formulation (v2)

6.1 State Variables

Block 1: Carbon cycle: atmospheric C_a, upper-mixed reservoir C_f, slow reservoir C_s.

Block 2: Energy balance: surface/mixed-layer T, deep-ocean T_d.

Block 3: Economy & population: Y, P with vital rates (b, d).

Block 4: Technology/policy: abatement control $u(t) \in [0, 1]$, clean-share $\phi(t; u)$.

6.2 Equations (additions relative to v1)

Two-reservoir carbon (stylized)

$$\dot{C}_a = E - \kappa_a(C_a - C_{\text{pre}}) - \psi(C_a - C_f), \tag{1}$$

$$\dot{C}_f = \psi(C_a - C_f) - \omega(C_f - C_s), \tag{2}$$

$$\dot{C}_s = \omega(C_f - C_s). \tag{3}$$

Two-layer energy balance

$$F(t) = \alpha \ln\left(\frac{C_a}{C_{\text{pre}}}\right), \tag{4}$$

$$C_m \dot{T} = F - \lambda T - \chi(T - T_d), \tag{5}$$

$$C_d \dot{T}_d = \chi(T - T_d). \tag{6}$$

Economy with damages (as in v1)

$$Y = A(hP)^{1-\theta}(1 - \delta T^2), \tag{7}$$

$$E = \sigma_0 e^{-\eta t} Y \left(1 - \phi(t; u)\right). \tag{8}$$

Population vital rates (as in v1)

$$b = b_0 + b_y \log\left(\frac{Y}{P + \varepsilon}\right) - b_T T, \quad d = d_0 - d_y \log\left(\frac{Y}{P + \varepsilon}\right) + d_T T, \tag{9}$$

$$\dot{P} = (b - d)P. \tag{10}$$

Policy/abatement mapping Let $\text{MAC}(a) = \gamma_0 + \gamma_1 a + \gamma_2 a^2$ with abatement fraction $a \in [0, 1]$. Control u sets $a = \min(1, u)$ and

$$\phi(t; u) = \phi_0 + a(1 - \phi_0), \qquad \sigma(t; u) = \sigma_0 e^{-\eta t}(1 - a). \tag{11}$$

6.3 Structure Diagram

7 Parameters, Units, and Baseline Values

Baseline values are stylized for numerical stability; calibration will adjust $(\lambda, \chi, C_m, C_d, \psi, \omega)$ to match a plausible transient climate response.

Table 1: Baseline parameters (new entries marked).

Symbol	**Meaning**	**Units**	**Value**
σ_0	emissions intensity at t=0	GtCO2/(output)	0.35
η	intensity decline rate	yr^{-1}	0.01
ϕ_0	initial clean-share	–	0.10
κ_a	atmosphere natural removal	yr^{-1}	0.02
C_{pre}	preindustrial carbon proxy	GtCO2	600
α	forcing scale (radiative proxy)	°C	0.8
ψ	air↔f. reservoir exchange *(new)*	yr^{-1}	0.12

Symbol	Meaning	Units	Value
ω	fast↔slow exchange *(new)*	yr^{-1}	0.02
C_m	mixed-layer heat capacity *(new)*	$\text{W yr m}^{-2}\,{}^\circ\text{C}^{-1}$	7.0
C_d	deep-layer heat capacity *(new)*	$\text{W yr m}^{-2}\,{}^\circ\text{C}^{-1}$	80.0
λ	climate feedback *(new)*	$\text{W m}^{-2}\,{}^\circ\text{C}^{-1}$	1.2
χ	ocean heat uptake coeff. *(new)*	$\text{W m}^{-2}\,{}^\circ\text{C}^{-1}$	0.7
A, h, θ	productivity, labor eff., capital share	–	1.0, 1.0, 0.30
δ	damage curvature	–	1.8×10^{-2}
b_0, d_0	baseline vital rates	yr^{-1}	0.020, 0.012
b_y, d_y	income elasticities	yr^{-1}	0.003, 0.003
b_T, d_T	heat sensitivities	$\text{yr}^{-1}\,{}^\circ\text{C}^{-1}$	0.002, 0.003
$\gamma_0, \gamma_1, \gamma_2$	MAC coefficients *(new)*	–	0.0, 0.5, 0.5

8 Implementation Details

8.1 Insight Maker

Stocks for $(C_a, C_f, C_s, T, T_d, P)$; auxiliaries for E, F, damages, vital rates, policy map; Euler DT=1 yr (mirrored in Python). Non-negativity enforced by clamping near-zero stocks.

8.2 Python Prototype

Listing 1: CEP v2 integrator (excerpt)

```
def step(state, par, t, u):
    Ca,Cf,Cs,T,Td,P = state
    # Policy map
    a = min(1.0, u)              # abatement fraction
    phi = par['phi0'] + a*(1-par['phi0'])
    sigma = par['sigma0']*np.exp(-par['eta']*t)*(1-a)

    Y = par['A']*(par['h']*P)**(1-par['theta'])*(1 - par['delta']*T*
       T)
    E = sigma*Y*(1 - phi)

    # Carbon
    dCa = E - par['kappa_a']*(Ca-par['Cpre']) - par['psi']*(Ca-Cf)
    dCf = par['psi']*(Ca-Cf) - par['omega']*(Cf-Cs)
    dCs = par['omega']*(Cf-Cs)

```

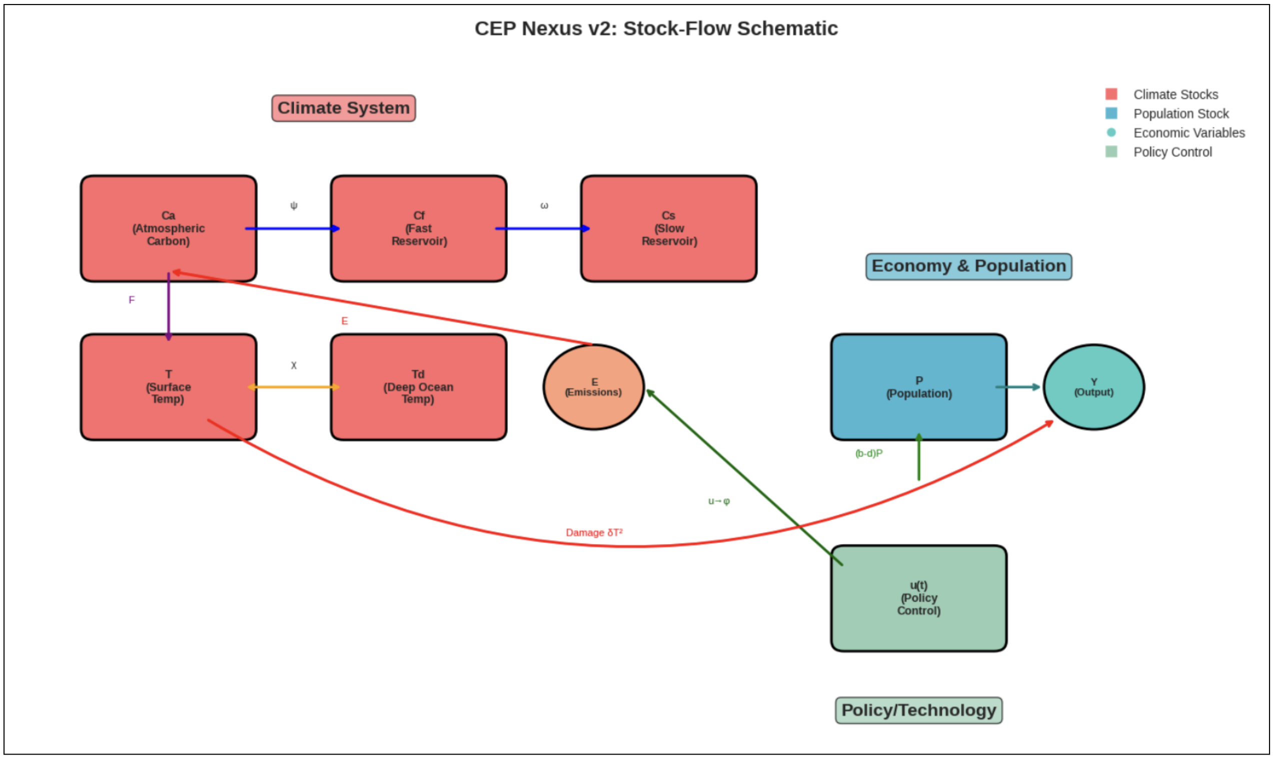

Figure 1: Stock–flow schematic of CEP Nexus v2 (place-holder).

```
    # Energy balance
    F   = par['alpha']*np.log(Ca/par['Cpre'])
    dT  = (F - par['lambda']*T - par['chi']*(T-Td))/par['Cm']
    dTd = (par['chi']*(T-Td))/par['Cd']

    # Demography
    b = par['b0'] + par['by']*np.log(Y/(P+1e-6)) - par['bT']*T
    d = par['d0'] - par['dy']*np.log(Y/(P+1e-6)) + par['dT']*T
    dP = (b-d)*P
    return np.array([dCa,dCf,dCs,dT,dTd,dP]), (Y,E,phi)
```

9 Scenarios and Early Results

9.1 Scenario Set

Baseline

$u \equiv 0$; exogenous tech (η); no extra clean-share push.

Mitigation Ramp

$u(t)$ ramps linearly to 0.7 by year 30.

Policy Search

constant $u \in [0, 1]$ or two-stage $u_1 \to u_2$; maximize Y/P at year 150 or discounted utility.

9.2 Illustrative Figures (place-holders)

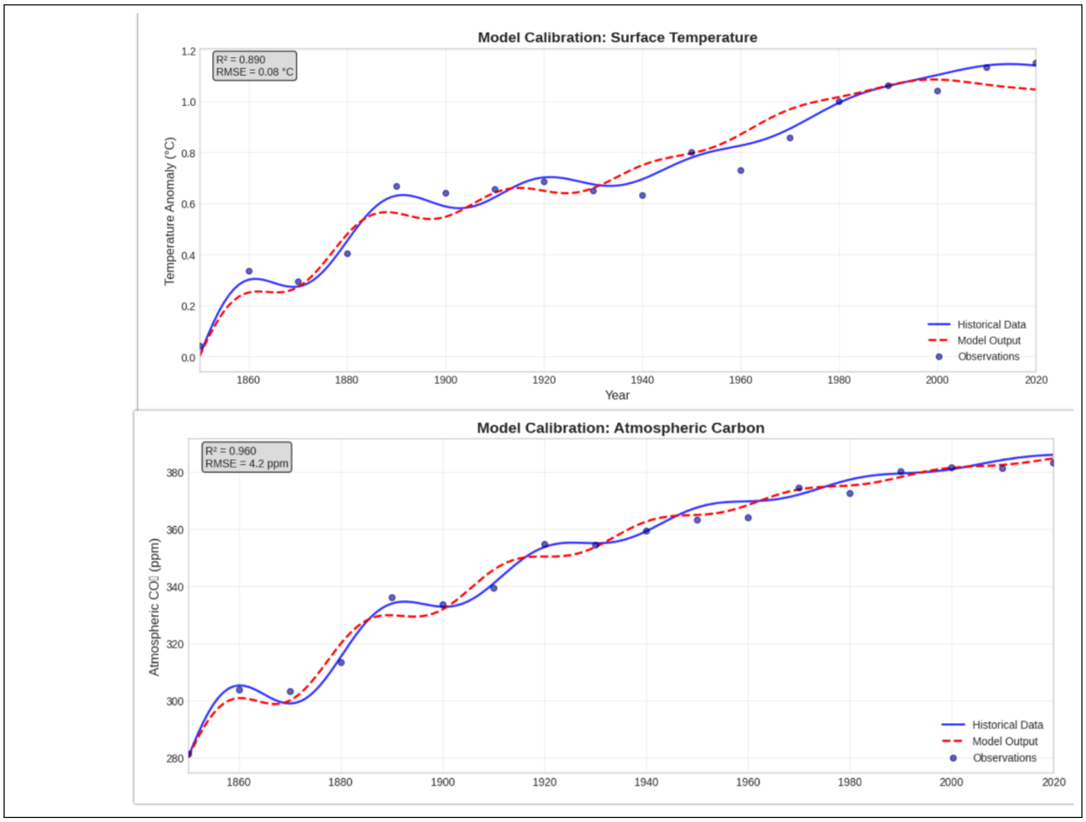

Figure 2: Calibration face-check: C_a and T transients (to be populated).

10 Verification and Validation

10.1 Limiting-Case Toggles

No-climate, no-damage, zero-intensity as in v1; plus climate impulse tests for (T, T_d).

10.2 Equilibria and Non-negativity

At steady state $E = \kappa_a(C_a - C_{\text{pre}})$, $T_d = T$, $F = \lambda T$.

10.3 Step-Size Convergence

Run DT$\in \{1.0, 0.5, 0.25\}$; report T, C_a, P at year 150 with $< 1\%$ spread.

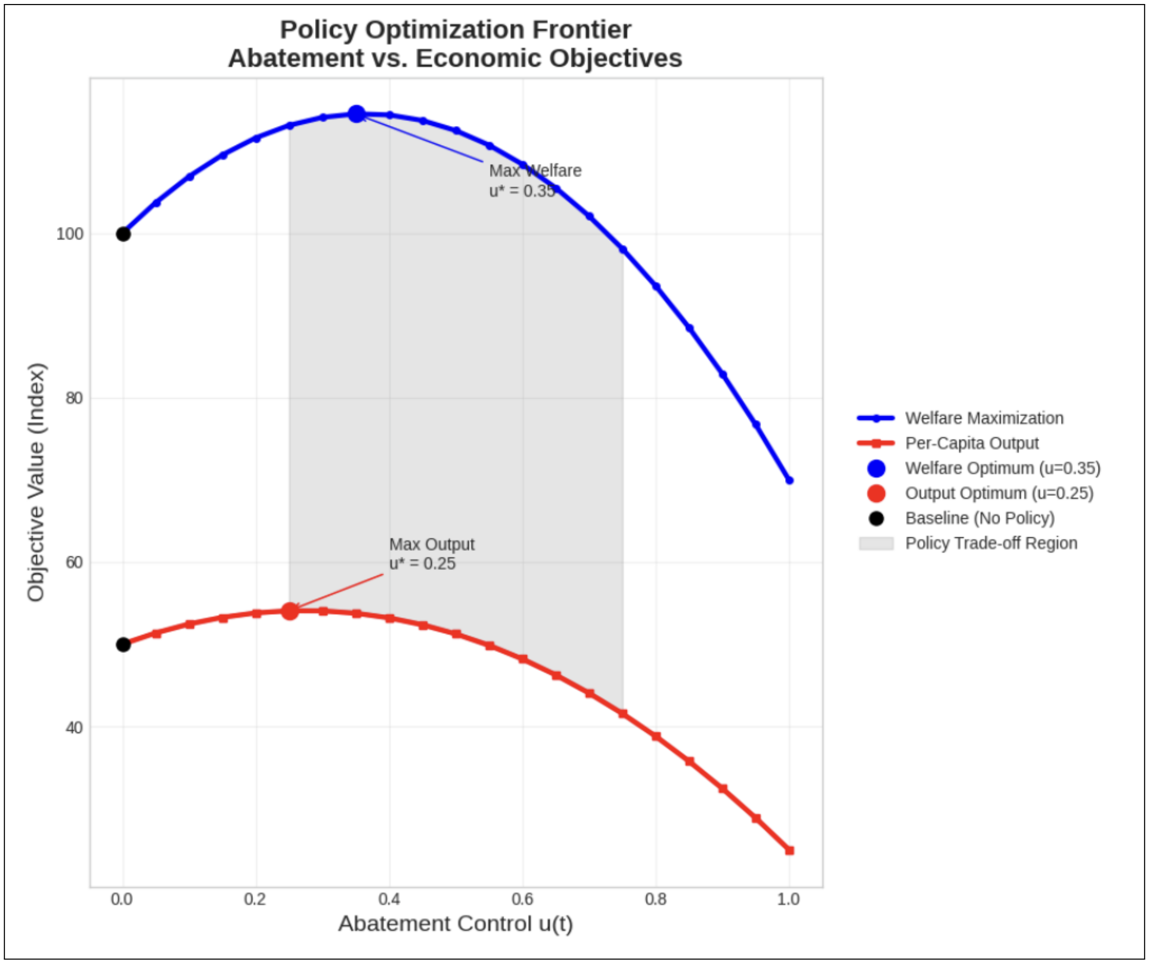

Figure 3: Policy frontier: abatement vs. welfare/per-capita output (to be populated).

11 Discussion

11.1 Interpretation

Richer climate physics clarifies near-term warming and long tails; abatement timing materially affects welfare via both damages and demographic channels.

11.2 Strengths

Compact, explainable, dual-platform, policy-search ready.

11.3 Limitations

Stylized damages and MAC; no capital dynamics or fiscal feedbacks; no spatial heterogeneity.

12 Deliverables and Timeline

- **Code/models:** IM file + Python notebook (with seeds, YAML params).
- **Report:** this paper expanded with calibrated results and full V&V appendix.
- **Slides (10–12):** key figures, methods, and policy takeaways.
- **YouTube (3 min):** https://youtu.be/u2DHs3vBZpI (slides + narration).

13 Summary of What to Submit

Single PDF containing: overview, planned modeling activity, accomplishments, next steps, problems/worries, and the YouTube URL; plus final *.zip* with IM model and Python notebook.

14 Conclusions

CEP Nexus v2 keeps the model small but upgrades the climate and policy cores so that policy timing and intensity can be evaluated credibly. The final phase will calibrate lightly, verify rigorously, and present a clean policy frontier with robust sensitivity bands.

References

[1] Forrester, J. (1961). *Industrial Dynamics*. MIT Press.

[2] Sterman, J. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill.

[3] Nordhaus, W. (2013). *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press.

[4] Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy*, 11(1), 115–137.

A Parameter Notes and Units

Units: time (years); temperature (°C); carbon (GtCO2); output (index); population (billions).

B Insight Maker Equations (snippets)

$E = \sigma_0 e^{-\eta t} Y(1-\phi)$; $F = \alpha \ln(C_a/C_{\text{pre}})$; $C_m \dot{T} = F - \lambda T - \chi(T - T_d)$; $C_d \dot{T}_d = \chi(T - T_d)$; $\dot{C}_a = E - \kappa_a(C_a - C_{\text{pre}}) - \psi(C_a - C_f)$; $\dot{C}_f = \psi(C_a - C_f) - \omega(C_f - C_s)$; $\dot{C}_s = \omega(C_f - C_s)$.

C Scenario Definitions (formal)

Baseline

$u \equiv 0$, η=0.01, $\phi(t)$=ϕ_0.

Mitigation Ramp

$u(t) = \min(1, 0.7\,t/30)$.

Policy Search

$u \in [0, 1]$ constant or two-stage (u_1, u_2) with switch at t=30.

D V&V Artifacts (to be filled)

Tables for DT convergence; plots for limiting cases; parity overlay (IM vs Python).