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Investigating Geothermal Energy Network System Dynamics

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ABSTRACT

Geothermal energy networks (GENs) offer a promising pathway for reducing emissions from building heating and cooling, especially in regions aiming to transition away from fossil fuels. This paper presents a systems-based analysis of how thermal demand patterns, equipment operation, and regional factors influence GEN performance. Using a System Dynamics (SD) model, we simulate hourly thermal demand from multifamily and office buildings in Washington, Illinois, and New York. The model includes both basic and hybrid GEN configurations – such as borehole heat exchangers and auxiliary cooling equipment – to explore seasonal and operational effects on energy use and system behavior. Results show that control strategies, along with local climate and formation properties, significantly affect electricity consumption and equipment cycling. While detailed engineering design is beyond the model's scope, the findings provide actionable insights for early-stage planning and policy discussions. This work highlights the value of using SD methods to test the performance of GENs under real-world operating conditions and support decision-making in low-carbon thermal infrastructure.

1 INTRODUCTION

The decarbonization of building heating and cooling is central to energy transition goals. In the United States and Canada, direct fossil fuel combustion for thermal comfort and domestic hot water (DHW) production represents over 30% of total greenhouse gas (GHG) emissions (Environment and Climate Change, 2024; US Environmental Protection Agency et al., 2024). The deployment of geothermal energy networks (GENs) or thermal energy networks (TENs) (Figure 1) is increasingly recognized as a scalable solution to electrify building heating and cooling through hydronic systems exchanging heat with the shallow subsurface (Fry et al., 2024). These networks replace combustion-based furnaces and chillers with distributed heat pumps and centralized thermal storage, achieving seasonal coefficients of performance (COP) greater than 4, where COP is an efficiency ratio equivalent to the amount of thermal energy out of a system to the amount of energy into the system (Andersson et al., 2003; Oh & Beckers, 2023). Most often the amount of energy into the heat pump supported systems is electricity, and this perceived reduction in electricity consumption from the widespread use of ground source heat pumps (GSHP) over alternatives such as air-source heat pumps (ASHP) may offer substantive utility infrastructure and social benefits (Buonocore et al., 2022; Liu et al., 2023).

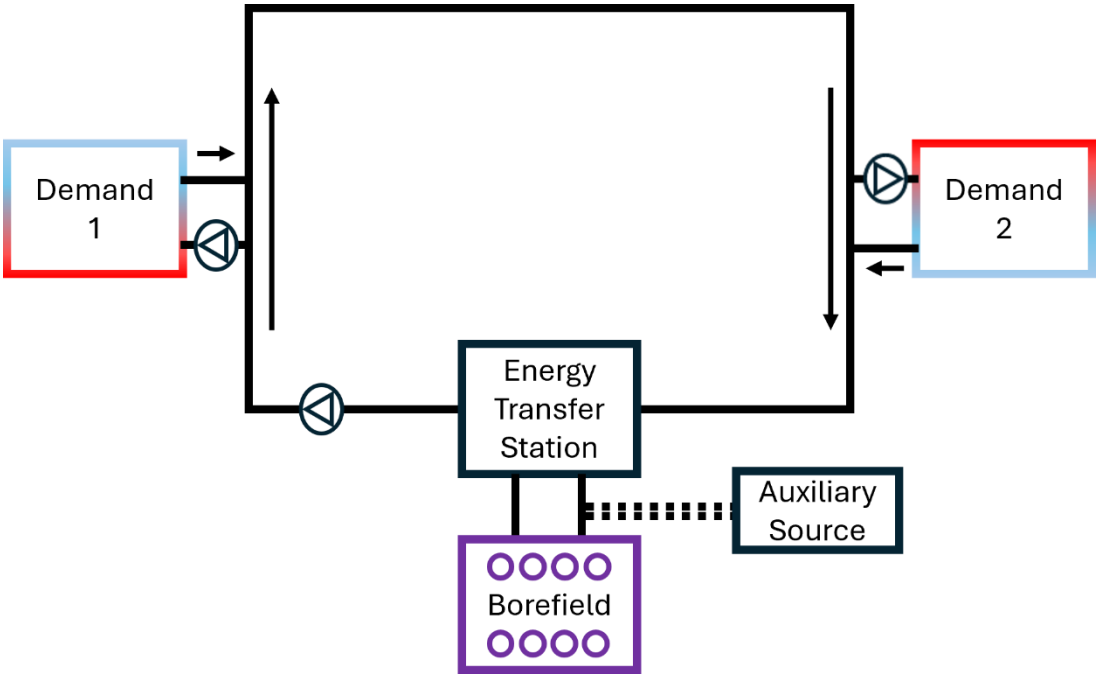


Figure 1 A typical geothermal energy network configuration where demands are also nodes on the system (Fry et al., 2025b).

Despite the potential, the dynamic performance of GENs is difficult to predict due to interacting feedbacks among load variability, ground temperature evolution, and equipment efficiency. Conventional building simulation tools (e.g., TRNSYS, EnergyPlus) or finite-element methods often require rigid, high-resolution time steps and lack the ability to integrate techno-economic or thermal behavioral feedbacks (Hu et al., 2020; Simpson & Zhu, 2024). This work applies a System Dynamics (SD) approach to GEN modeling, capturing nonlinear cause-effect relationships and feedbacks among system components, across multi-year horizons.

The present research builds upon a validated SD model developed for geothermal networks (Fry et al., 2024, 2025a), extending it to explore regional thermal demand behavior and operational strategies under different climatic and regulatory contexts. The investigation focuses on three representative U.S. states – Washington, Illinois, and New York – that have active policy initiatives promoting thermal energy networks. The work aims to inform how climatic variations, auxiliary systems, and control logic affect GEN efficiency, parasitic electricity use, and long-term stability.

2 METHODS

2.1 System Dynamics Framework

System Dynamics (SD) is a feedback-based modeling approach that represents physical and socio-technical systems as interacting stocks and flows over continuous time (Forrester, 1971; Sterman, 2010). The GEN SD model captures thermal and hydraulic processes using integrals of energy and mass balances. Causal feedback loops link physical subsystems (heat exchangers, borehole arrays, pumping systems) to operational and economic variables such as equipment degradation, maintenance cycles, and electricity consumption. The simulation operates with an hourly timestep, resolving both short-term transients and long-term accumulation effects across a 70-year horizon. The structure satisfies the five defining principles of quantitative SD modeling (Naugle et al., 2023): causal feedback representation, explicit stock-flow relationships, equation-based logic, continuous time, and feedback-focused analysis.

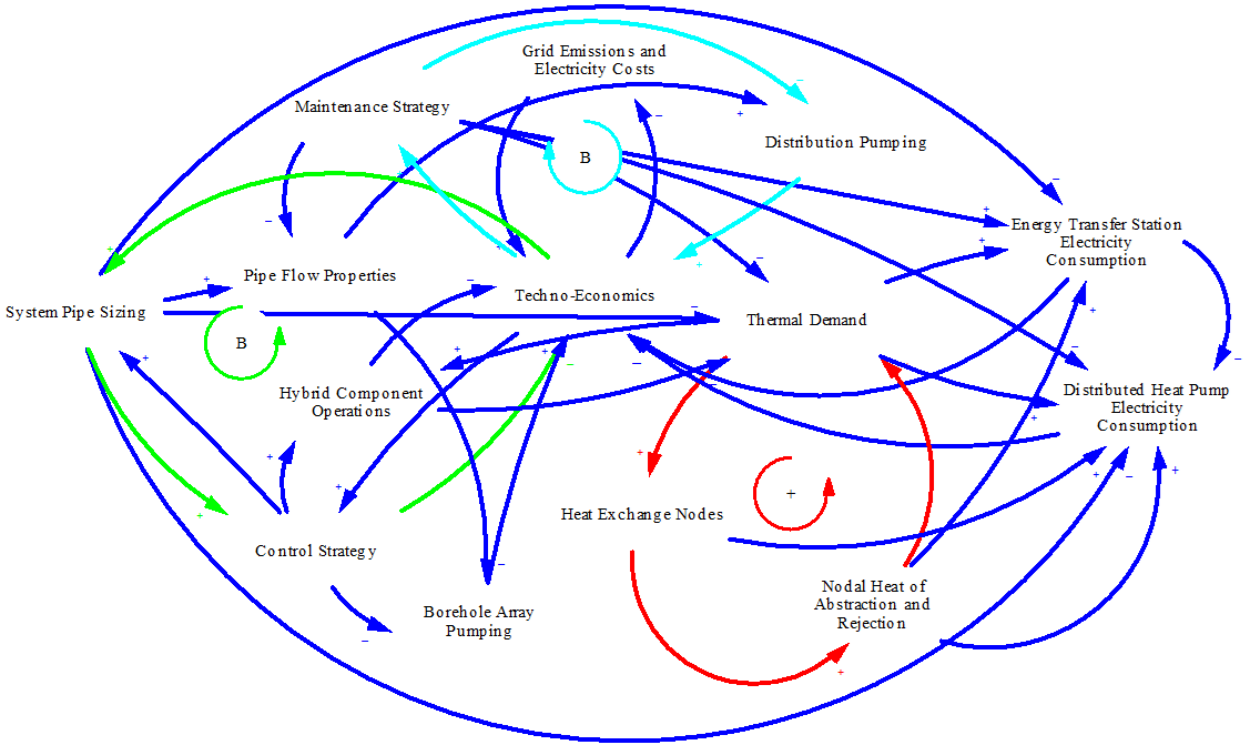


Figure 2 High level causal loop diagram of the GEN SD model (Fry et al., 2025b).

Key feedback structures include:

- Balancing loops between heat extraction and ground temperature recovery.
- Reinforcing loops where increased demand raises power consumption, further influencing heat pump cycling.
- Delayed responses representing borehole thermal inertia and control lag in temperature regulation.

These structures allow the model to reveal non-intuitive dynamics that traditional steady-state or high-fidelity transient models might overlook.

2.2 Model Configuration

The SD model represents a ring-type district loop hydraulically separated from a borehole heat exchanger field through an energy transfer station (ETS) (see: Figure 1). Each demand node represents a building cluster with either heating or cooling dominance. The ETS contains central heat pumps that maintain target supply temperatures via a first-order lag control, enabling thermal inertia (Fry et al., 2025b). Distributed heat pumps at the nodes meet end-use demands and interact dynamically with the GEN loop temperature.

Thermal demand inputs are derived from ResStock and ComStock hourly profiles for 15-story multifamily and medium office buildings (NREL, 2024; Parker, 2023). Each regional scenario applies standardized profiles scaled to a peak load of 880 kW for both heating and cooling. Climatic parameters for near-surface soil temperature amplitudes and phase lags are from Xing (2014).

2.3 Energy Balancing

The core energy balance for each node follows from equation 1.

$$Q = \dot{m} * c_p * \Delta T \tag{1}$$

where Q is the thermal load, $\dot{m}$ the mass flow rate, c_p the specific heat, and ΔT the temperature differential between inlet and outlet flows.

To prevent floating-point divergence at low ΔT, minimum threshold are enforced, following the implementation strategy described in Fry et al. (2025a).

Further explanations of equations for the control of dynamic pumping and auxiliary equipment, such as dry coolers, are described in Fry et al. (2025b).

2.4 Regional and Economic Parameterization

Each region employs similar soil conductivities, with unique electricity tariffs, and grid emission intensities (US Energy Information Administration, 2025; U.S. Environmental Protection Agency, 2024). Table 1 summarizes these key parameters.

Table 1 Key modeling parameters for simulations by regional scenario.

Parameter	WA	IL	NY
Mean Ground Temperature (°C)	11.8	11.1	13.6
Effective Thermal Conductivity (W/m.K)	1.5	1.5	1.5
Electricity Rate (USD/kWh)	0.0637	0.0916	0.0910
Grid Emissions ($kgCO_2e/kWh$)	0.287	0.413	0.392

3 RESULTS AND DISCUSSION

3.1 Baseline GEN Operations

The GEN model replicates system-wide behavior for borehole-supported configurations under equal heating and cooling peaks. Across all regions, the mean base case COP ranges from 3.4 – 5.9, consistent with measured seasonal COPs of 5 – 7 for operational systems (Andersson et al., 2003; Barney et al., 2025; Oh & Beckers, 2023). Climate exerts strong influence on borehole fluid temperatures (Figure 3). In Washington, lower annual ground temperatures lead to declining fluid temperatures during cooling-dominant months, while in New York, higher soil temperatures sustain more stable operation (Figure 4).

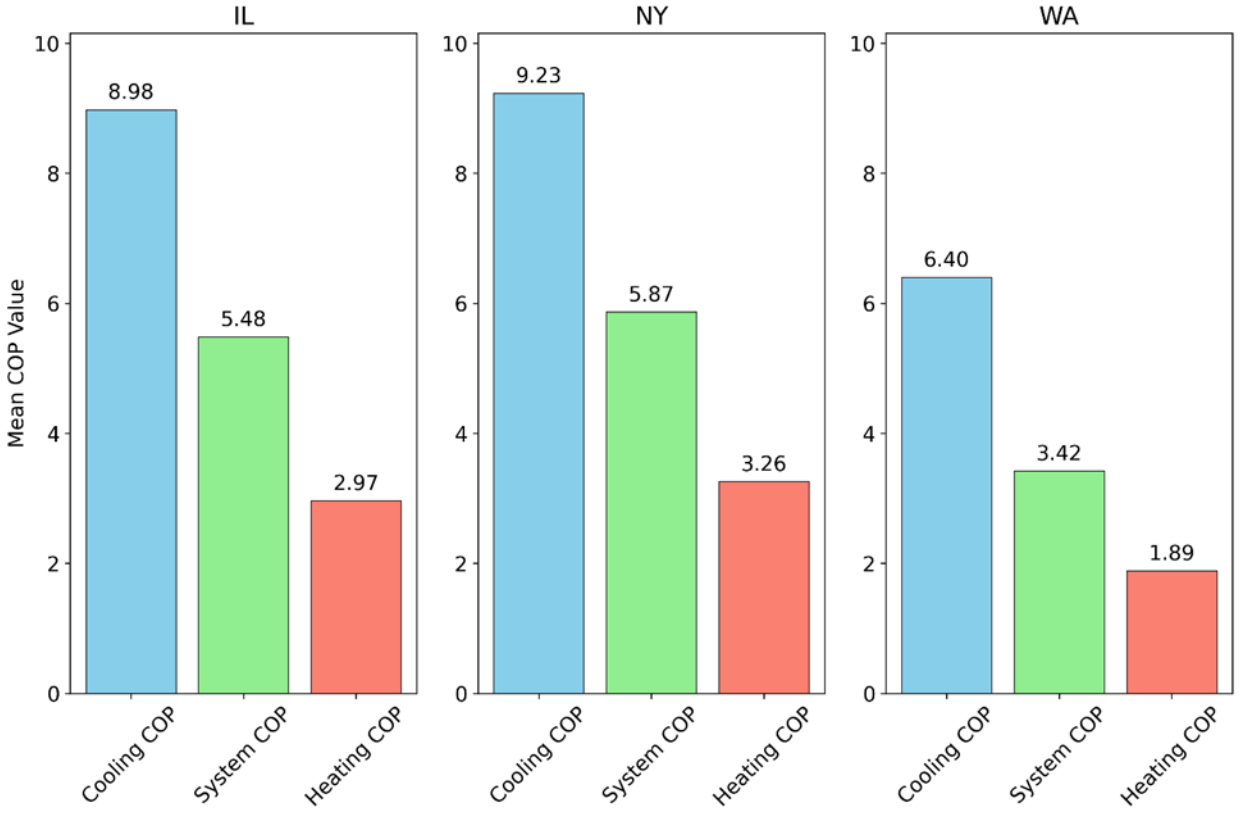


Figure 3 Base case system performance without auxiliary equipment operations (Fry et al., 2025b).

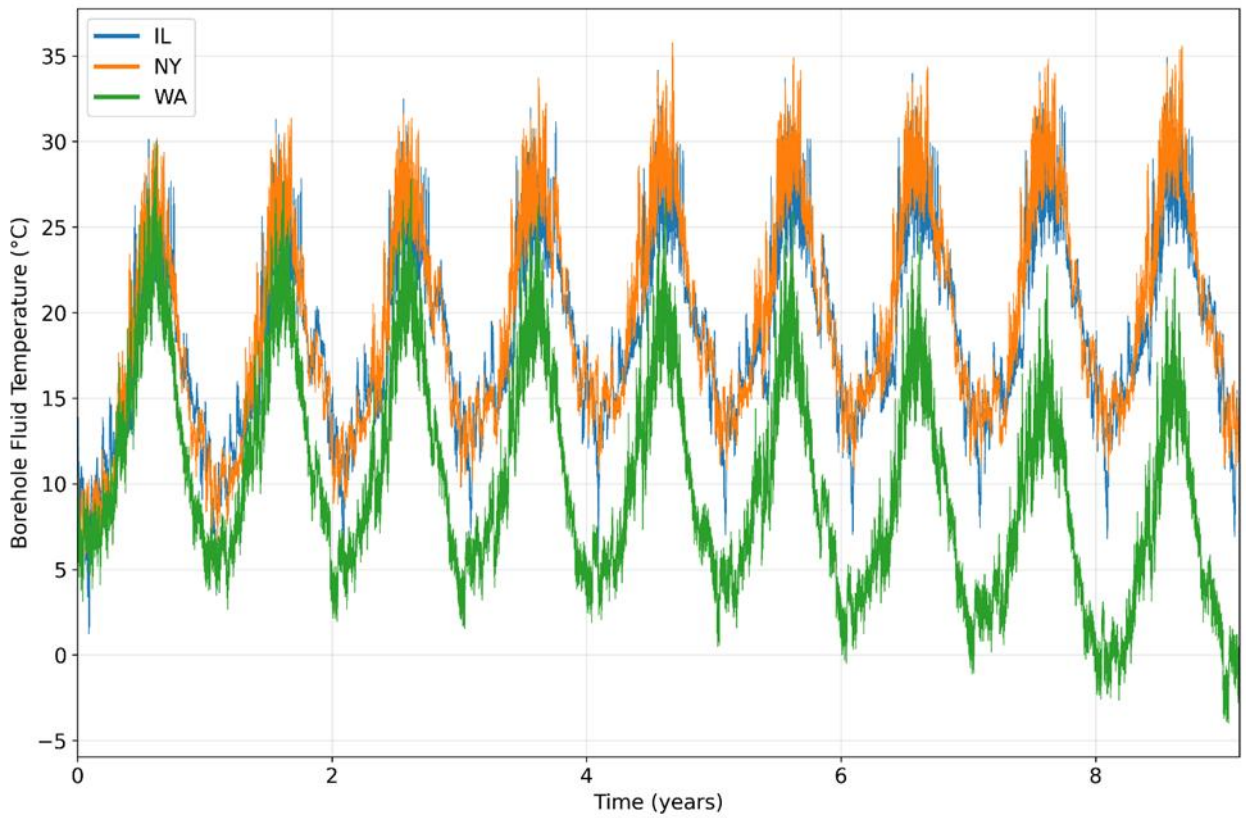


Figure 4 Abbreviated base case of 1.5 W/m.K thermal conductivity by regional load profile (Fry et al., 2025b).

System efficiency follows the relationship between entering fluid temperature (EFT) and heat pump performance. When borehole fluid temperatures fluctuate above or below the GEN supply temperature, compressor lift increases and COP declines substantially. Other indicators of system performance include the overall heating or cooling dominance of aggregated loads, the initial ground starting temperature, and the demand overlap coefficient (see: Wirtz et al. (2020)), which drive overall electricity consumption.

3.2 Auxiliary and Hybrid Configurations

Hybrid GENs with auxiliary dry coolers or waste heat repurposing may improve system temperature stability and longevity. The GEN SD model incorporates auxiliary equipment control activation when borehole fluid temperatures exceed upper or lower thresholds of 25°C and 4°C, respectively. For cooling dominant loads in New York and Illinois, hybridization with a dry cooler mitigates long-term temperature drift compared to monovalent borehole systems (Figure 5). While this may not result in an overall levelized cost of heat (LCOH) decrease, it does create the conditions for a sustainable energy system.

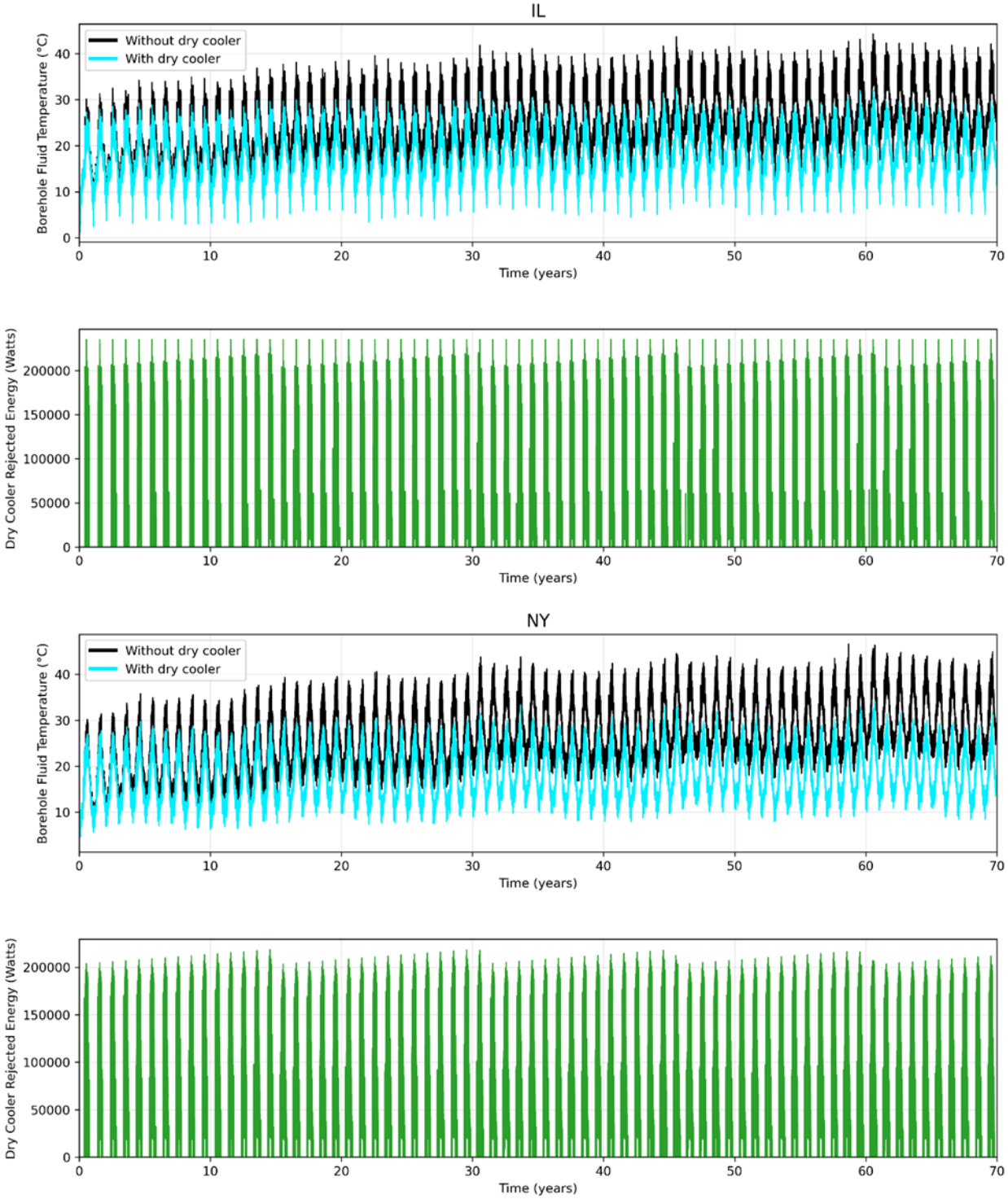


Figure 5 Geothermal energy network hybridization for scenarios using load profiles from New York and Illinois (Fry et al., 2025b).

Similarly, the implementation of waste heat injection to the borehole array in the heating dominant regime of the Washington state example stabilizes the borehole heat exchangers over decades (Figure 6).

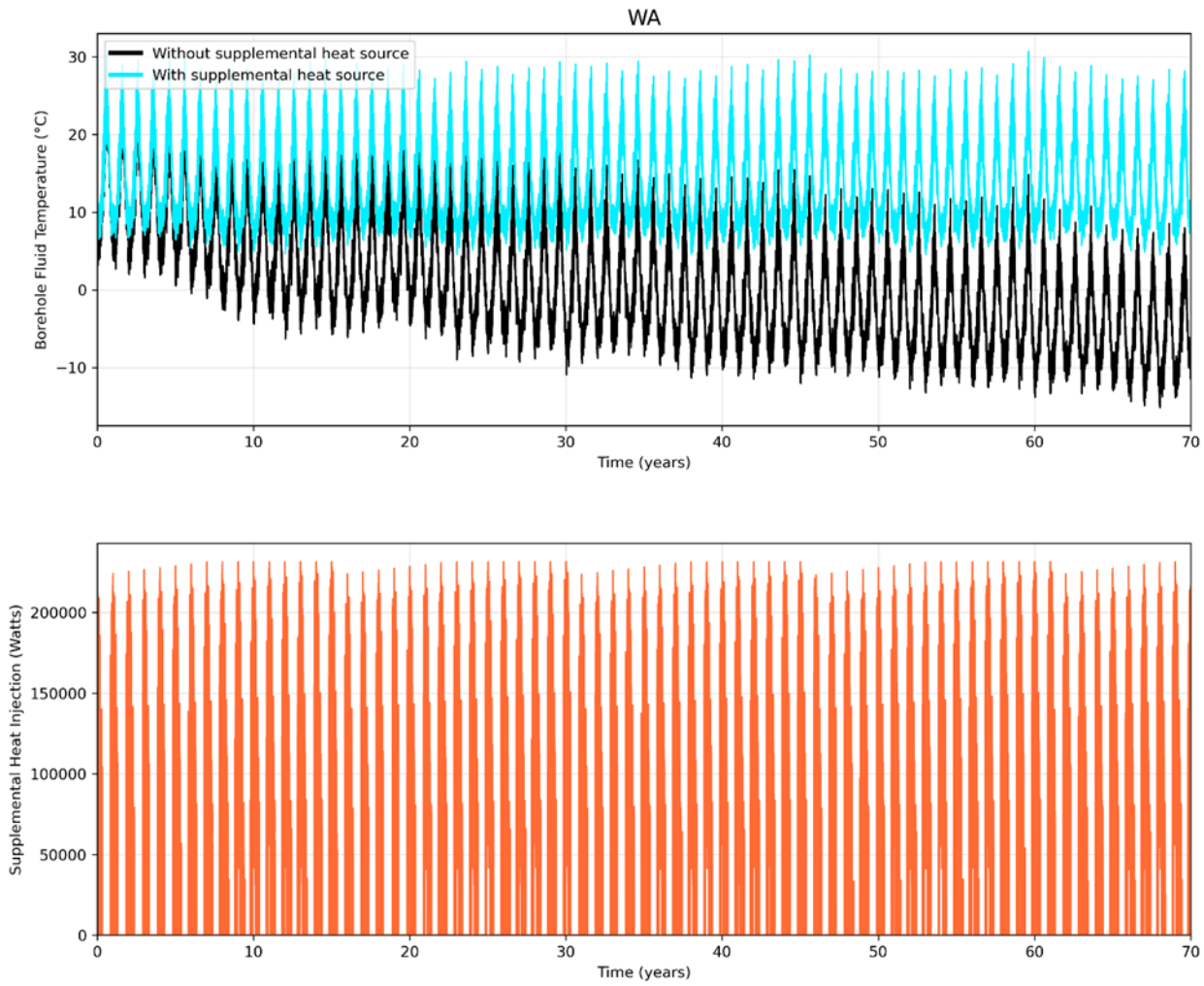


Figure 6 Geothermal energy network hybridization for scenarios using load profiles from Washington (Fry et al., 2025b).

Auxiliary cooling effectiveness depends on control hysteresis. Tighter temperature control bands produce more frequent cycling, while wider bands lower energy use but increase temperature excursions across the system. These dynamics emphasize the importance of control coupled co-design of the surface systems and subsurface heat exchangers, as suggested by Zanetti et al. (2023).

3.3 Thermal Flywheeling Behavior

Thermal flywheeling occurs when residual heat within the distribution network substitutes for active heat pump operation and controls allow the bypass of ground heat exchangers. The GEN SD model applies an integral delay between return and target supply temperatures, bypassing ETS operation when $| T_{return} - T_{target} | < dT_{max} |$. Figure 2 illustrates the hysteretic cycling of supply and return temperatures during a representative 9-year period in spring for Illinois.

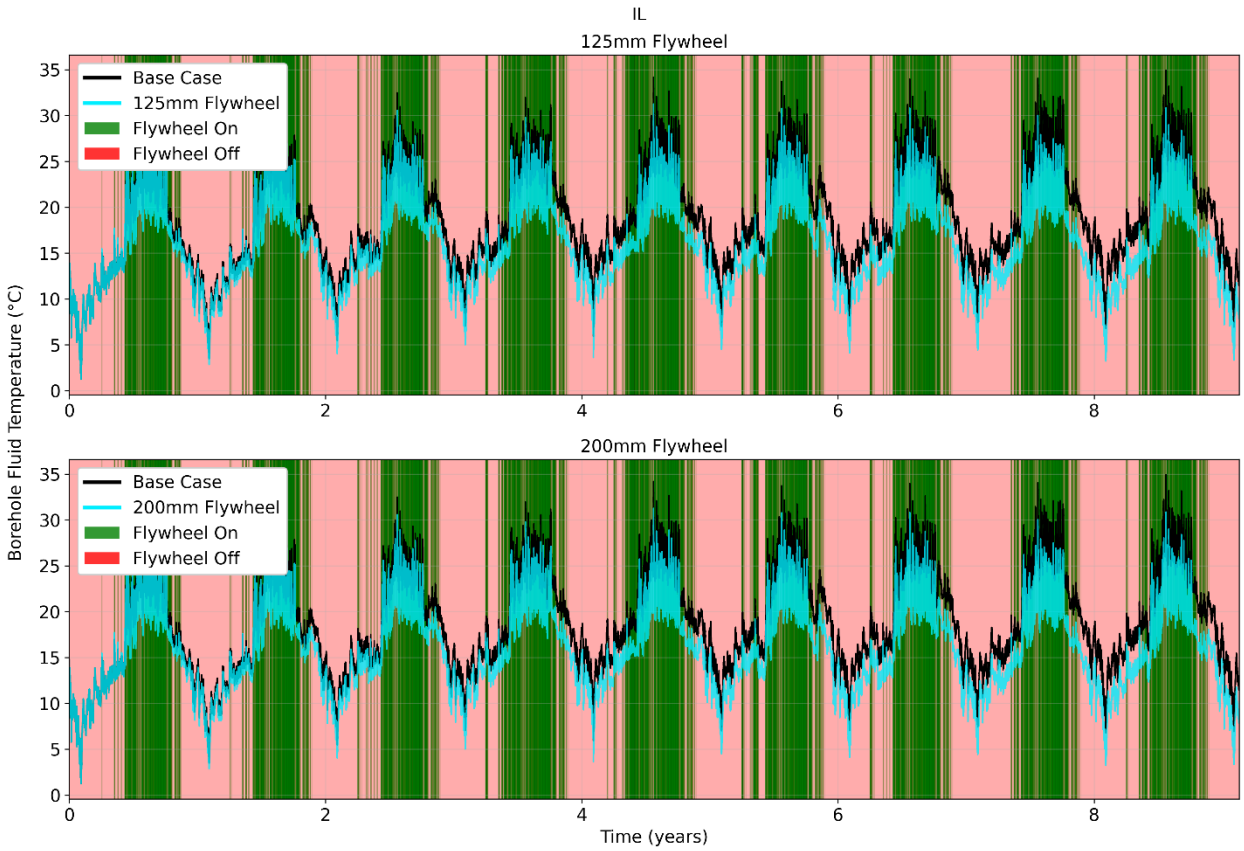


Figure 7 Dynamic response of GEN thermal flywheel control under Illinois load profiles (Fry et al., 2025b).

This phenomenon provides both energy savings from reductions in vapor compression cycle and circulator pump operations. The feedback-based representation in GEN SD highlights the system-level advantage of allowing small temperature drifts rather than rigid setpoint enforcement.

3.4 Long-term Energy and Emissions Performance

On a 70-year timescale, under today's grid emissions profile, GENs avoid between 16 – 39% of emissions from a business as usual case consisting of methane gas combustion and conventional uni-directional air conditioning units, per 880 kW network.

Thermal degradation in the borefield is easily controlled with auxiliary equipment, ensuring that a undersizing of the borehole arrays does not present significant risks to the operator or end-users. This validates the concept of active thermal management as essential to GEN sustainability, originally noted by Wirtz (2024).

4 POLICY AND PLANNING IMPLICATIONS

System Dynamics modeling provides a bridge between engineering simulation and policy planning. By coupling hourly operational behavior with long-term economic performance, the SD GEN model identifies leverage points for investment and control.

Key findings include:

- GEN control regimes must reflect local ground thermal properties and building demand patterns, but thermal behavior patterns are readily identifiable in early stage design.
- Introducing low-cost auxiliary systems can extend subsurface asset sustainability and derisk undersizing of borehole arrays.
- Encouraging mixed-use development within GEN service areas enhances load simultaneity and reduces thermal imbalance.
- Early-stage techno-economic modeling with feedback structure enables policymakers to assess emissions and infrastructure tradeoffs prior to regulated deployment policy implementation.

These insights are directly applicable to utilities, energy service companies, and municipalities exploring geothermal district energy as part of decarbonization mandates.

5 CONCLUSIONS

This paper demonstrates how a System Dynamics framework can elucidate the complex thermal behavior of GENs across different regional and operational contexts. The model integrates feedback-driven representations of thermal demand, heat exchange, and control behavior to simulate hourly and multi-decade GEN performance. Results confirm that climatic variations, auxiliary systems, and operational strategies critically determine electricity use, system stability, and emission outcomes.

The approach extends beyond deterministic design, offering a dynamic perspective that informs both engineering optimization and policy decision-making. Future work will integrate market penetration forecasting and multi-variate sensitivity analysis, advancing GEN research toward utility-scale deployment.

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