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Multi-Objective Optimization of Geothermal Systems: Optimizing Well Placement and Control to Balance Economic Returns and Reservoir Longevity

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INTRODUCTION

Conduction-dominated geothermal systems are key contributors to the decarbonization of the built environment, particularly in densely populated regions with high heat demand. However, their design requires balancing two conflicting objectives: maximizing economic returns through heat extraction while ensuring long-term reservoir sustainability. In the West Netherlands Basin (WNB), development has progressed under a "first-come, first-served" model, where individual operators independently select well sites. This fragmented approach has resulted in suboptimal utilization of subsurface resources (Willems and M. Nick, 2019).

Two critical factors govern geothermal system performance: well placement and operational control strategies. Poorly coordinated well placement can induce early thermal breakthrough (Daniilidis et al., 2021), while unoptimized flow rates may accelerate reservoir depletion (Zhang et al., 2021). Despite advances in geothermal optimization, simultaneous optimization of spatial and operational parameters remains limited. Existing studies often treat these components separately, neglecting their coupled influence on economic and thermal performance (Daniilidis et al., 2020; Kane et al., 2025).

This work introduces an integrated Multi-Objective Optimization (MOO) framework employing the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to optimize well placement and control simultaneously. The framework aims to identify Pareto-optimal configurations balancing Net Present Value (NPV) and system lifetime, using high-fidelity geothermal simulations of the WNB.

1 METHODOLOGY

1.1 Optimization Framework

The integrated optimization framework (Figure 1) couples three main components: (1) NSGA-II for multi-objective optimization (Deb et al., 2002), (2) the Delft Advanced Research Terra Simulator (DARTS) for fully coupled geothermal reservoir simulation (Voskov et al., 2024), and (3) constraint-aware operators for solution generation and feasibility enforcement.

The optimization problem maximizes two competing objectives:

$$\max\ f_1(x) = NPV(x) \tag{1}$$

$$\max\ f_2(x) = \text{Lifetime}(x) \tag{2}$$

where x represents the decision vector containing well locations. The framework incorporates explicit enforcement of constraints including boundary offsets, minimum well spacing, and bottom-hole pressure (BHP) regulations.

A key innovation is the capacity-dependent rate allocation: flow rates are determined through configuration-aware presimulation that runs BHP-controlled simulations to find maximum sustainable rates respecting pressure limits and well interference effects, rather than treating rates as fixed decision variables.

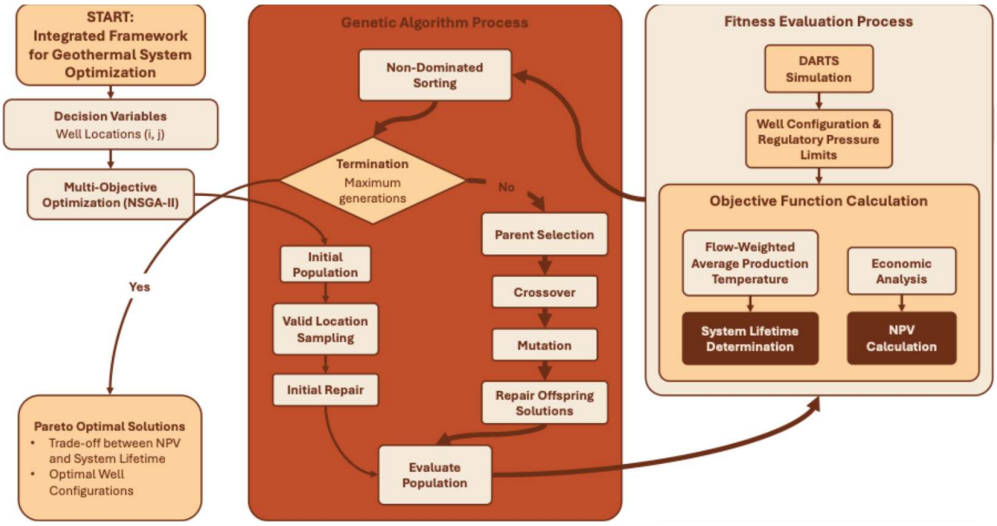


Figure 1. Workflow of the multi-objective optimization framework integrating DARTS and NSGA-II.

1.2 Reservoir Model and Simulation

A realistic geological model of the WNB incorporates corner-point geometry discretization and heterogeneous fluvial architecture. The Delft Sandstone Member, representing the primary geothermal target, consists of stacked fluvial sandstone channels deposited by meandering rivers, interbedded with claystone and lignite. Porosity and permeability are correlated using an empirical relationship.

Three stochastic geological realizations were generated using identical parameters to account for subsurface uncertainty while maintaining consistent geological properties. The model grid comprises 102 × 102 × 20 cells with 205,834 active cells.

System lifetime is defined as the period until thermal breakthrough, detected when the flow-weighted production temperature drops below:

$$T_{\text{weighted}} \leq T_{\text{initial}} - \alpha(T_{\text{initial}} - T_{\text{injection}}) \tag{3}$$

where $\alpha = 0.15$ (15% temperature threshold). Economic evaluation incorporates capital costs (drilling, equipment), operational costs (pumping electricity), and revenue from thermal energy sales, with a discount rate of 7%.

1.3 Experimental Design

Multiple well configurations (10, 12, and 20 doublets) were systematically evaluated across different geological realizations. The 20-doublet configuration employed a population size of 160 individuals and a maximum of 150 generations. NSGA-II parameters included crossover probability ($p_c = 0.9$, $\eta_c = 10$) and mutation probability ($p_m = 1/n_{\text{var}}$, $\eta_m = 10$). Custom constraint-aware operators ensured initial population feasibility and repaired infeasible solutions generated during evolution. Parallel evaluation of individuals using multiprocessing was implemented to handle computational demands.

2 RESULTS

2.1 Multi-Configuration Optimization Performance

Optimization results across three well configurations demonstrate that higher well densities achieve superior economic performance but require more generations to reach maximum lifetime objectives. The 20-doublet configuration achieved the highest NPV values (1.4–1.6 billion euros), while the 10-doublet configuration demonstrated faster convergence to 100-year lifetimes due to increased spatial flexibility. The 12-doublet runs showed intermediate performance with NPV typically in the range of 1.2–1.4 billion euros.

Restart experiments extending optimization from 100 to 250 generations confirmed algorithm convergence: while NPV continued to improve slightly (approximately 0.1 billion euros over 150 additional generations), this represented substantially reduced progress compared to the initial 100 generations, which achieved 0.95 billion euros improvement.

2.2 Pareto-Optimal Solutions and Trade-offs

The optimization framework consistently identified broad Pareto fronts spanning NPV ranges of 0.8–1.6 billion euros and system lifetimes of 35–100 years (Figure 2). A strong correlation emerged between total injection capacity and economic performance: solutions utilizing higher flow rates consistently achieved superior NPV. Three representative solutions from the 20-doublet configuration illustrate distinct operational strategies:

- **Best NPV**: 1.557 billion euros over 53 years with average injection rate 8,855 m^3/day
- **Best Lifetime**: 1.481 billion euros over 100 years with average injection rate 8,063 m^3/day
- **Best Overall**: 1.537 billion euros over 83 years with average injection rate 8,369 m^3/day (capturing 98.7% of maximum NPV while achieving 83% of maximum lifetime)

All solutions satisfied operational constraints with zero water balance error and no BHP violations.

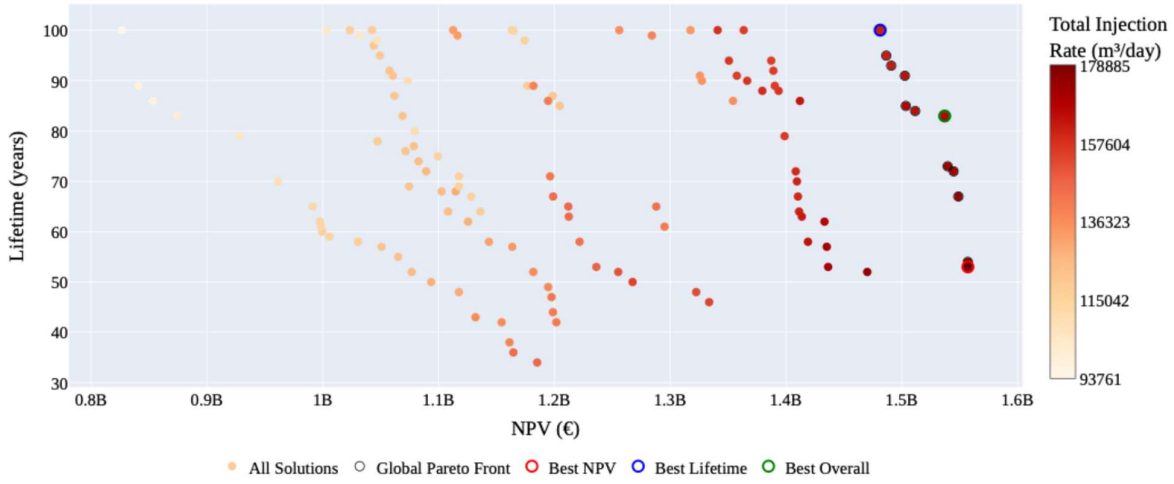


Figure 2. Pareto fronts for 10-, 12-, and 20-doublet systems, colored by total injection rate.

2.3 Spatial Well Placement Strategies

Spatial patterns of well placement for the best-performing solutions of the 20-doublet configuration are shown in Figure 3. The optimization consistently revealed a distinctive spatial strategy across multiple configurations and geological realizations. Injection wells are preferentially positioned along the northern boundary where the reservoir is thickest (up to ~235 m) and highest-permeability fluvial channels are concentrated. Production wells follow a U-shaped configuration along the southern, eastern, and western boundaries, balancing two competing objectives: maximizing separation from injectors to delay thermal breakthrough while positioning wells in deeper, warmer regions that enhance production efficiency.

Analysis of the Pareto-optimal solutions shows that certain well locations were repeatedly selected in up to eight of the twelve configurations, indicating strong recurrence of specific injector and producer sites and demonstrating the robustness of the identified spatial strategy across different trade-off scenarios. Marker sizing proportional to flow rates reveals that clustering of wells occurs in high-capacity zones, suggesting that similar system performance could potentially be achieved through fewer, strategically placed wells operating at higher rates.

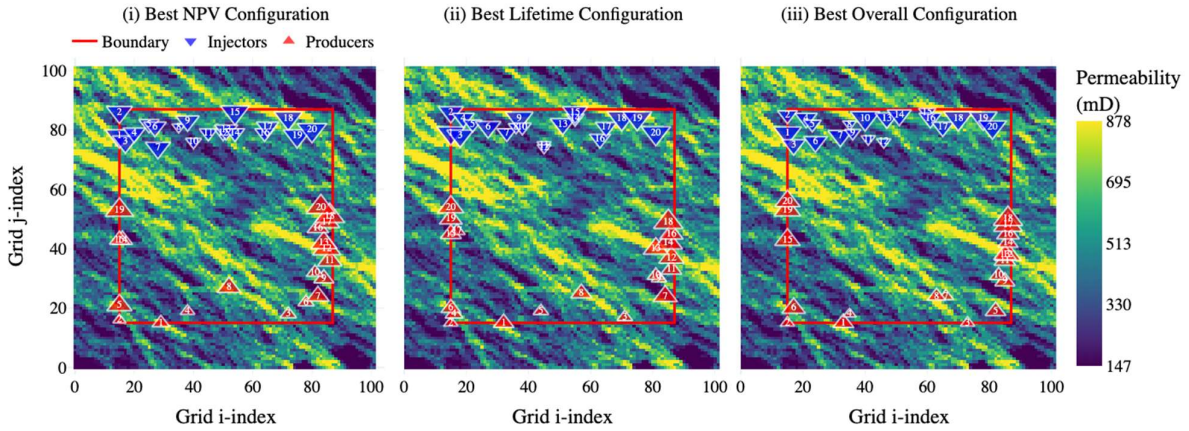


Figure 3. Optimal well configurations for best NPV, best lifetime, and best overall solutions, overlaid on vertically averaged horizontal permeability field.

3 DISCUSSION

3.1 Optimization Insights and Operational Implications

The optimization framework demonstrates that coordinated planning yields superior performance compared to current "first-come, first-served" strategies. The identification of location-dependent flow rates, accounting for well interference and pressure constraints, contrasts sharply with uniform rate allocation practices. Achieving maximum system longevity does not require uniform protection of all wells; rather, the Best Lifetime solution demonstrates that strategic sacrifice of some production wells to thermal breakthrough, while maintaining others at stable temperatures, extends overall system operation. This finding suggests significant potential for adaptive control strategies where breakthrough wells could be shut down, and flow redistributed in real-time.

3.2 Robustness to Geological Uncertainty

Sensitivity analysis across three geological realizations demonstrates framework robustness: while realization 3 achieved the highest NPV solution, all realizations produced solutions within comparable NPV-lifetime ranges. The fundamental spatial optimization strategy—northern injectors in thick, high-permeability zones and U-shaped producer configuration—remained consistent across all realizations, indicating that core well placement principles are robust despite local variations in permeability patterns. Small adjustments to injector positioning reflect adaptation to local geological features while maintaining the overall strategic approach.

3.3 Methodological Contributions

This framework represents an integrated spatial-operational optimization approach that treats well placement and flow allocation as interdependent decision variables. Unlike conventional approaches that fix well locations while optimizing rates or vice versa, capacity-dependent rate allocation enables true coupled optimization. Custom constraint-aware operators improve simulation feasibility and reduce wasted evaluations. The framework provides quantitative evidence supporting the transition from isolated doublet design toward coordinated, regional-scale development strategies.

4 CONCLUSIONS AND RECOMMENDATIONS

Multi-objective optimization with NSGA-II, integrated with high-fidelity geothermal reservoir simulation and constraint-aware solution generation, effectively identifies optimal trade-offs between economic returns and reservoir longevity. Applied to a realistic model of the West Netherlands Basin, the framework consistently produced Pareto-optimal solutions spanning 0.8–1.6 billion euros NPV and 35–100 year lifetimes across multiple well configurations and geological realizations.

Three generalizable principles emerge from the optimization:

1. Injectors should target zones combining maximum thickness and high permeability for optimal injection capacity

2. Producers should balance high-temperature access with sufficient separation from injectors

3. Flow rates must be location-dependent, determined by well interference effects and pressure constraints

For industry implementation, this framework supports evidence-based pre-development multi-objective optimization studies and guides the transition to configuration-aware rate allocation. Future work should explore fixed lifetime constraints, dynamic operational frameworks with adaptive control mechanisms, and ensemble-based optimization for geological uncertainty quantification. This framework supports the evidence-based decision-making needed to maximize geothermal energy's contribution to renewable energy transition while ensuring long-term resource sustainability.

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