Rock Flow Dynamics

Enhanced Planning for Geothermal Development: Economic Assessment of Potential Projects Using Integrated Uncertainty Workflows

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Geothermal

Diversifying & Energy Security
Decarbonising the Energy mix for a low carbon future with a focus on renewables and security of supply

Technology Advancements
Closed loop systems that reduce water losses and environmental impact & enhanced drilling and stimulation techniques unlocking new areas, including superhot rocks (>400°C)

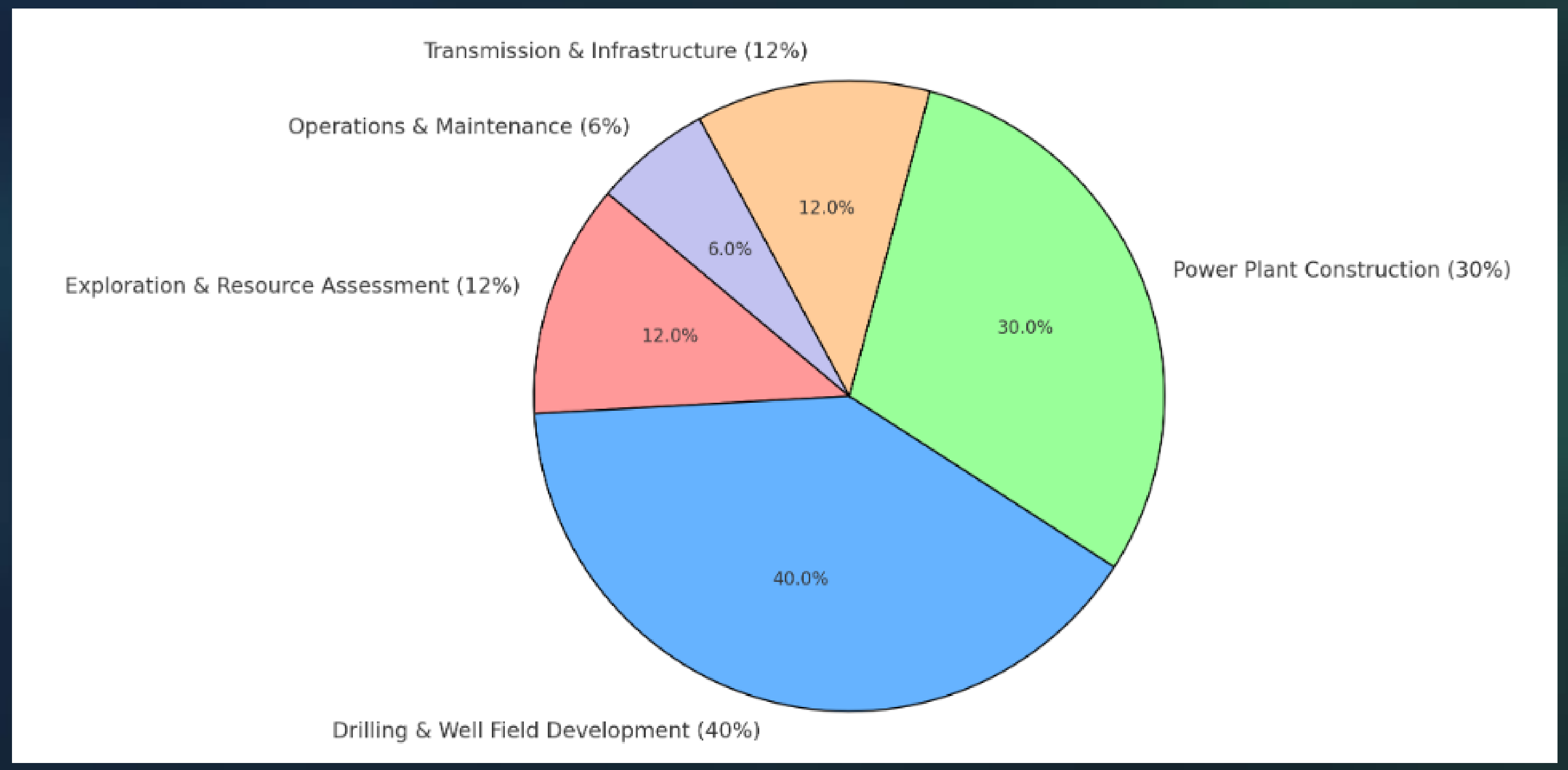
Rising Energy Prices
Spike in fossil fuels makes geothermal more competitive; notability with long-term stability costs and dual use in electricity and heating. Europe consumes half of its energy for heating and cooling

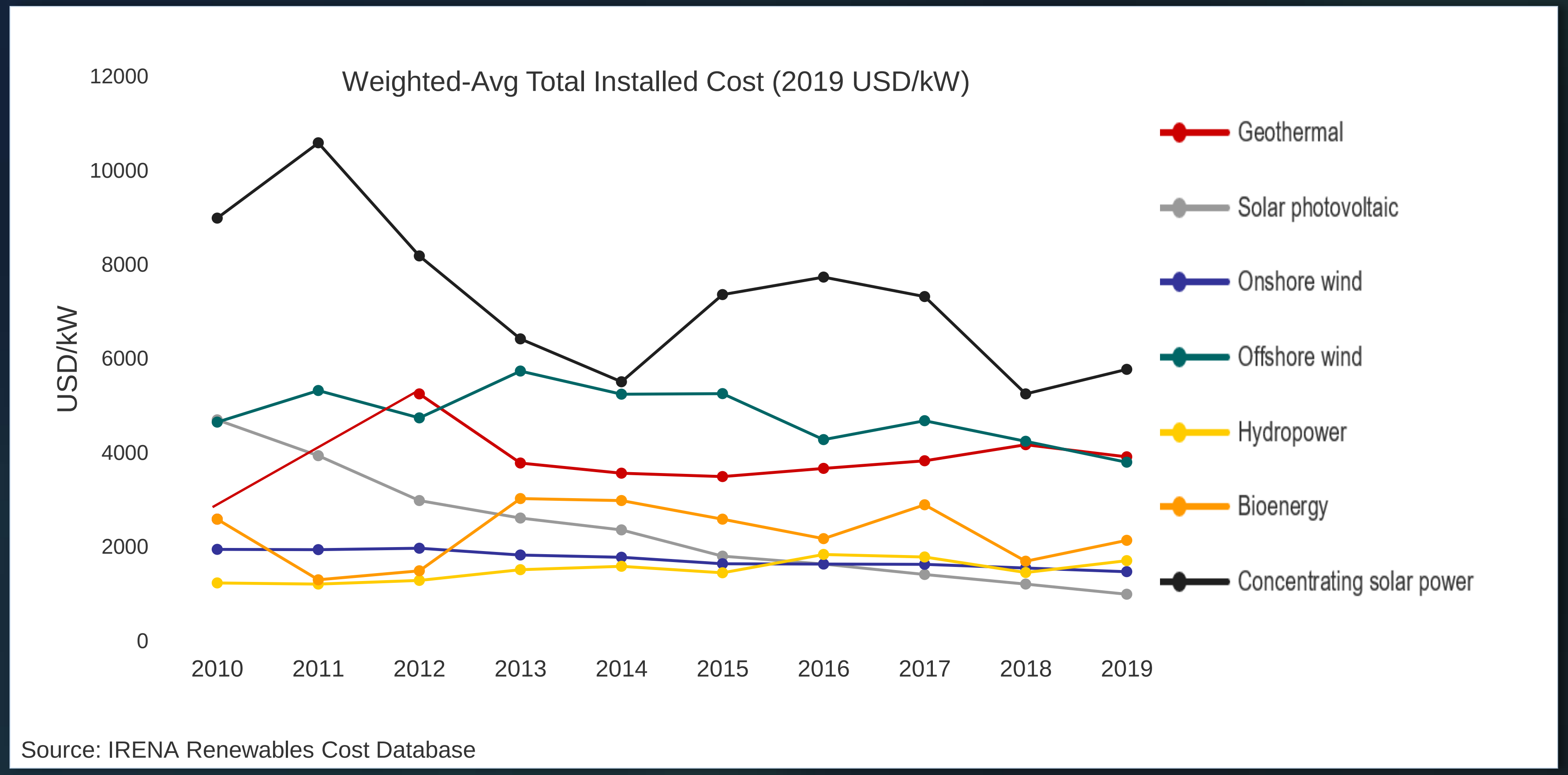
Government Policies
Move towards tax credits and subsidies, regulatory mandates e.g. Renewable Portfolio Standards (RPS)

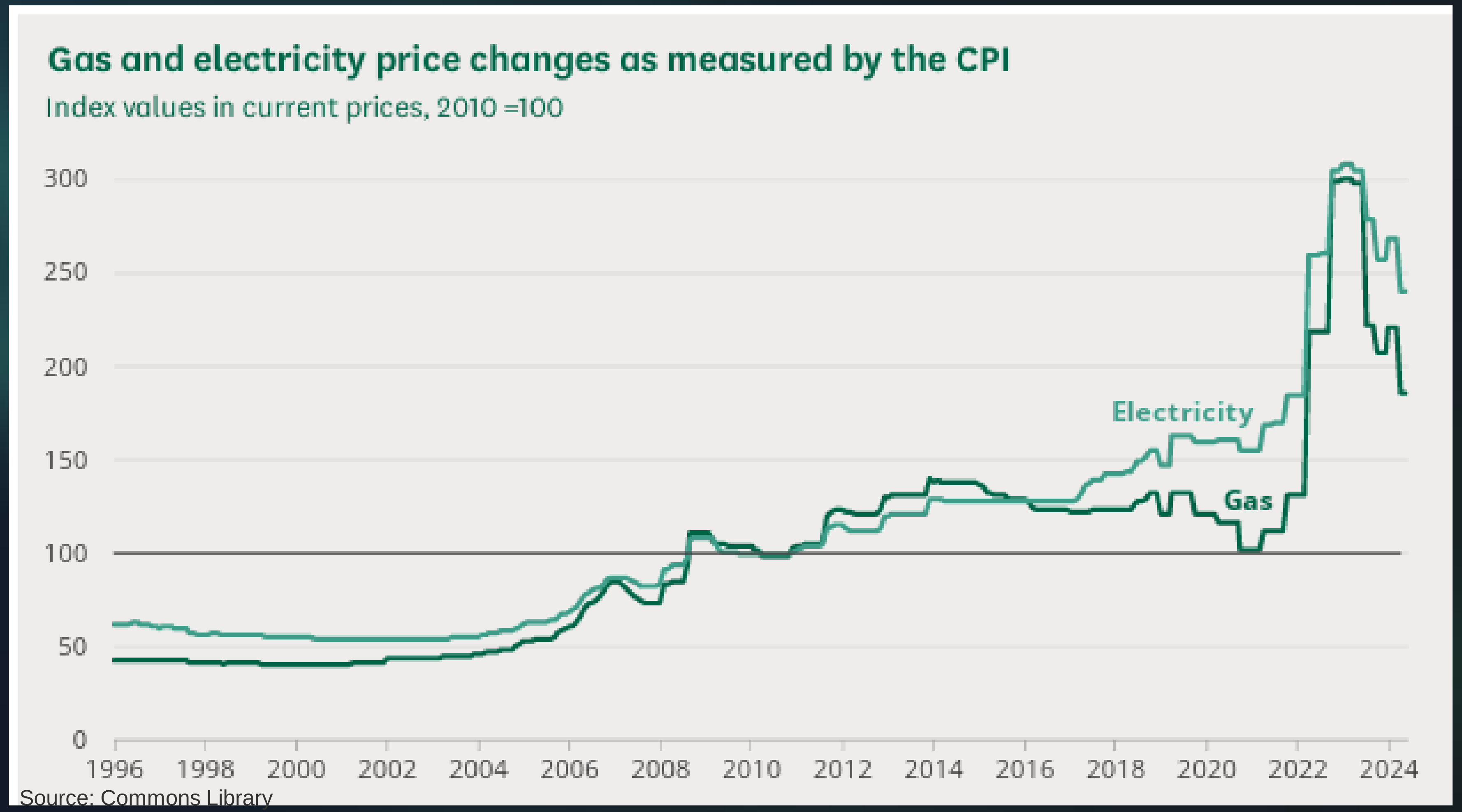
Growing interest in Associated Mining
Increasingly relevant commerciality; especially Lithium

Geothermal Risks

- Subsurface Uncertainty
  - Reservoir quality (heterogeneity)
  - Drilling challenges and circulation losses
- High Upfront Costs
  - 40-50% of project costs in Exploration and Drilling (CAPEX)
  - Tighter Margins with high appraisal commercial risk
- Location dependent & Proximity to habitation
- Market Volatility

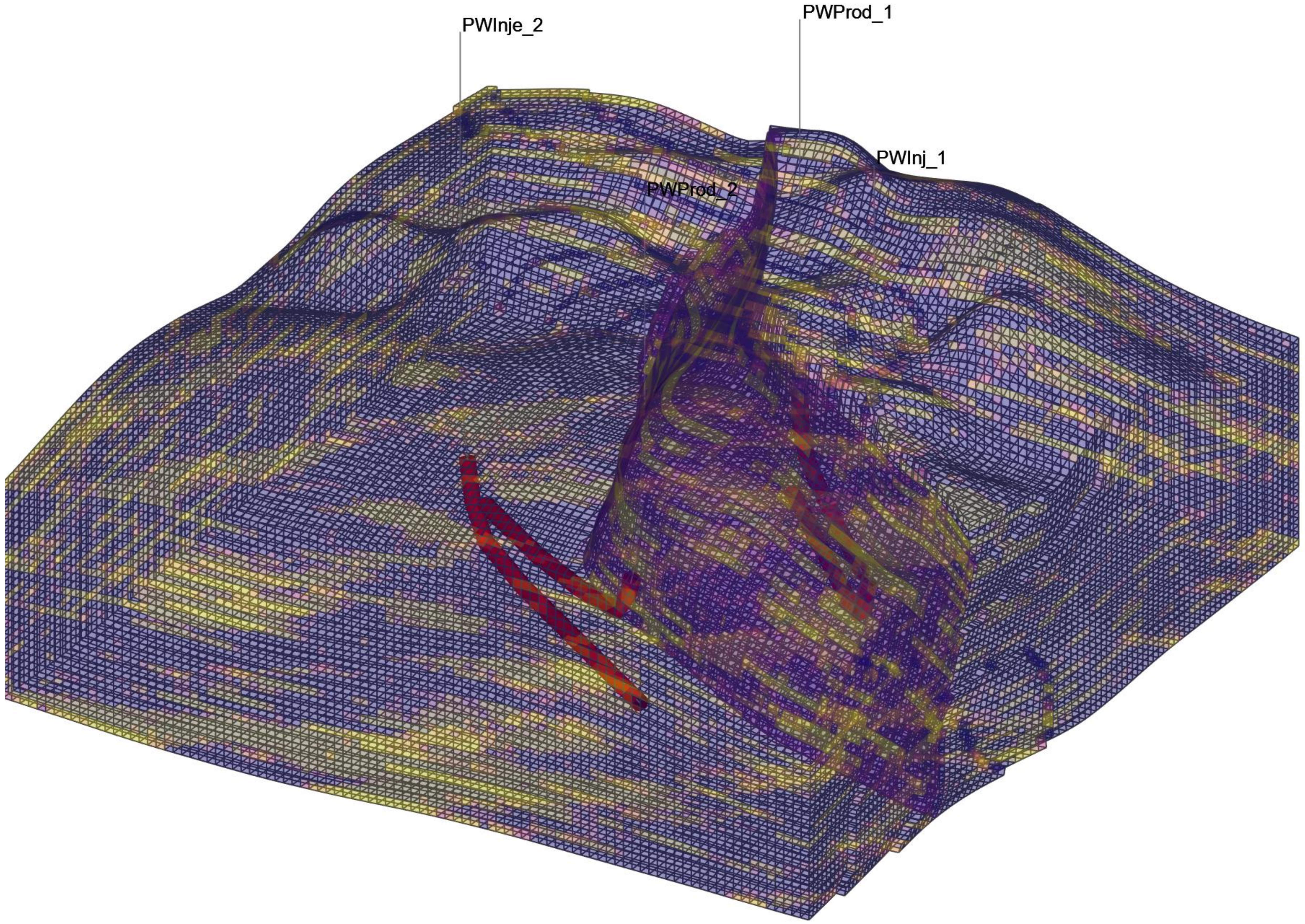






Objectives

- Optimize development of a Geothermal development
- SPE Forge synthetic dataset
- Fully integrated uncertainty workflow accounting for subsurface uncertainty
- Test three common development strategies
- Link with on-the-fly project economics
- Identify project enablers or inhibitors at each stage of project development under prevailing market conditions



Objectives

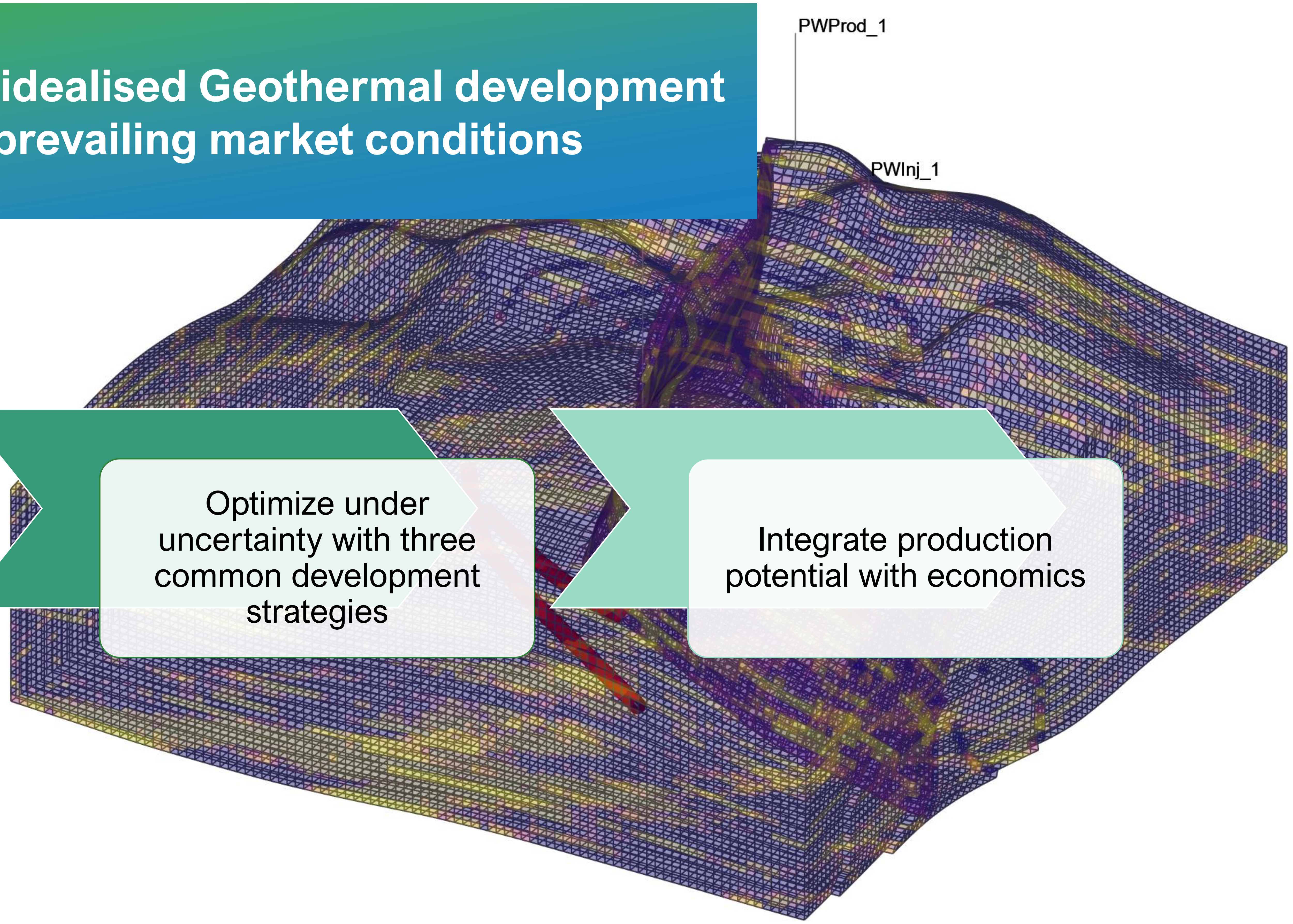
Optimise the development of an idealised Geothermal development under uncertainty under prevailing market conditions

Fully Integrated Ensemble

Identify and optimize key uncertainties

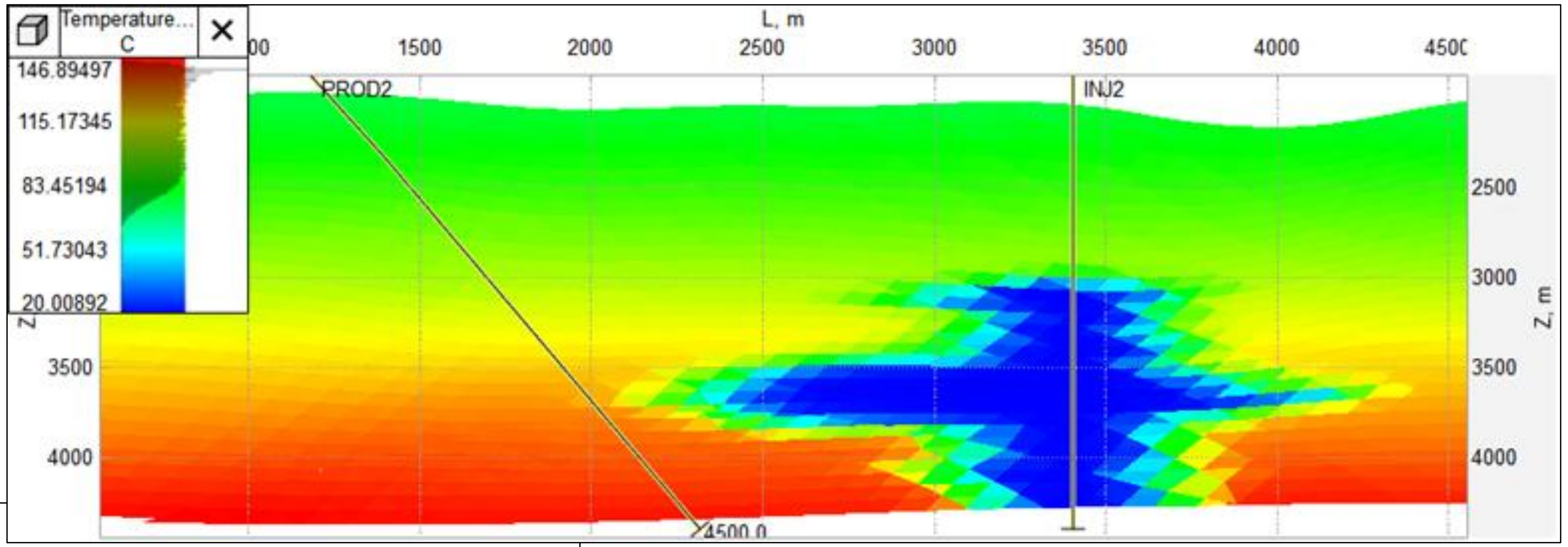
Optimize under uncertainty with three common development strategies

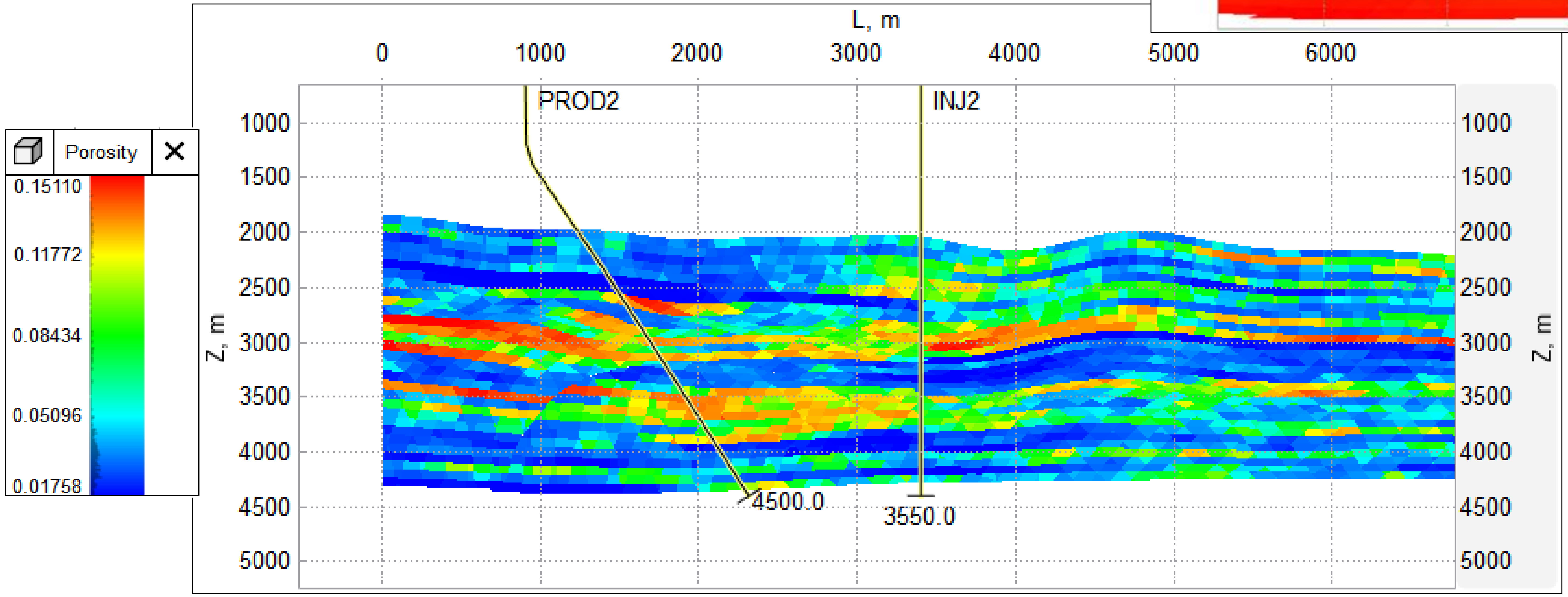
Integrate production potential with economics

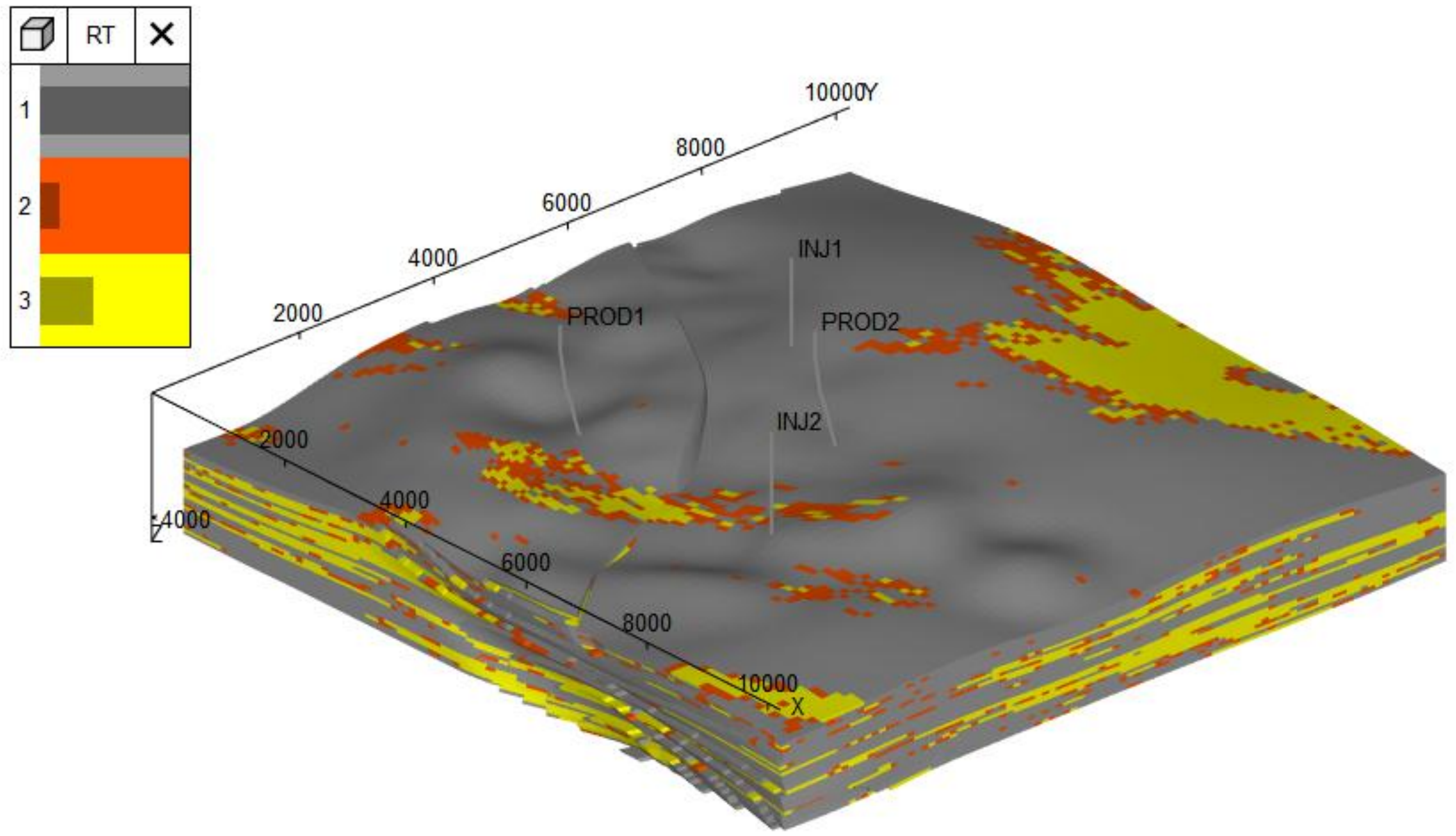


Geological Setting

- Multi-story sandstone channel system interbedded with sandy siltstones
- High uncertainty on channel continuity and connectivity
- High vertical and horizontal heterogeneities

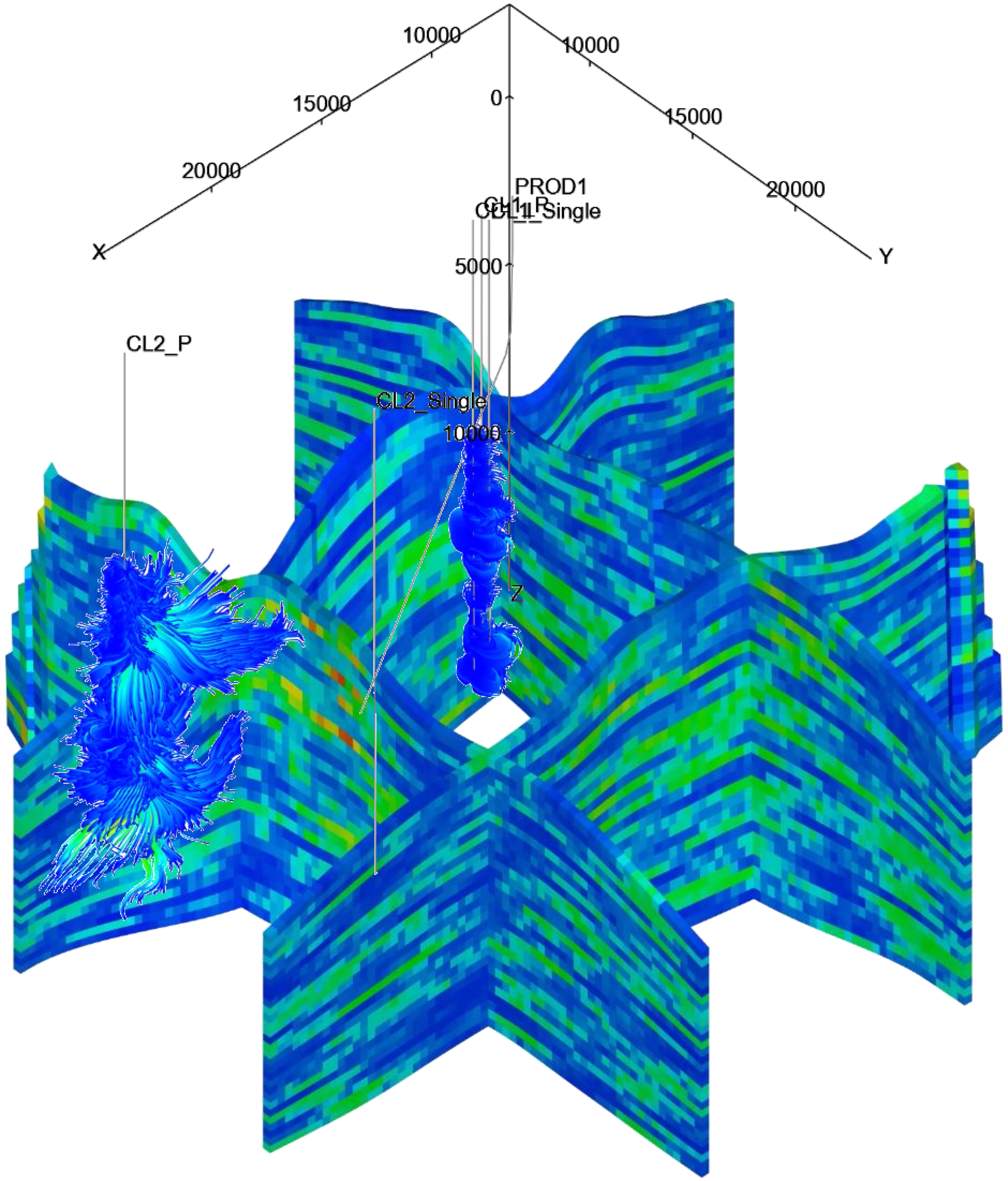






Model Overview

- Northern African Geothermal field of ≈ 5 bln sm^3
- Single major fault
- Developed by 4 wells
- Depth ~2500m
- Initial Reservoir Temperature 160ºC and pressure of 260 bar at reservoir depth
- Limited information available



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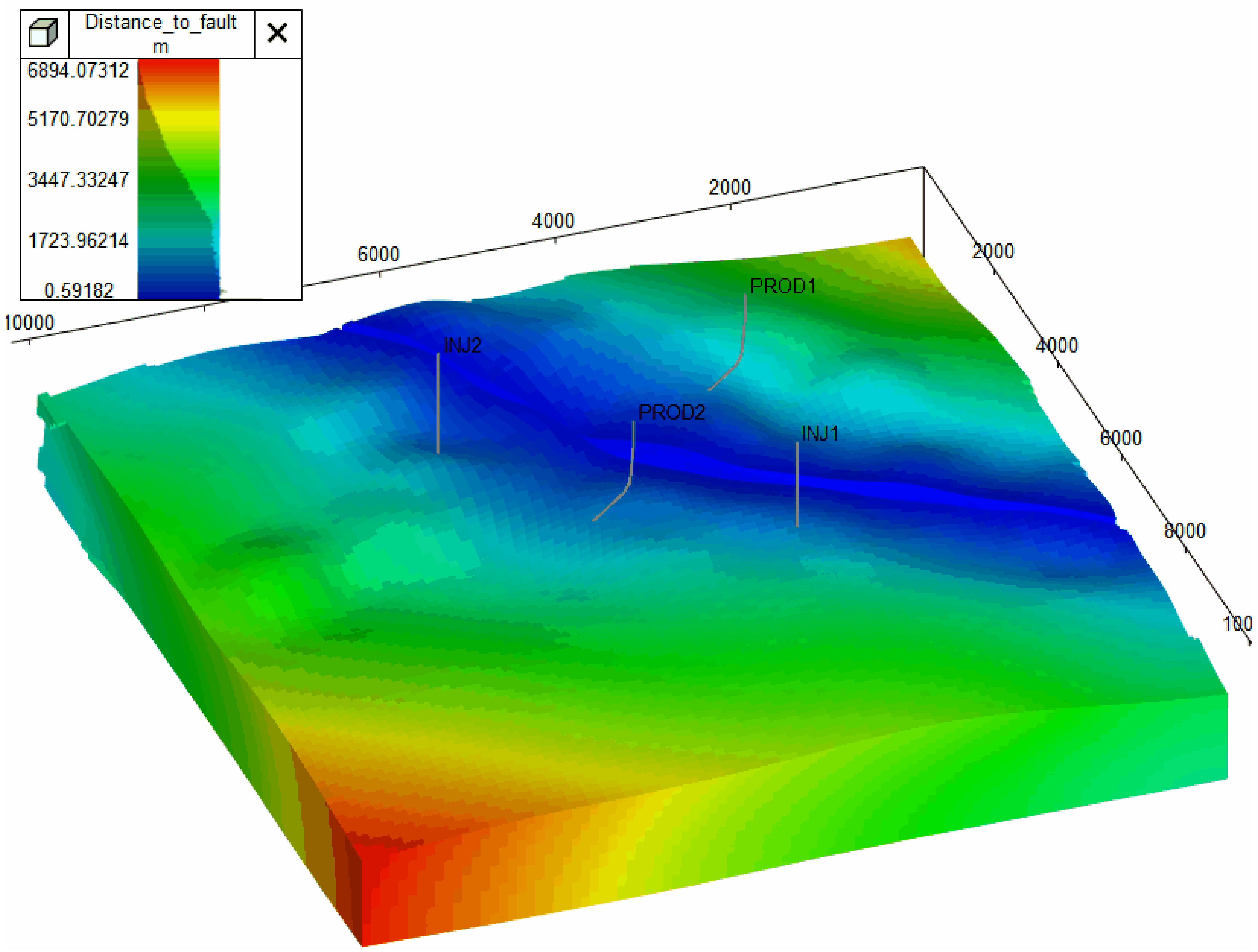
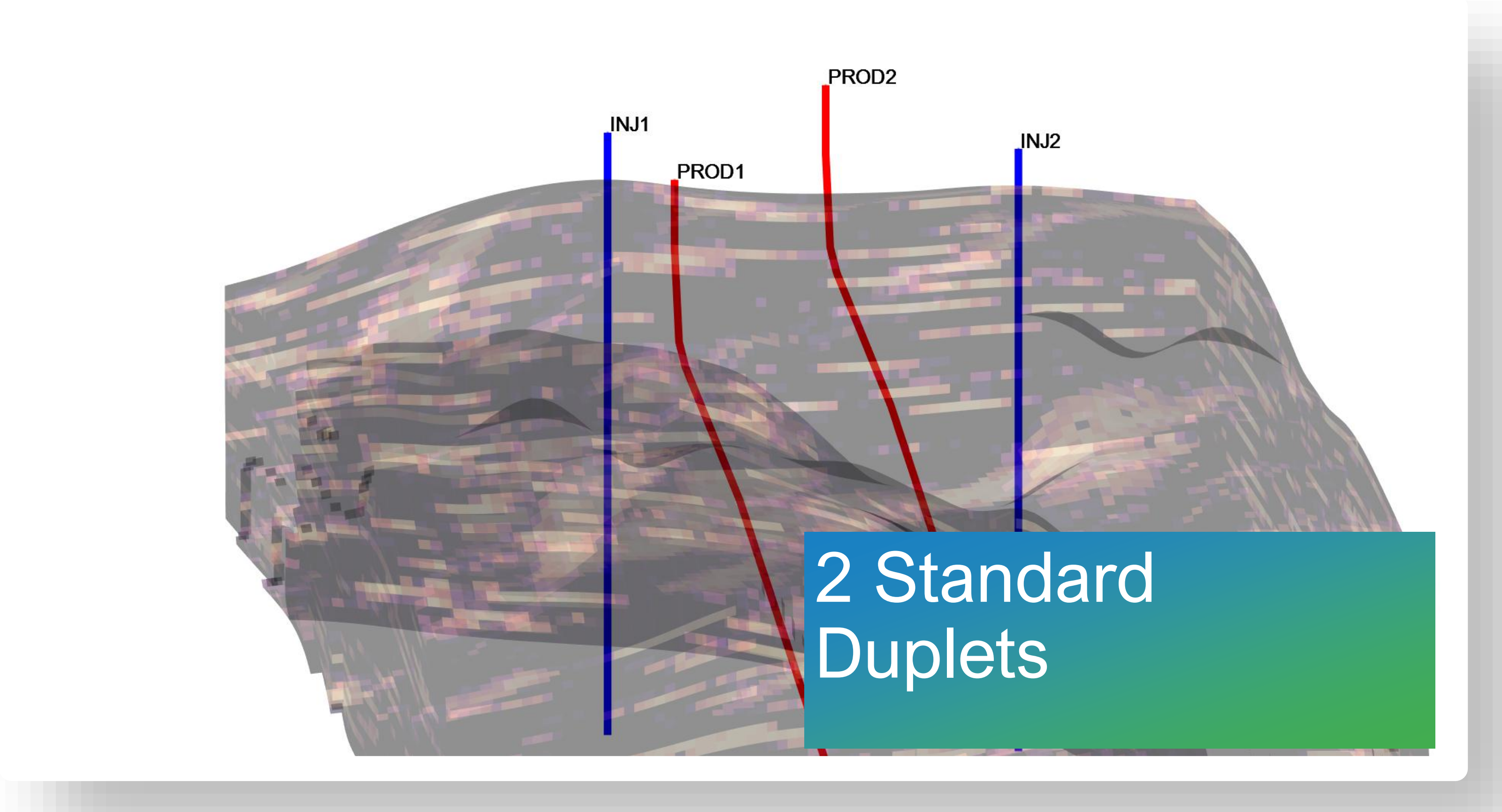
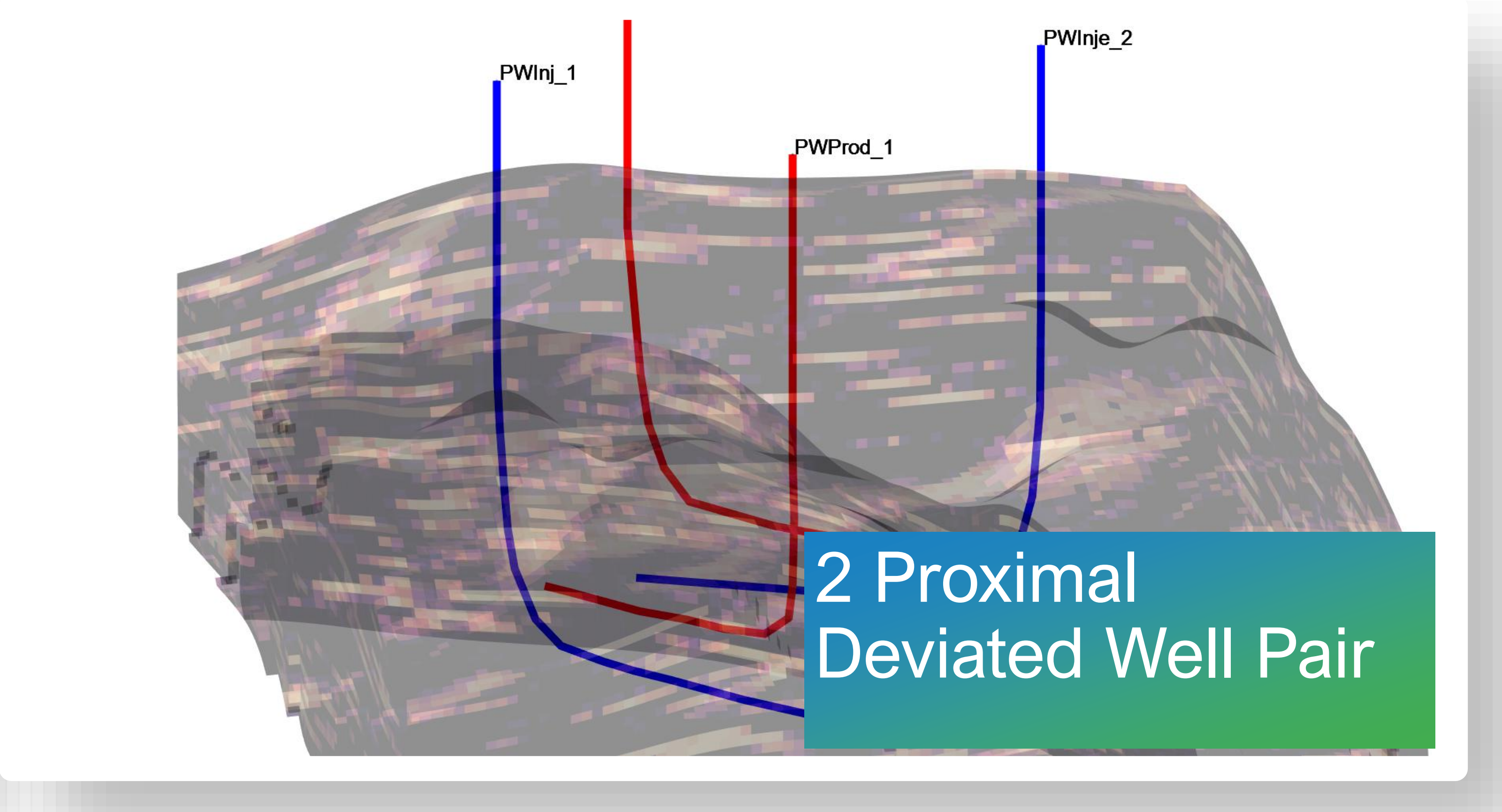
Fault Model Overview

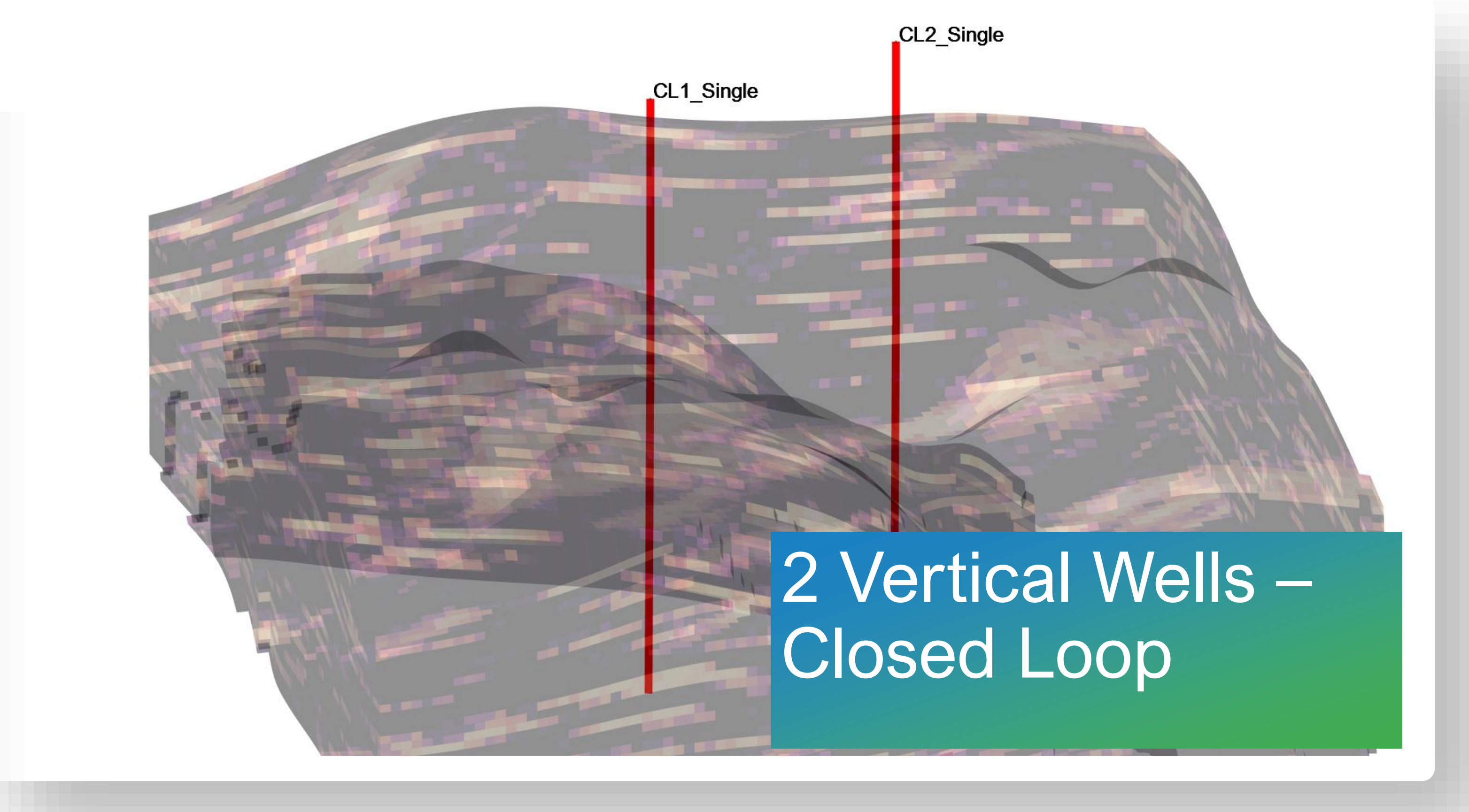


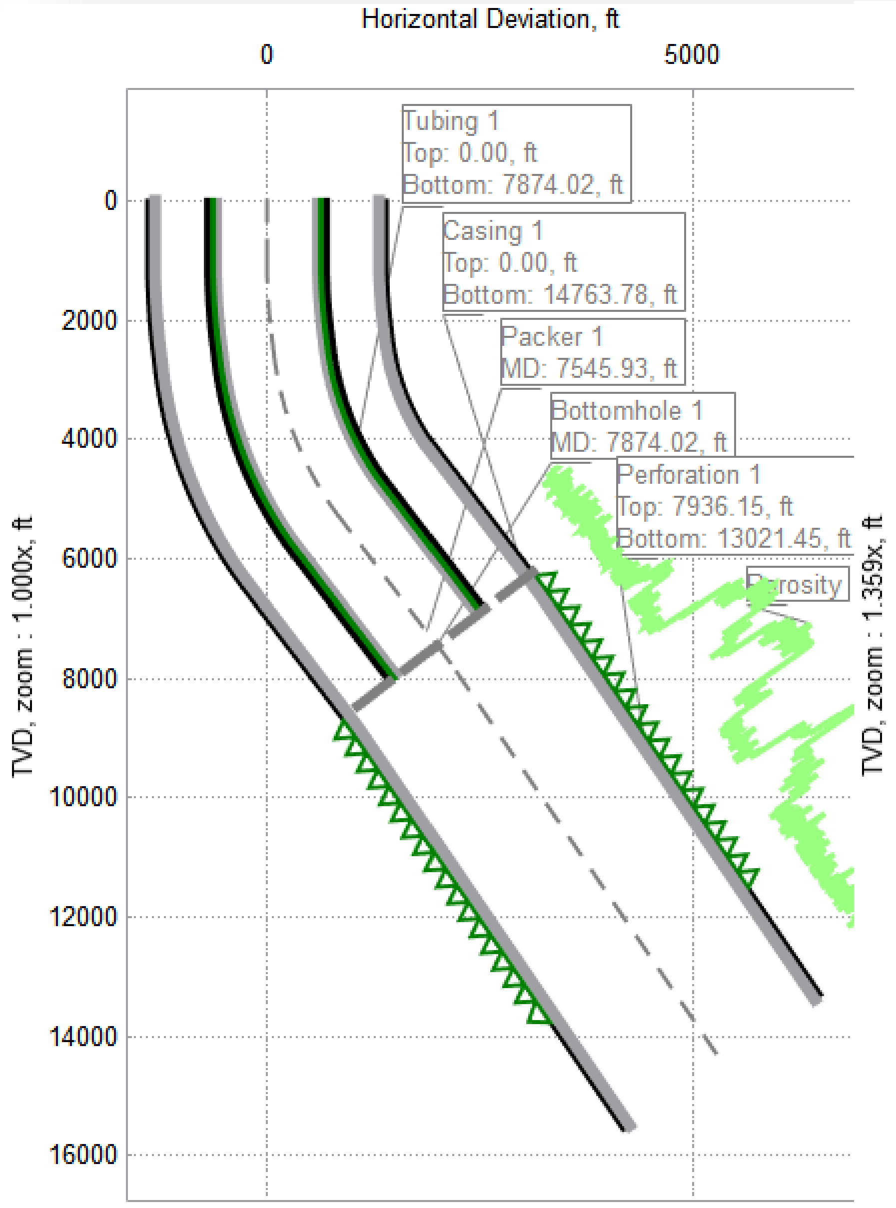
- Two injector wells crossing large fault with NW-SE orientation
- Intense fracturing subparallel to the fault plane
- Impact on horizontal and vertical perm?
- 8 degrees temperature anomaly associated to the fault was detected
- Decreased with distance to the fault increased
- Indicative of a fluid pathway for deeper (hot) groundwater.

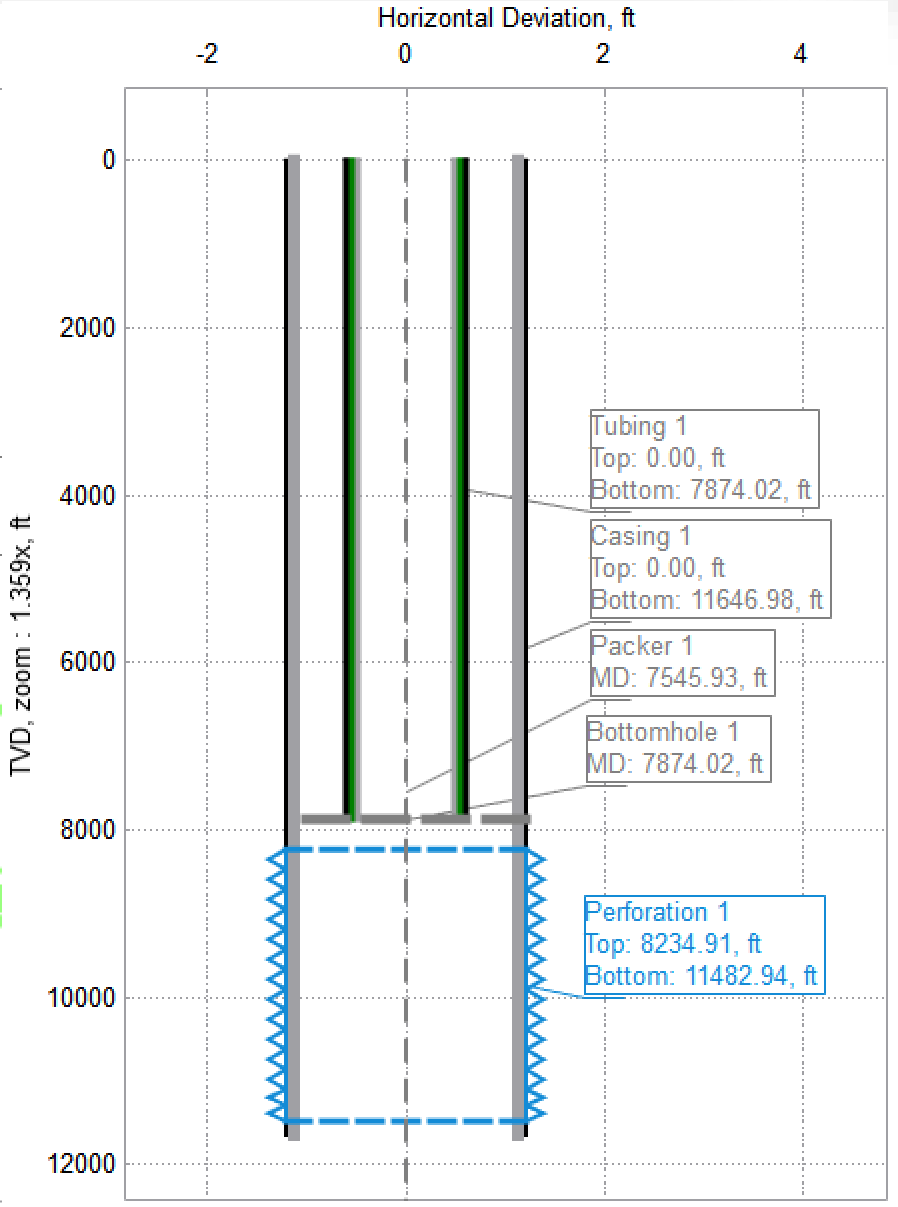
Three Development Strategies





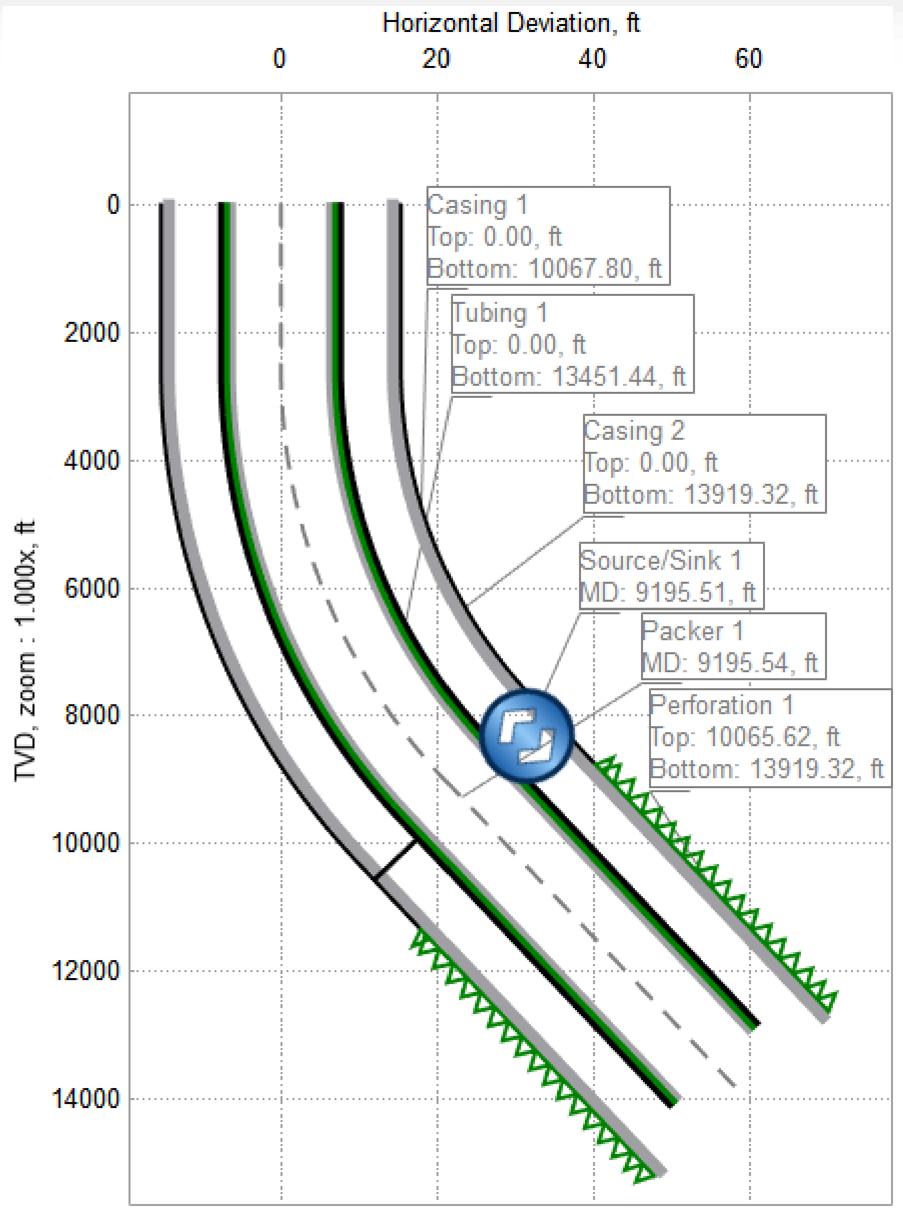






Inverse Voidage Replacement

```python
import datetime

import numpy as np

def voidage_controlled_production():

    # define script execution intervals
    script_set_options(min_interval=datetime.timedelta (days = 90))

    # define group names for producers and injectors and get current date
    field = get_group_by_name ('FIELD')
    g_prod=get_group_by_name('PROD')
    g_inj=get_group_by_name('INJ')
    today= get_current_date()

    # print current date and rates
    print(today)
    text_prd=str('Field wATER production rate =')+str(fwpr)
    text_inj=str('Field Water injection rate =')+str(fwir)
    print(text_inj)
    print(text_prd)

    # if field water injection rate is 5% larger than field liquid producion rate, reduce production by X
    if fwir>1.005*fwpr:

        fwir_new = fwpr-6000
        set_group_inj_limit(g_inj,control_mode='rate',fluid='water',rate=fwir_new)
        print('Reducing field water injection rate from {} to {}'.format(fwir,fwir_new))

    # if field water injection rate is 5% smaller than field liquid producion rate, increase injection by X
    elif fwir<0.995*flpr:

        fwir_new = fwir+6000
        set_group_prod_limit(g_prod,control_mode='lrat',lrat=fwir_new ,lrat_workover='RATE')
        print('Increasing field water injection rate from {} to {}'.format(fwir,fwir_new))

    # do nothing if non of the above criteria are met
    elif is_report_step ( ):

        print('Stable field water injectio - no changes required')
```




0000 - 01/01/2021
3D 1
2D 1
Histogram
Crossplot
Table
3D 3
Wells
Perm_X_with_anomaly
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
PROD2
INJ1
PROD1
INJ2

Integrated Uncertainty Workflows

1 FAULT_DISTANCE
2 Arithmetics [if (Distance_to_fault<@DISTANCE_TO_FAULT@,Distance_to_fault/@DISTANCE_TO_FAULT@,0)]
3 Arithmetics [if (Distance_Normalized==0,0,1-Distance_Normalized)]
4 INITIAL_TEMPERATURE
5 Arithmetics [@DELTA_TEMP@]
6 Arithmetics [Temp_calculator_F+Distance_Normalized*@DELTA_TEMP@]
7 PORO PERM
8 Property Interpolation (Zones, Regions)
9 Calculator [Perm_X_Master*@PERMLOG_SCALAR@]
10 Calculator [Perm_X]
11 Create Blocked Wells by Well Log
12 Create Blocked Wells by Well Log
13 Property Interpolation (Zones, Regions)
14 Property Interpolation (Zones, Regions)
15 Arithmetics [if (Distance_Normalized==0,Perm_X,Perm_X+Distance_Normalized*@FAULT_PERM_MULT@)]
16 Arithmetics [if(Perm_X_with_anomaly<0,0,Perm_X_with_anomaly)]
17 Arithmetics [Perm_X_with_anomaly]
18 Arithmetics [Perm_X_with_anomaly*@KV_KH@]
19 THERMAL_COND
20 Arithmetics [@THCROCK@]
21 Arithmetics [if (Distance_Normalized==0,THCROCK,THCROCK+Distance_Normalized*@FAULT_PERM_MULT@)]
22 Arithmetics [if(THCROCK<0,0,THCROCK)]
23 Arithmetics [@THCWATER@]
24 AQUIFER
25 Set local variables
26 Calculate Aquifer by Polygon
27 Calculate Aquifer by Polygon
28 Calculate Aquifer by Polygon
29 Calculate Aquifer by Polygon
30 Calculate Aquifer by Polygon
31 Constant Head/Pressure Water Aquifer Settings
32 Constant Head/Pressure Water Aquifer Settings
33 Constant Head/Pressure Water Aquifer Settings
34 Constant Head/Pressure Water Aquifer Settings
35 Constant Head/Pressure Water Aquifer Settings
36 DEVELOPMENT STRATEGY
37 Well Production Limits (Forecast)
38 Well Injection Limits (Forecast)

	Base value	Min. value	Max. value
DISTANCE_TO_FAULT	250	0	500
FAULT_PERM_MULT	8	0.1	10
DELTA_TEMP	10	0	20
THCROCK	200	20	200
THCWATER	50	20	50
KV_KH	0.1	0.01	1
AQ_TEMP	320	212	392
AQ_PRESS	3770	1450	4351
FAULT_TX	1	0	10
PORO_VAR_VRT	135	100	200
PERM_VAR_VRT	135	100	200
SEED	1	0	100000
WATER_RATE_PROD1	100000	60000	150000
WATER_RATE_PROD2	100000	60000	150000
WTEMP_INJ	68	68	194
PERMLOG_SCALAR	1	0.01	5

- Integrated workflow to automatically generate geological and dynamic properties
- Launch sensitivity analysis to identify key variables and underlying drivers
- Consider optimized scenarios under uncertainty

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Integrated Uncertainty Workflows

Fault distance

Temperature anomaly

Facies controlled porosity and perm

Fault controlled dynamic perm for simulation

Thermal calculations

Aquifer boundary conditions

Development scenario

Calculation

1	FAULT_DISTANCE
2	Arithmetics [if (Distance_to_fault<@DISTANCE_TO_FAULT@,Distance_to_fault/@DISTANCE_TO_FAULT@,0)]
3	Arithmetics [if (Distance_Normalized==0,0,1-Distance_Normalized)]
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Variable

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Fault impact

Temperature anomaly

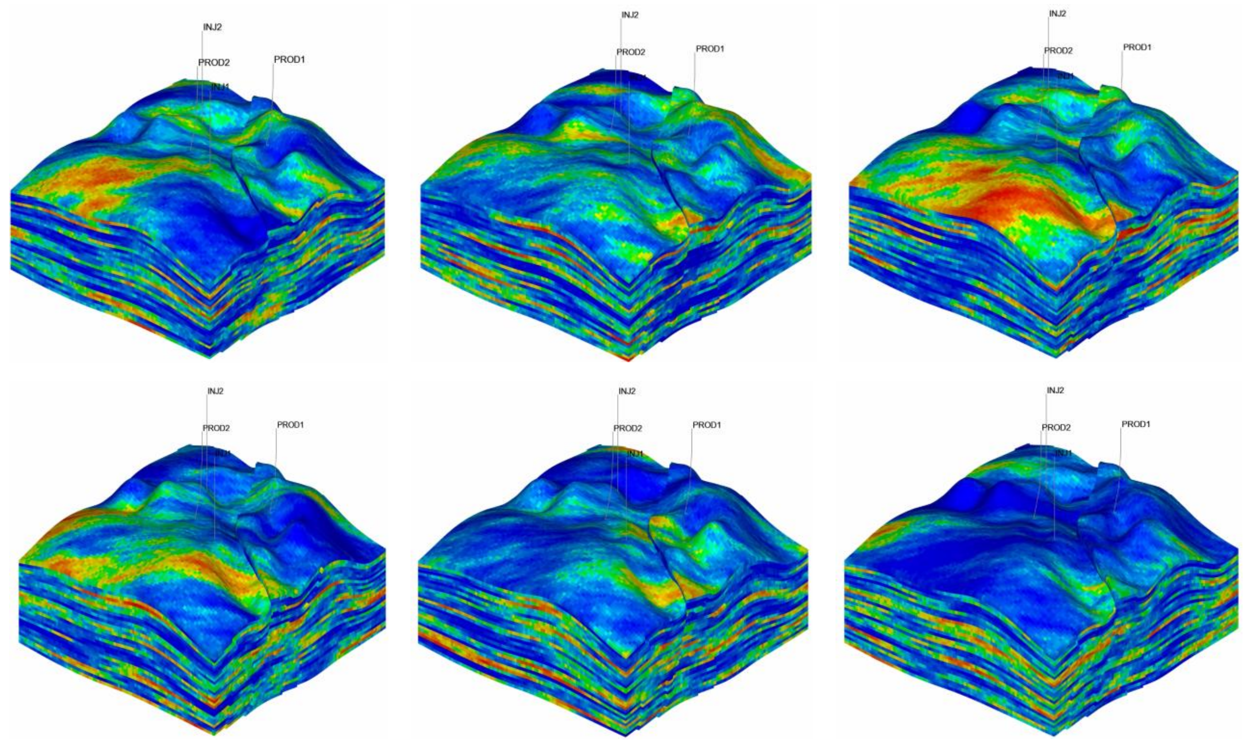
Fault transmissibility

Rock properties

Development strategy

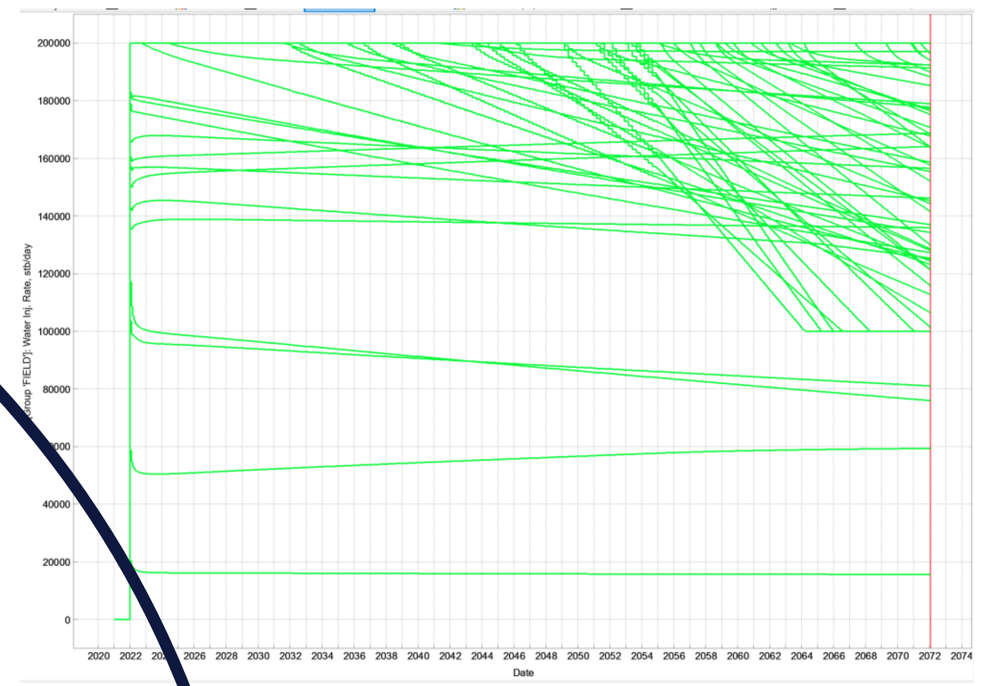
Geological heterogeneity and uncertainty

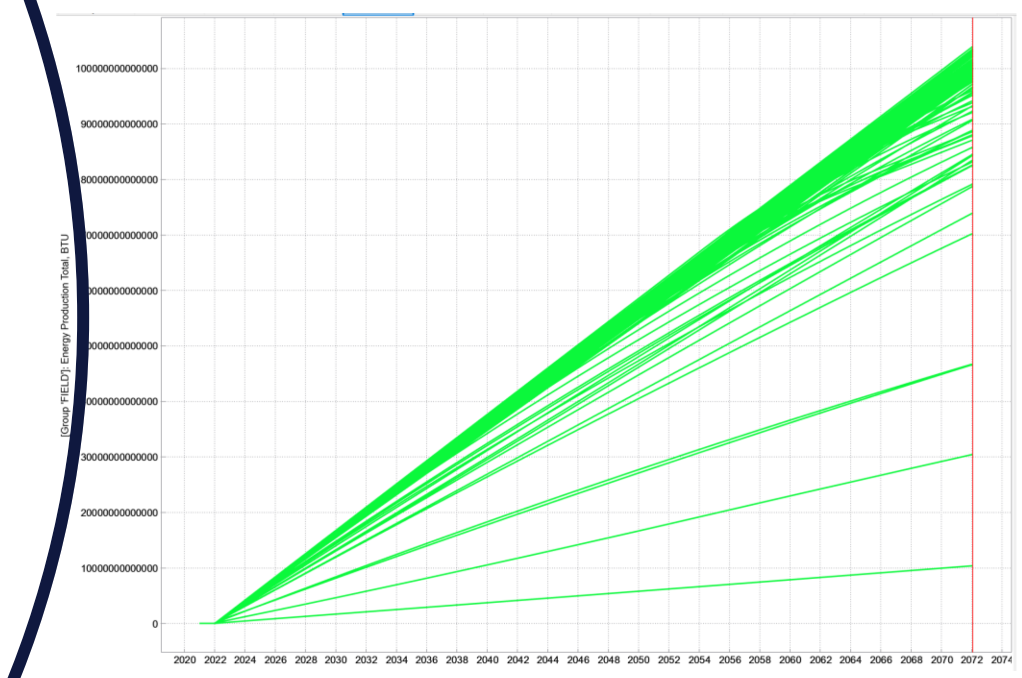
A New Approach for Geothermal Reservoirs



Project Geothermal Investment Model									
Year of Operation		Pre-Operating			1	2	3	4	5
Year		2018	2019	2020	2021	2022	2023	2024	2025
SECTION I: INCOME STATEMENT/CASH FLOW									
Revenue				€ -	########	########	########	########	########
Interest Receipts					€ -	€ -	€ -	€ -	€ -
Expenses									
Opex				€ -	########	########	########	########	########
Operations Costs (Pre-Drilling)		########							
Operations Costs (After Pre-Drilling)			########	########					
Management Services and Fee	5%	€ -	€ -	€ -	########	########	########	########	########
Total Expenses		########	########	########	########	########	########	########	########
EBITDA	0% Risk Adjustment	########	########	########	########	########	########	########	########
Other Expenses									
Interest on term loan			€ -	########	########	########	########	########	########
Interest on 1-yr short term debt \c		€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
ADS SL Dep	10 Recovery Years			########	########	########	########	########	########
ADS SL Dep	8 Recovery Years	€ -	€ -	########	########	########	########	########	########
ADS SL Dep	11 Recovery Years	€ -	€ -	########	########	########	########	########	########
Income									
Taxable Income		########	########	########	########	########	########	########	########
Net Operating Loss (NOL)		€ 833,000	########	########	€ -	€ -	€ -	€ -	€ -
Taxable Income (adjusted for NOL)		€ -	€ -	€ -	########	########	########	########	########

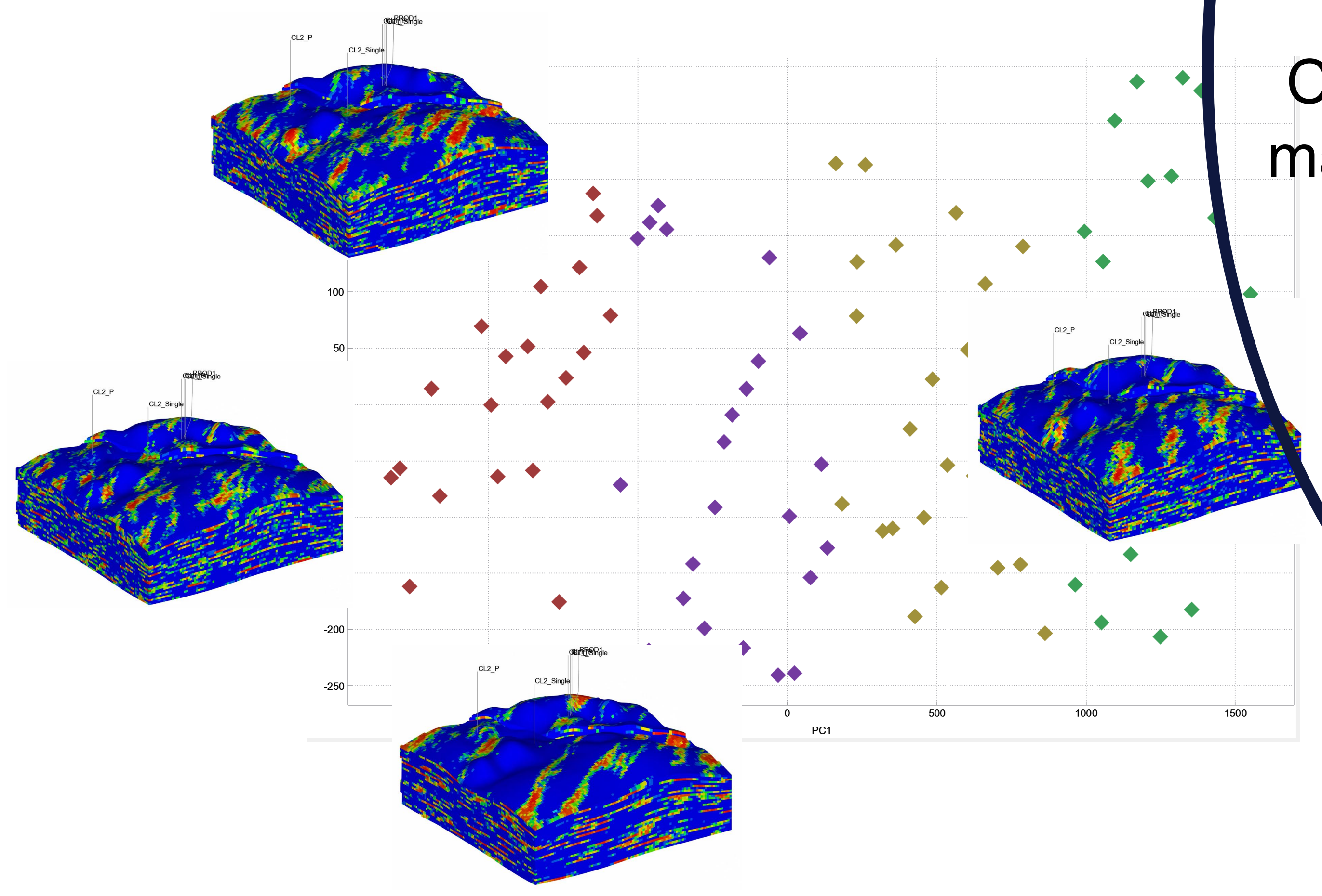
Project economics



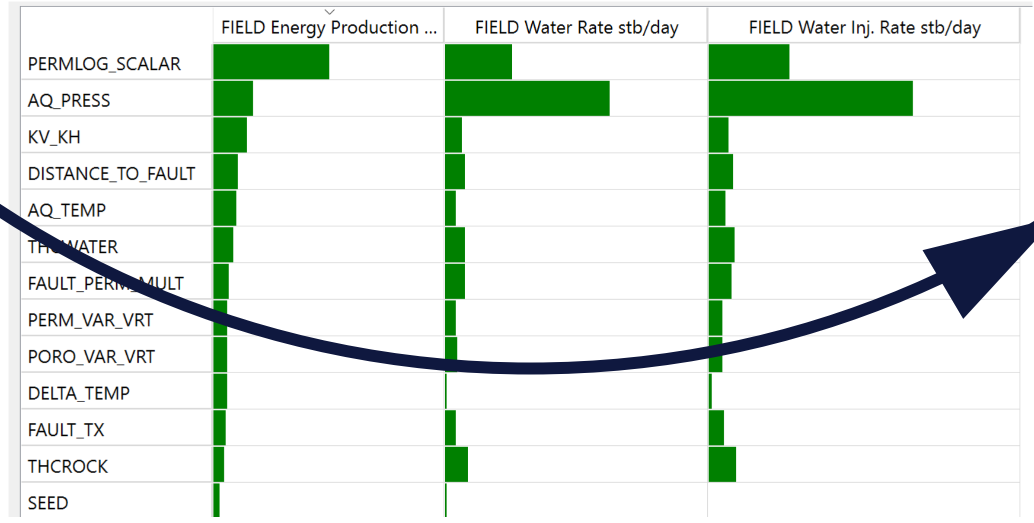


Forecast optimisation under uncertainty

Cluster analysis to maintain ensemble variability



Analysis of impactful variables



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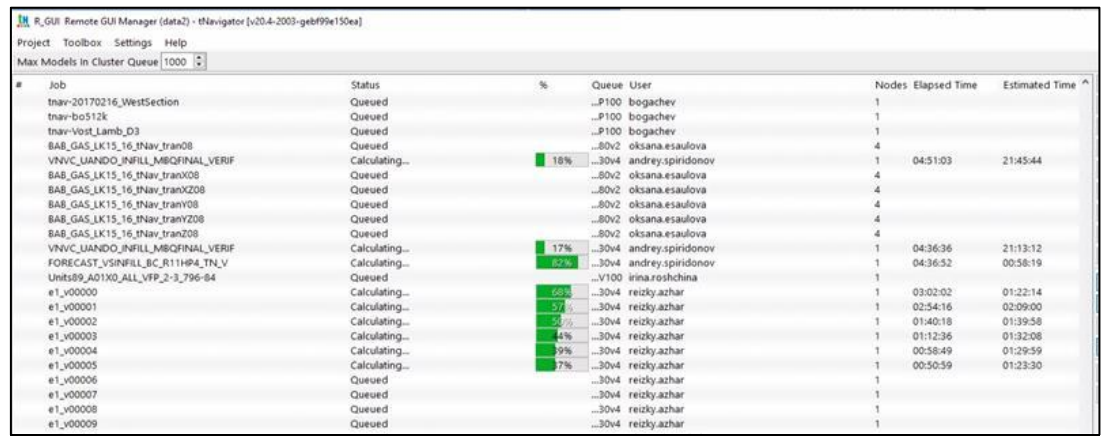

Parallelization

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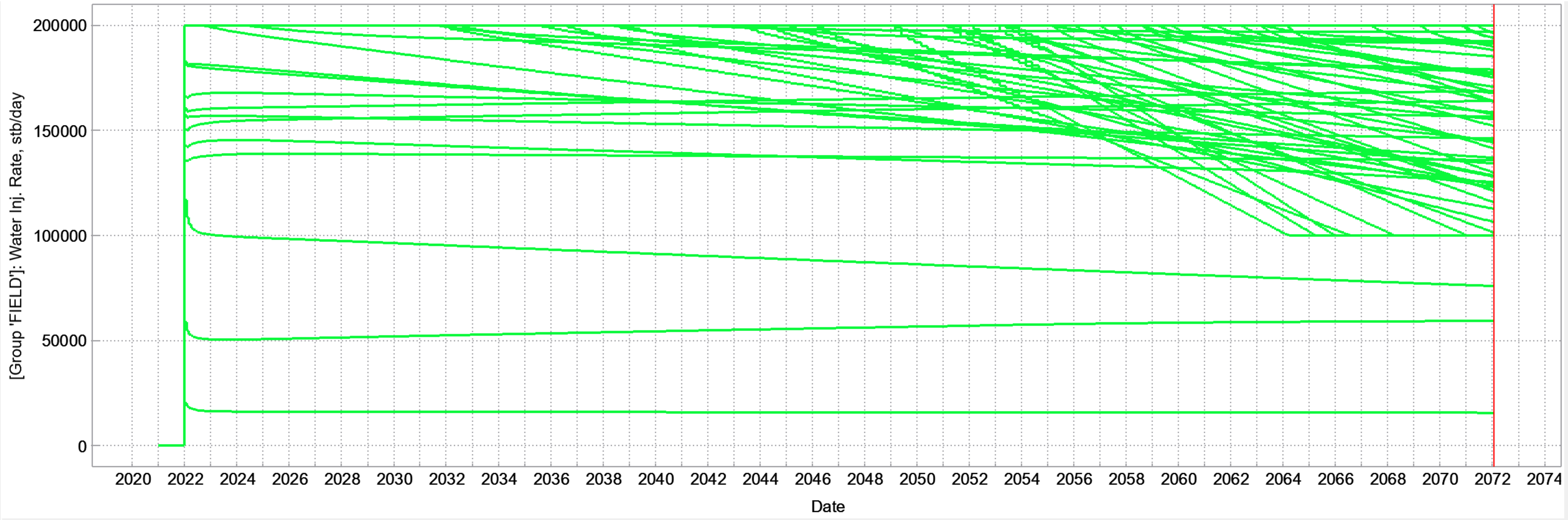
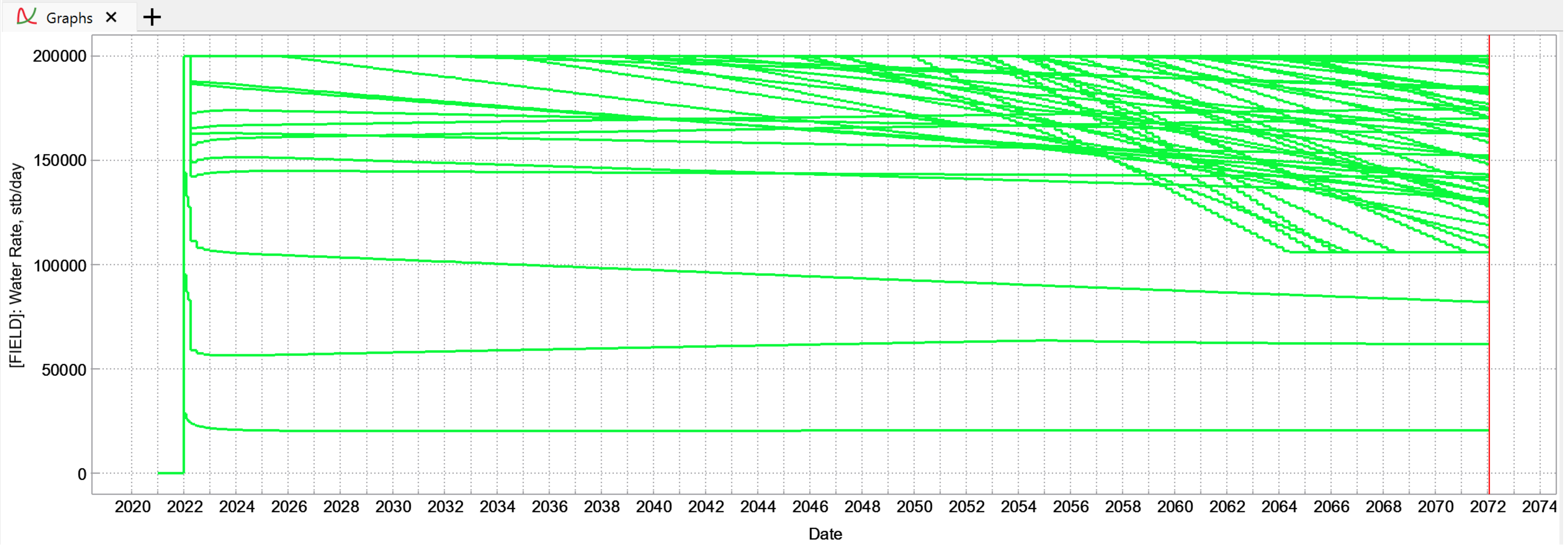
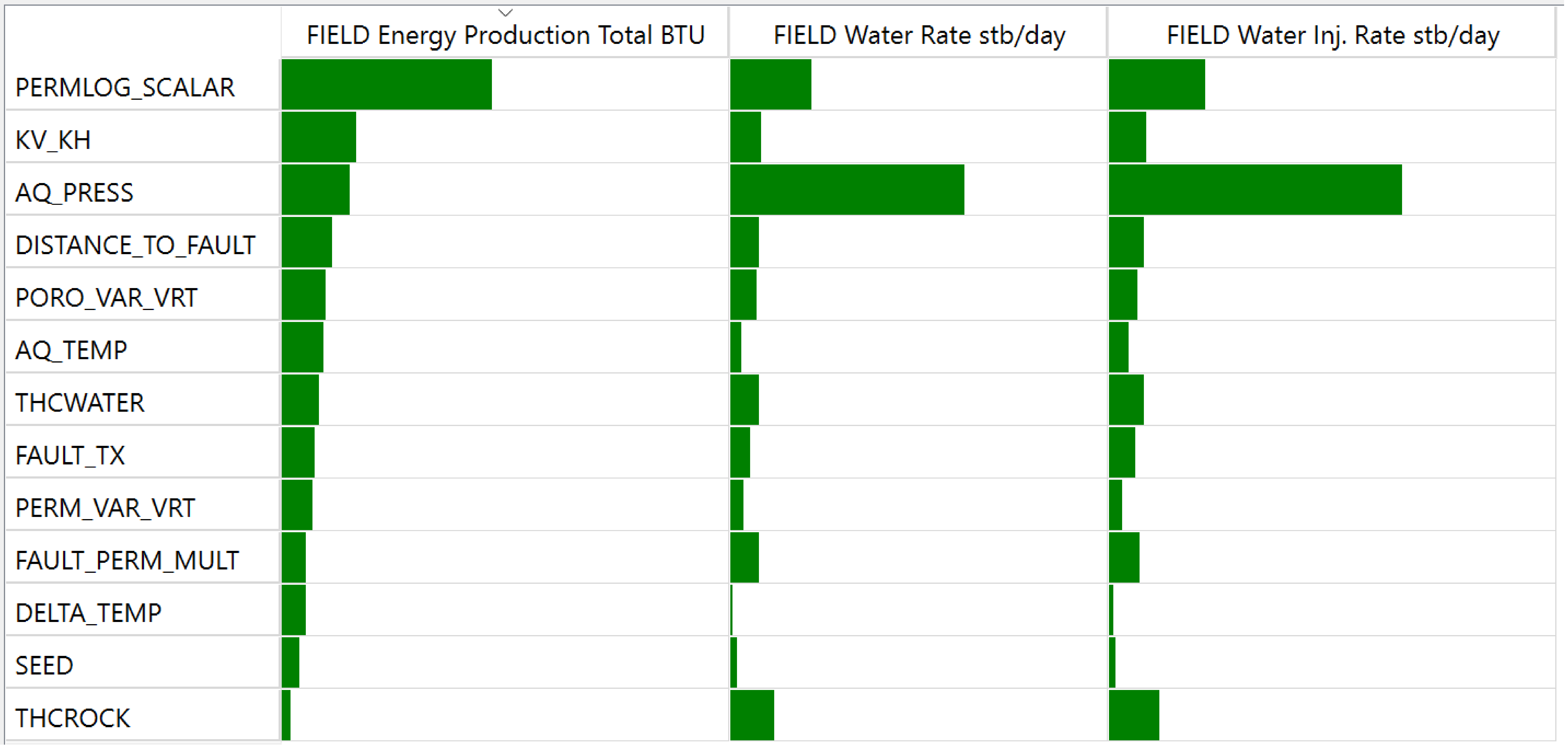
Uncertainty Analysis: 2 Producers & 2 Injectors



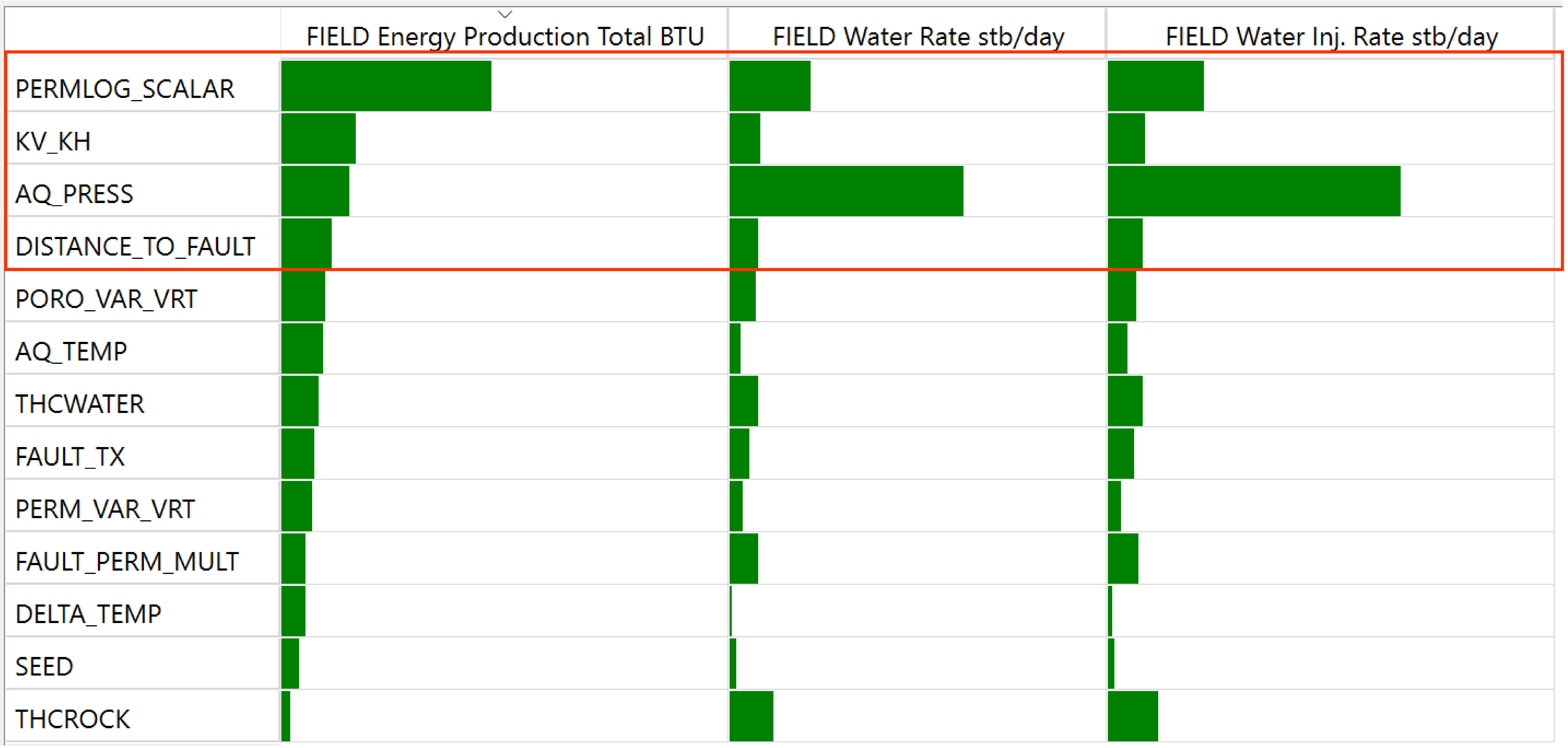


- Wide response of production & injection rates based on geological uncertainties

Uncertainty Analysis: Tornado

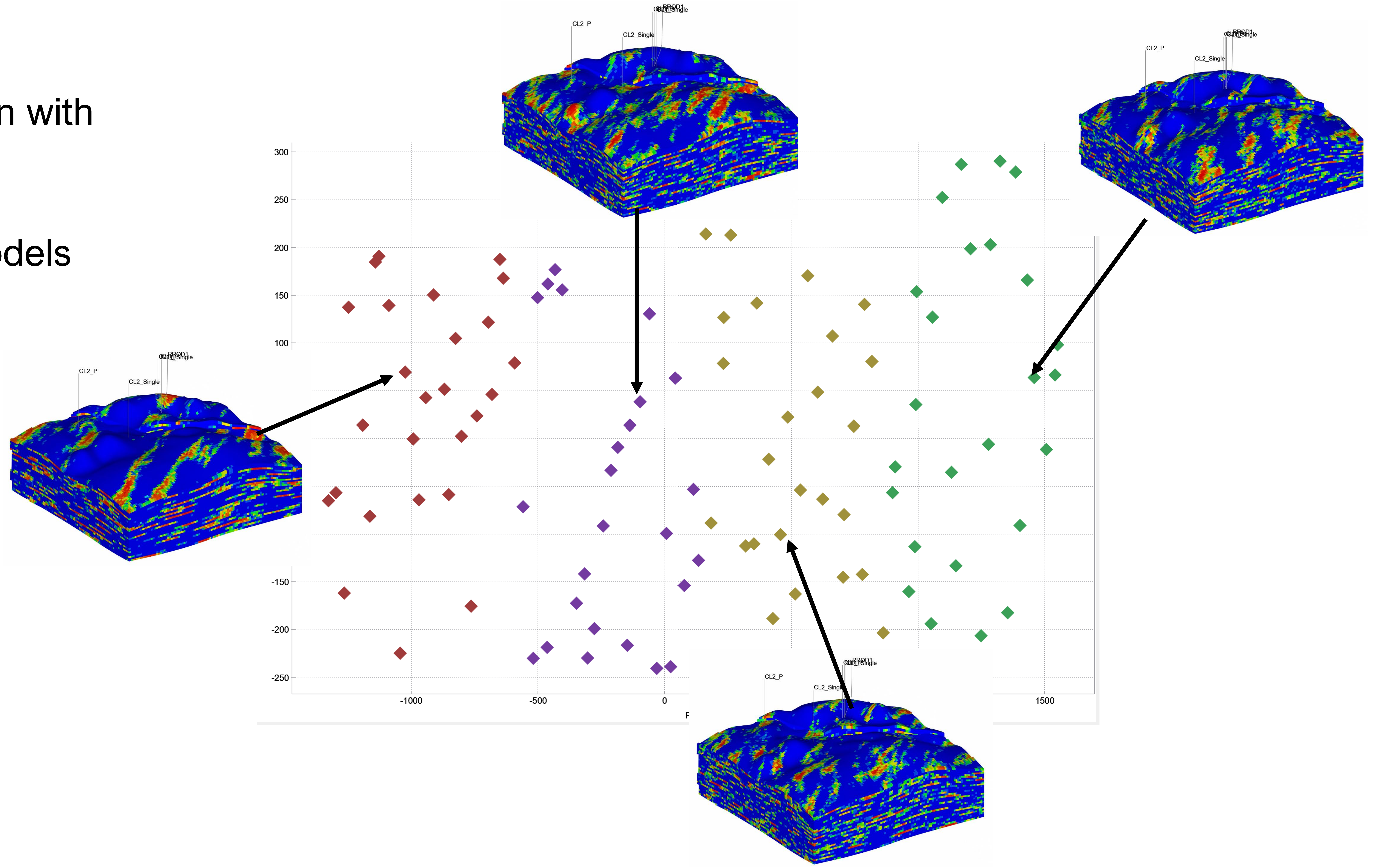


Uncertainty Analysis: Tornado

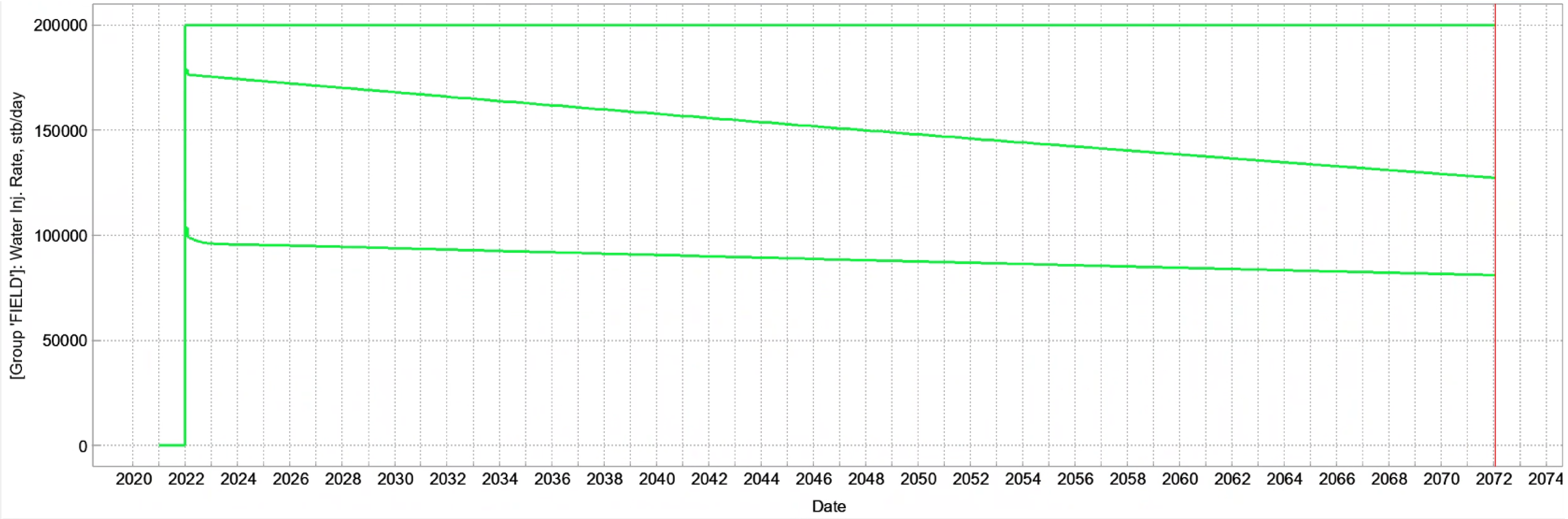


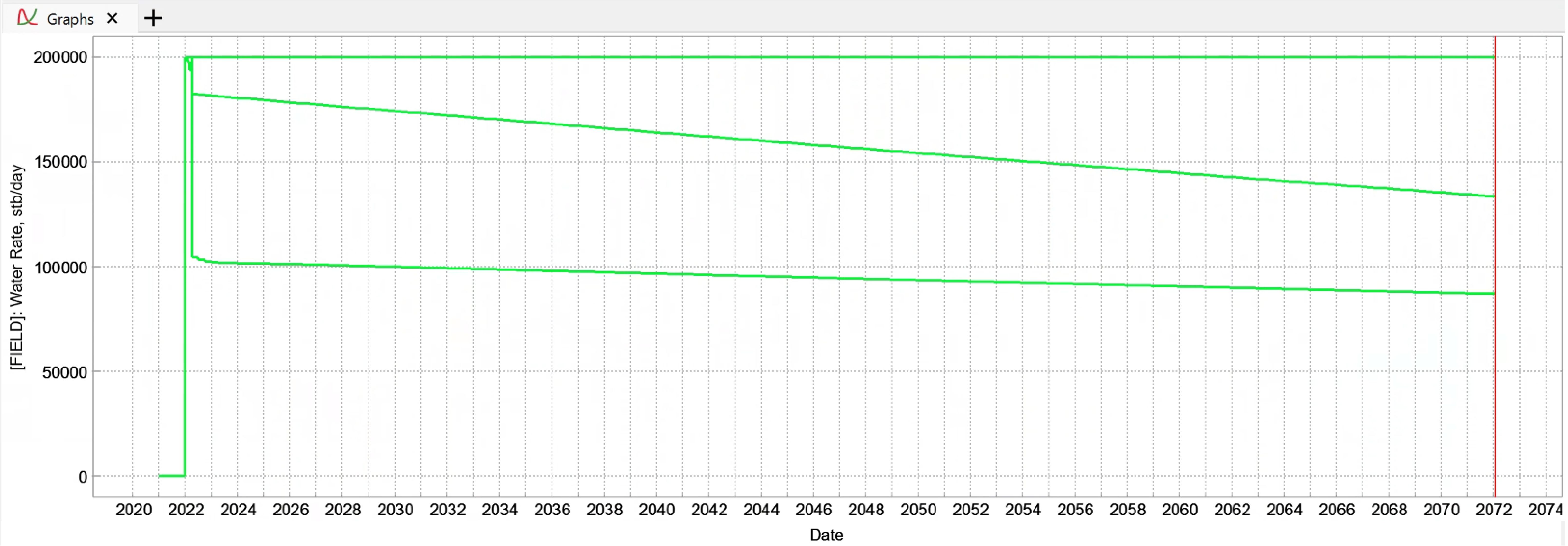
Model selection with unsupervised machine learning

- Dimension reduction with MDS or PCA
- K-means clustering
- 4 representative models



Uncertainty Analysis: 2 Producers & Injectors

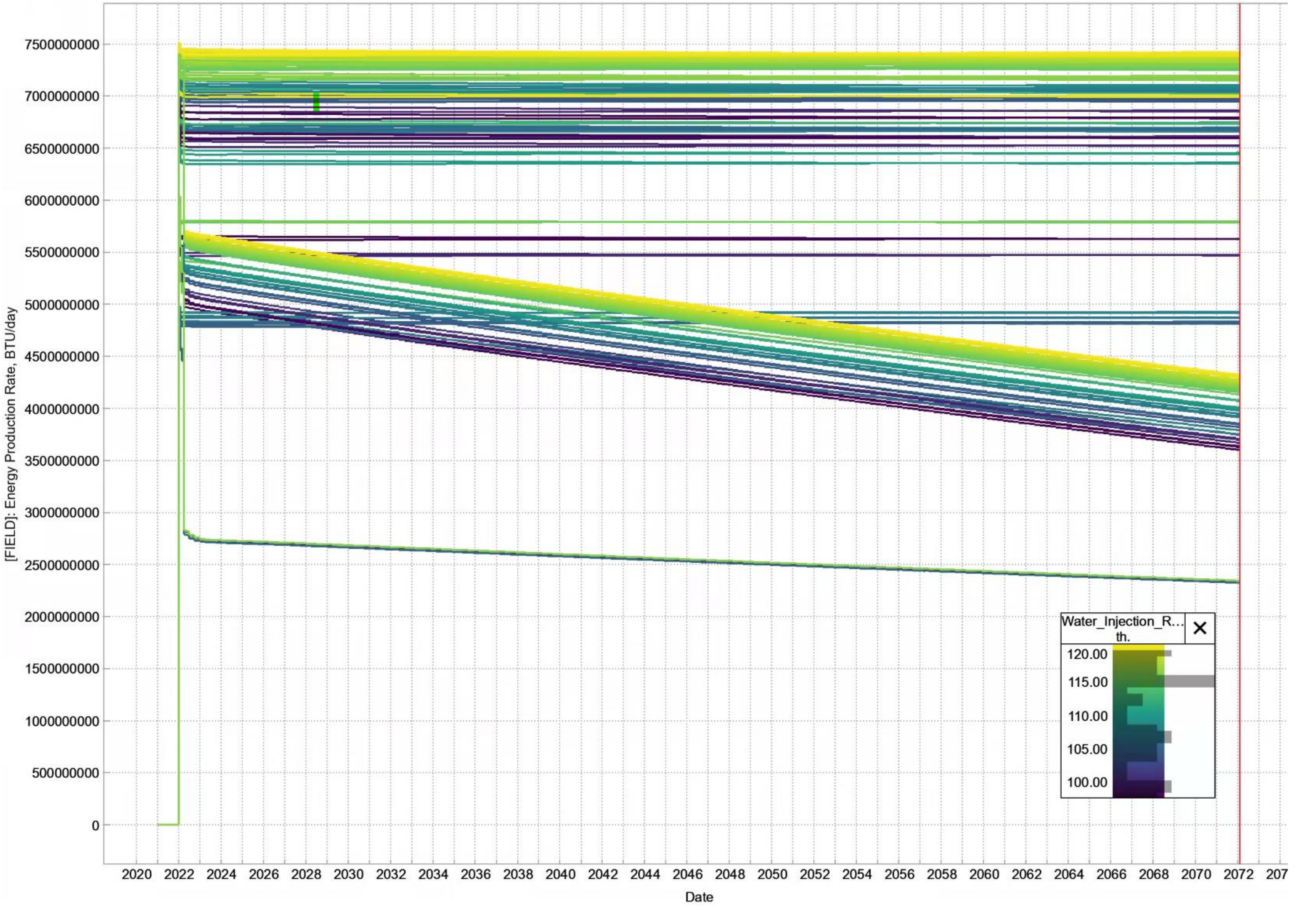




- Maintain spread of production & injection response with only a subset of geological models
- Take subset of models forward for production optimization under uncertainty

Forecast Optimization under Uncertainty

- Objective:
  - Maximize Energy
- Control Variables:
  - Production rates
  - Injection rates
  - Temperature of the injected water
- Optimizer:
  - Differential Evolution



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Forecast Optimization under Uncertainty

- Objective:
  - Maximize Energy
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  - Temperature of the injected water
- Optimizer:
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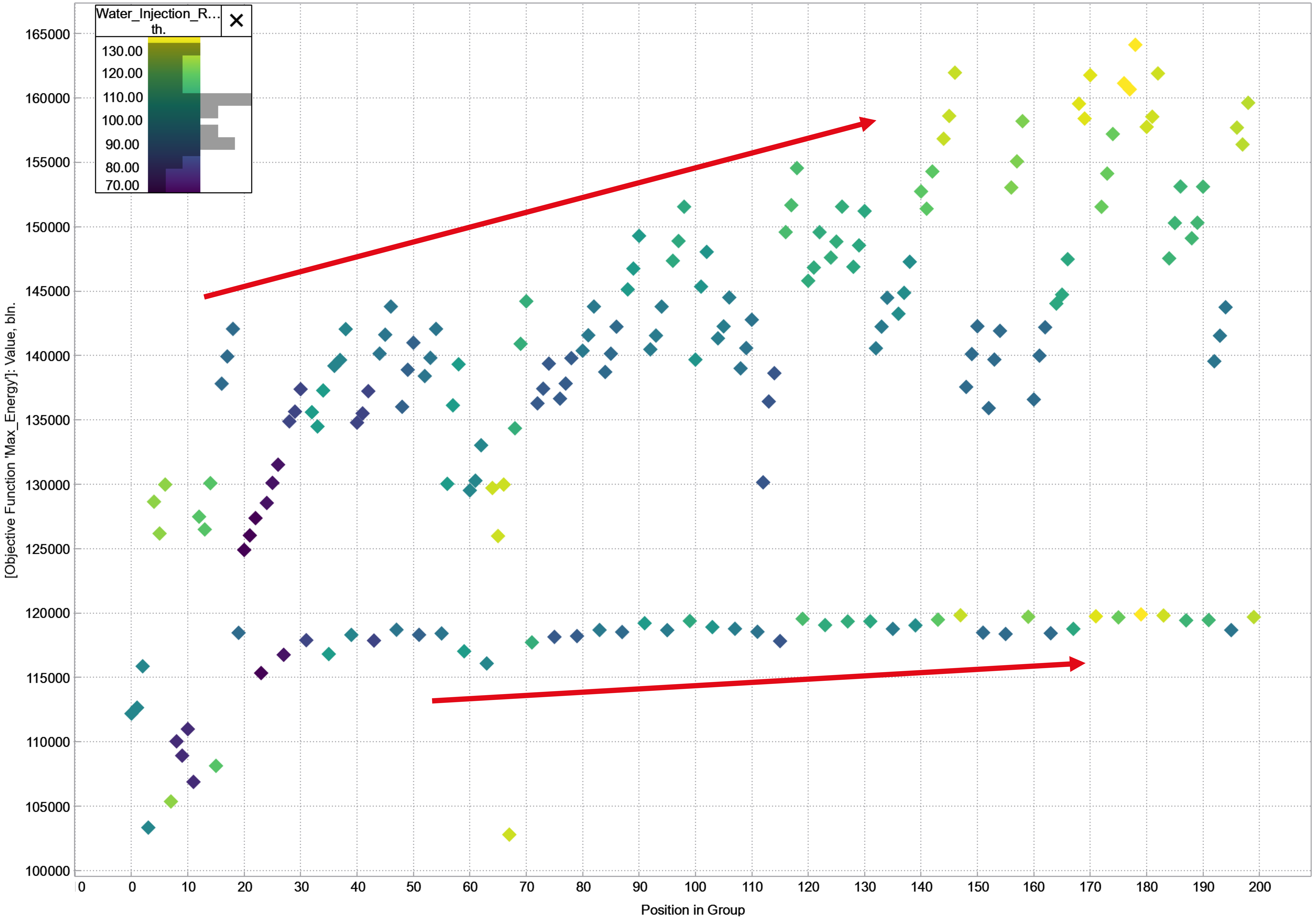
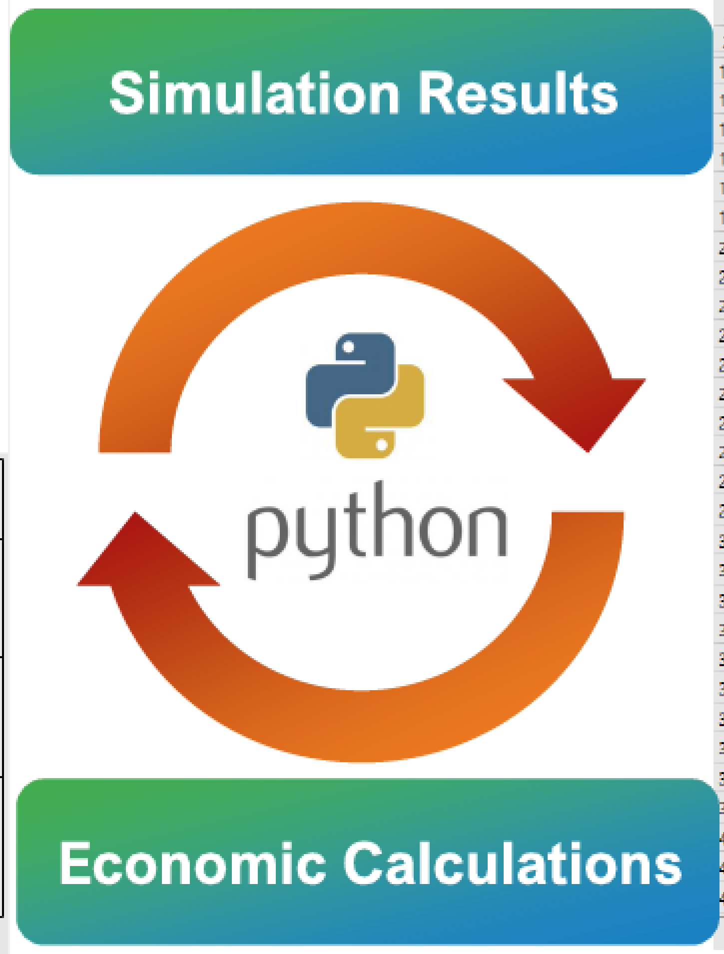
- Increasing initial water production not always influences energy production due to geological reservoir constrains



NPV Calculation

2 vertical wells (closed loop)
4 horizontal wells (doublets)

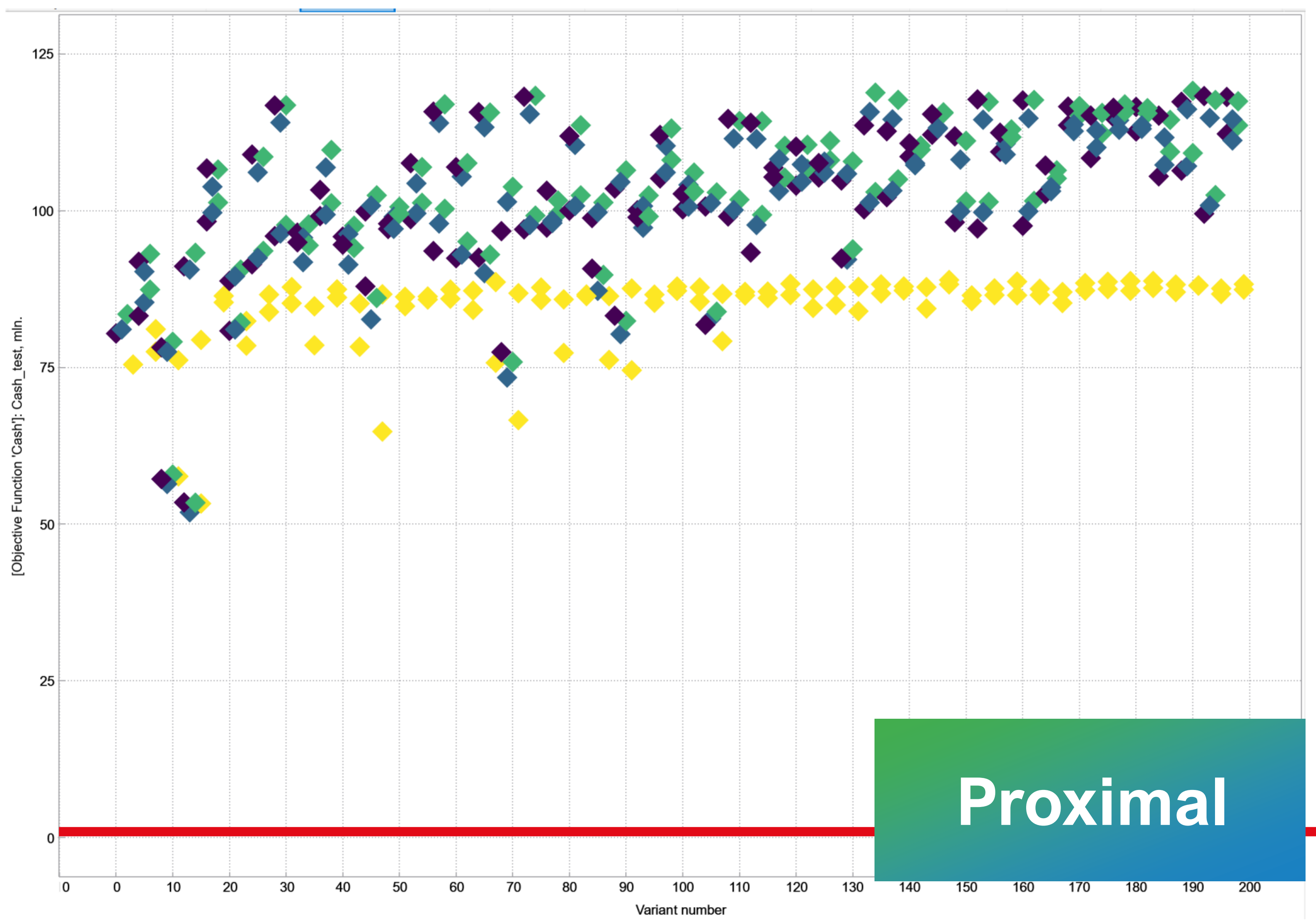
Cost of heating up water
Facility cost based on water capacity
Simplified Optimization on NPV

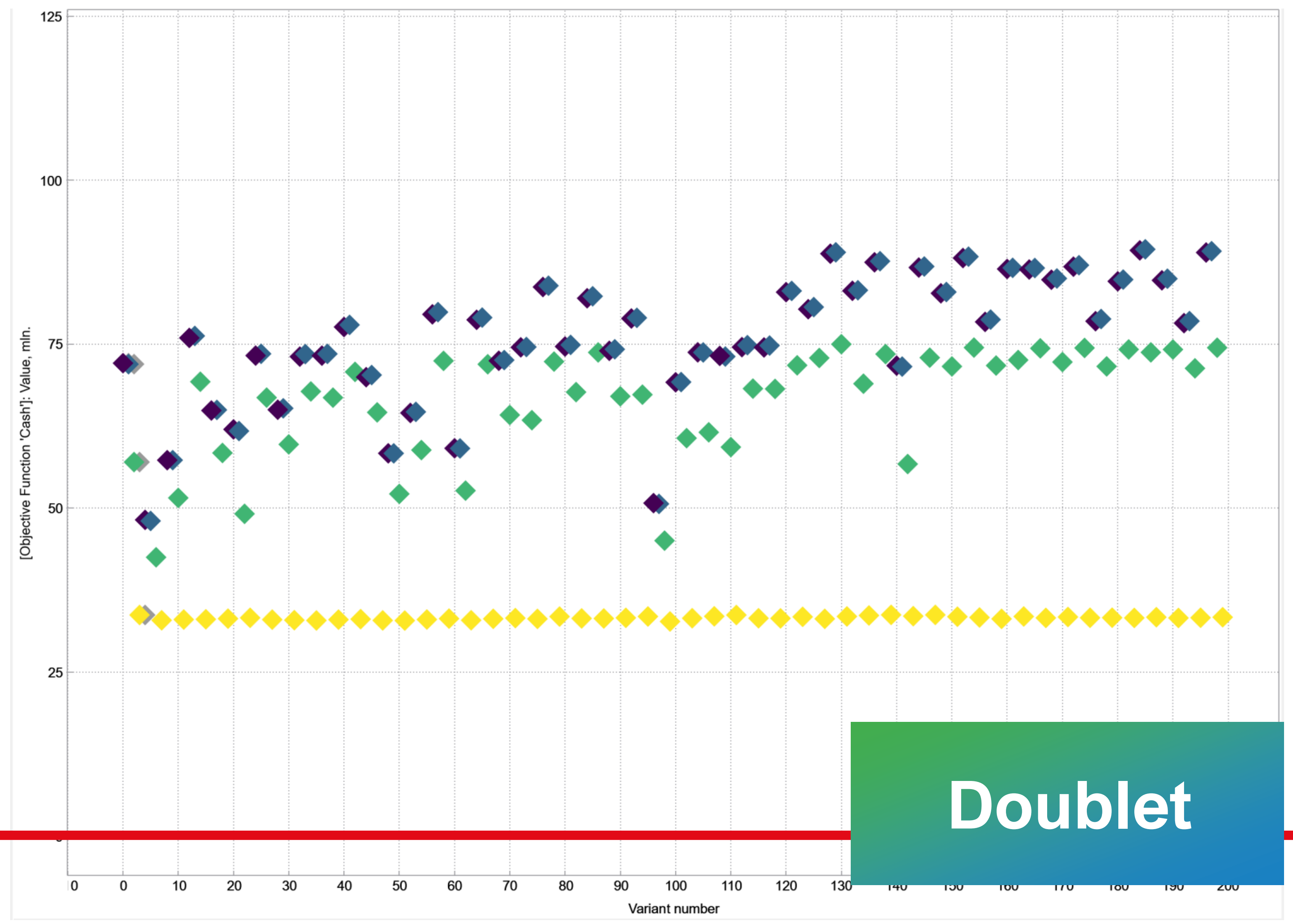


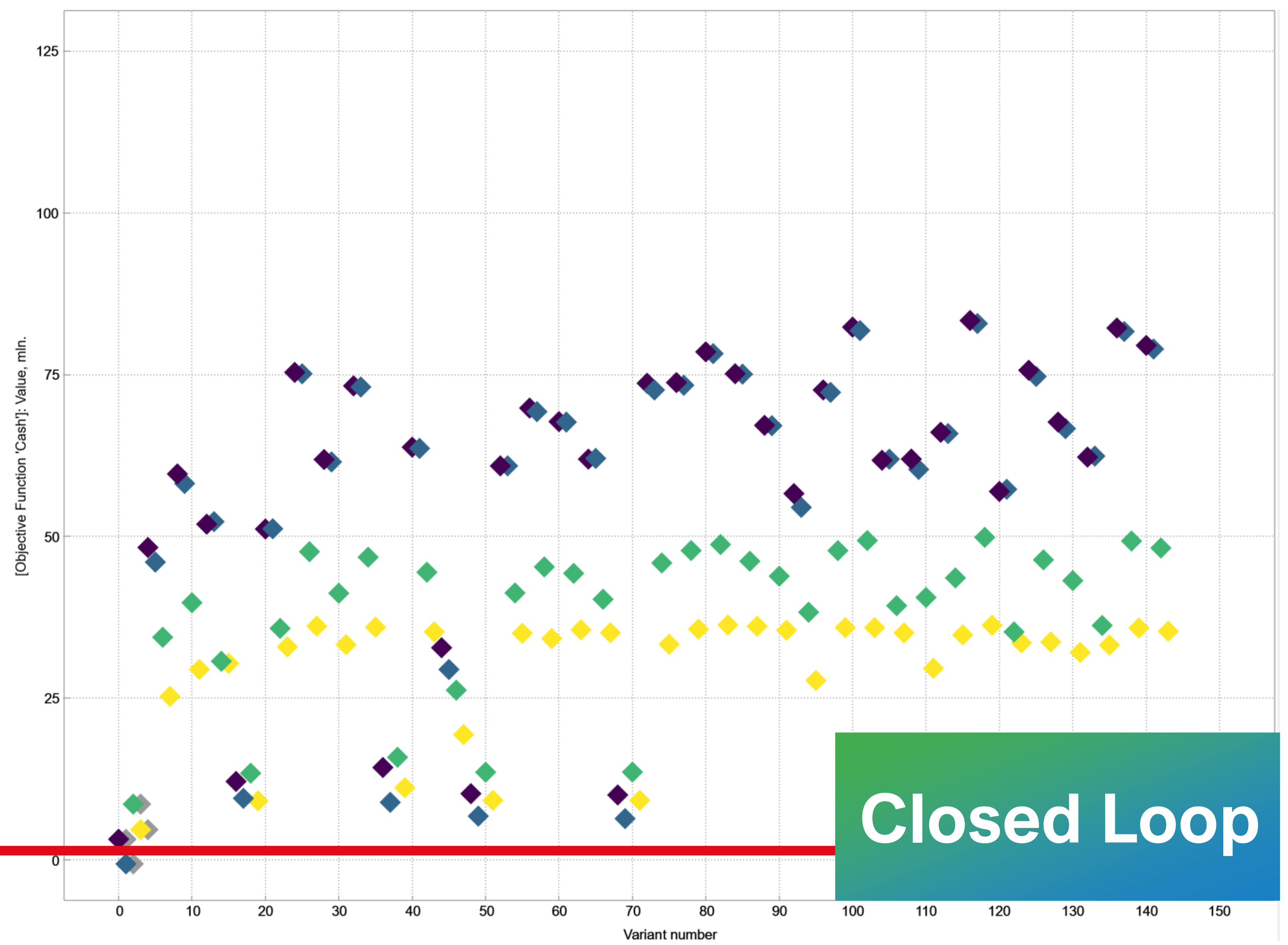
	A	B	C	D	E
2	Parameters	Units	2020	2021	2022
14	Operational Expenses (OPEX)	mln. $	16,365	19,283	22,432
15	- Expense on Liquid Production	mln. $	0,315	0,533	0,982
16	- Expense on Water Injection	mln. $	0,000	0,000	0,000
17	- Wells Maintenance (active wells)	mln. $	4,050	6,750	9,450
18	- Wells Maintenance (inactive wells)	mln. $	0,000	0,000	0,000
19	- Other annual expenses	mln. $	12,000	12,000	12,000
20	Revenue	mln. $	39,563	66,948	114,141
21	Profit before taxes	mln. $	18,698	44,665	88,708
22	Income Tax	mln. $	3,740	8,933	17,742
23	Wealth Tax	mln. $	0,087	0,144	0,198
24	Severance Tax	mln. $	3,956	6,695	11,414
25	Financial Income	mln. $	10,915	28,893	59,355
26	Discount Coefficient	fraction	1,000	0,909	0,826
27	Cash Flow	mln. $	6,415	25,893	56,355
28	Present Value (PV)	mln. $	6,415	23,539	46,574
29	Net Present Value (NPV)	mln. $	6,415	29,954	76,528
30					
31					
32	Incremental Benefits	mln. $	39,563	66,948	114,141
33	Incremental Costs	mln. $	28,798	38,355	55,386
34	Discounted value of incremental benefits	mln. $	39,563	60,862	94,331
35	Discounted value of incremental costs	mln. $	28,798	34,868	45,774
36					
37					
38	Benefit-Cost Ratio (BCR)	fraction	1,436063153		
39	Discounted Profitability Index (DPI)	fraction	9,816975548		
40					
41					
42	Assets Depriciation calculation				

Initial Data | tNav_output | Calculations

NPV Optimization

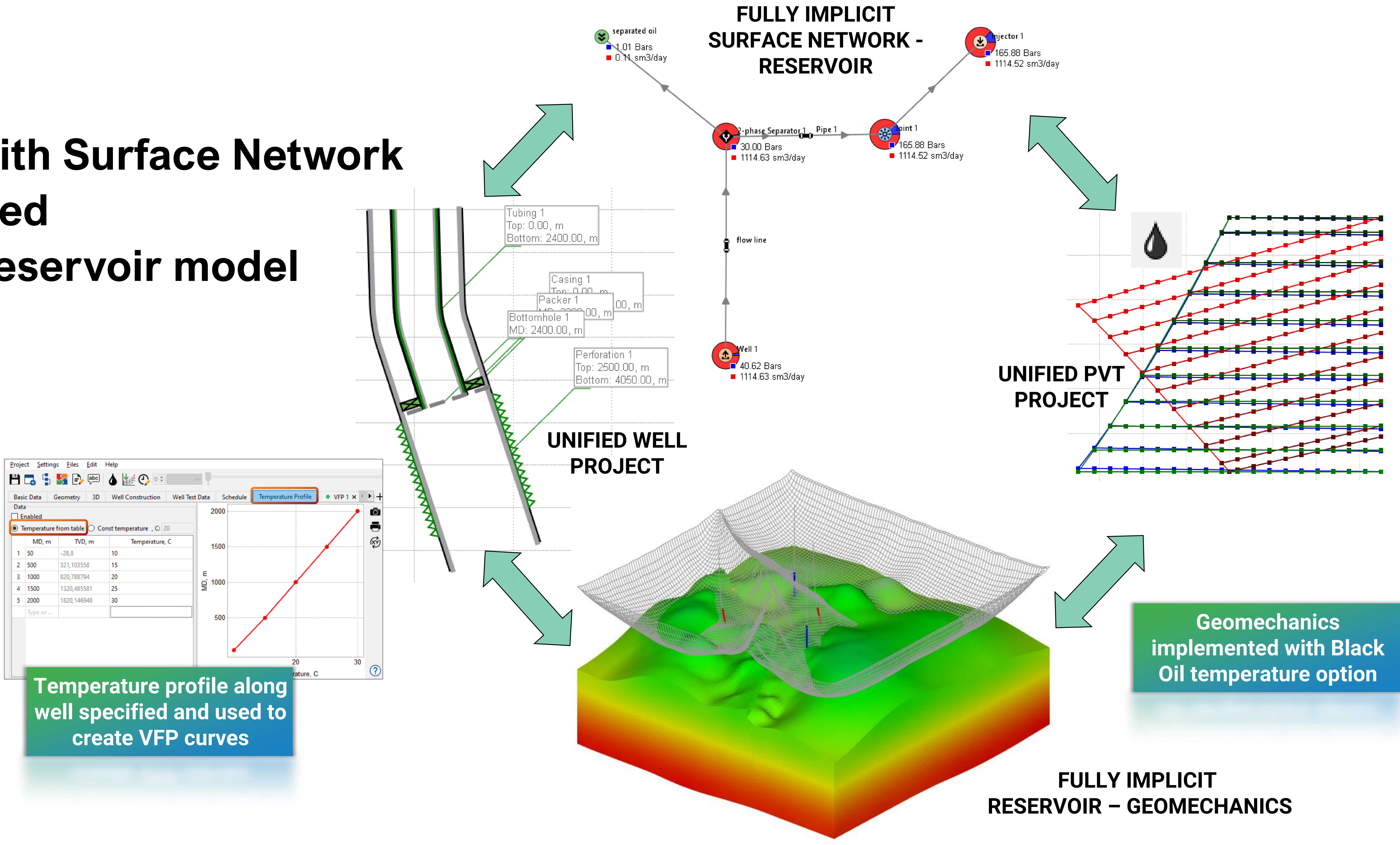






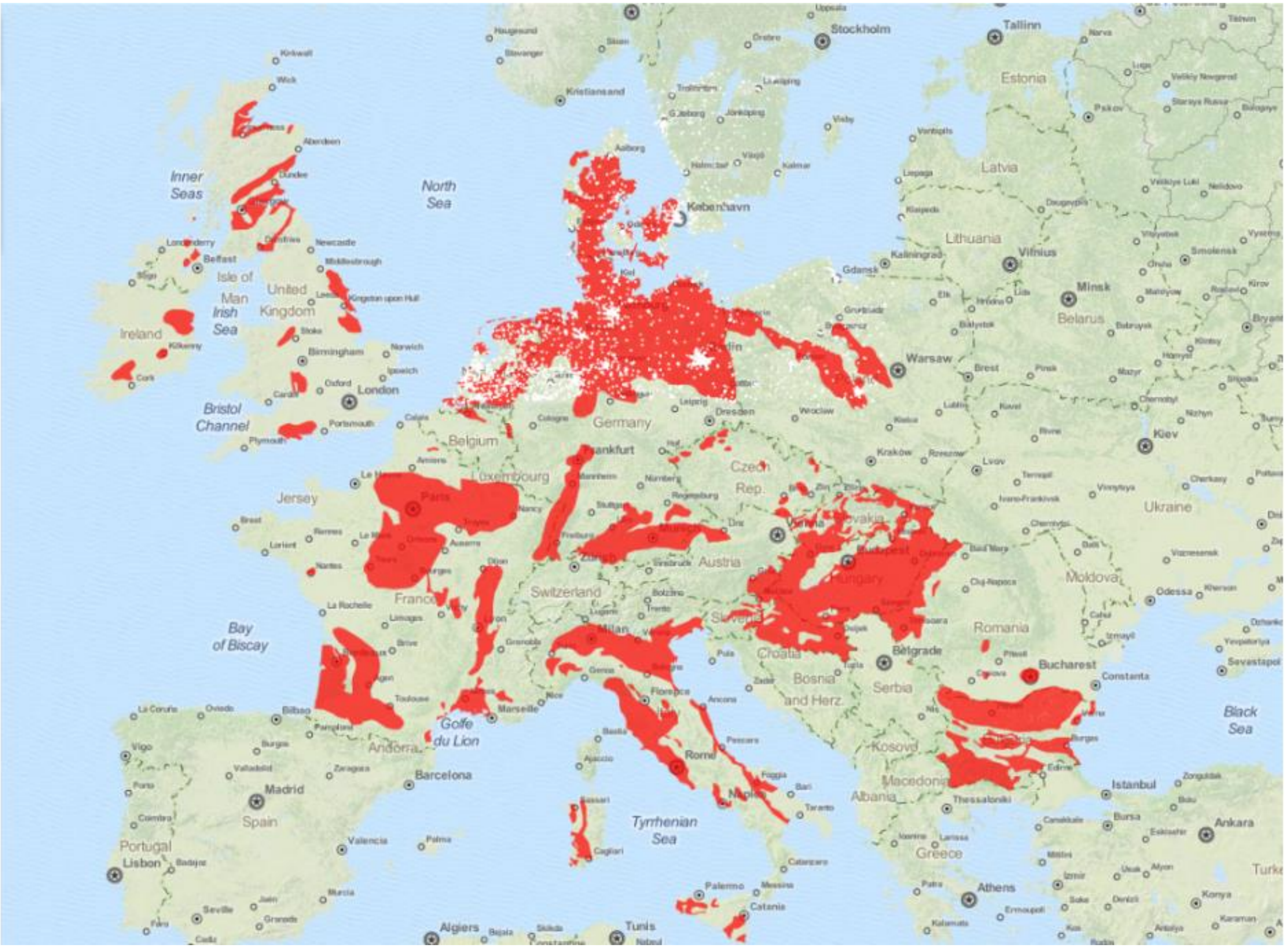
Next Steps…

- **Integration with Surface Network**
- **Fully integrated geothermal reservoir model**



Geothermal Roadmap

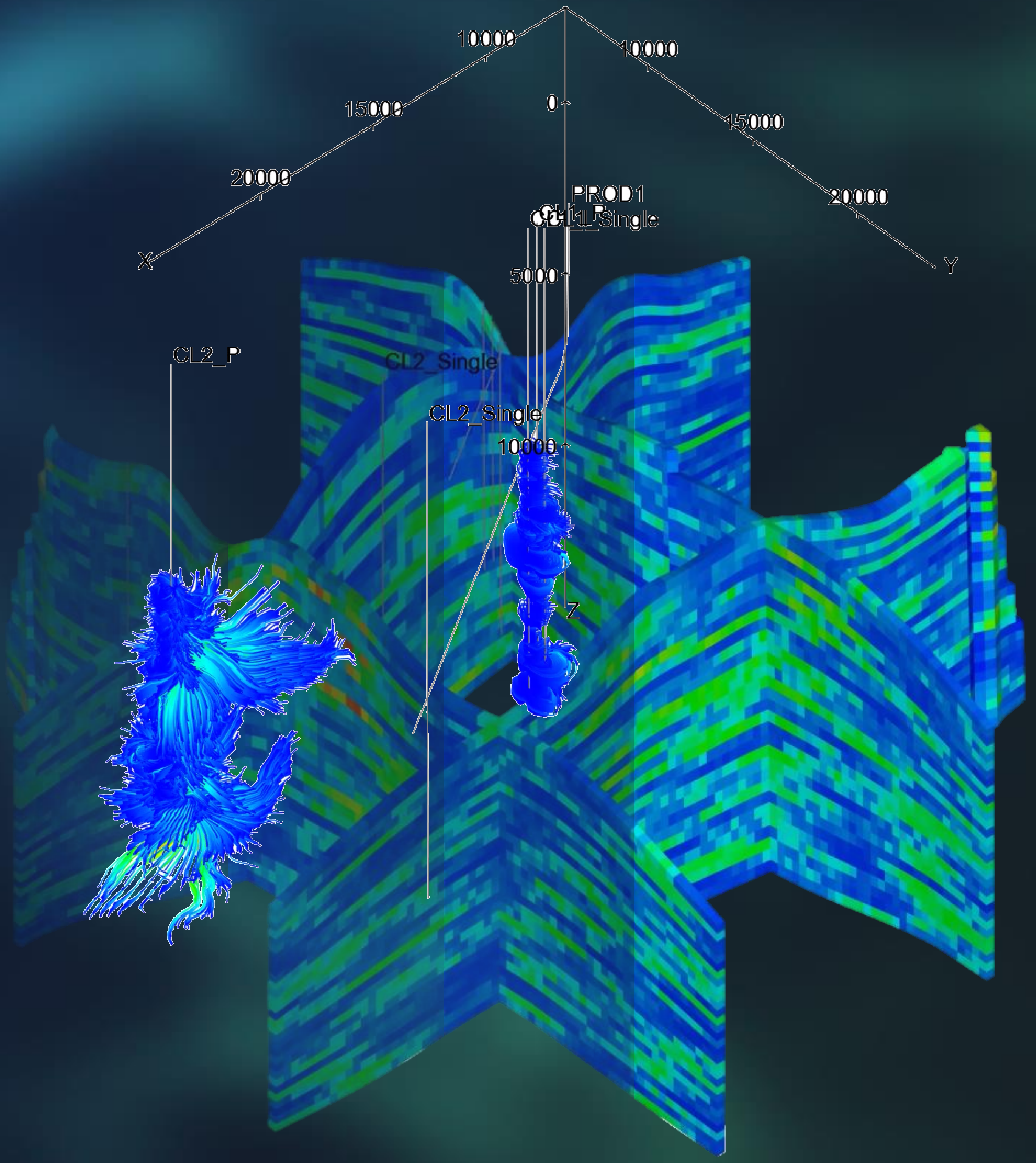
- Thermal demand and (geothermal) district heating potential (2050)
- Current trend for local solutions highlighting need for improved accuracy, forecasting and risk mitigation



Pan-European Thermal Atlas
Heatroadmap.eu

Conclusions

- Novel approach to explore subsurface uncertainties Benchmark uncertainty across all technical disciplines
- Workflow-based optimizing on NPV
- Promotes greater understanding of the system
- Assess the impact of development options with time saving potential
- Updatable over asset life-cycle
- Informed decision making



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