DIAMONDS

Advisory Committee – 23 March 2026

University of Antwerp
GHENT UNIVERSITY
TU Delft
Geological Survey of Belgium

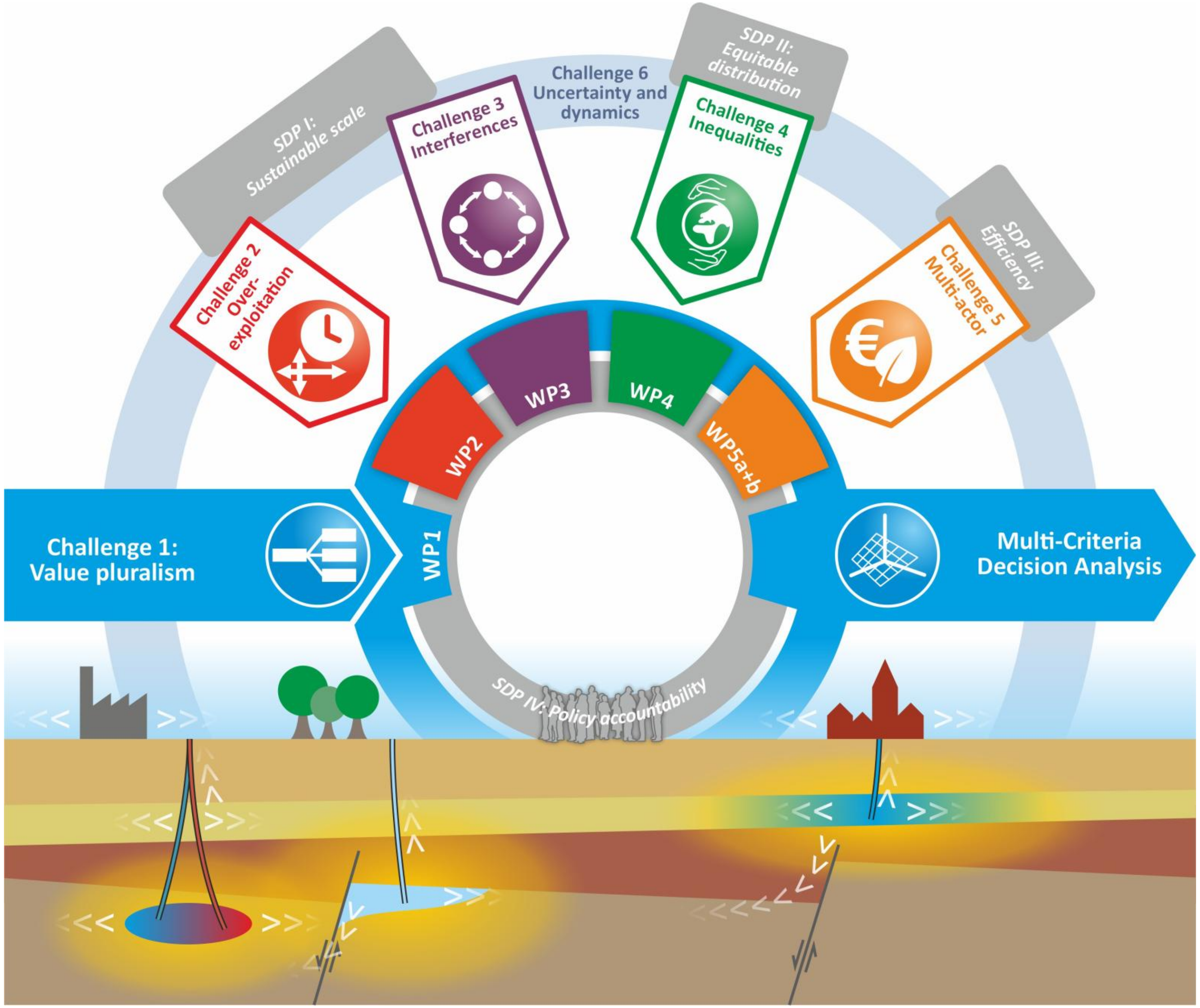
Research funded by
fwo

DIAMONDS
Dynamic Integrated Assessment Methods
for Sustainable Development of the Subsurface

Welcome

Advisory Committee

DIAMONDS


SDP I: Sustainable scale
Challenge 3 Interferences
Challenge 6 Uncertainty and dynamics
SDP II: Equitable distribution
Challenge 4 Inequalities
SDP III: Efficiency
Challenge 2 Over-exploitation
Challenge 5 Multi-actor
WP2
WP3
WP4
WP5a+b
WP1
Challenge 1: Value pluralism
Multi-Criteria Decision Analysis
SDP IV: Policy accountability

Subsurface Multifunctional Use Cases

- Groundwater vs. Aquifer Thermal Energy Storage (ATES)
- Gas storage vs. Deep Geothermal Energy
- Deep Geothermal Energy with multiple doublet systems

Agenda

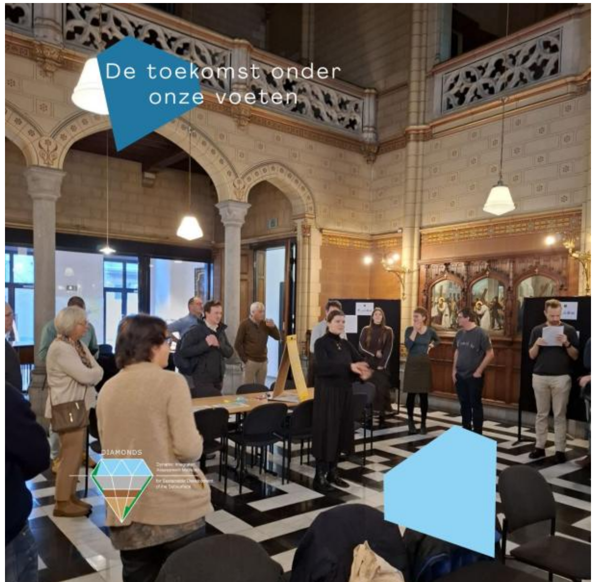
- **08h30 – 09h00** Arrival at VITO, Mol
- **09h00 – 09h05** Welcome & introduction to DIAMONDS
- **09h05 – 09h15** Outreach
- **09h15 – 09h30** WP1: Integrative sustainability framework
- **09h30 – 09h45** WP4: Social impact assessment
- **09h45 – 10h30** WP 2, 3 & 5a: geological & economic impacts of the Deep Subsurface Multifuctional use cases
- **10h30– 10h45** Discussion on the Deep Subsurface Multifunctional use cases
- *10h45– 11h00 Break*
- **11h00 – 11h30** WP 2, 3, 5a & 5b: Geological, economic & environmental impacts of the Shallow Subsurface Development Scenario
- **11h30 – 12h15** An interactive session on the Shallow Subsurface Development Scenario
- **12h15 lunch**
- **13h10 leave for the guided tour (start 13h30)**

Outreach

DIAMONDS
Dynamic Integrated Assessment Methods
for Sustainable Development of the Subsurface

DIAMONDS event 5/12/2025

- Justice
- Subsurface as a public good
- Communication about the subsurface

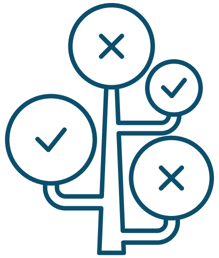


Workshops & Tools

Workshops

Demonstration and hands-on experience with the 'interAcTES' tool

Demonstration of the (Real Options) Game, with a discussion on policy implications



Tools

Application to quickly check (hydrogeologically) the risk of interaction between ATES and drinking water production

Decision tree for ATES developer and groundwater company

Stay informed!

DIAMONDS | sustainable subsurface management

Dynamic Integrated Assessment Methods fOr the sustaiNable Development of the Subsurface

Onderzoeksdiensten · 198 volgers · 11-50 medewerkers

Philippe en 18 andere connecties volgen deze pagina

Bericht sturen | ✓ Aan het volgen

Home | Info | Bijdragen | Vacatures | Personen

University of Antwerp | Login

DYNAMIC INTEGRATED ASSESSMENT METHODS FOR THE SUSTAINABLE DEVELOPMENT OF THE SUBSURFACE

The project | Researchers | Relevant publications | Activities

DIAMONDS

Dynamic Integrated Assessment Methods fOr sustaiNable Development of the Subsurface

Introduction to

DIAMONDS

Dynamic Integrated Assessment Methods for Sustainable Development of the Subsurface

Integrative sustainability framework

WP 1

Hannelore Peeters

WP1 - Aim

1. Define the principles that represent the **value pluralism**, which serve as a basic outline.
2. Combine the knowledge gathered by the other WPs and stakeholders to formulate a **Principles, Criteria & Indicator (PC&I) framework**.

Principles, Criteria & Indicators framework

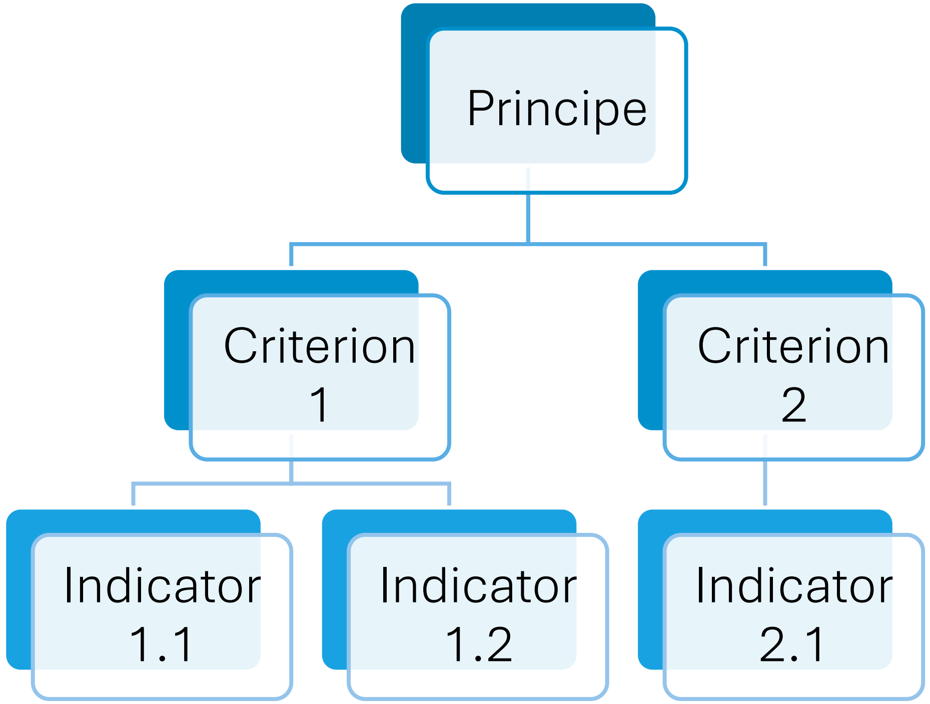
A **hierarchical** framework to **assess the sustainability** of certain economic activities consisting of three hierarchical levels. Here within the context of **ecological economics**, meaning that all economic activities have to take place within the **ecological and social boundaries** (sustainable scale).

WP1 – front end - PC&I

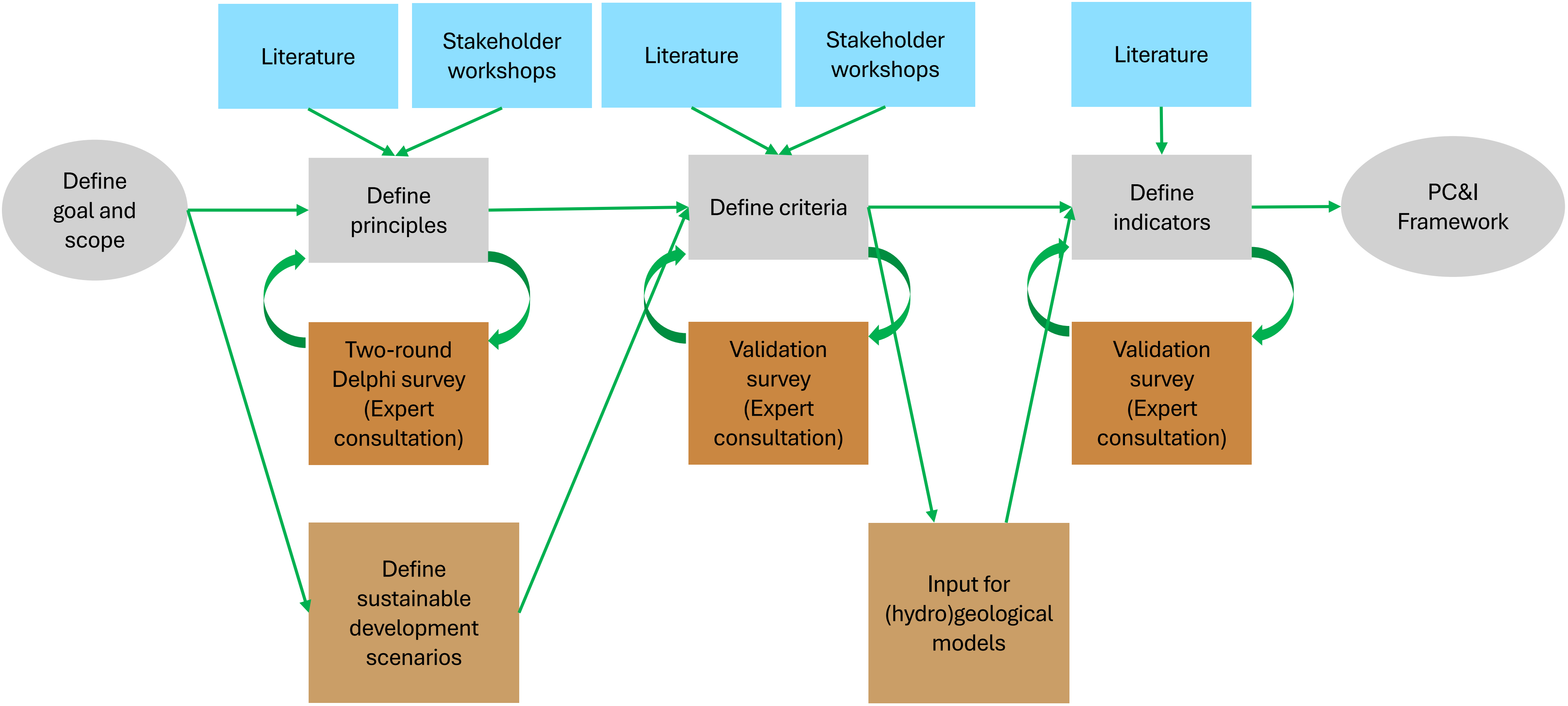
Principle: Universal value that determines sustainability

Criterion: Measurable condition for the level of applicability of the principle; qualitative or quantitative

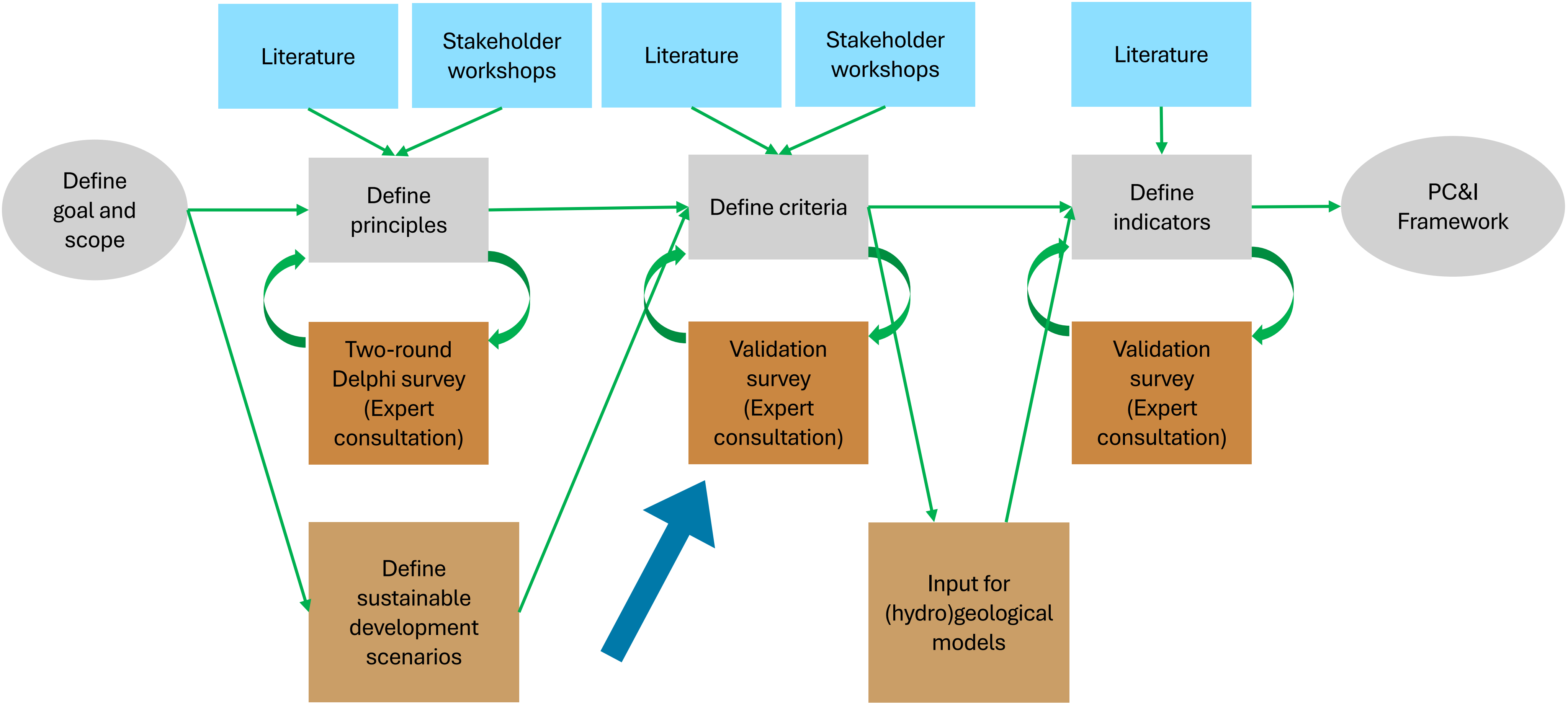
Indicator: Observable expression that describes the characteristics of the real situation using one or more variables to compare to a reference value/benchmark; **qualitative or quantitative**



WP1 – PC&I - schematically



WP1 – PC&I - schematically



WP1 – PC&I - Principles

Determined based on:
- literature review
- two-round Delphi survey of national and international experts
- workshop with Flemish stakeholders

VPO assignment

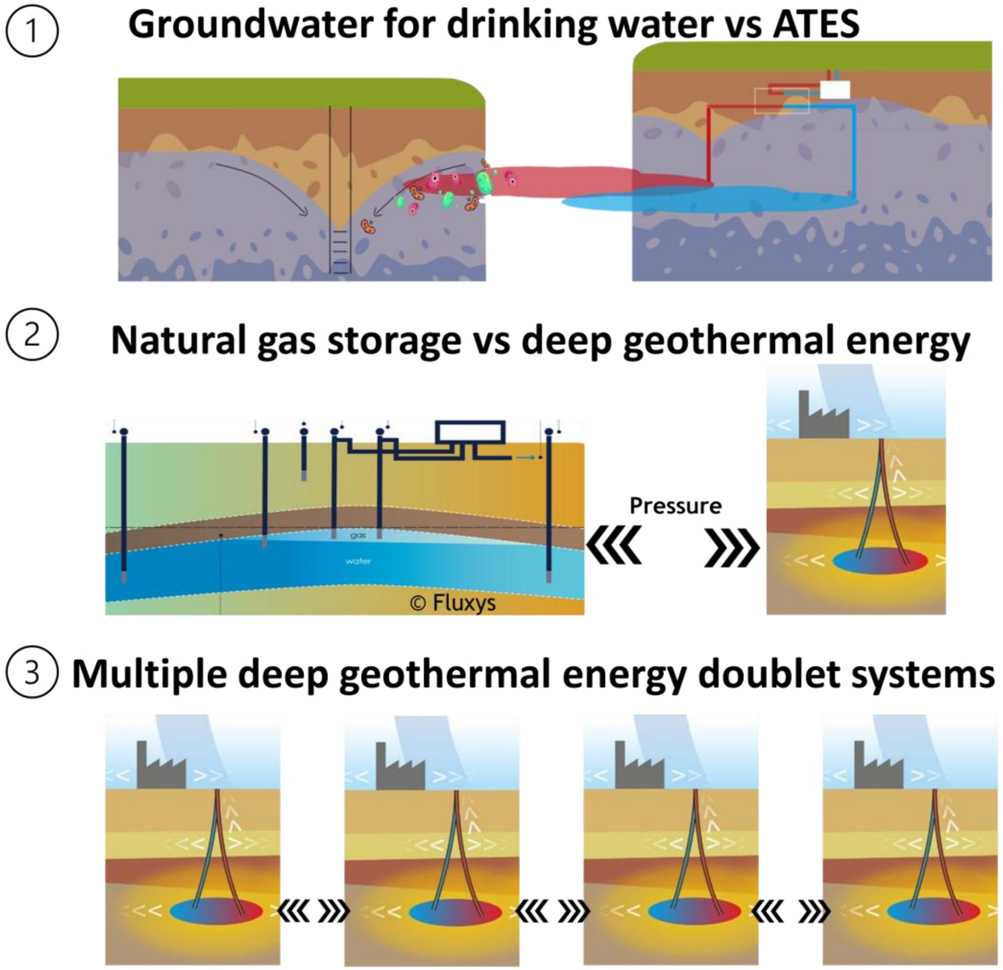
1. Principle of conserving resources and assimilative capacity
2. Principle of efficient allocation
3. Principle of fair (or just) distribution
4. Principle of transparency
5. Principle of inclusive governance
6. Principle of responsible risk management

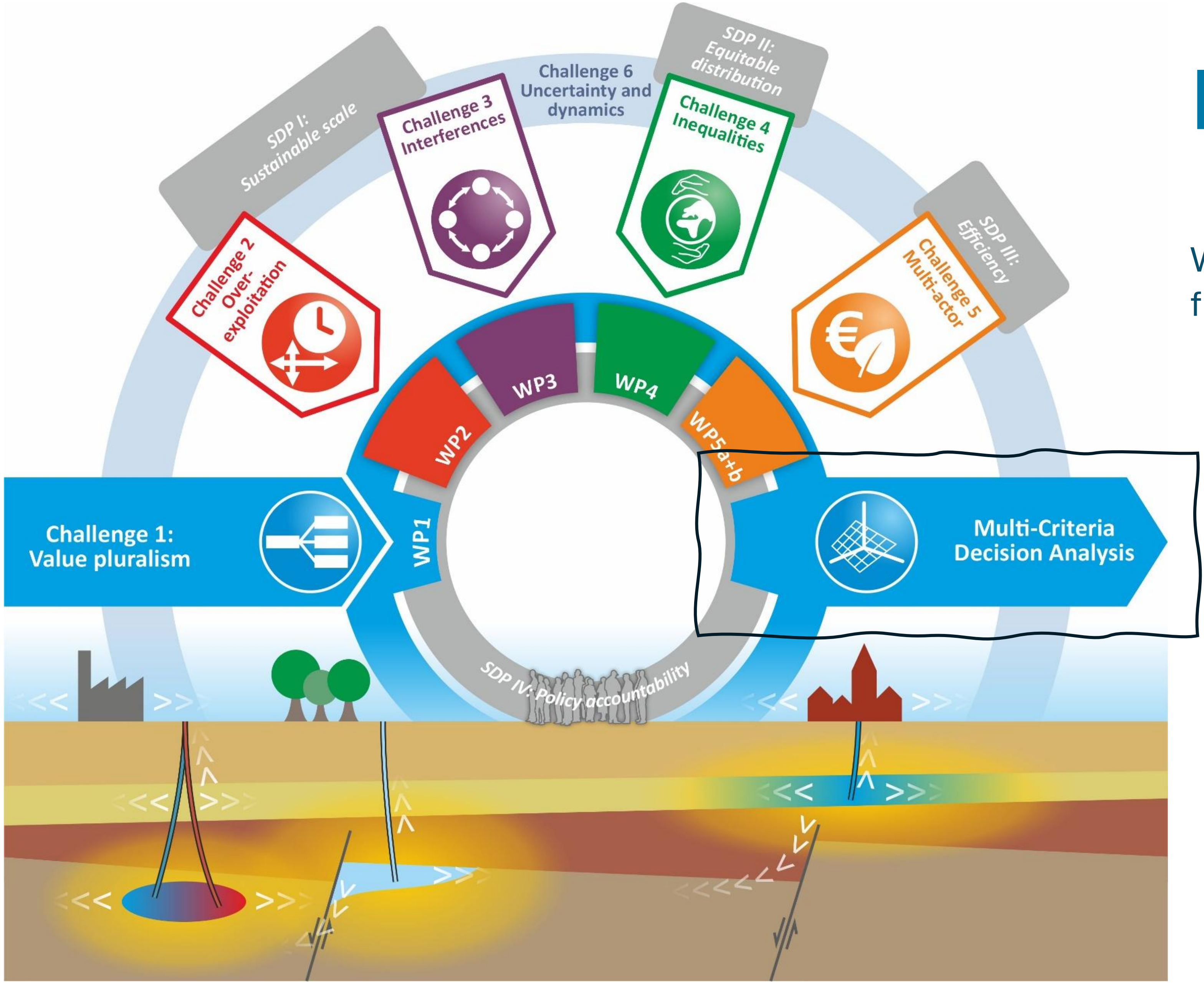
WP1 – PC&I - Update

1. Criteria ATES – GW defined
   - ➢ Validation survey

2. Criteria NS – DGE
   - ➢ Refine
   - ➢ Validation survey

3. Criteria multiple DGE
   - ➢ Define
   - ➢ Refine
   - ➢ Validation survey

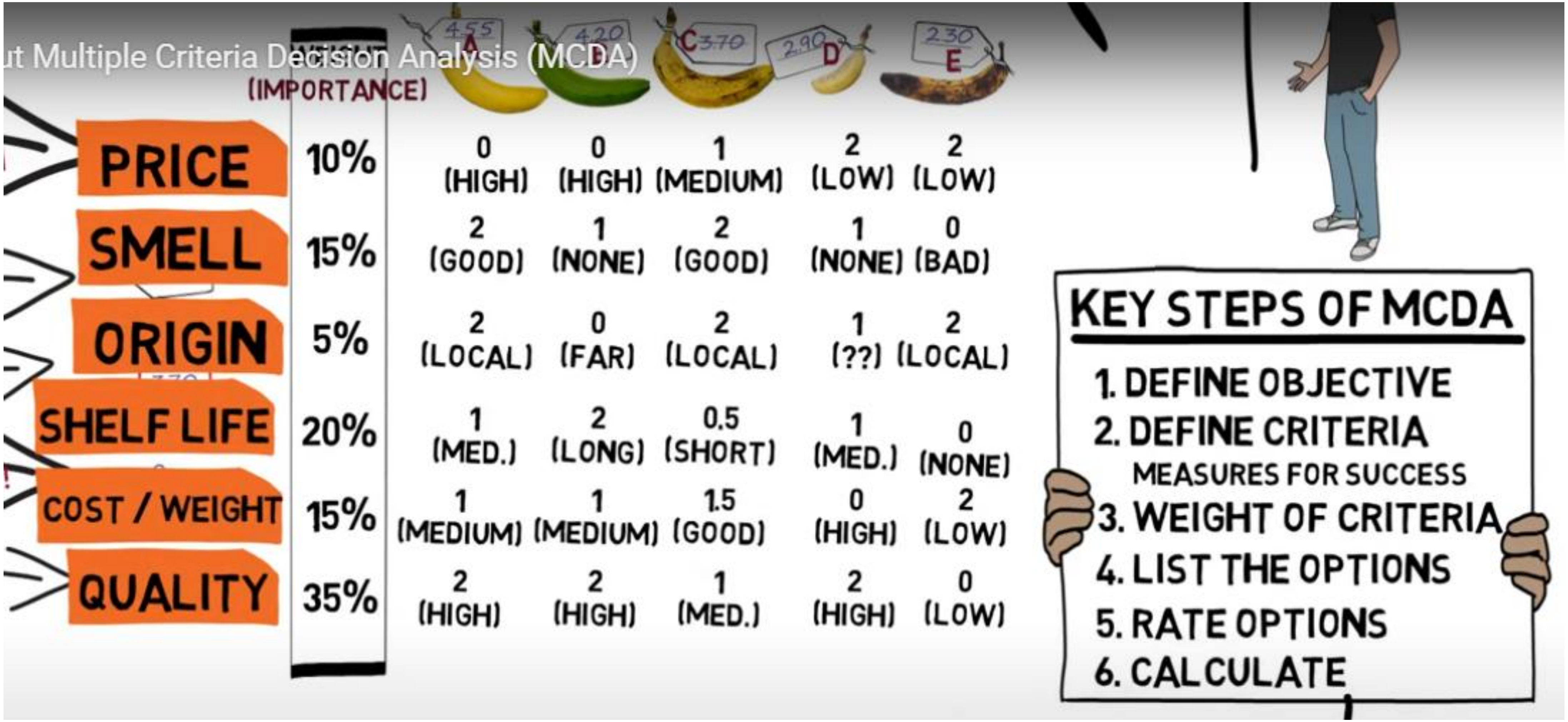




DIAMONDS

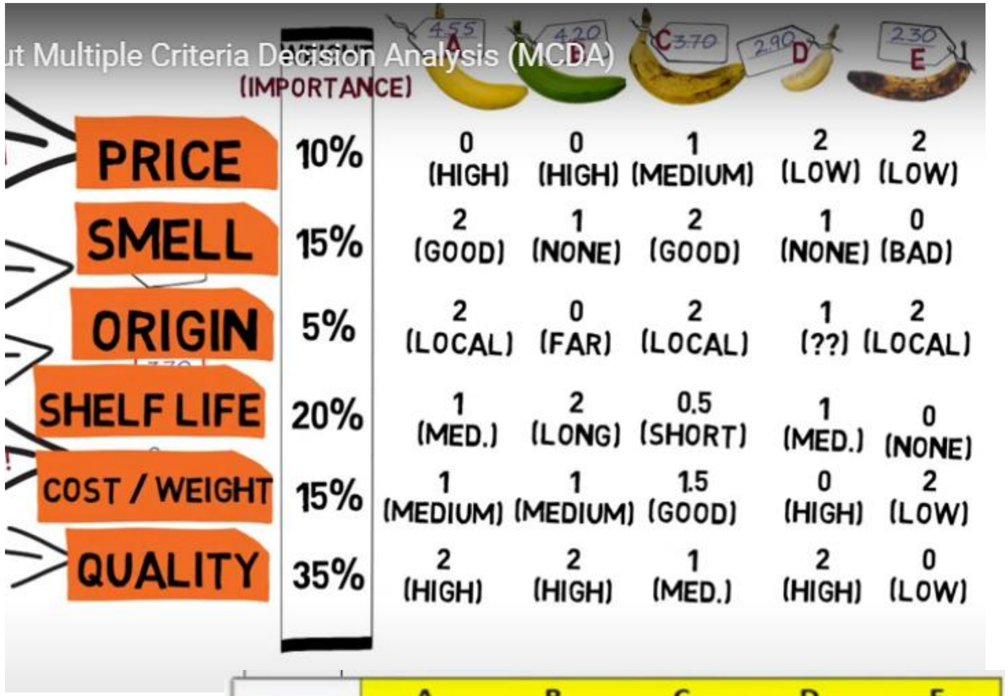
WP1. Integrative sustainability framework

WP1 – back end - MCDA
the banana example



https://youtu.be/7OoKJHvsUbo

WP1 - MCDA – the banana example

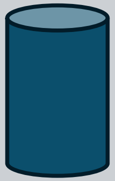
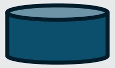
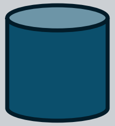


		A	B	C	D	E
PRICE	10%	0.00	0.00	0.10	0.20	0.20
SMELL	20%	0.30	0.15	0.30	0.15	0.00
ORIGIN	5%	0.10	0.00	0.10	0.05	0.10
SHELF LIFE	15%	0.20	0.40	0.50	0.20	0.00
COST / WEIGHT	15%	0.15	0.15	0.23	0.00	0.30
QUALITY	35%	0.70	0.70	0.35	0.70	0.00
Total	100%	1.45	1.40	1.58	1.30	0.60

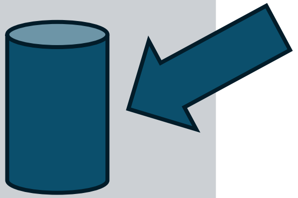
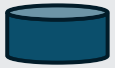
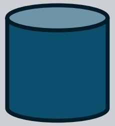
HIGHEST SCORE

https://youtu.be/7OoKJHvsUbo

WP1 - MCDA

Alternative	Principle	Criterion	Indicator value	Weight	Weighted value	Total
1	1 2 3 …	1.1	★	0.a	0.a x ★	
		1.2	●	0.b	0.b x ●	
		…	■	0.c	0.c x ■	
2	1 …	1	…	0.a		
		2	…	0.b		
		3	…	0.c		
3	1 …	1	…	0.a		
		2	…	0.b		
		3	…	0.c		

WP1 - MCDA

Alternative	Principle	Criterion	Indicator value	Weight	Weighted value	Total
1	1 2 3 …	1.1	★	0.a	0.a x ★	
		1.2	●	0.b	0.b x ●	
		…	■	0.c	0.c x ■	
2	1 …	1	…	0.a		
		2	…	0.b		
		3	…	0.c		
3	1 …	1	…	0.a		
		2	…	0.b		
		3	…	0.c		

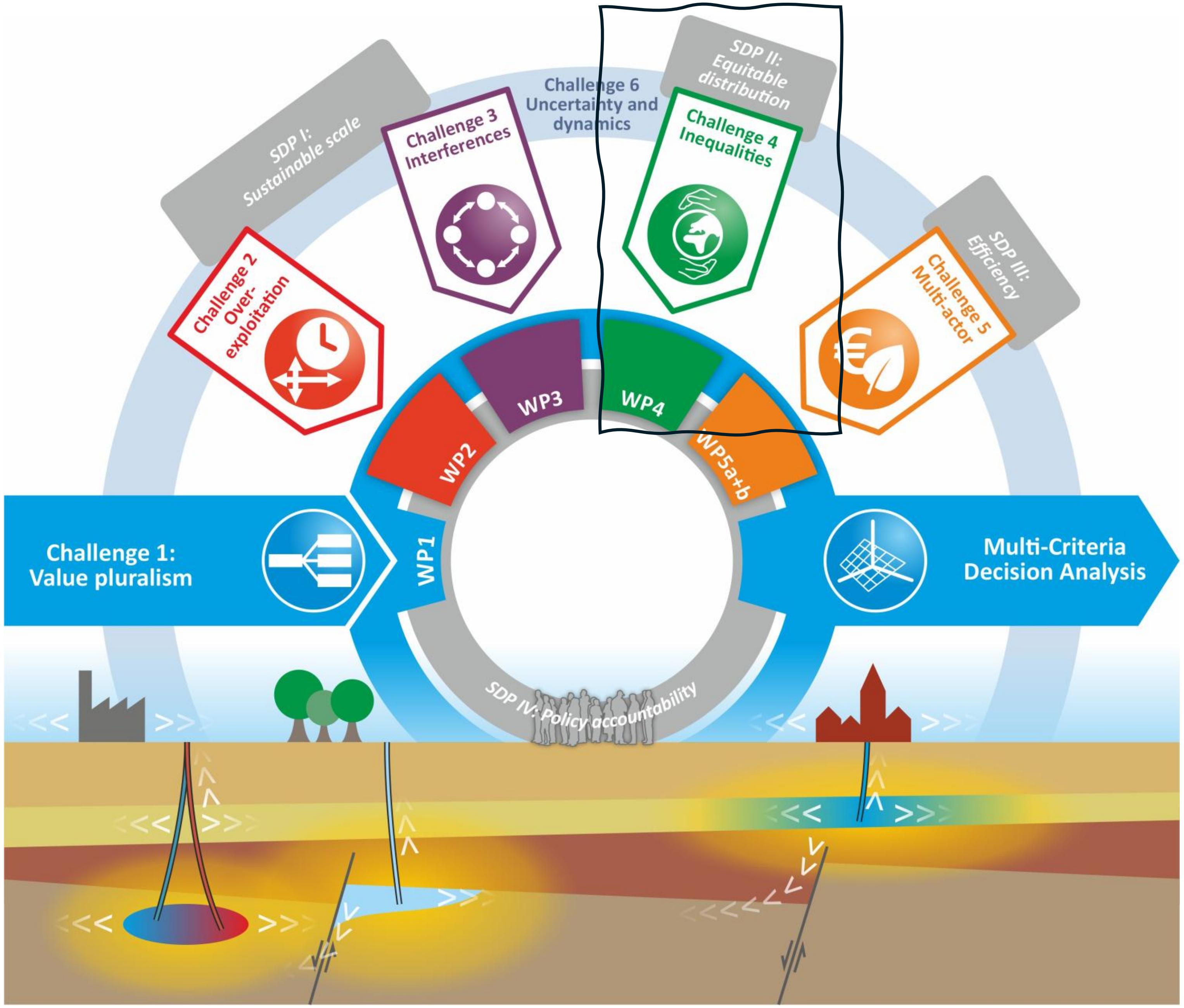
WP1 - MCDA

	Alternative 0	Alternative 1	Alternative 2	Alternative 3
I	Groundwater for drinking water production & ATES	Groundwater for drinking water production & (Air) heat pumps	Surface water for drinking water production & ATES	Surface water for drinking water production & (Air) heat pumps
II	Natural gas storage & Deep geothermal energy (for district heating)	Natural gas storage & Waste burning district heating	Surface natural gas storage & Deep geothermal energy (for district heating)	Surface natural gas storage & Waste burning district heating
III	Deep geothermal energy with multiple doublet systems configuration A	DGE with multiple doublet systems configuration B	(DGE with multiple doublet systems configuration C)	(DGE with multiple doublet systems configuration D)

Social impact assessment

WP 4

Kyra Verbruggen



DIAMONDS

WP4. Social impact assessment

Aim

Determine social indicators and impacts that influence the just use of subsurface resources

Consider a variety of justice dimensions that must be considered for the cases in the Campine Basin

Recognition justice

*"the aim to accept "the **diversity of perspectives and experiences, conflicting interests and socio-cultural characteristics**"" (Thaler & Seebauer, 2025)*

→ Aim: Uncover which values, justice principles and justice recipients are recognized (in which ways) in policy regarding the Flemish subsurface

Research questions

- Which (types of) **values** are recognized in the policy for Flanders' subsurface policy?
- Which **principles of justice** are recognized in the policy for Flanders' subsurface policy?
- Which **recipients of justice** are recognized in the policy for Flanders' subsurface policy?

→ Flemish, Belgian and EU policy

Policy document analysis

54 documents

Flemish, Belgian and European

Legislation, licenses, advice, structural documents – Directives & Regulations

Groundwater, ATES, deep geothermal energy, gas/hydrogen storage, CO_2 storage, nuclear waste disposal

Analysis

Keywords

Matrix of keywords and documents

Degree of discussion; comparison between activities, categories and policy levels; tone of discussion of different categories

Value category	Subsurface use	Flemish / Belgian	EU
Social (excl. safety)	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Economic	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Technical	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Sustainability	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Environmental	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Safety	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Health	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		

Strong presence of keywords representing the value category

Moderate presence of keywords representing the value category

Minimal presence of keywords representing the value category

No presence of keywords representing the value category

Value category	**Subsurface use**	**Flemish / Belgian**	**EU**
Social (excl. safety)	GW	yellow	dark red
	ATES	dark red	grey
	GT	dark red	grey
	Gas	dark red	dark red
	CO_2	dark red	dark red
	Nuclear waste	yellow	dark red
Economic	GW	green	red
	ATES	dark red	grey
	GT	green	grey
	Gas	red	green
	CO_2	green	green
	Nuclear waste	yellow	green
Technical	GW	green	yellow
	ATES	green	grey
	GT	green	grey
	Gas	red	green
	CO_2	green	green
	Nuclear waste	green	green
Sustainability	GW	yellow	dark red
	ATES	dark red	grey
	GT	yellow	grey
	Gas	dark red	dark red
	CO_2	dark red	dark red
	Nuclear waste	dark red	red
Environmental	GW	green	green
	ATES	red	grey
	GT	yellow	grey
	Gas	dark red	dark red
	CO_2	green	green
	Nuclear waste	yellow	yellow
Safety	GW	yellow	red
	ATES	yellow	grey
	GT	yellow	grey
	Gas	green	yellow
	CO_2	green	green
	Nuclear waste	green	green
Health	GW	yellow	green
	ATES	dark red	grey
	GT	dark red	grey
	Gas	dark red	dark red
	CO_2	yellow	green
	Nuclear waste	dark red	yellow

Winners?

"*They shall **not unduly distort competition or the proper functioning of the internal market** in gas*" (Regulation (EU) 2022/1032)

"*Overwegende dat de aanvrager voldoende aangetoond heeft deels **over de nodige technische mogelijkheden te beschikken***" (Opsporingsvergunning aardwarmte Janssen Pharmaceutica nv, Beerse)

*Vergunningsaanvragen [worden] beoordeeld op basis van de volgende criteria: de overeenkomstig artikel 39 verkregen resultaten (…) uit **de beoordeling van de verwachte veiligheid van opslag**"* (Decreet Diepe Ondergrond)

- (green) Strong presence of keywords representing the value category
- (yellow) Moderate presence of keywords representing the value category
- (red) Minimal presence of keywords representing the value category
- (dark red) No presence of keywords representing the value category

Losers?

Value category	Subsurface use	Flemish / Belgian	EU
Social (excl. safety)	GW	Yellow	Dark red
	ATES	Dark red	Grey
	GT	Dark red	Grey
	Gas	Dark red	Dark red
	CO_2	Dark red	Dark red
	Nuclear waste	Yellow	Dark red
Economic	GW	Green	Red
	ATES	Dark red	Grey
	GT	Green	Grey
	Gas	Red	Green
	CO_2	Green	Green
	Nuclear waste	Yellow	Green
Technical	GW	Green	Yellow
	ATES	Green	Grey
	GT	Green	Grey
	Gas	Red	Green
	CO_2	Green	Green
	Nuclear waste	Green	Green
Sustainability	GW	Yellow	Dark red
	ATES	Dark red	Grey
	GT	Yellow	Grey
	Gas	Dark red	Dark red
	CO_2	Dark red	Dark red
	Nuclear waste	Dark red	Red
Environmental	GW	Green	Green
	ATES	Red	Grey
	GT	Yellow	Grey
	Gas	Dark red	Dark red
	CO_2	Green	Green
	Nuclear waste	Yellow	Yellow
Safety	GW	Yellow	Red
	ATES	Yellow	Grey
	GT	Yellow	Grey
	Gas	Green	Yellow
	CO_2	Green	Green
	Nuclear waste	Green	Green
Health	GW	Yellow	Green
	ATES	Dark red	Grey
	GT	Dark red	Grey
	Gas	Dark red	Dark red
	CO_2	Yellow	Green
	Nuclear waste	Dark red	Yellow

- Green: Strong presence of keywords representing the value category
- Yellow: Moderate presence of keywords representing the value category
- Red: Minimal presence of keywords representing the value category
- Dark red: No presence of keywords representing the value category

Principle of justice

Principle of justice	Subsurface use	Flemish / Belgian	EU
Justice in general	GW	red	dark red
	ATES	dark red	grey
	GT	yellow	grey
	Gas	dark red	red
	CO_2	red	red
	Nuclear waste	red	yellow
Distributional	GW	yellow	yellow
	ATES	red	grey
	GT	yellow	grey
	Gas	yellow	green
	CO_2	yellow	yellow
	Nuclear waste	yellow	yellow
Procedural	GW	yellow	red
	ATES	dark red	grey
	GT	red	grey
	Gas	dark red	yellow
	CO_2	red	red
	Nuclear waste	green	green
Recognition	GW	dark red	red
	ATES	dark red	grey
	GT	dark red	grey
	Gas	dark red	red
	CO_2	dark red	red
	Nuclear waste	dark red	dark red
Ecological	GW	yellow	green
	ATES	dark red	grey
	GT	dark red	grey
	Gas	dark red	dark red
	CO_2	yellow	red
	Nuclear waste	dark red	dark red
Intergenerational	GW	dark red	red
	ATES	dark red	grey
	GT	red	grey
	Gas	dark red	dark red
	CO_2	yellow	yellow
	Nuclear waste	yellow	yellow
Deep time	GW	dark red	red
	ATES	dark red	grey
	GT	red	grey
	Gas	dark red	dark red
	CO_2	yellow	yellow
	Nuclear waste	yellow	yellow

- Green: Strong presence of keywords indicating the justice principle
- Yellow: Moderate presence of keywords or evidence of the principle in a limited and/or partial interpretation
- Red: Minimal presence of keywords or only a very narrow interpretation of the principle
- Dark red: No presence of keywords indicating the justice principle

Principle of justice	Subsurface use	Flemish / Belgian	EU
Justice in general	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Distributional	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Procedural	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Recognition	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Ecological	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Intergenerational	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Deep time	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		

Winners?

*"(…) without putting a **disproportionate burden** on Member States, gas market participants, storage system operators or consumers"* (Regulation (EU) 2022/1032)

*"(…) door met name **deliberatieve processen of representatieve panels** samengesteld uit experten en burgers"* (Koninklijk Besluit Nationale Beleidsmaatregel, 2022)

*"taking into account the likelihood of adverse **effects on associated aquatic ecosystems or dependent terrestrial ecosystems**"* (Directive (2006/118/EC))

- Strong presence of keywords indicating the justice principle
- Moderate presence of keywords or evidence of the principle in a limited and/or partial interpretation
- Minimal presence of keywords or only a very narrow interpretation of the principle
- No presence of keywords indicating the justice principle

Principle of justice	Subsurface use	Flemish / Belgian	EU
Justice in general	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Distributional	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Procedural	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Recognition	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Ecological	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Intergenerational	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		
Deep time	GW		
	ATES		
	GT		
	Gas		
	CO_2		
	Nuclear waste		

Losers?

Strong presence of keywords indicating the justice principle

Moderate presence of keywords or evidence of the principle in a limited and/or partial interpretation

Minimal presence of keywords or only a very narrow interpretation of the principle

No presence of keywords indicating the justice principle

Discussion points

- Distributional paradigm → narrowed down to (financial) costs and compensations
- No other justice principles structurally recognized
- Dominance of technical aspects <-> absence of soci(et)al aspects (except safety)
- Concrete language (technical aspects) vs. vague / ideological language (justice)
- Long-term aspects remain vague

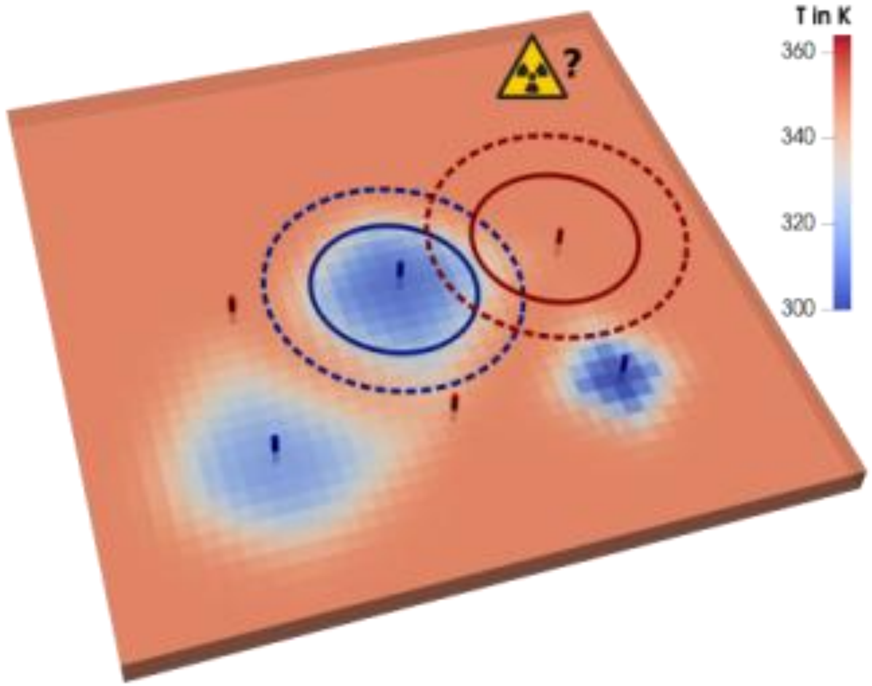
Multifunctional Use Case in the Deep Subsurface

Geological & economic impacts

DIAMONDS

Dynamic Integrated Assessment Methods

for Sustainable Development of the Subsurface

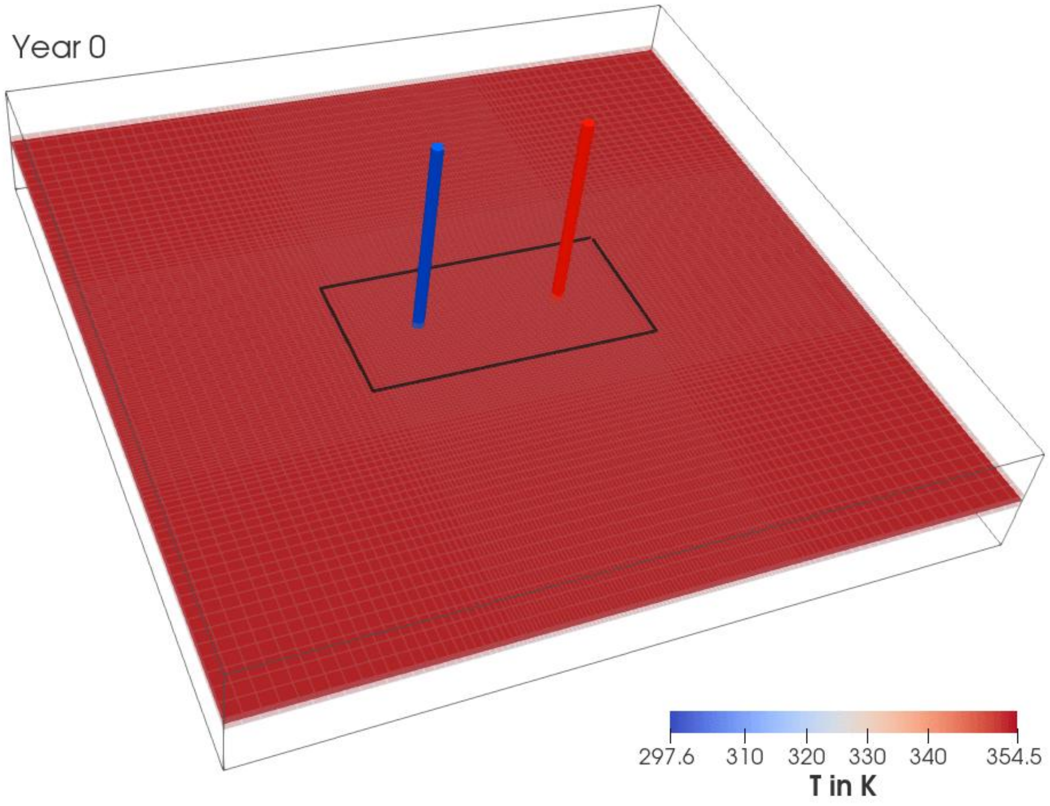


Deep Subsurface

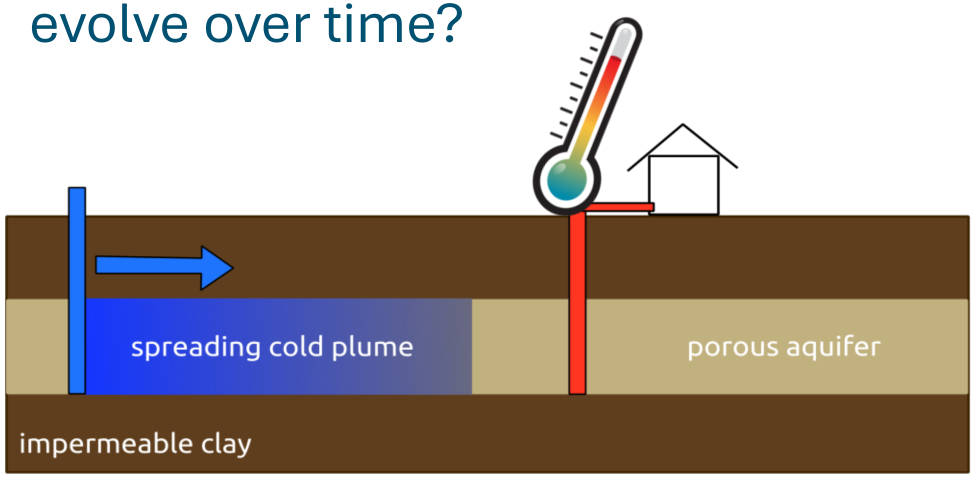
WP 2: Impacts of individual systems

Carolin Wallmeier

How long does DGE affect the subsurface?

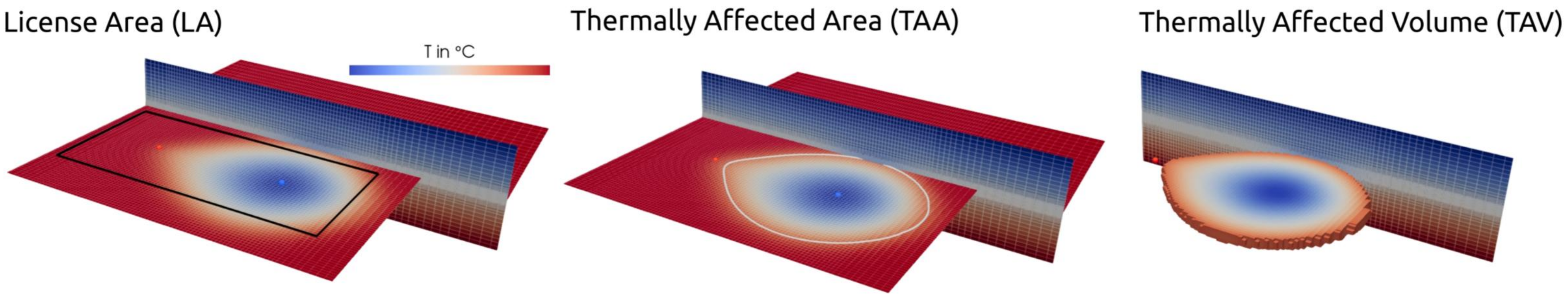


How does production temperature evolve over time?



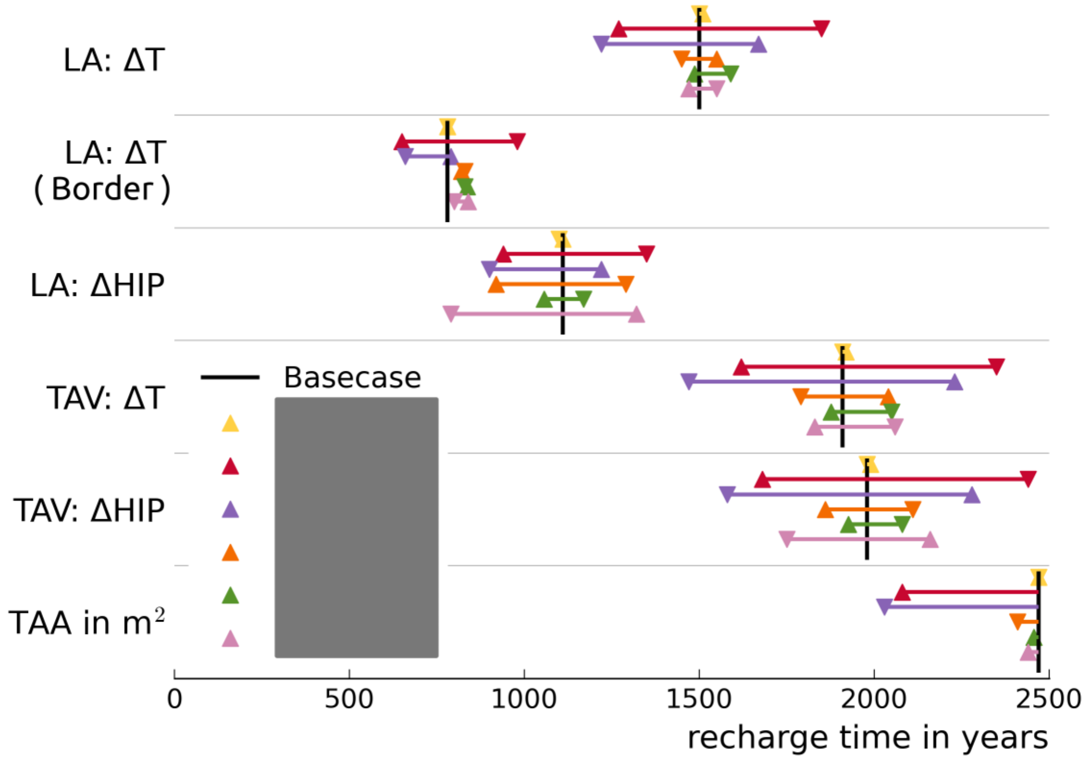
DGE – Recharge of the subsurface

- Step 1: Define "thermally recharged"



DGE – Recharge of the subsurface

- Step 2: Simulate recharge



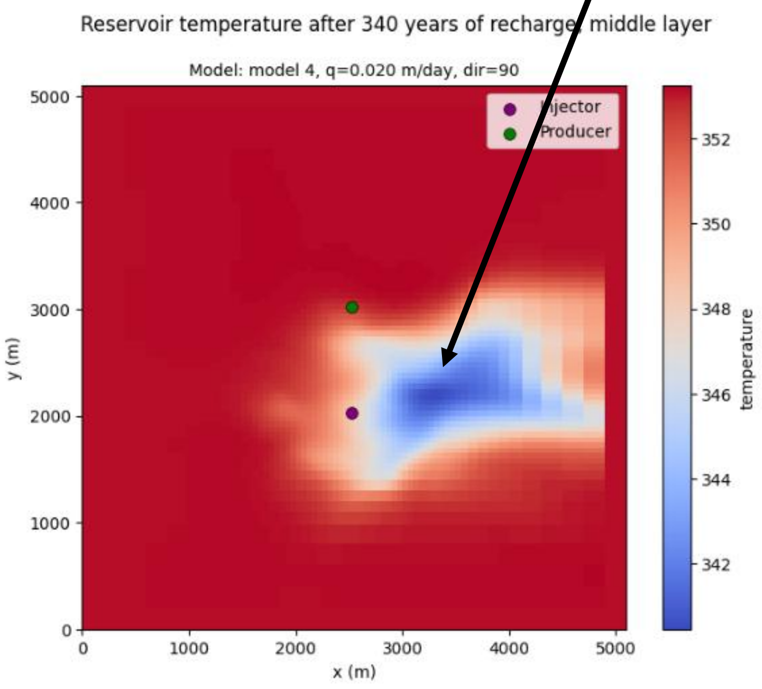
<u>The answer:</u>
It depends.
But long.

<u>The long answer:</u>
Wallmeier, Vardon, Daniilidis:
A lingering cold – Thermal recharge of geothermal systems after production stop.
Proceedings of the European Geothermal Workshop (2025)

DGE – Recharge of the subsurface

- Step 3: Heterogeneity and groundwater flow

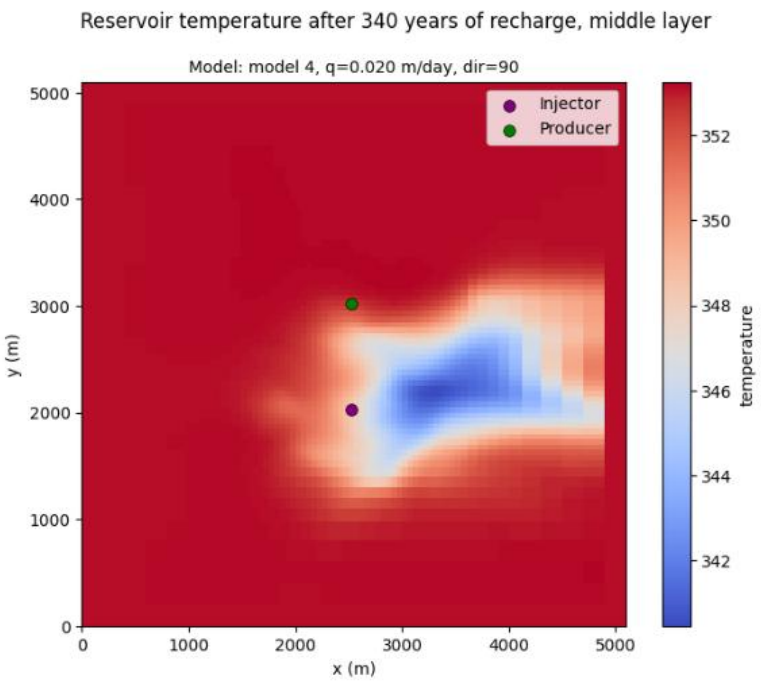
Cold plume has drifted



K. E. Abildgaard, M. Sc. project 2026

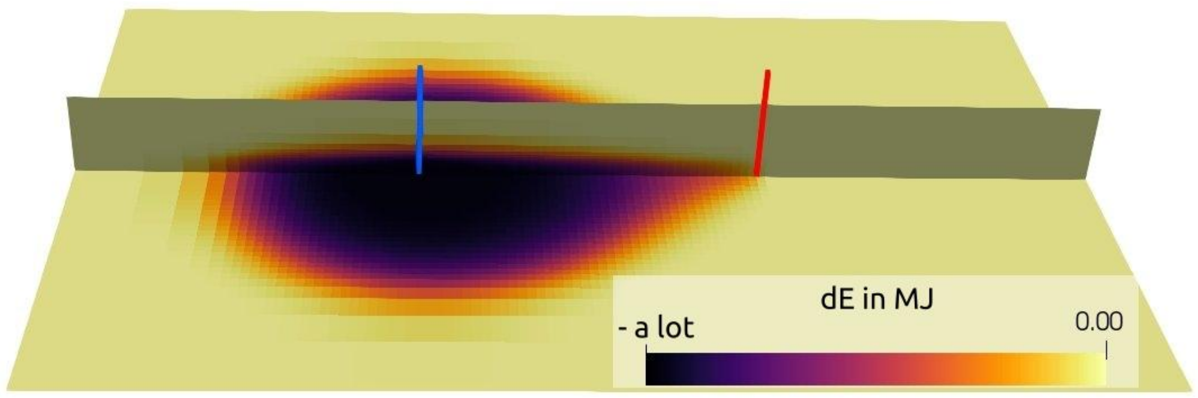
DGE – Recharge of the subsurface

- Step 3: Heterogeneity and groundwater flow



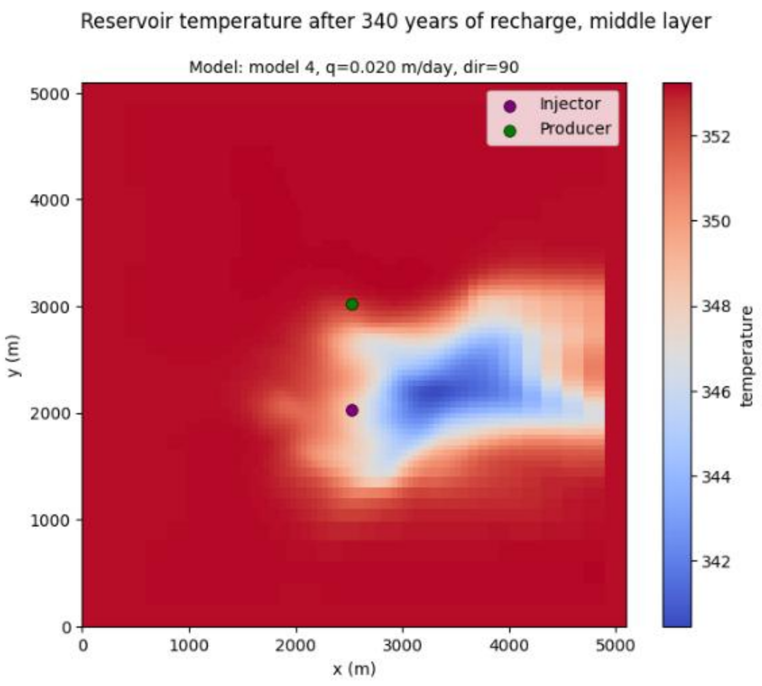
K. E. Abildgaard, M. Sc. project 2026

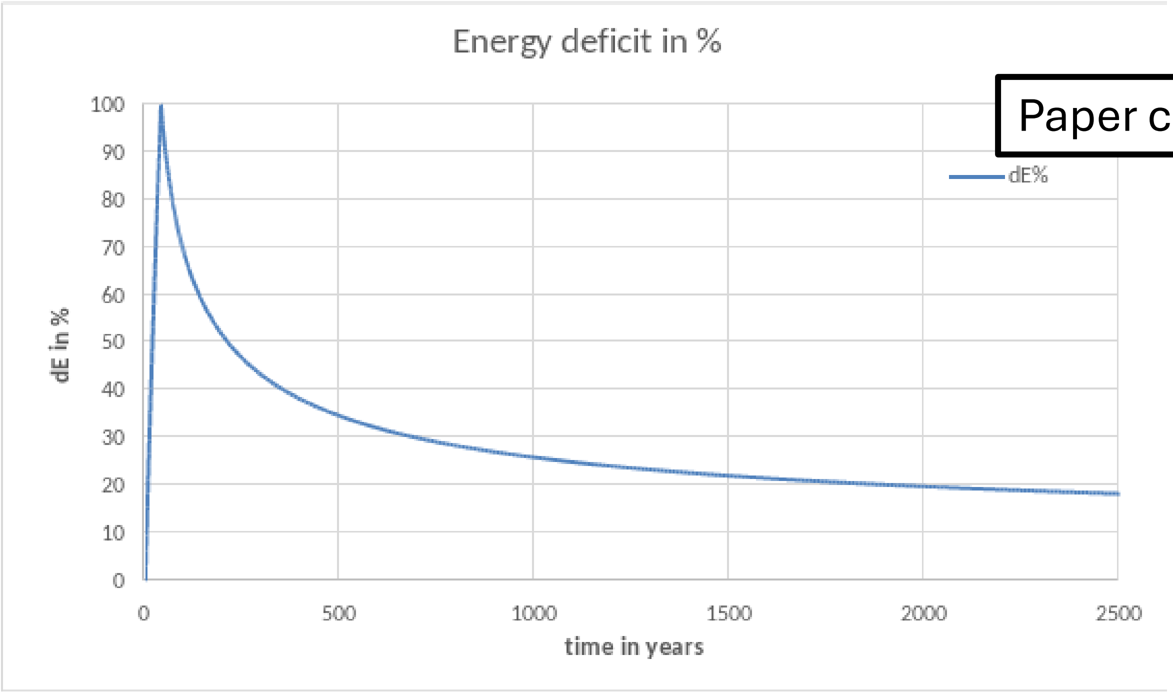
Alternative Approach:
Total subsurface energy deficit



DGE – Recharge of the subsurface

- Step 3: Heterogeneity and groundwater flow



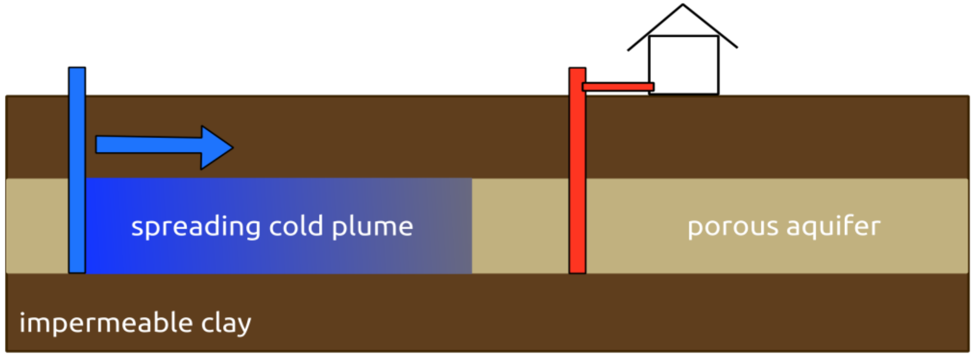


Paper coming

K. E. Abildgaard, M. Sc. project 2026

DGE – Temperature Evolution

- Predict $T_{Prd}(t)$ with an equation: **T(t) = …**



Input for
- ○ Technoeconomic
- ○ Social
- ○ Environmental
- ○ …

Analysis

- ○ No more homogeneous numerical models
- ○ Just plug parameters into an equation!

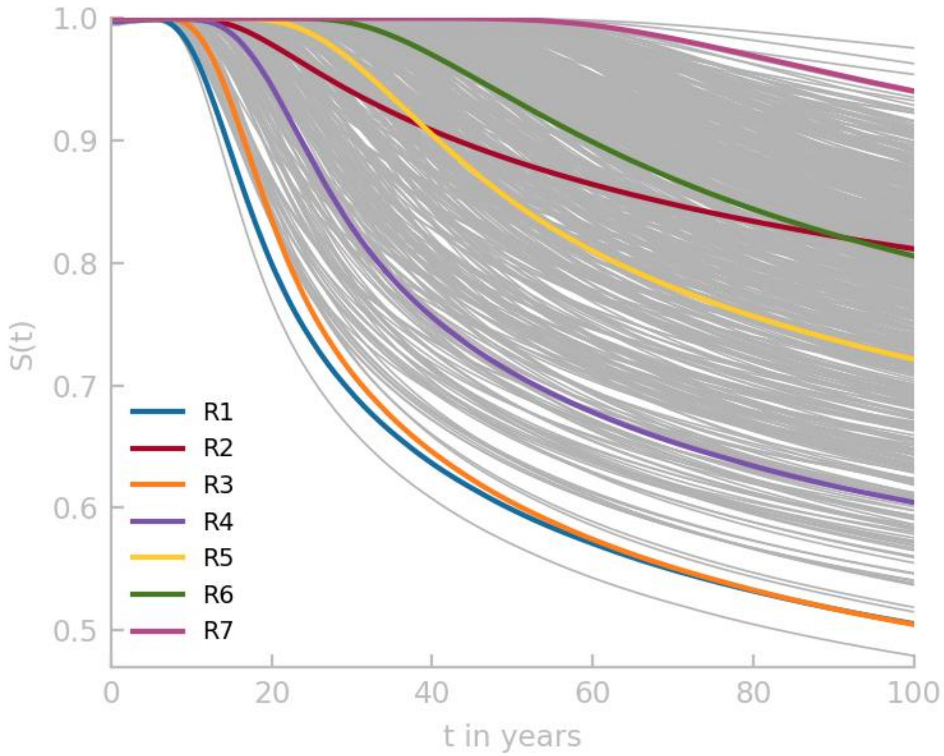
DGE – Temperature Evolution

- Predict $T_{Prd}(t)$ with an equation **T(t) = ...**

Description	Variable	Unit	Value
Reservoir thickness	H	m	20 - 160
Reservoir depth	D	m	1000 - 3500
Thermal gradient	$grad_T$	K/m	0.02 - 0.04
Porosity	ϕ	-	0.15 - 0.25
Well spacing	L	m	400 - 1600
Flow rate	Q	m^3/s	150 - 450
Extracted temperature	ΔT	K	10 - 100

  - Just plug in estimated parameters

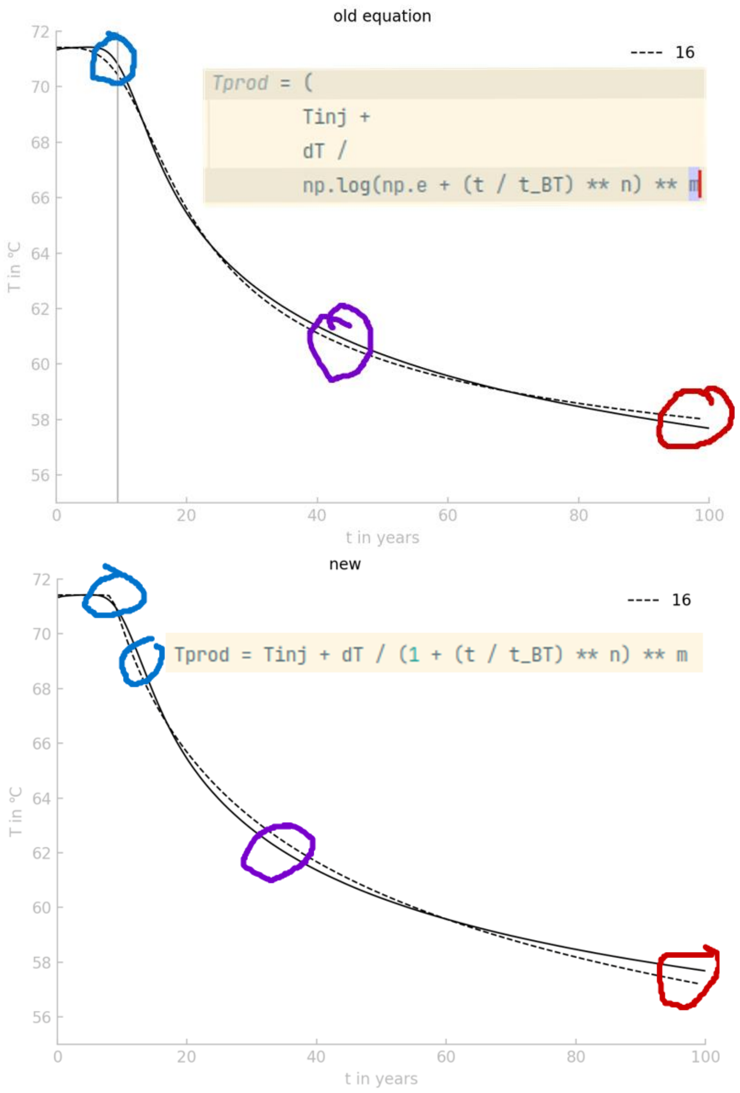
700 homogeneous numerical models



DGE – Temperature Evolution

- Step1: Find a type of equation

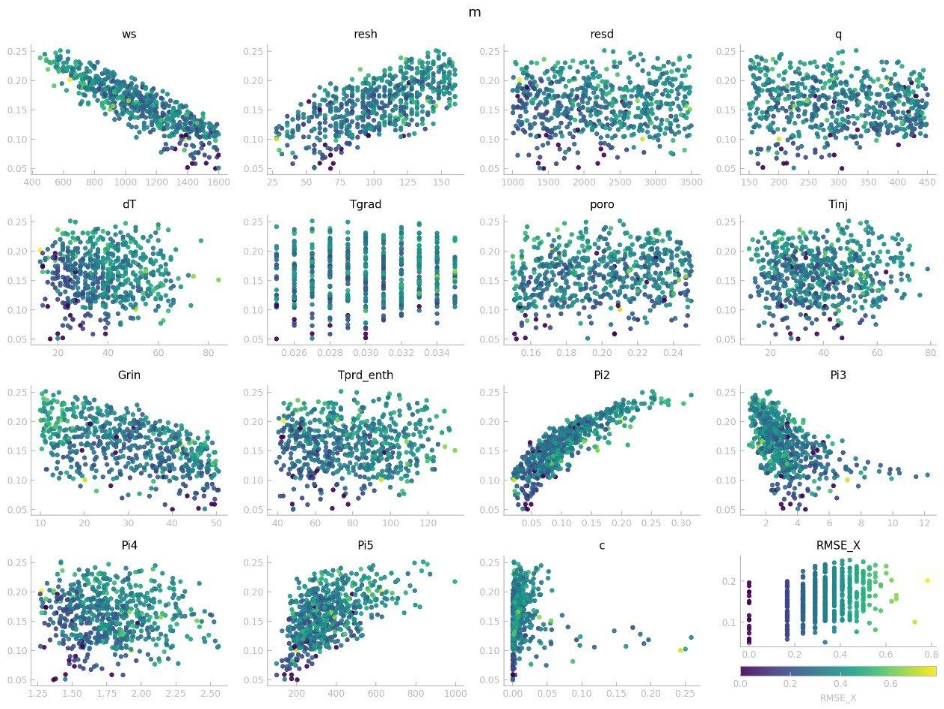
- T(t) = $$T_{prd}(t) = T_{Inj} + \frac{\Delta T}{log_{10}\left(10 + c(a^t - 1)\right)^m}$$



DGE – Temperature Evolution

- Step 2: Find a, c & m

- T(t) = $$T_{prd}(t) = T_{Inj} + \frac{\Delta T}{log_{10}\left(10 + c(a^{t} - 1)\right)^{m}}$$



DGE – Temperature Evolution

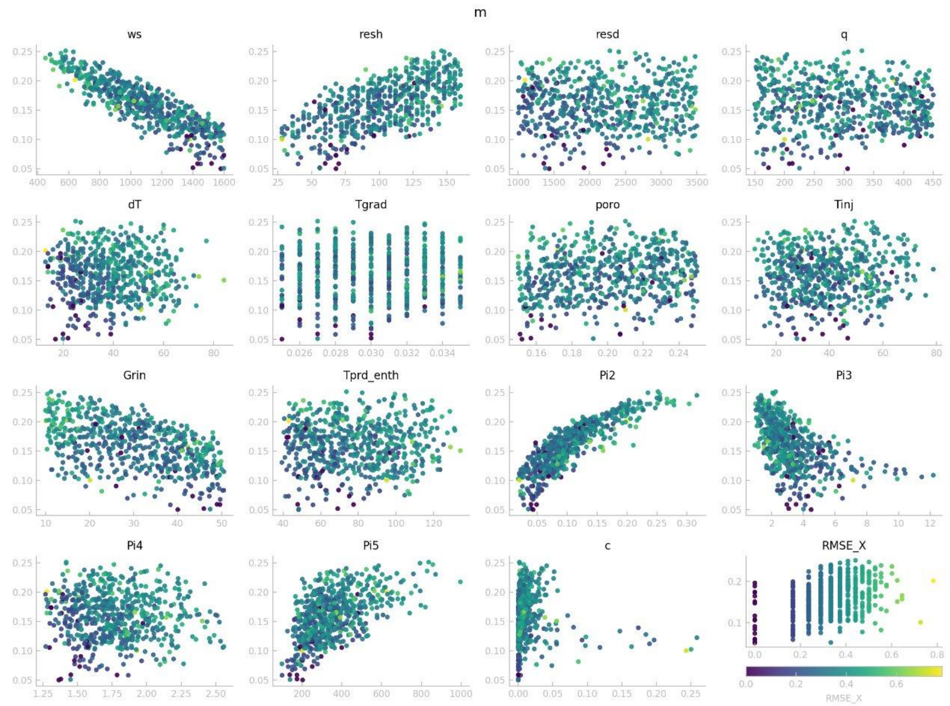
- Step 2: Find a, c & m

- T(t) = $$T_{prd}(t) = T_{Inj} + \frac{\Delta T}{log_{10}\Big(10 + c(a^t - 1)\Big)^m}$$

$$m = 0.2966 - L\Big(\frac{0.0138}{Q} + 0.000094\Big).$$

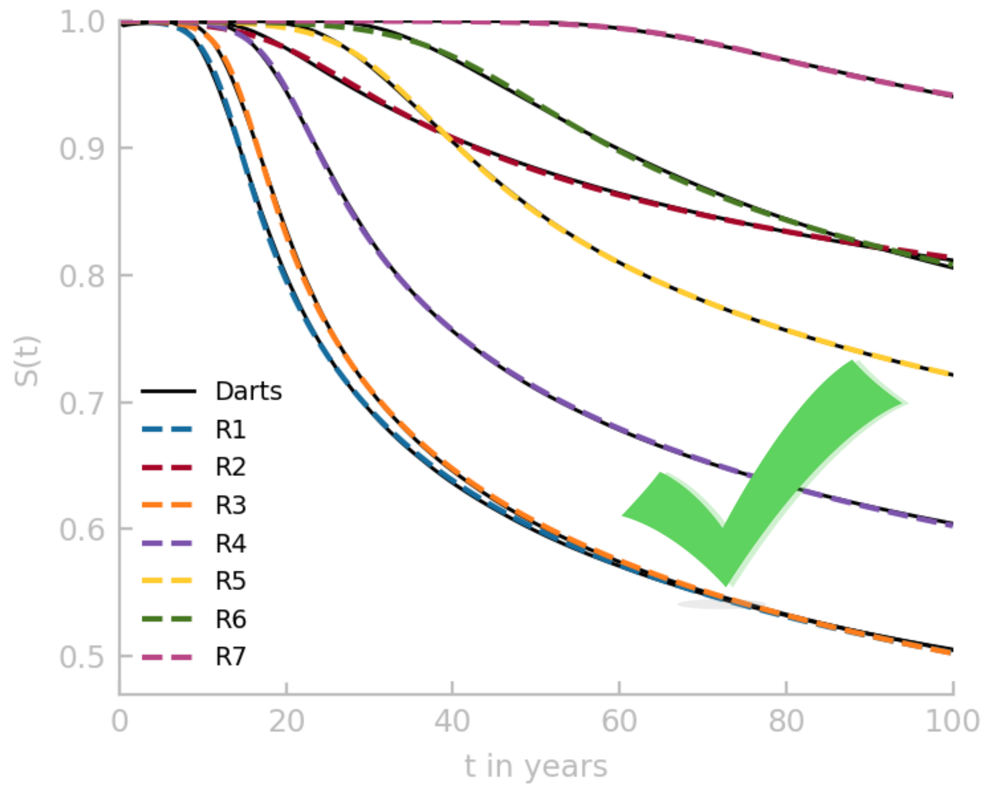
$$a = 1.044 + \frac{8.903}{\mu_{Rel} t_{Grin} + \frac{882.6}{H} - 12.02}$$

$$log_{10}(c) = \frac{1}{0.35 + \mu_{Rel}}\Big(\frac{80.35}{t_{Grin} + \frac{H}{t_{Grin}}} - 7.642\Big)$$



DGE – Temperature Evolution

- Step 3: Predict T_{Prd} without simulation



Paper coming (under review):
Wallmeier, Vardon, Daniilidis:
Cooling Behavior of Geothermal Doublets: A Closed-Form Model.

T-Drop

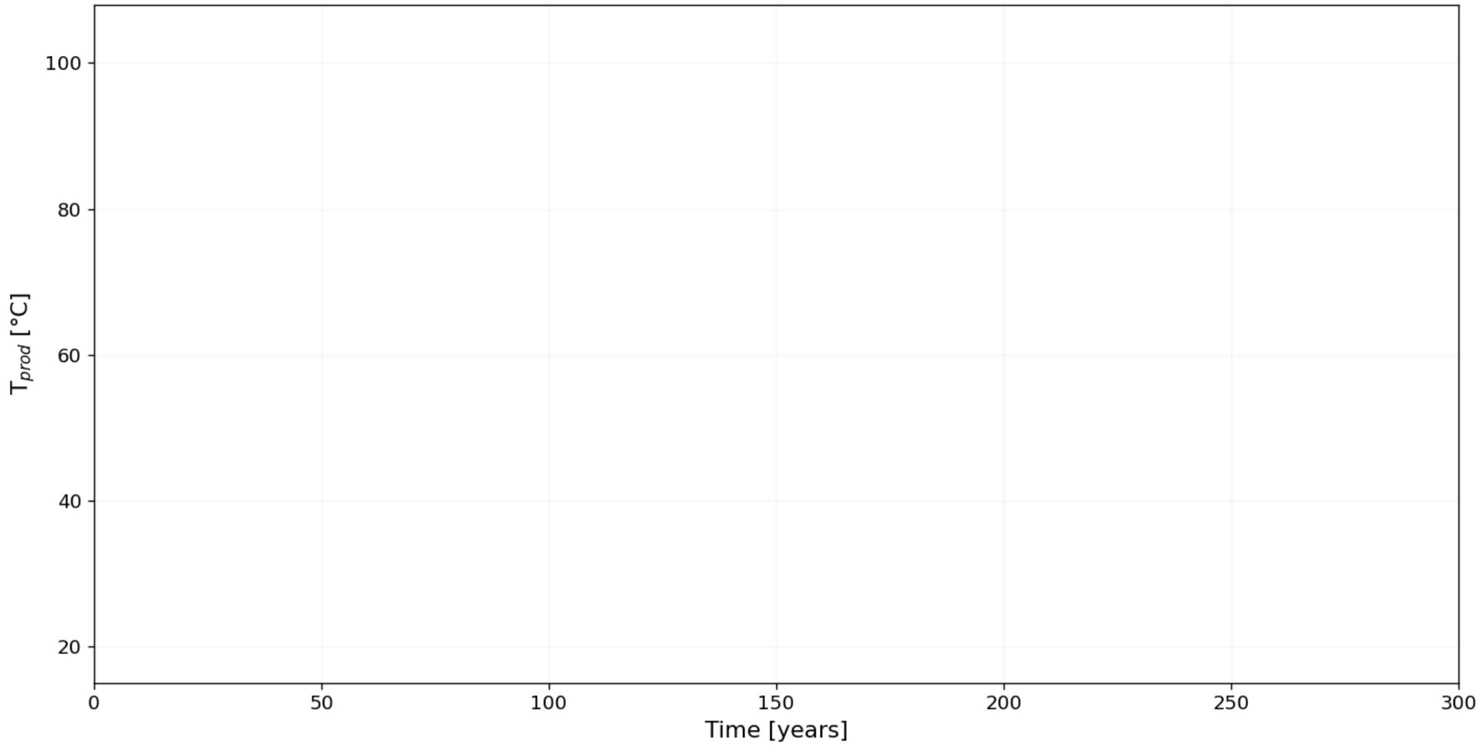
https://gitlab.com/carowall/T-drop
c

Deep Subsurface

WP 5a: Economics of DGE Use

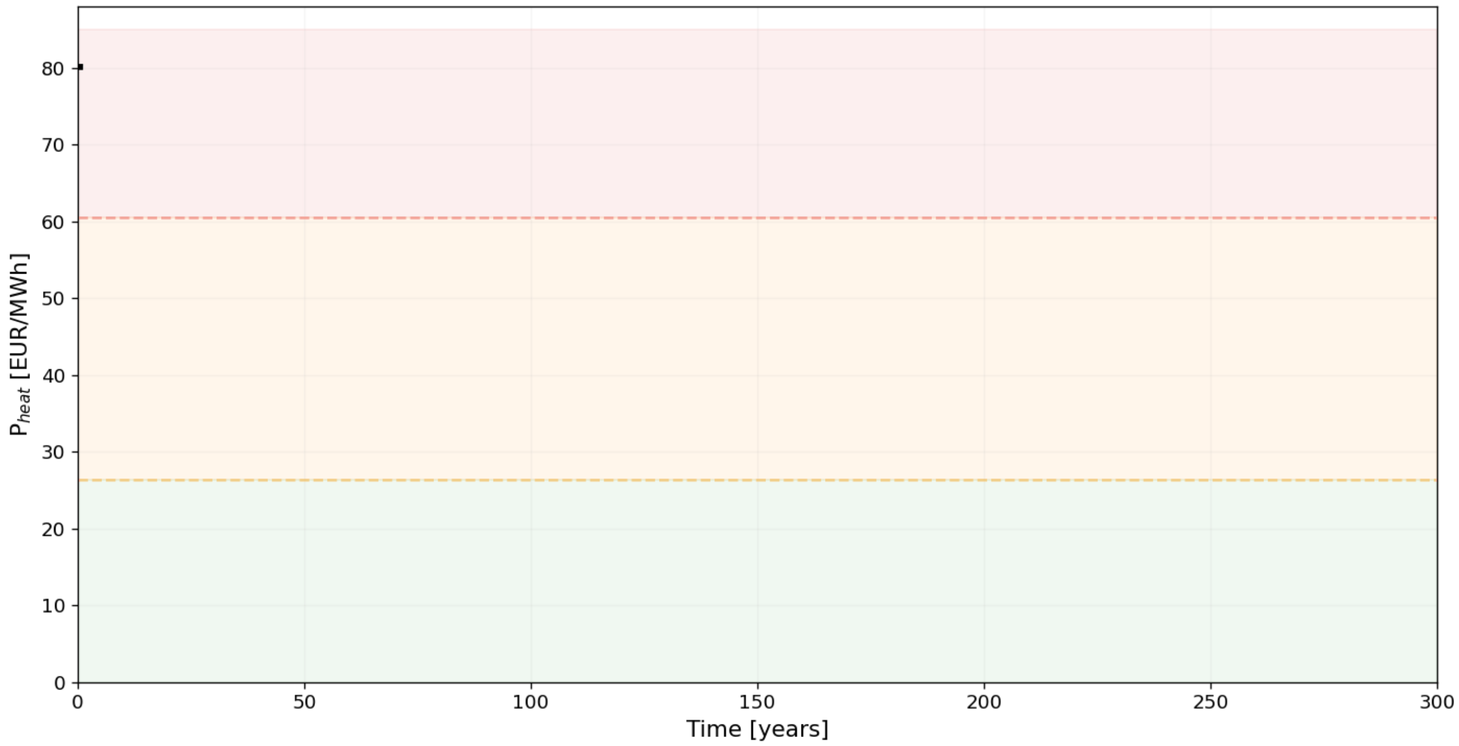
Adithya Eswaran

As the reservoir cools, the doublet can serve different applications



→ *But how fast this happens depends on choices*

But the value of each degree is not the same and it declines with temperature

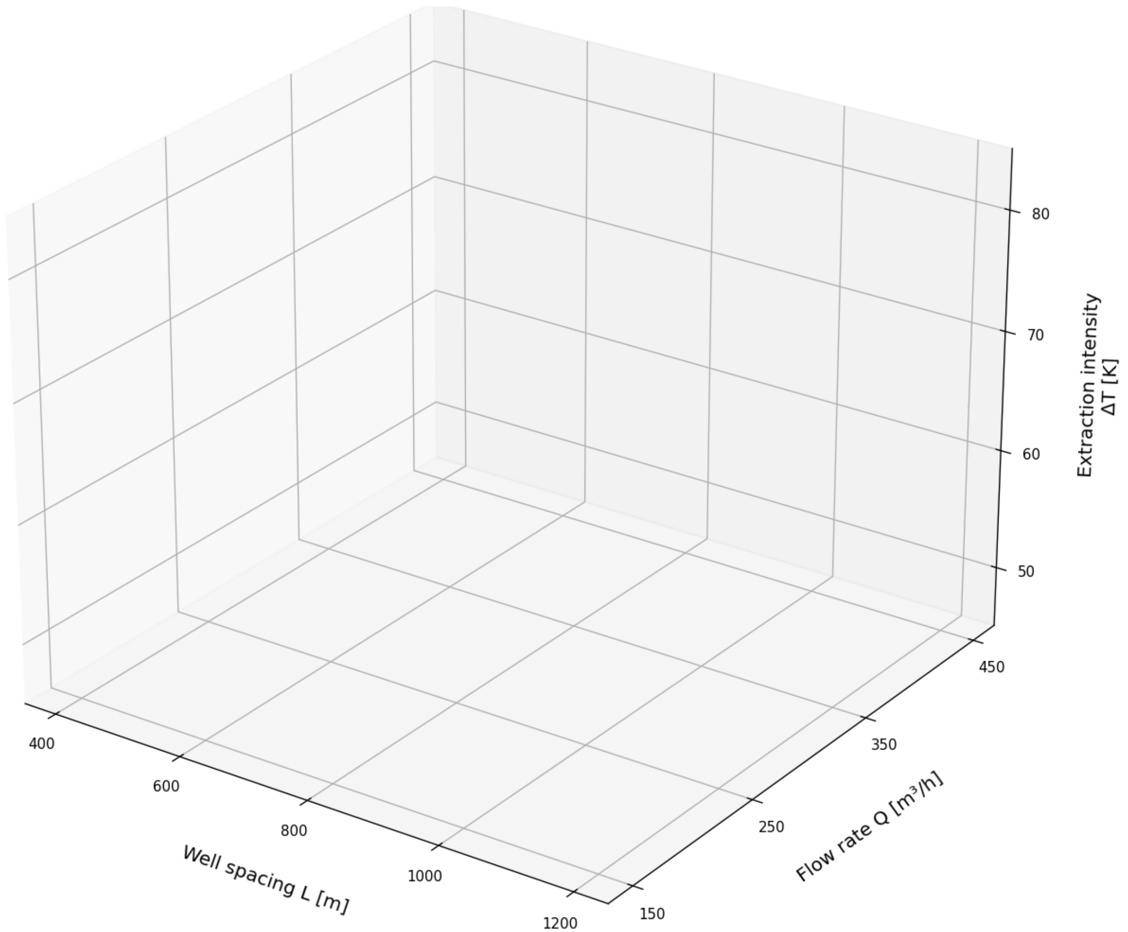


→ *But how fast this happens depends on three design choices: how aggressively we extract, how far apart the wells are, and how fast we*

The cooling of the reservoir raises three questions for the intergenerational sustainability

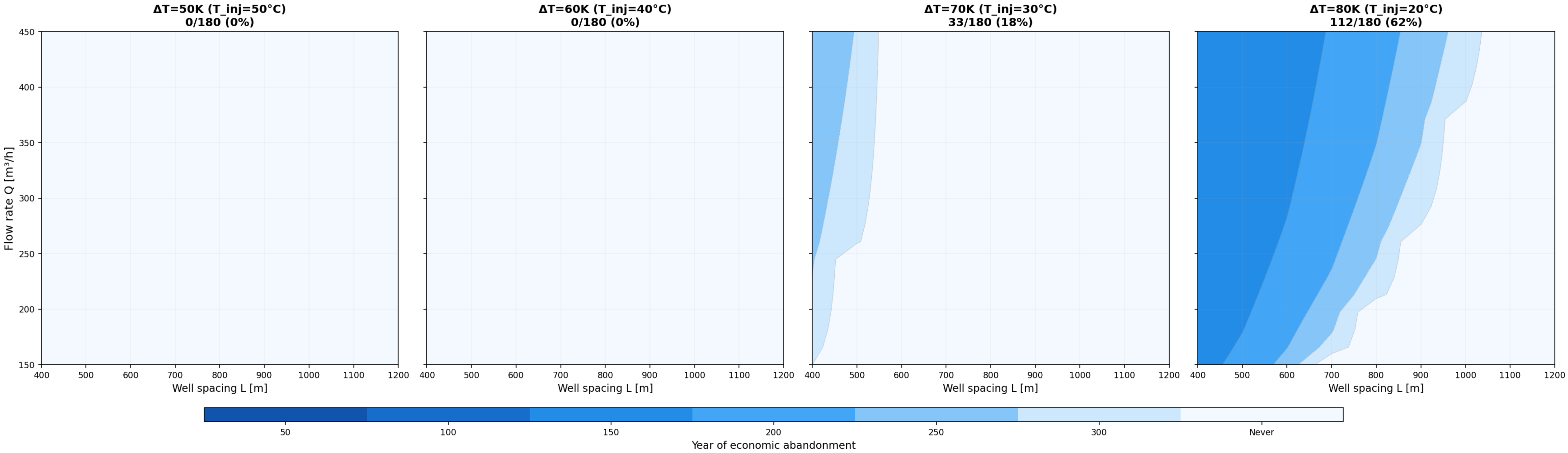
- **When does the operator stop?** As the reservoir cools, the heat becomes less valuable. At some point, revenue falls below costs. When?
- **Who benefits?** The first generation gets the hottest, most valuable heat. What do later generations get?
- **How unequal is the distribution across generations?**

We answer these questions across a wide solution space



The doublet is rarely abandoned - there is always a lower-grade end use to keep it profitable

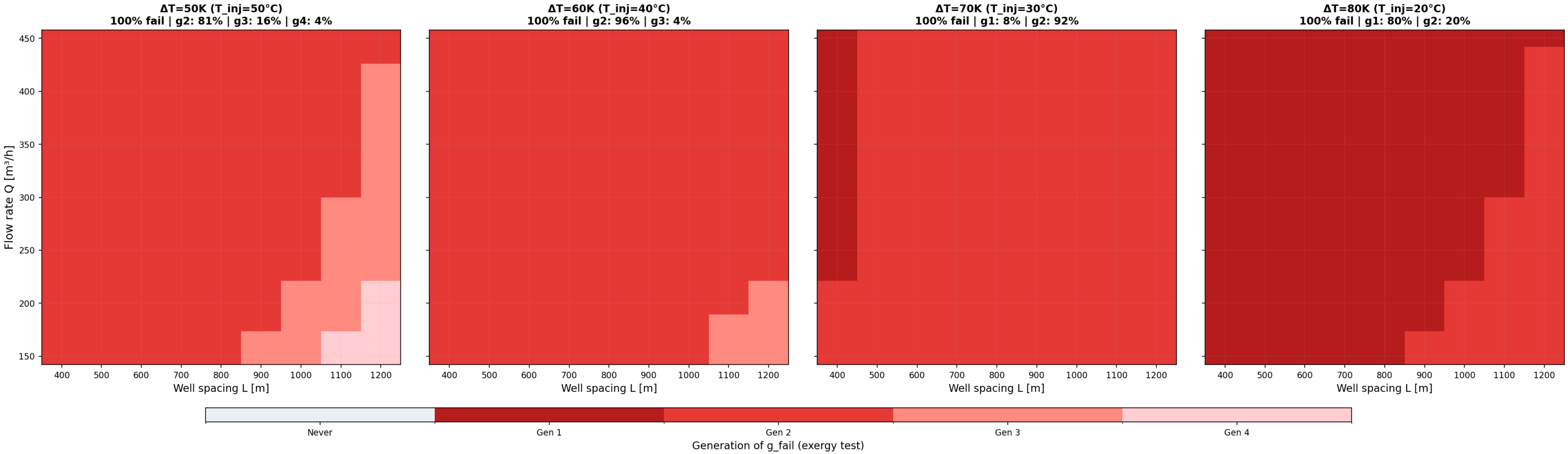
Economic Abandonment = First year where annual revenue falls below costs



Colour = year of shutdown
White (never) → dark blue (early)

Yet the future generations inherit less than a quarter of the exergy available to the first generation

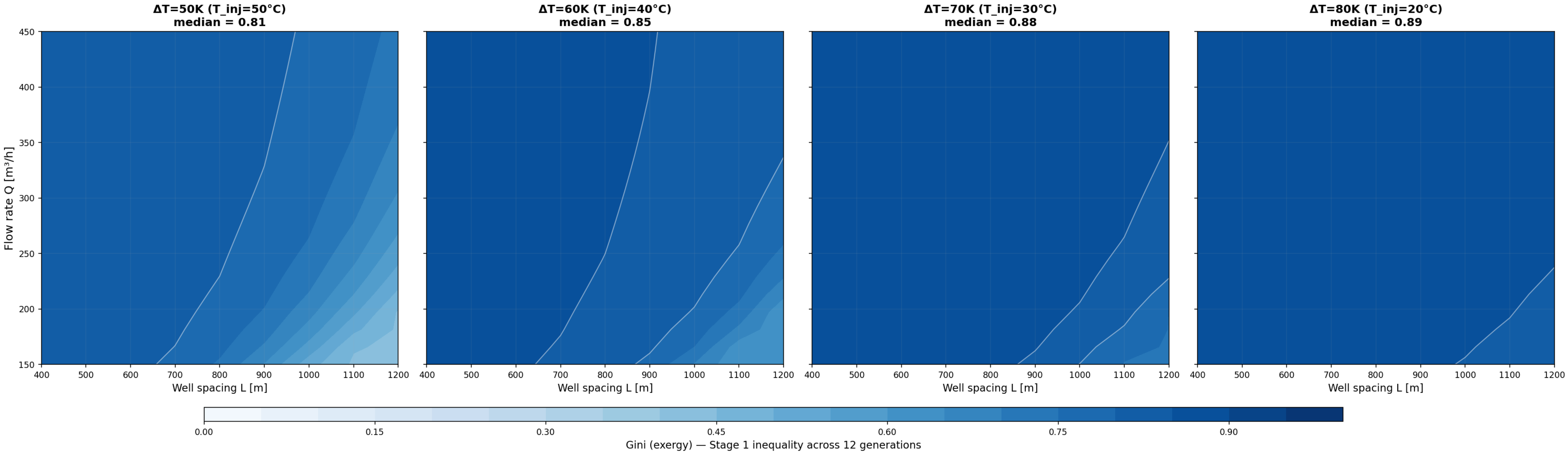
First generation, where the next generation's exergy inheritance drops below 25% of generation 1



Colour = generation of high-grade resource loss
Light (later) → dark red (earlier)

The first two generations capture nearly all high-grade heat — no design choice changes this

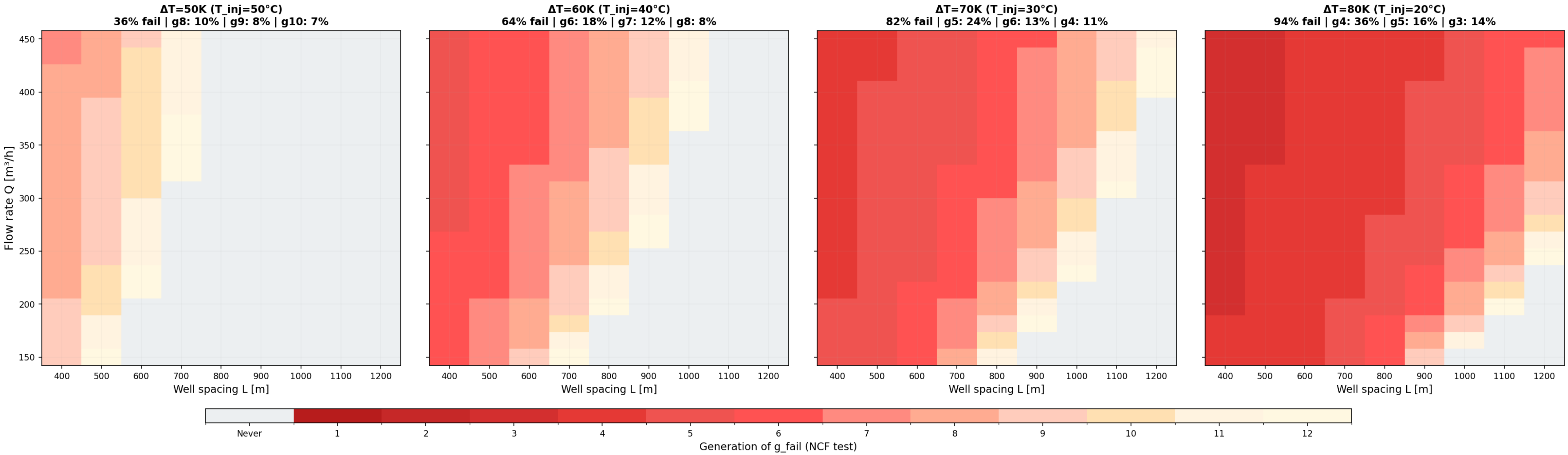
Gini (exergy): How equal is the distribution of accessible exergy amongst the different generations



Colour = inequality of high-grade heat across 12 generations. Light (equal) → dark blue (unequal)

However the economic case for the future generations is different

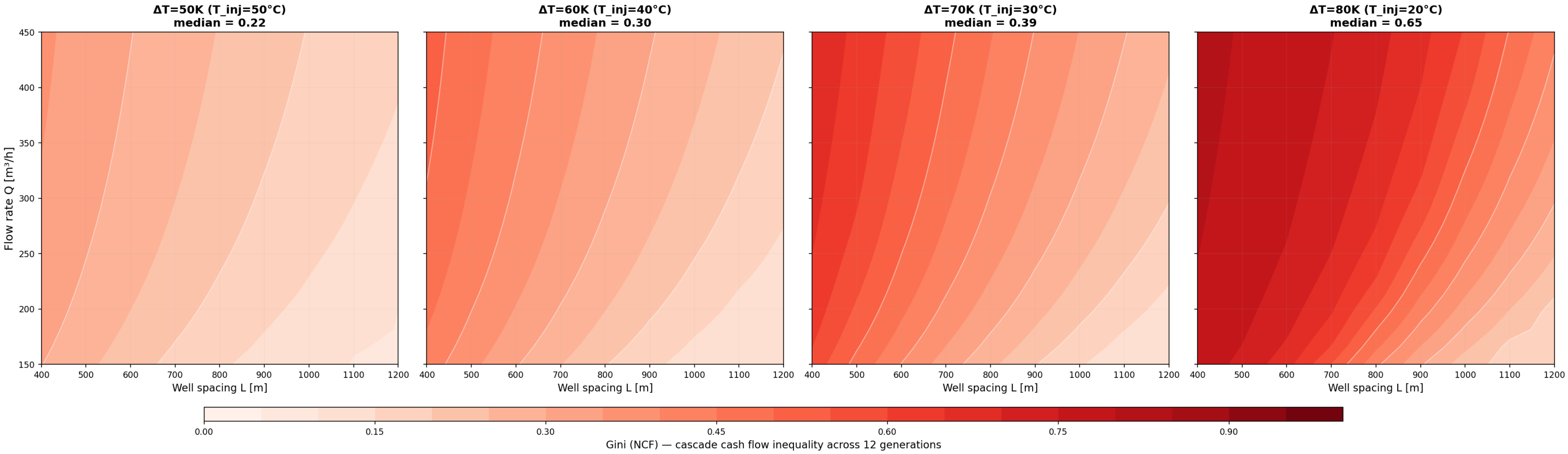
First generation where cumulative net cash flow drops below 25% of generation 1



Colour = generation of economic return decline
Grey (never) → dark red (earlier

Economic inequality is lower, but still significant at aggressive extraction

Gini (NCF): How equal is the distribution of accessible exergy amongst the different generations



Colour = inequality of economic returns across 12 generations
Light (equal) → dark red (unequal)

What we measure determines what we manage

- A geothermal doublet can be economically viable while the high-grade resource is depleted within 25 years.
- Lower-grade end uses keep the system running and make the intergenerational problem invisible to the market.

Deep Subsurface

WP 3: Geological impacts (interference and uncertainties)

José Rodriguez

1. Prior Geological Model

- Task 3.1: Setting up a prior geological model to act as a stochastic framework that makes current understanding and uncertainties explicit.

Geological Model

1. Semantic Model

- Lithotectonic Framework

Incremental improvements

Cascading updates

2. Implicit Geological Model

- Embed constraints (Drillings, profiles, etc)
- Reality check
- Add virtual controls
- Introduce fault systems
- Test geological hypotheses

Incremental improvements

Cascading updates

3. Hydrogeological Model

- Once geological model stable/reliable:
  - *Create link to reservoir parameters*
  - *Extrapolate geologically to required detail, with realistic variability*

Incremental improvements

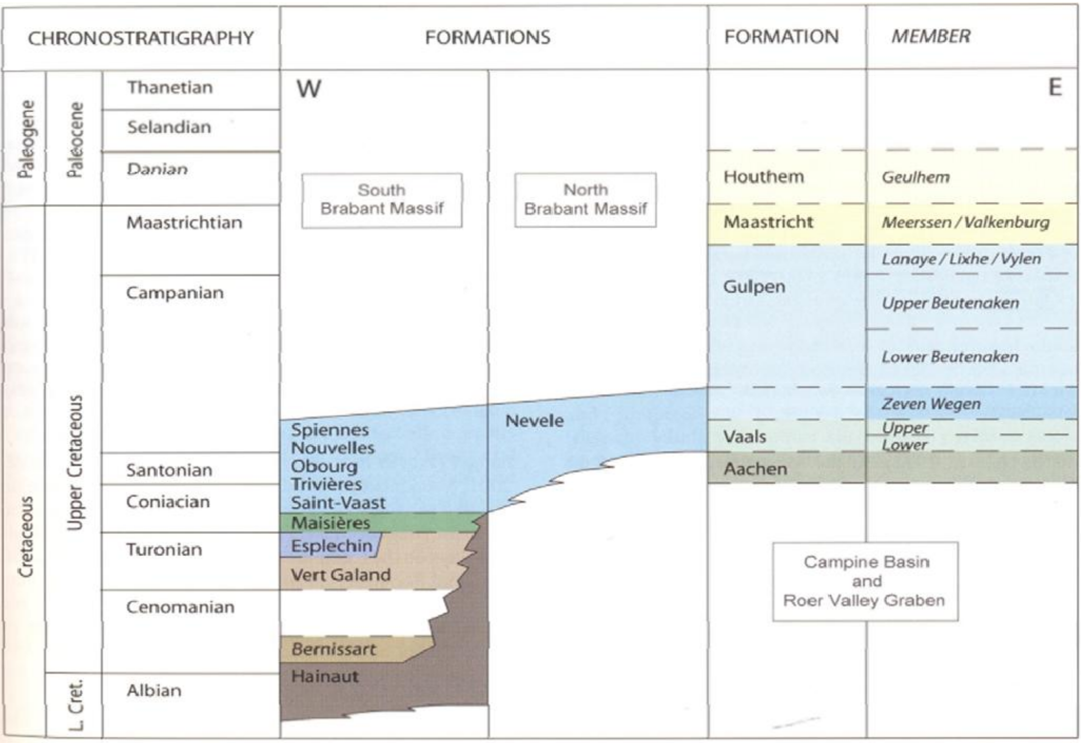
Supporting Traditional Geology with the Lithotectonic Framework

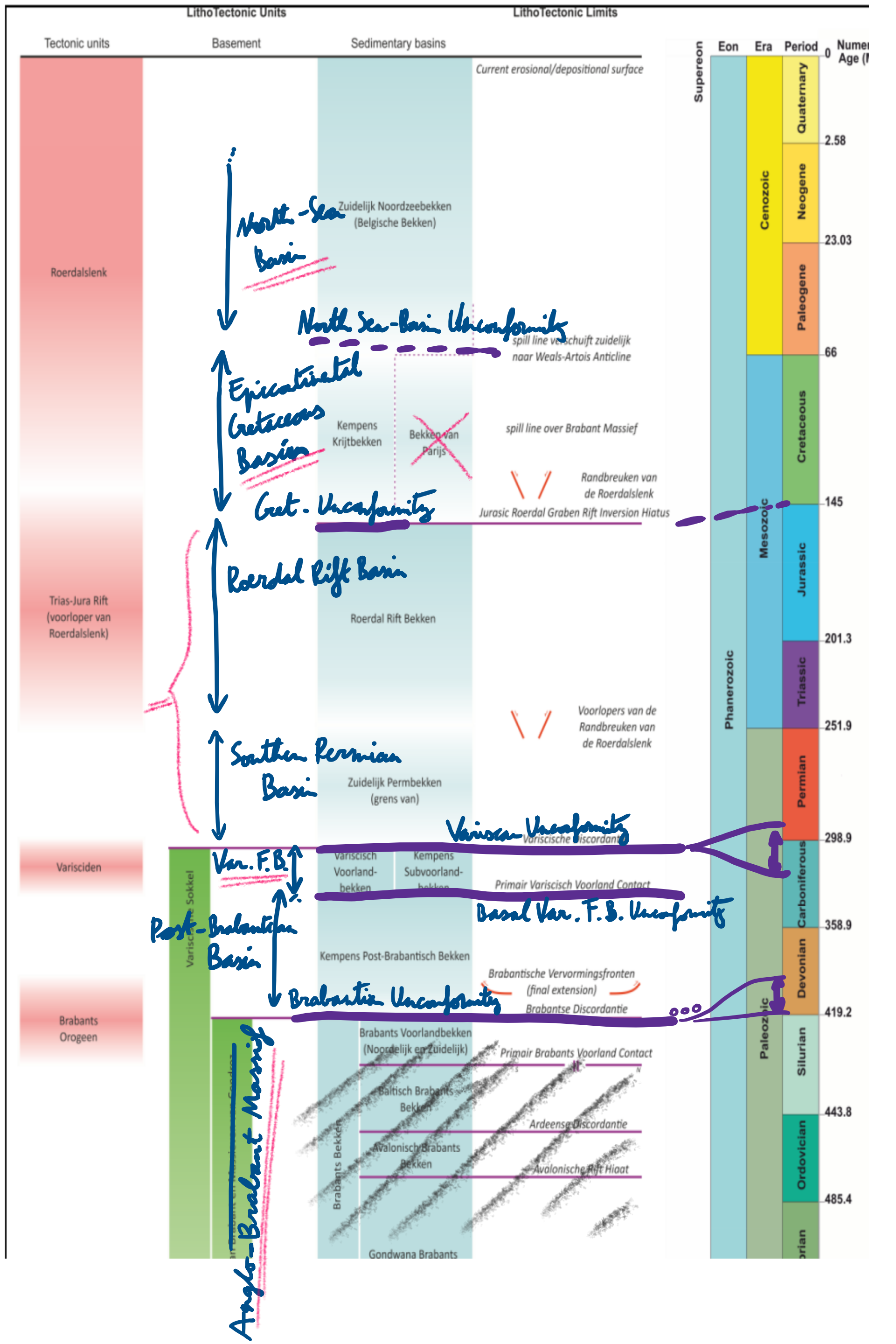
Traditional Geology

- Commonly based on Lithology characteristics
- Have some relations with periods of time
- More detail for sedimentary recent layers

How lithotectonic framework improves this?

- Tells a story of the events in the area
- Create new units based on the events that modified the crust at specific moments
- Show the relation between different Elements





Training LLM in Lithotectonic Framework

Phase 1

Knowledge Seeding via Few-Shot Prompting

Phase 2

Developing Reasoning via Interactive Socratic Dialogue (In-Context Learning)

Phase 3

Distillation into a Portable Reasoning Protocol

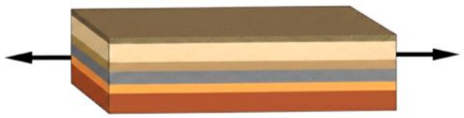
Protocol structure:

```
LTF Protocol Structure (Summary)
│
├── 1. Conceptual Foundations (The "Why")
│   └── 📄 LTFConceptualNature_v05_Complete.md
│
├── 2. Core Knowledge Base (The "What")
│   ├── 📄 LithotectonicFramework_v11_RefinedDefinitions.md
│   └── 📄 LTFDefinitionCompendium_v02_RefinedDefinitions.md
│
├── 3. Application & Methodology (The "How-To")
│   └── 📄 LTFApplicationProtocol_v07_EnhancedPrecision.md
│
└── 4. Validation & Evolution (The "Feedback Loop")
    └── 📄 LTFTrainingLog_v05_Complete.md
```

Building the Geological Model

LITHOTECTONIC FRAMEWORK

Events
(Geological Processes)

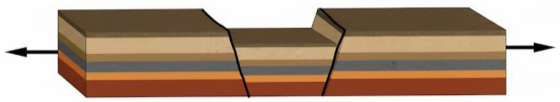


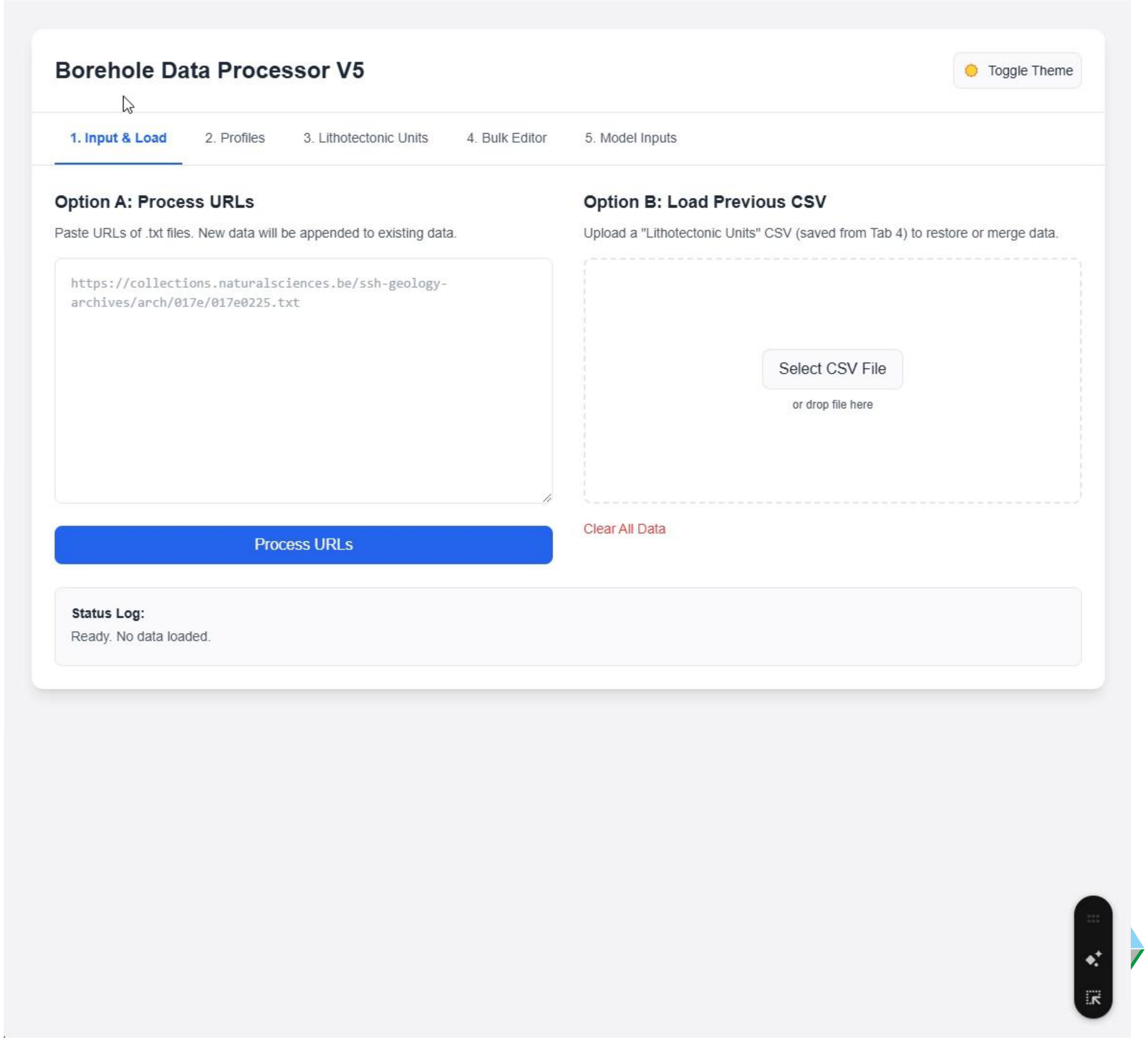
Create (or destroy)

Limits
(Boundaries)

Define

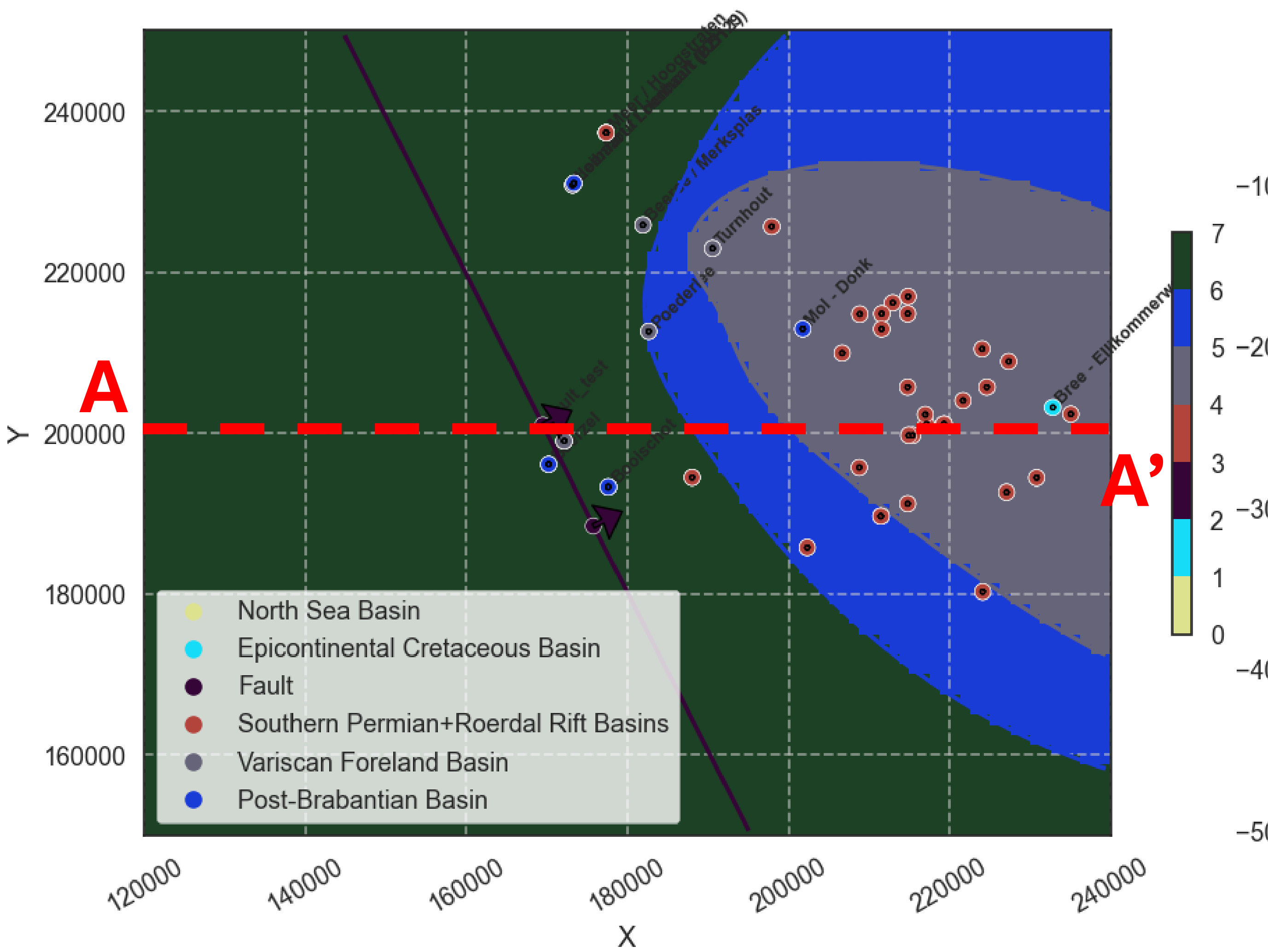
Units
3D Volumes ✅
≠
2D Features ❌

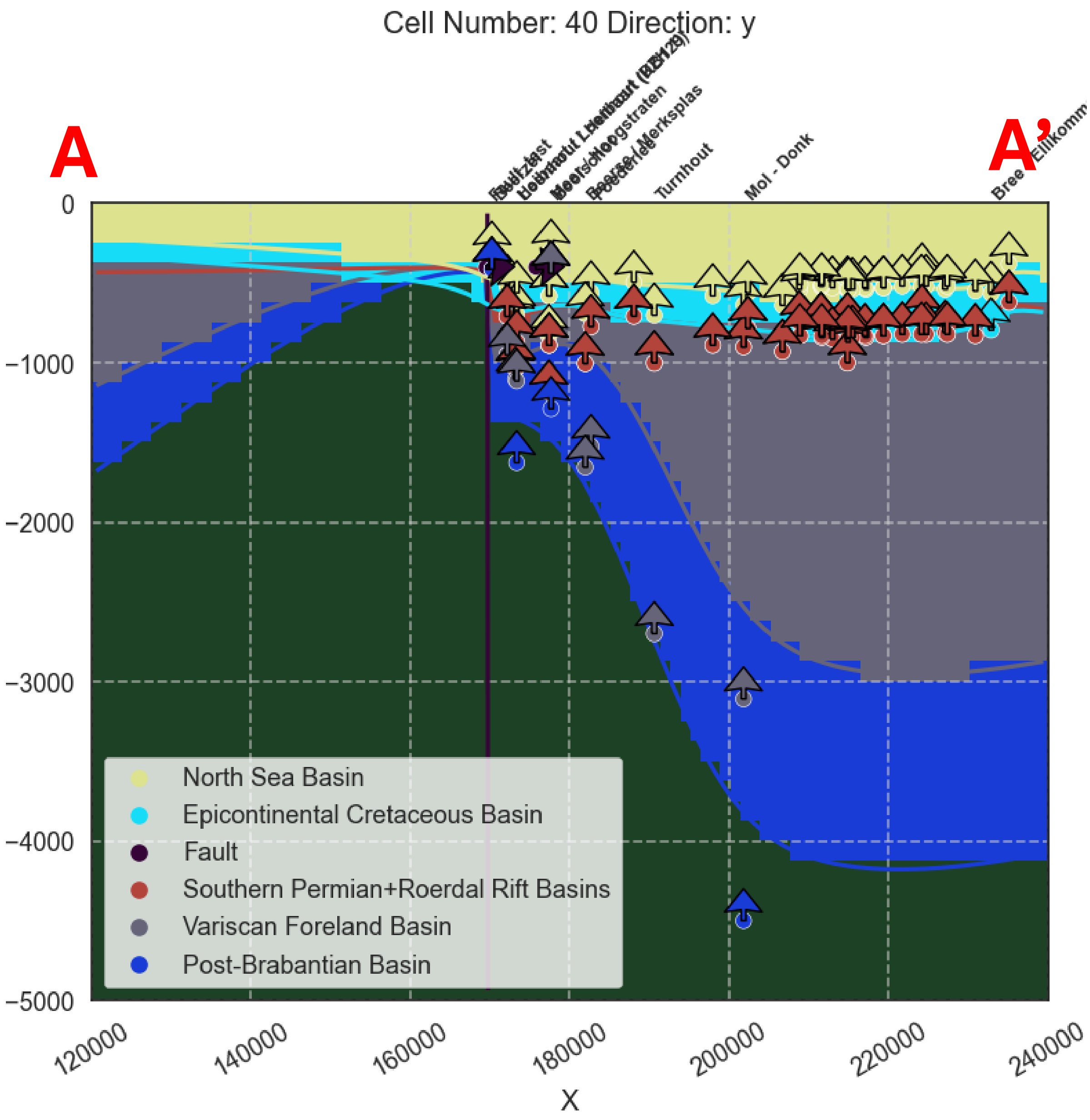




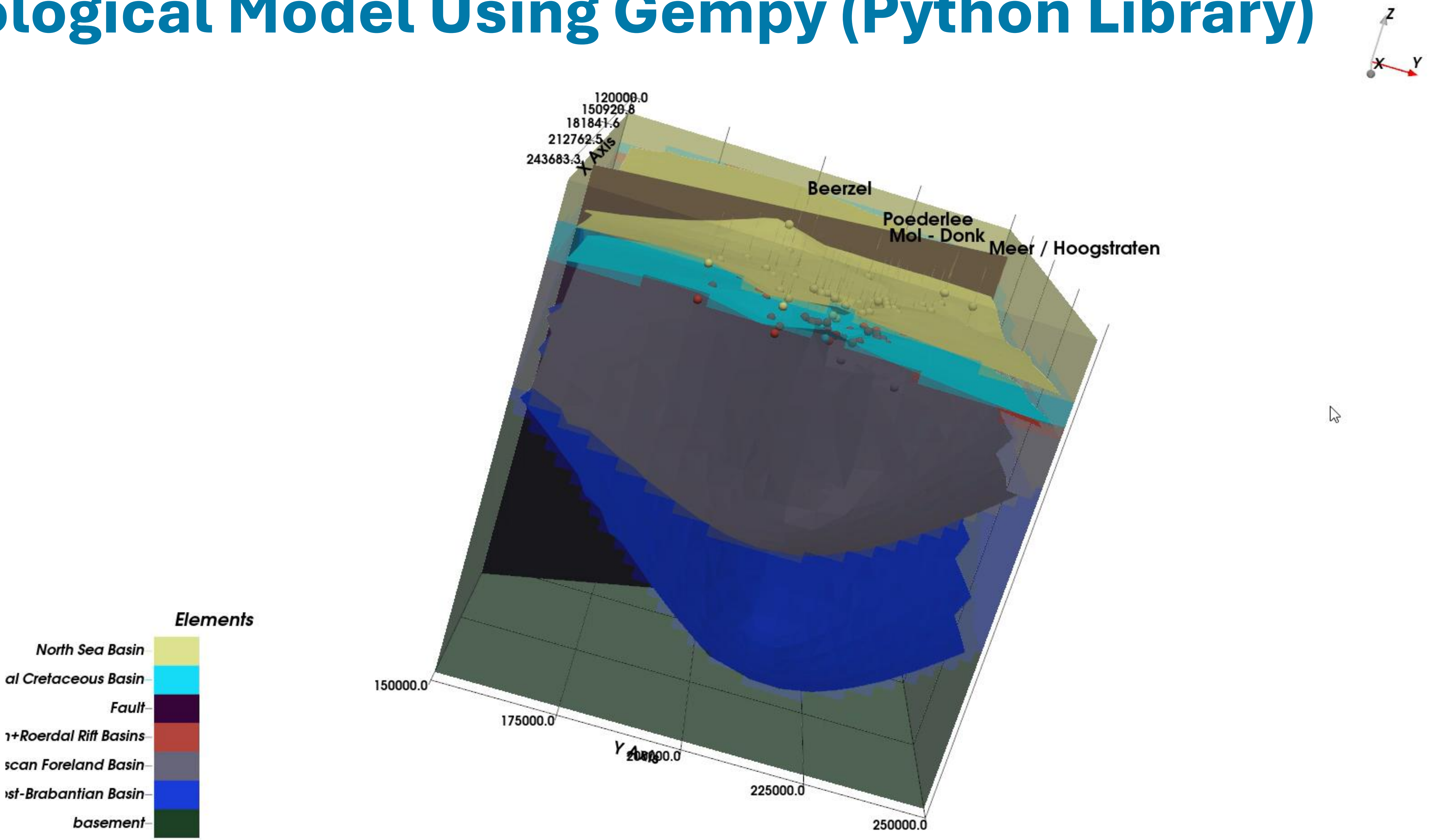
Geological Model Using Gempy (Python Library)

Top View (Z= -2000)





Geological Model Using Gempy (Python Library)

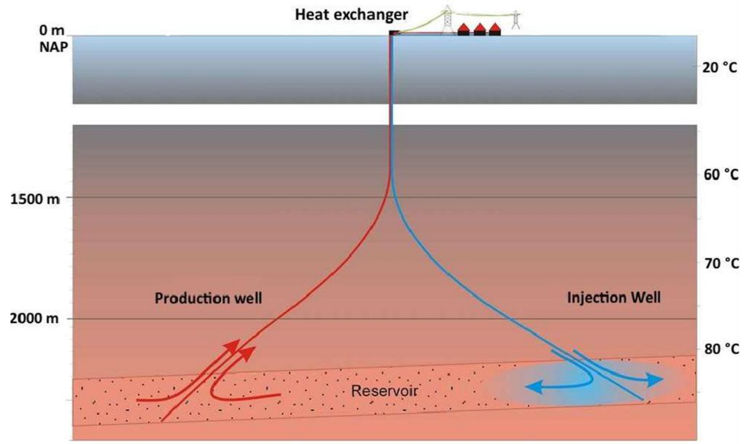


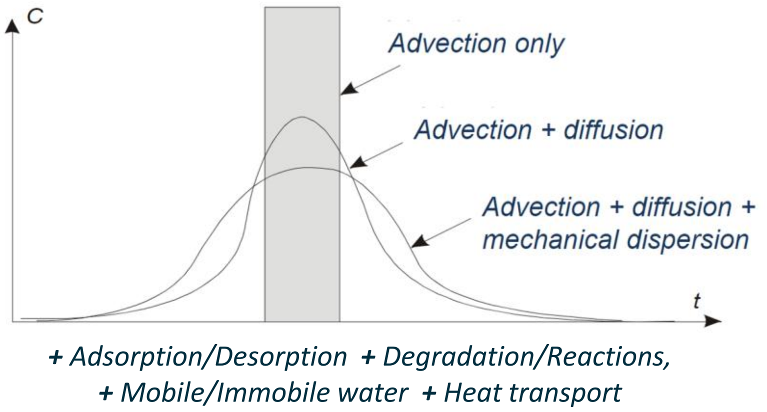
2. Uncertainties and Activities Interaction

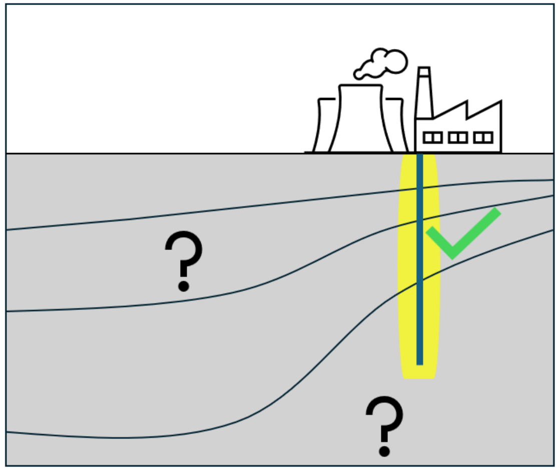
- Task 3.2: Siting the activities in the reservoir to qualitatively explore possible interaction pathways.
- Task 3.3: Further developing the model into a box-type reservoir model to facilitate the setting of boundary conditions for detailed modeling.
- Task 3.4: Integrating essential aspects for setting up the model, such as selecting input parameters, describing uncertainties, and evaluating overall sensitivities.

Challenges for Subsurface Management Models

The activities in the subsurface are:







DYNAMIC

Flexibility

- Easy to modify
- Integration with external variables (non-geological data)
- Relevance over time
- Scenarios validation

COMPLEX

Speed and Accuracy

- Reduce computational demand in regional models
- Improve simulation times
- Maintain reliable results
- Easy Calibration

UNKNOWN IN DETAIL

Uncertainties and Interactions

- Heterogeneity
- Generalization of data
- Geological features (Fractures)
- Effects on neighbors
- Long–term Behaviour

Telescoped reservoir Modeling:

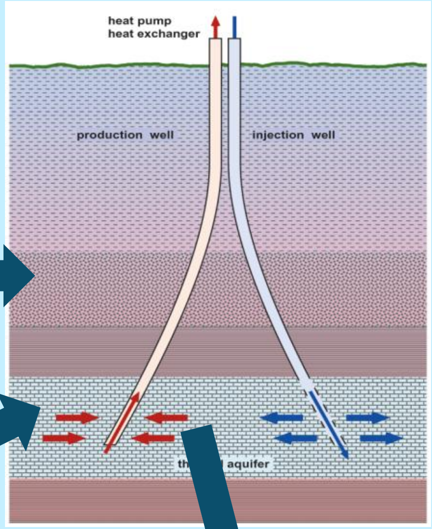
Geo-thecnical RBINS-GSB

LOCAL

External variables:
- Social
- Environmental

1st stage

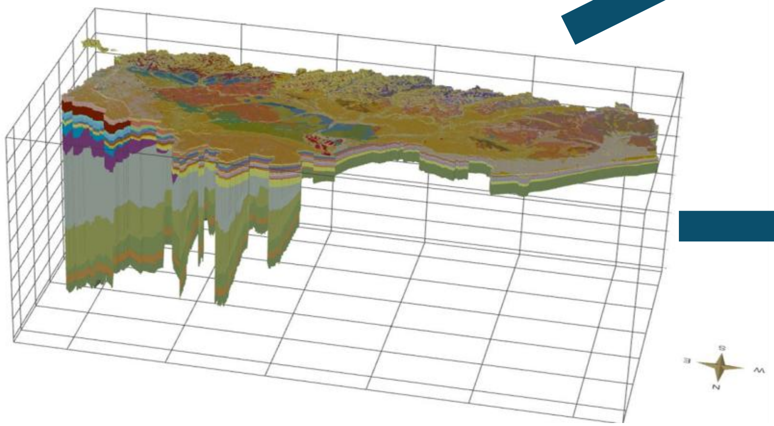
- Economic



Integration

REGIONAL

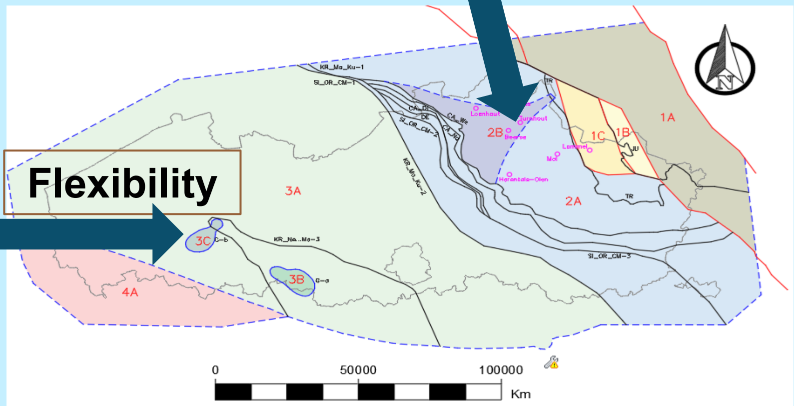
Geology



Interactions

2nd stage

Flexibility



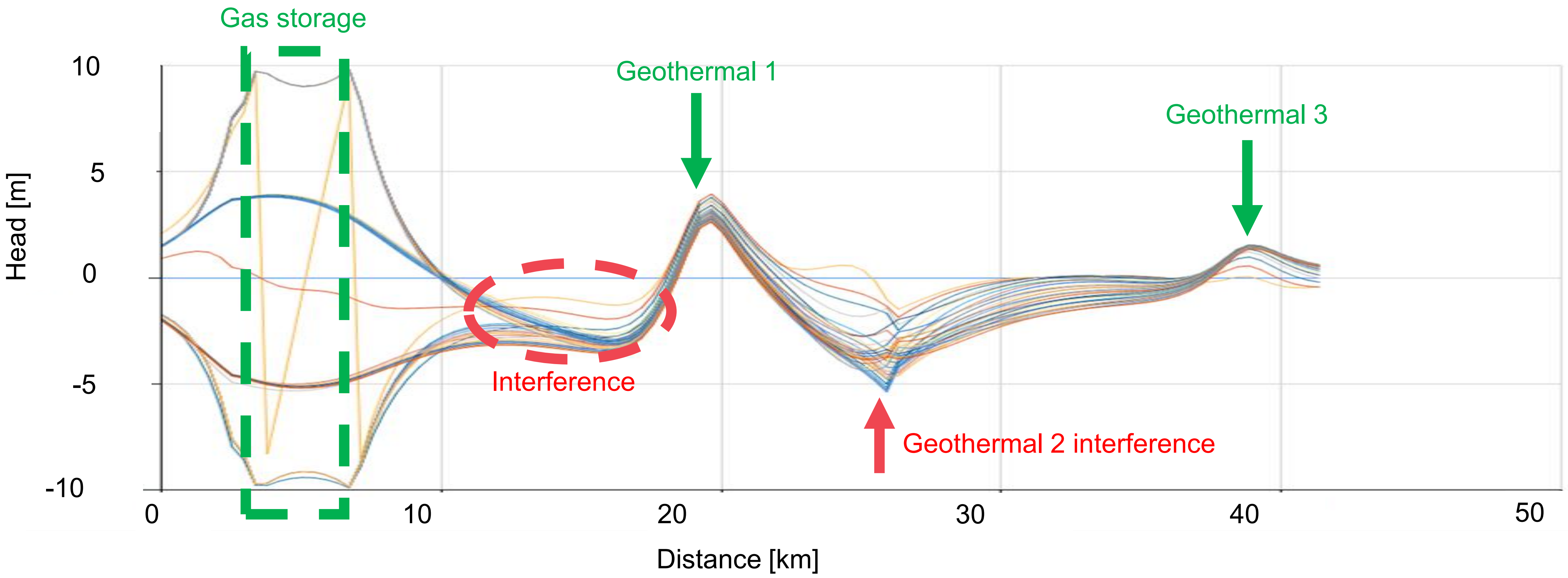
Probabilistic approach

Goals:
- Reduce uncertainties
- Multiple scenarios evaluation (Sensitivity)
- Long-term behaviour
- Impacts analysis
- Data-driven decisions

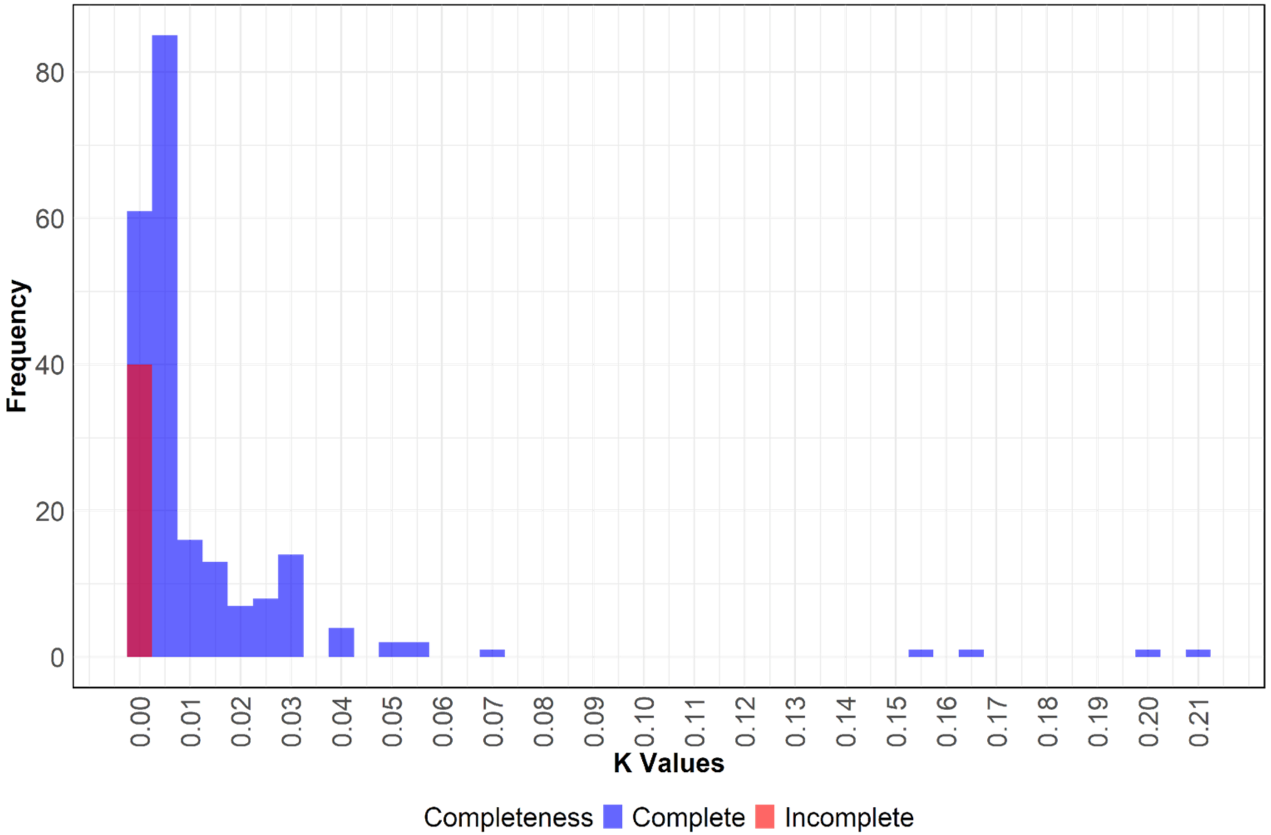
Current Results

Interferences
- Regional pressure prediction for different scenarios
- Activities interference detection

Parameter sensitivity
- Hydraulic conductivity (K):



Technical Challenges

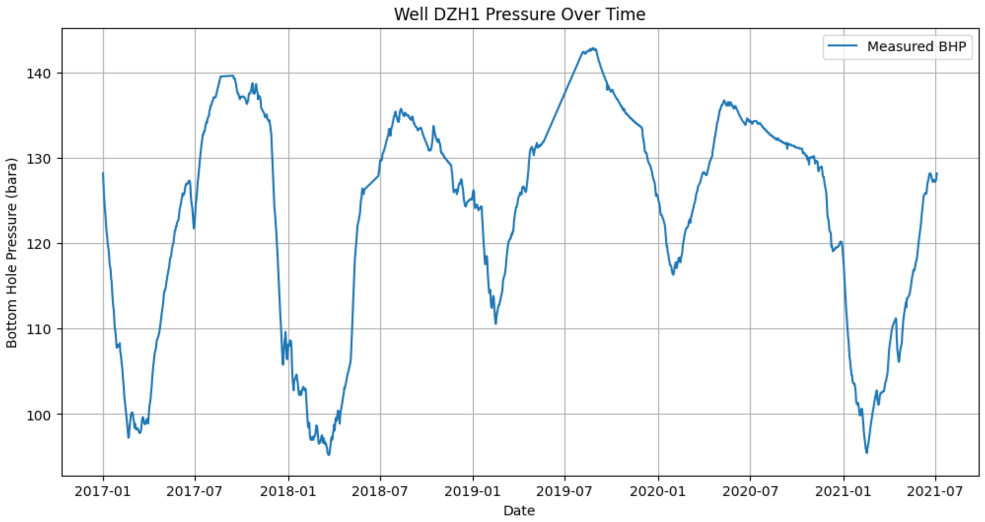


- Lack of data
- Input process and control
- Automation
- Replicability
- Methods limitations
- Generalization
- Optimization

Can AI help us to solve them?

Predicting parameters and pressure response in a gas storage site using PINNs

OBJECTIVE: To predict reservoir pressure (P) as a function of time (t), location (r), and operational flow rate (q).



What is a Physics-Informed Neural Network (PINN) ?

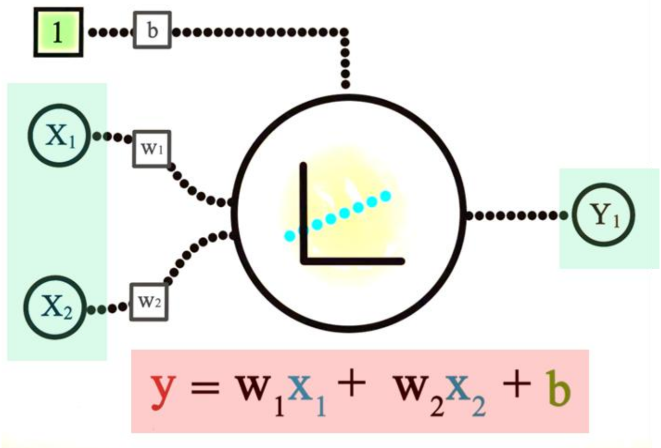
Equation

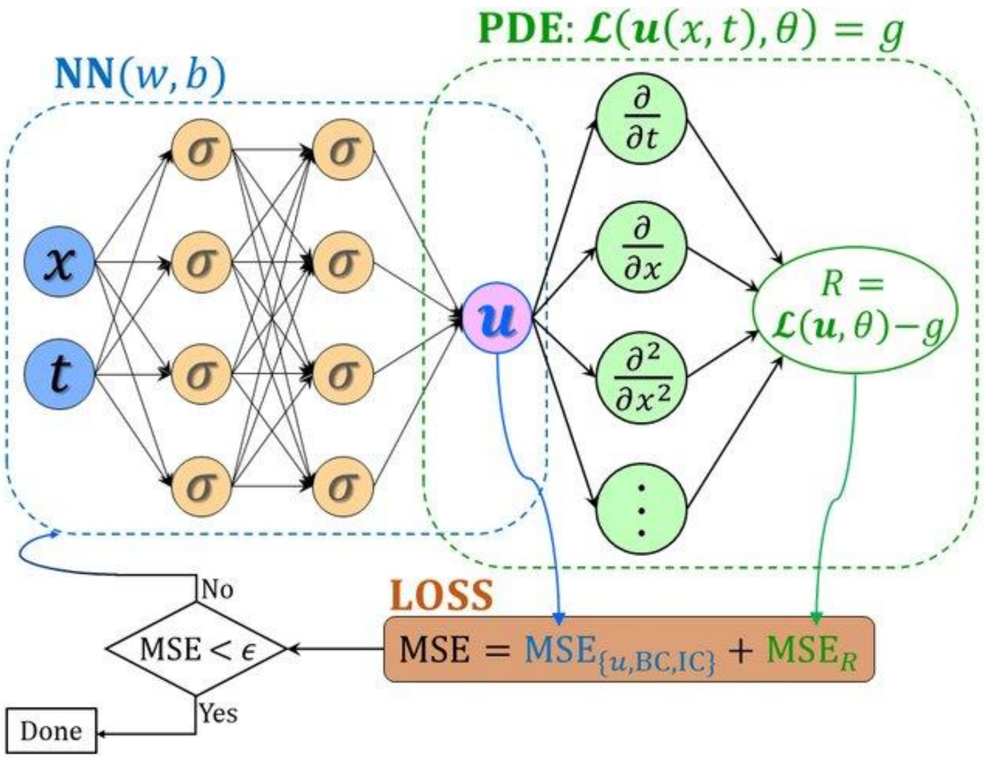
X=3
b=0
m=1

$Y = mX + b$

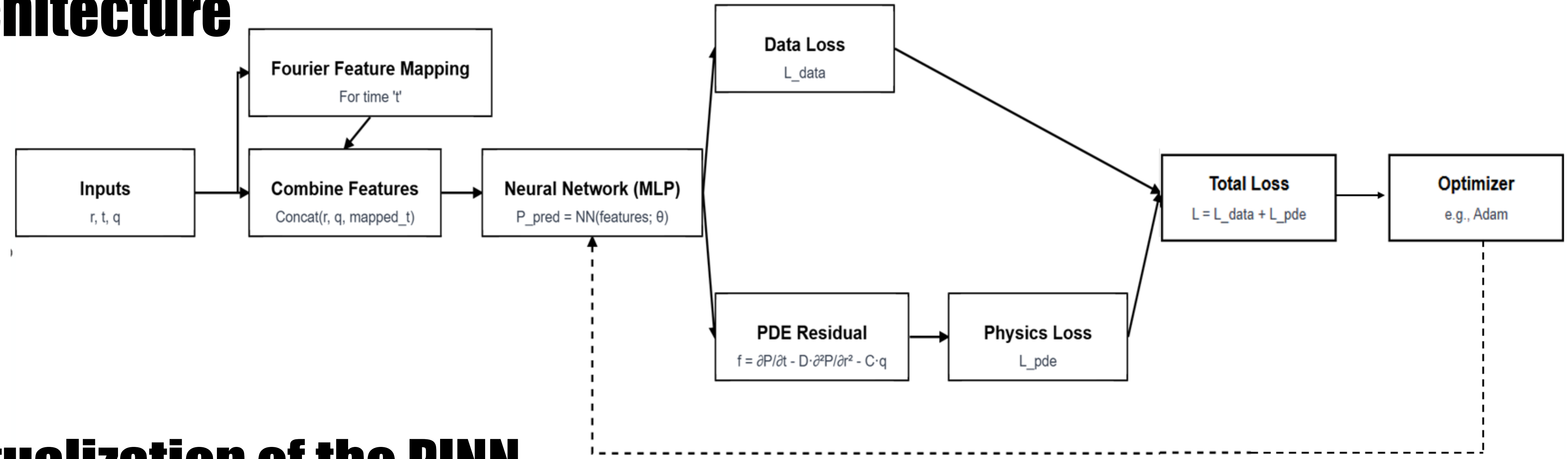
Y=3

Neuron





PINN Architecture



Conceptualization of the PINN

Mass conservation

$$-\nabla \cdot (\rho v) = \frac{\partial(\phi\rho)}{\partial t}$$

Darcy's Law

$$v = -\frac{k}{\mu}(\nabla P)$$

Continuity Equation

$$\nabla \cdot \left(\rho \frac{k}{\mu} \nabla P\right) = \frac{\partial(\phi\rho)}{\partial t}$$

Pseudo pressure

$$m(P) = 2\int_{P_{base}}^{P} \frac{p'}{\mu(p')Z(p')} dp'$$

Diffusivity Equation

$$\nabla^2 m(P) = \frac{\phi\mu c_t}{k} \frac{\partial m(P)}{\partial t}$$

1D radial version

$$\frac{\partial P}{\partial t} = D \cdot \frac{\partial^2 P}{\partial r^2} + C \cdot q(t, r)$$

$$f(r, t, q) = \frac{\partial P}{\partial t} - D \cdot \frac{\partial^2 P}{\partial r^2} - C \cdot q(t, r)$$

Residual Equation

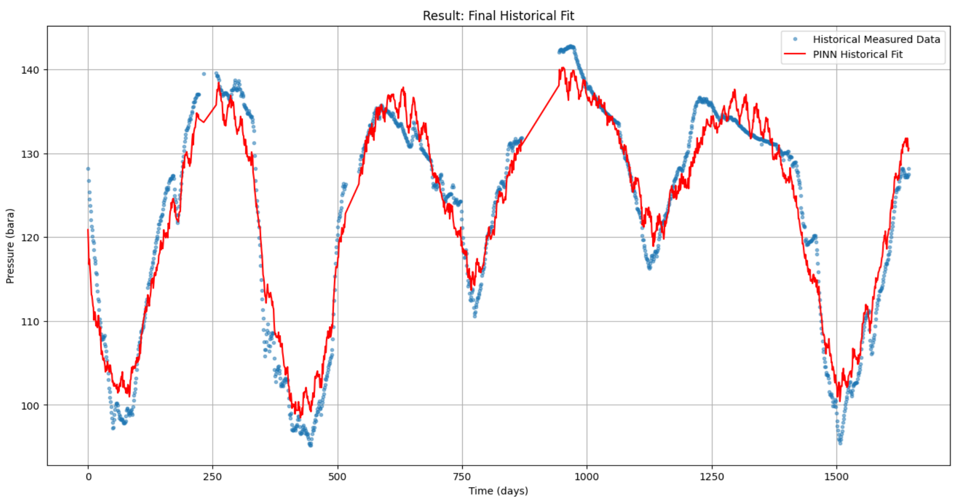
Total Loss Function

$$L_{total} = L_{data} + L_{pde}$$

$$q(t) \propto \frac{dP}{dt}$$

$$q(t) = C_{res} \cdot \frac{dP}{dt}$$

Estimating Parameters



Epoch [12000/12000], Loss: 0.8754, Data Loss: 0.004092

Final Discovered Diffusivity (D): 0.2954

Final Discovered Flow Coefficient (C): 0.9652

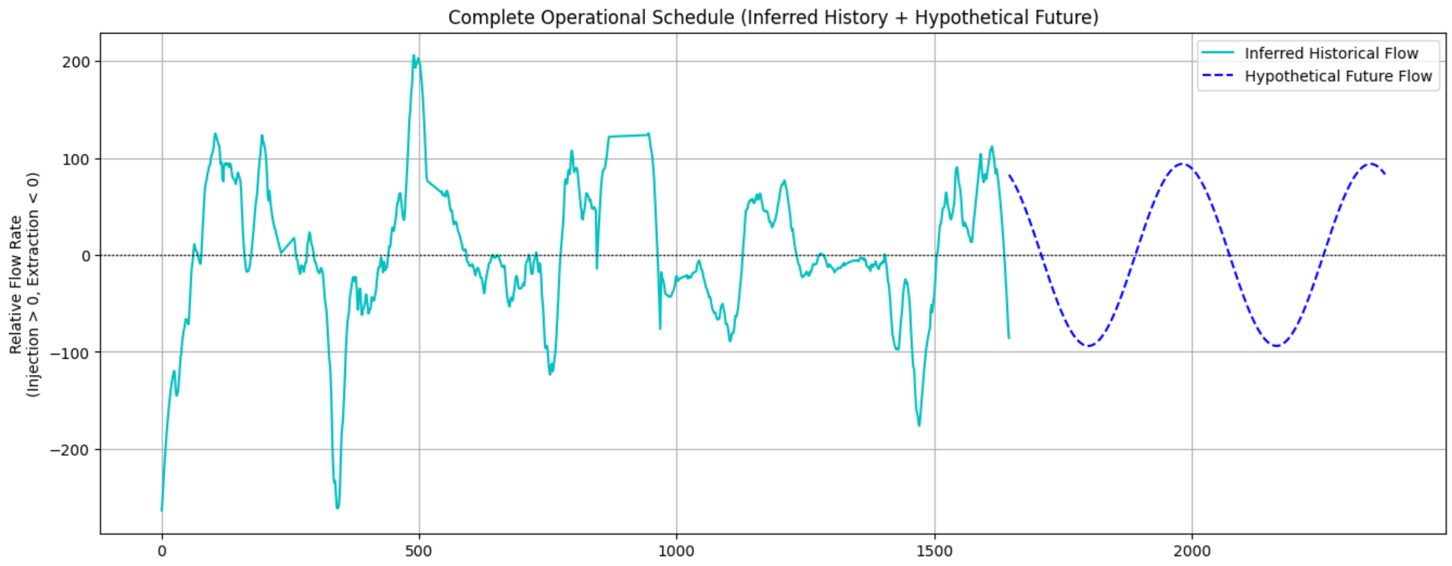
Diffusivity 1D radial Equation

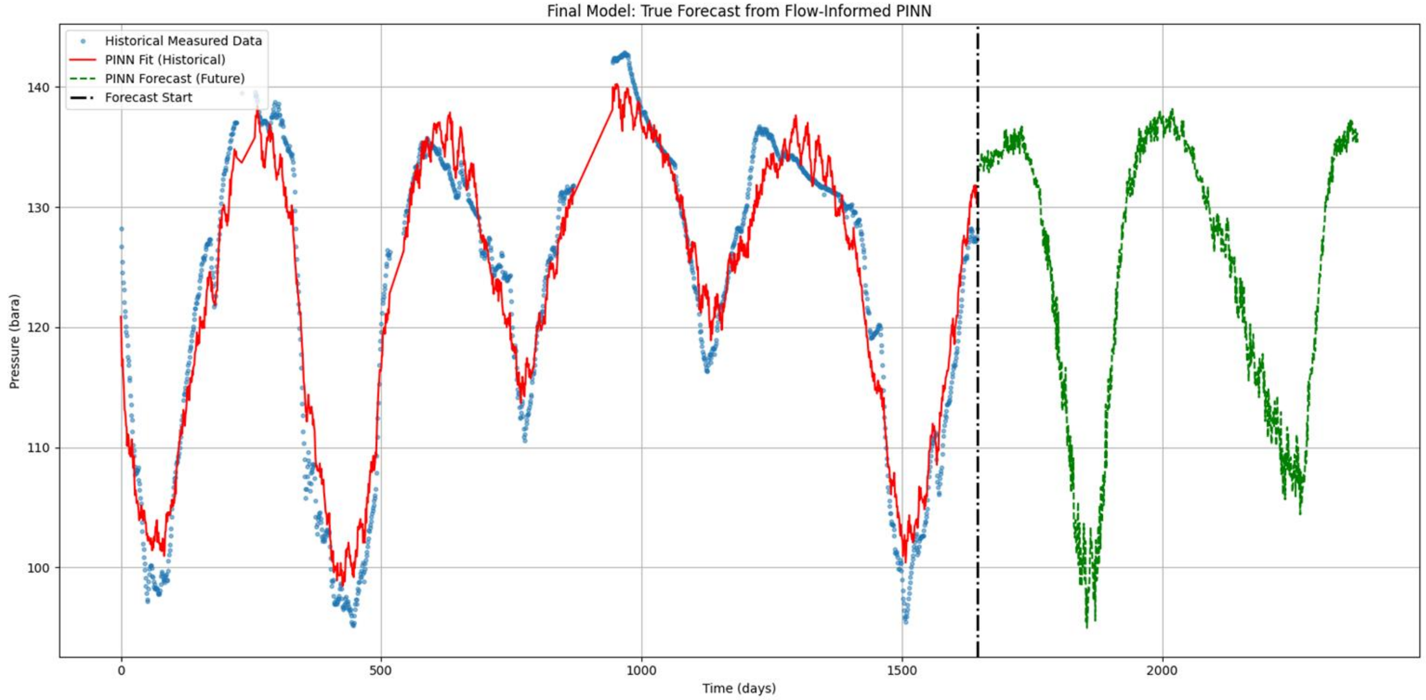
$$\frac{\partial P}{\partial t} = D \cdot \frac{\partial^2 P}{\partial r^2} + C \cdot q(t, r)$$

$$f(r, t, q) = \frac{\partial P}{\partial t} - D \cdot \frac{\partial^2 P}{\partial r^2} - C \cdot q(t, r)$$

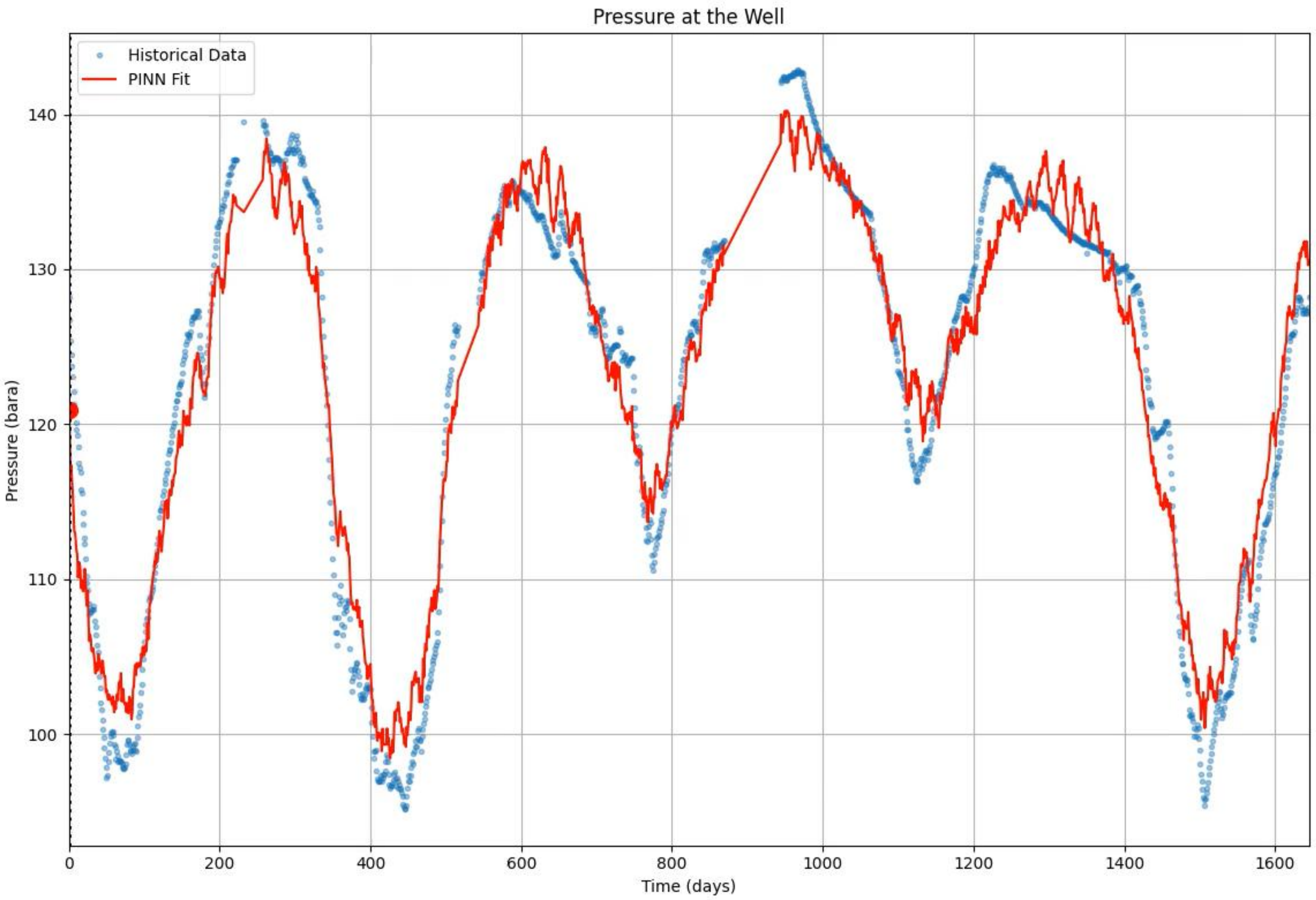
Residual Equation

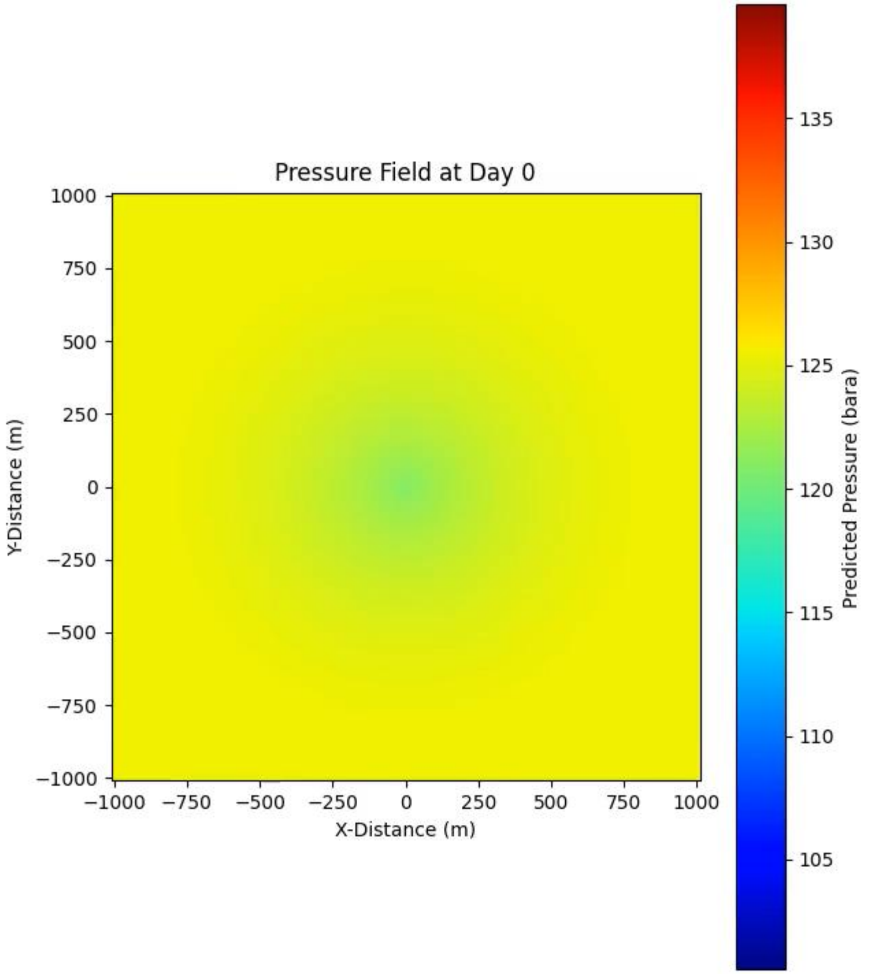
Predicting Future response





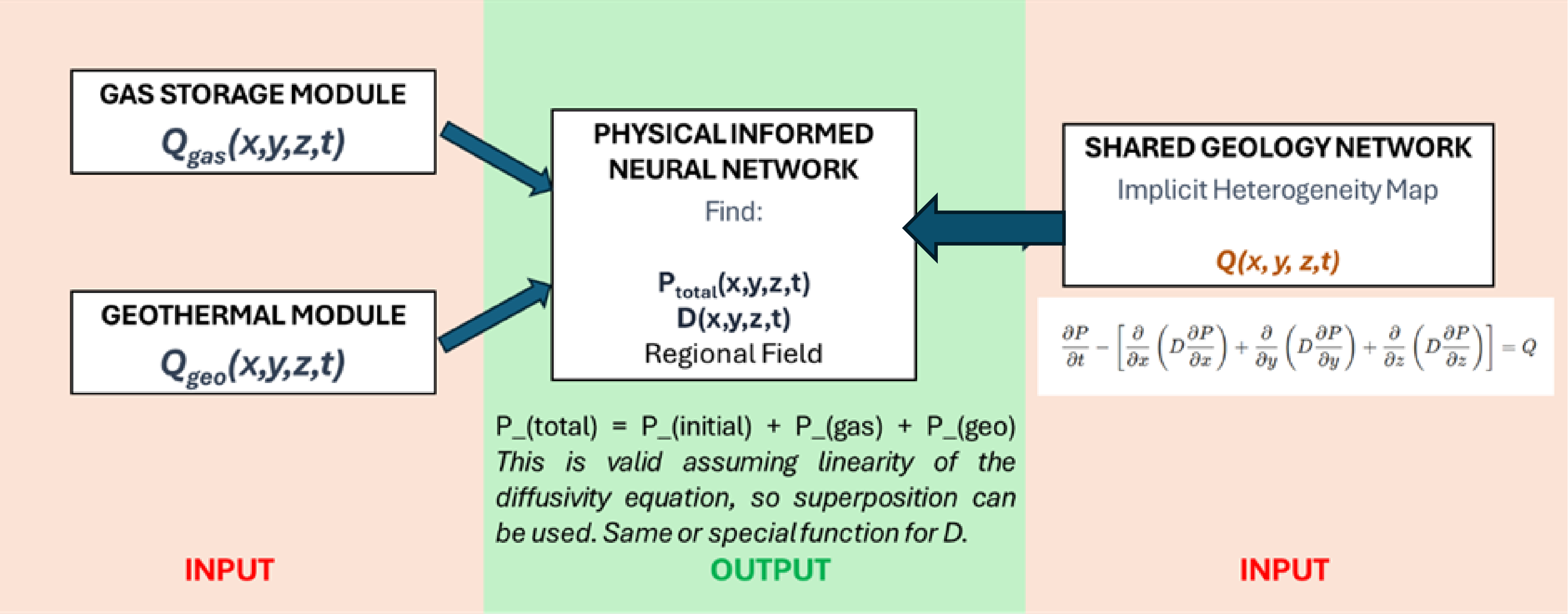
Estimating Pressure Field





The next step: Case 2

Modular PINN Framework



1. Create PINN for specific activities

2. Create the PINN for the pressure and parameters field estimation

Multifunctional Use Case in the Deep Subsurface

Discussion

DIAMONDS

Dynamic Integrated Assessment Methods

for Sustainable Development of the Subsurface

MCDA

	Alternative 0	Alternative 1	Alternative 2	Alternative 3
I	Groundwater for drinking water production & ATES	Groundwater for drinking water production & (Air) heat pumps	Surface water for drinking water production & ATES	Surface water for drinking water production & (Air) heat pumps
II	Natural gas storage & Deep geothermal energy (for district heating)	Natural gas storage & Waste burning district heating	Surface natural gas storage & Deep geothermal energy (for district heating)	Surface natural gas storage & Waste burning district heating
III	Deep geothermal energy with multiple doublet systems configuration A	DGE with multiple doublet systems configuration B	(DGE with multiple doublet systems configuration C)	(DGE with multiple doublet systems configuration D)

Useful insights?

- What do you find useful? Interesting?
- What is missing?
- Expected future insights?

Knowledge transfer tools?

- In what format would you like to receive results / insights?
- How to use the results after the project has finished?

→co-creation trajectory

→Identification of next steps

Multifunctional Use Case in the Shallow Subsurface

Geological, economic & environmental impacts

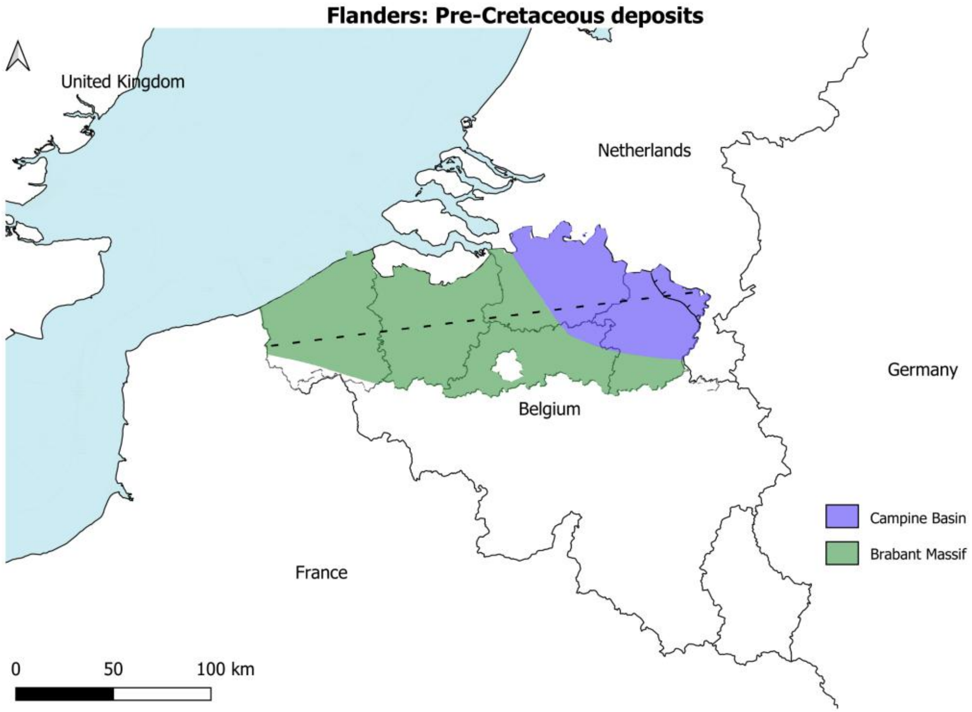
DIAMONDS

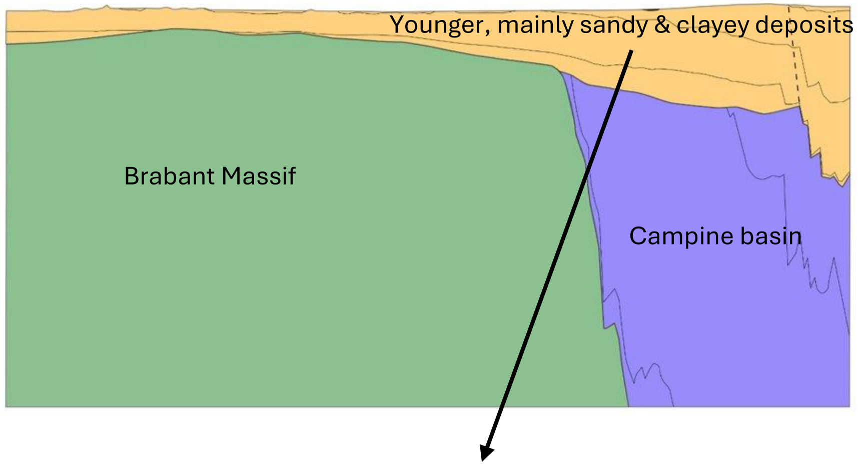
Dynamic Integrated Assessment Methods

for Sustainable Development of the Subsurface

Multifunctional Use Case in the Shallow Subsurface

ATES and groundwater extraction in the shallow sandy deposits of the Campine area

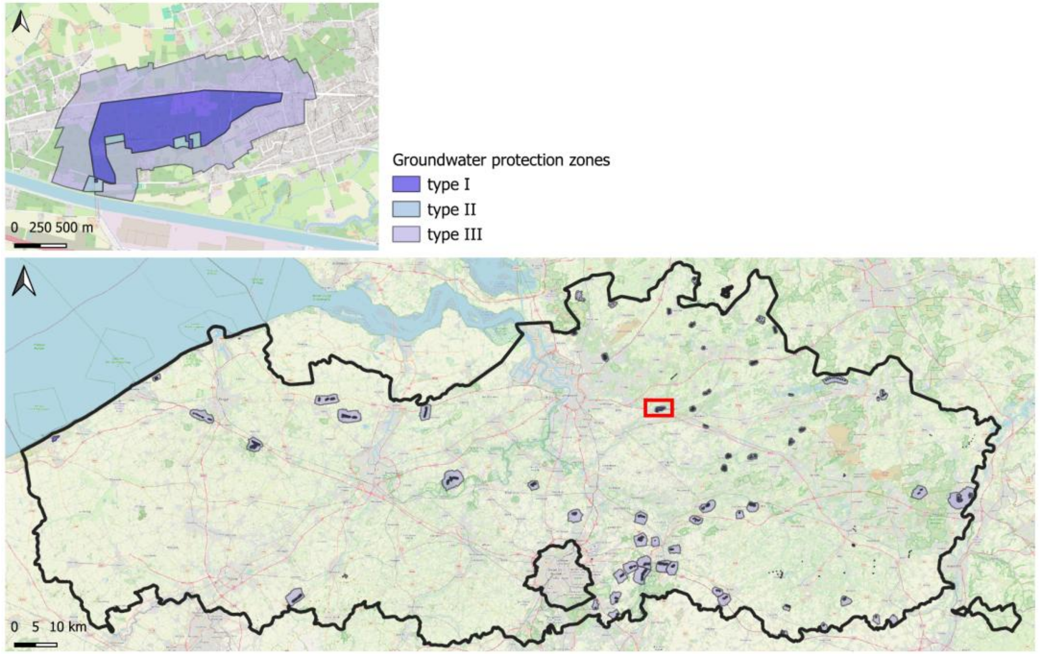





Drinking water production


Sustainable heating and cooling (with ATES)

ATES and groundwater extraction



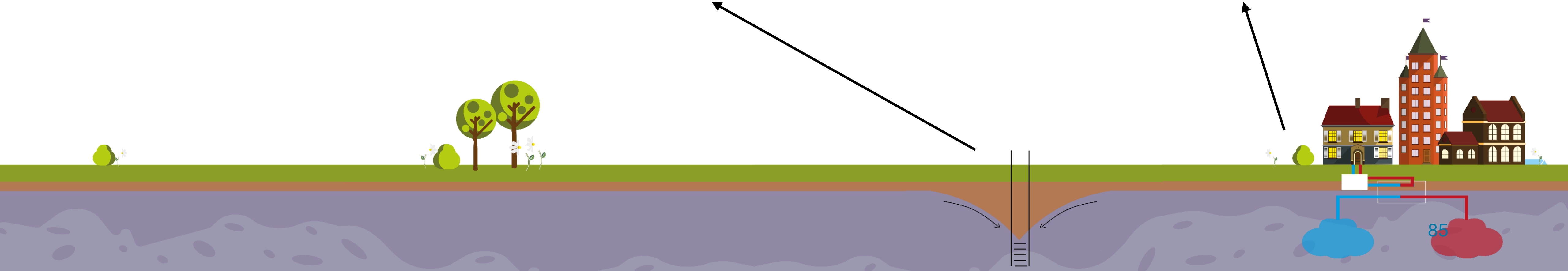
In Flanders, 40% of drinking water originates from groundwater

Aquifer Thermal Energy Storage = seasonally storing waste heat and cool in the shallow subsurface

Can provide large thermal demand (schools, hospitals, offices, neighborhoods, ..)

Needs at least 1 pair of wells
Needs a heat pump for heating, cooling can be passive

Volume of pumped water ~ energy produced



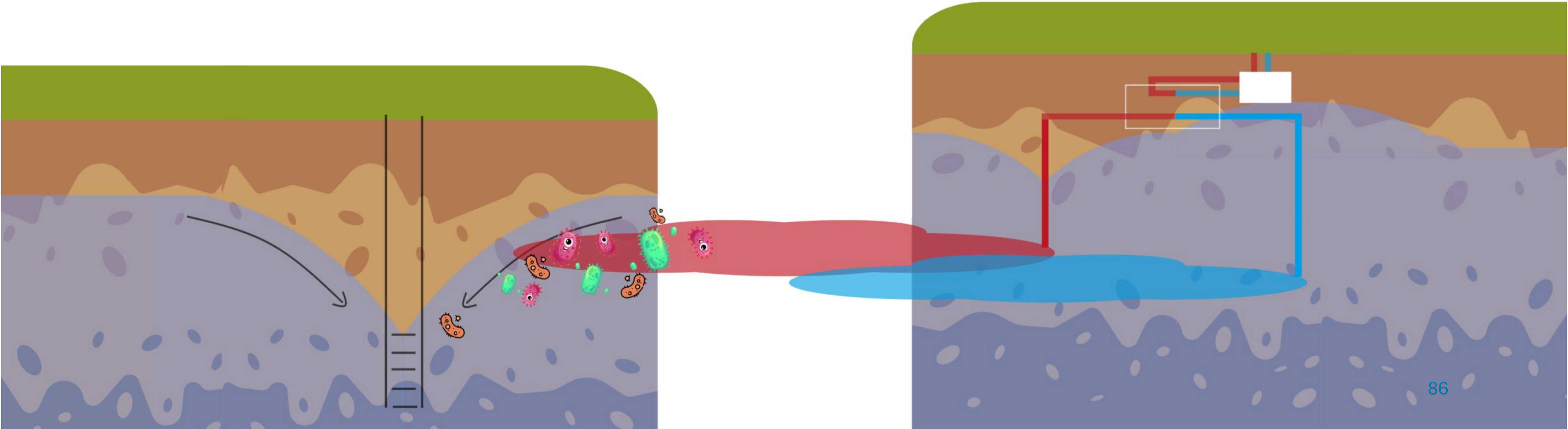
Potential inteference and interactions

determined with numerical (hydrogeological) modelling

1. Influence of introducing temperature difference in aquifer on groundwater quality

2. Influence on ATES system efficiency

3. Influence of drillings on confing layer integrity (risk of contamination)



Shallow Subsurface

WP 2 & 3: Geological impacts

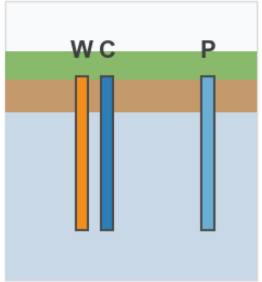
Zerui Mi & Luka Tas

1. Thermal interference assessment

Identify where ATES operation is favorable, conditional, or unfavorable near a drinking-water pumping well

Step 1

Define System Setup



Pair a drinking water pumping well with an ATES warm/cold doublet.

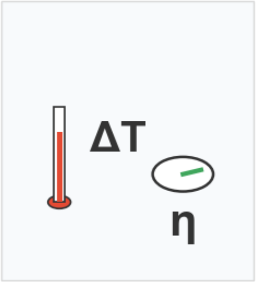
Step 2

Adjust System Parameters

Test different parameters: R, I, K, Q...

Step 3

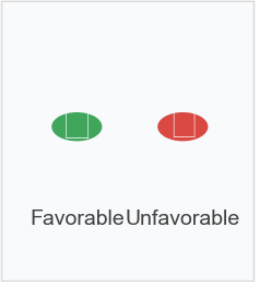
Monitor Key Indicators



Assess temperature rise at the well and overall thermal efficiency.

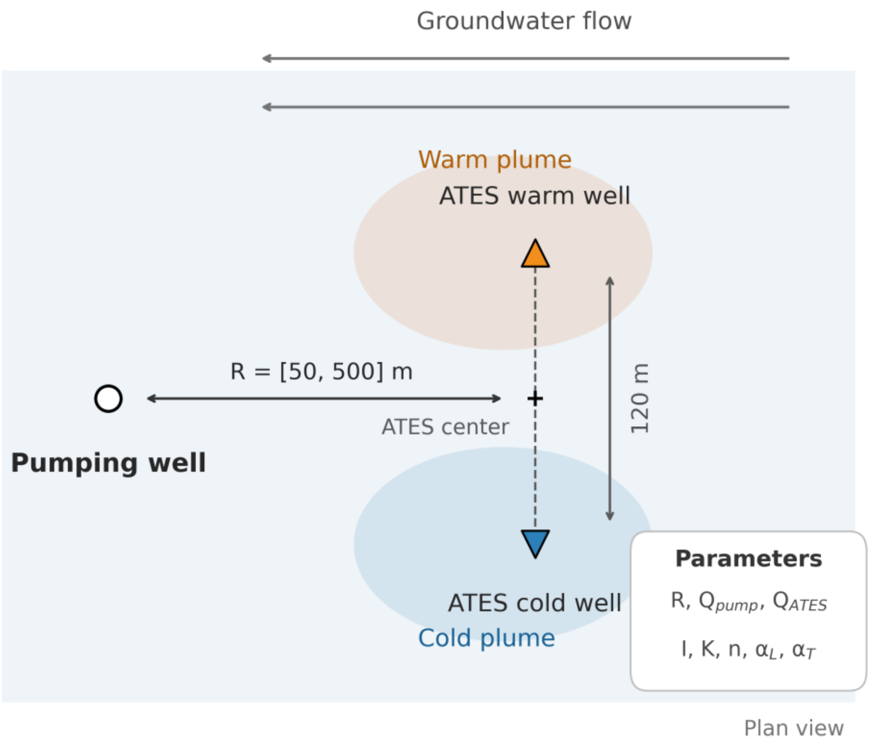
Step 4

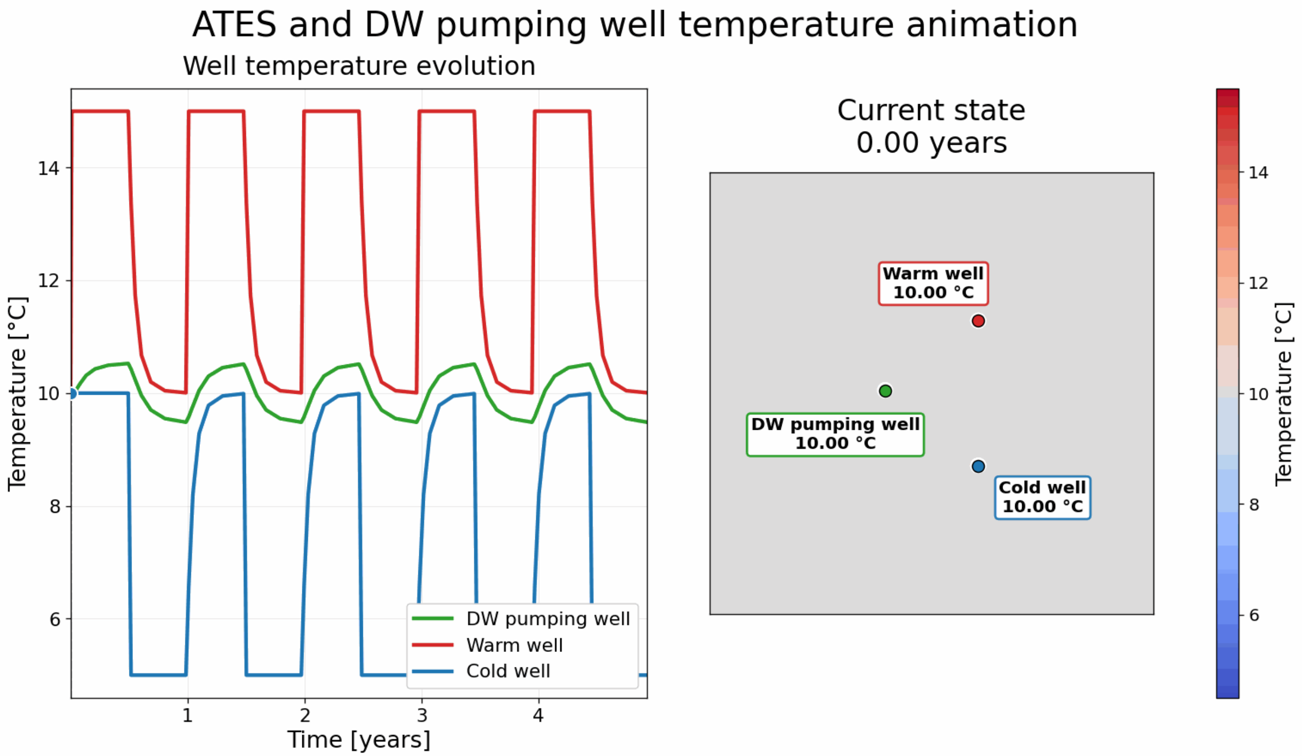
Evaluate Site Suitability



Determine if the site is favorable\ unfavorable\ conditional

Conceptual model, key parameters, and response indicators



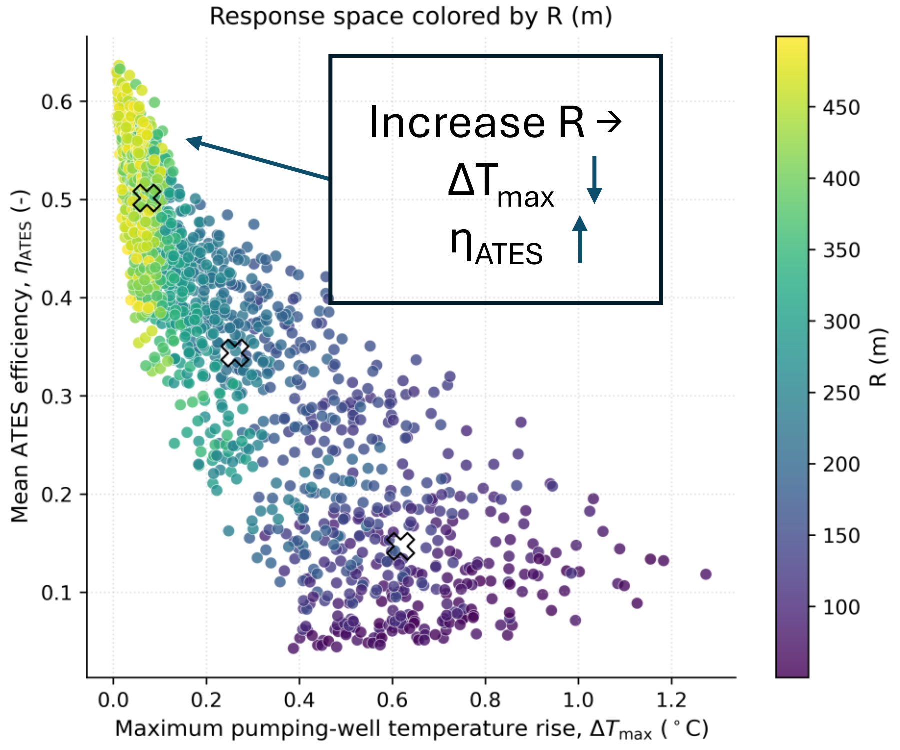


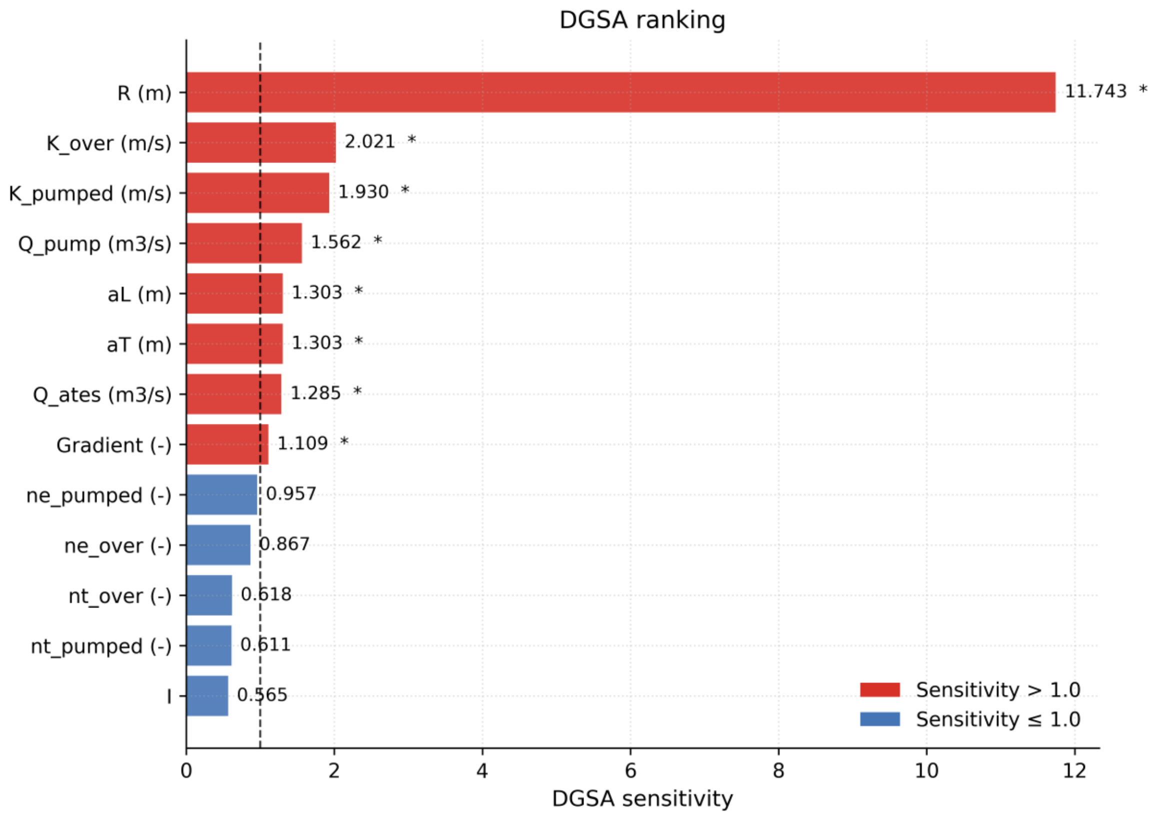
Inputs: geometry + operation + aquifer properties

Outputs:

- ΔT_{max} of DW pumping well
- η_{ATES} of ATES

Thermal interference is primarily distance-controlled



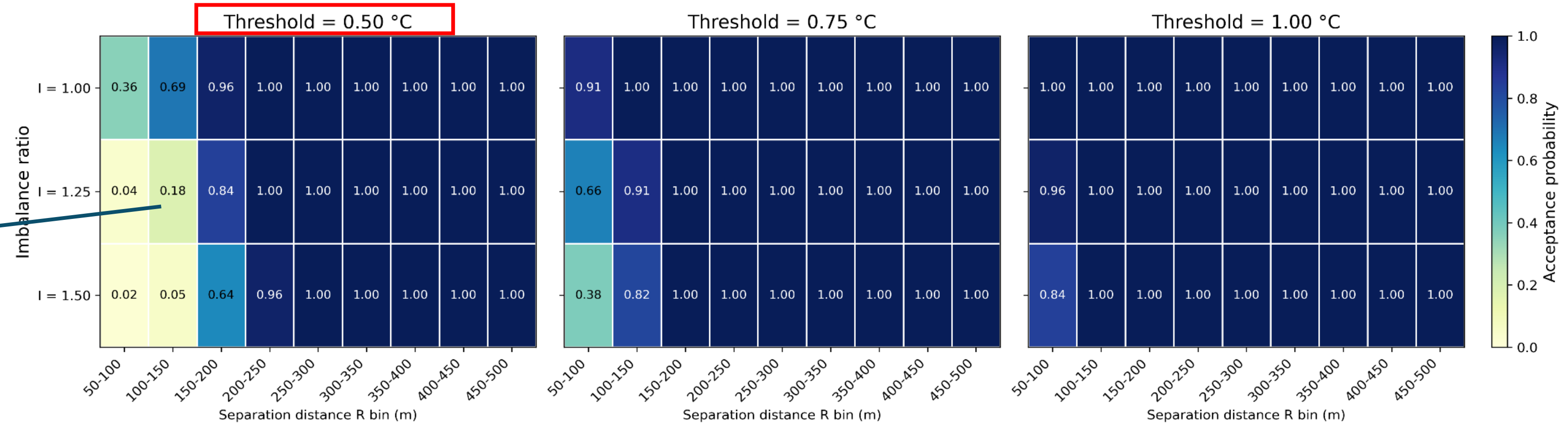


- Distance is the dominant control, while aquifer properties and operating parameters mainly impact the response within a given distance range.

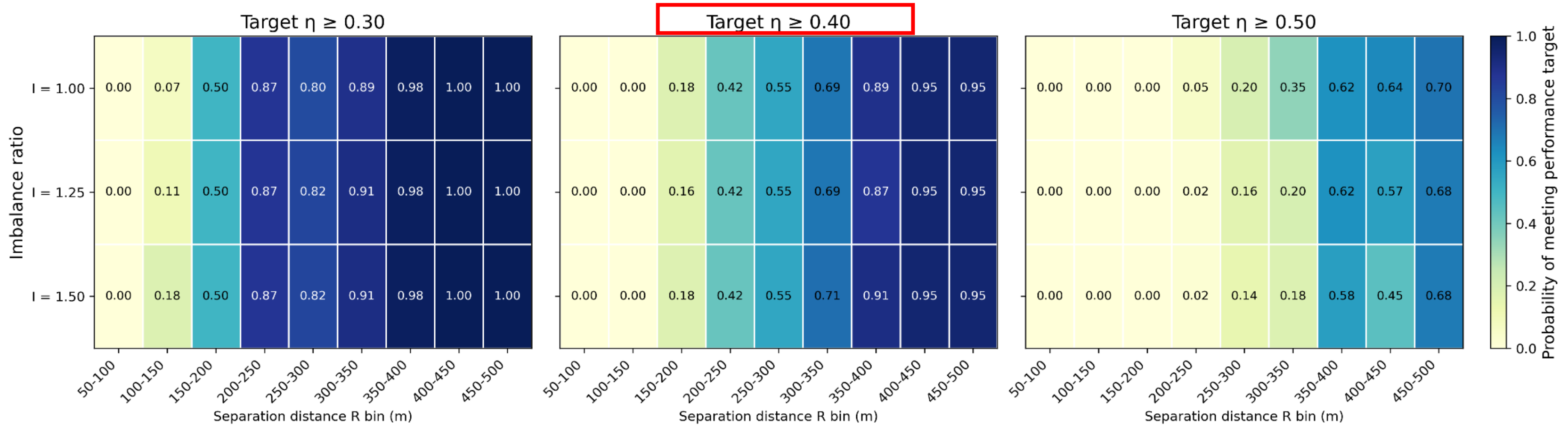
Thermal threshold and performance target choices

- **Temperature-rise threshold**

For each distance R and imbalance ratio I, each panel shows how often the simulations meet the selected threshold or target



- **ATES Efficiency target**



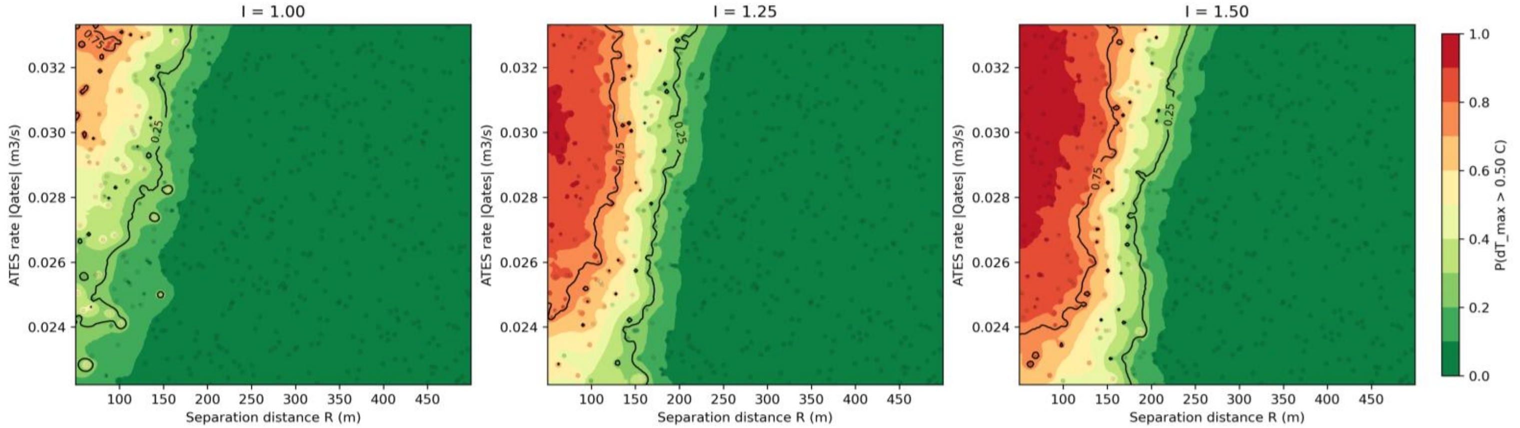
- **Different threshold and target choices lead to different acceptable ranges, and therefore to different zoning results.**

Thermal risk and ATES performance in (R, Q_{ATES}) space

- **Illustrative case: $\Delta T_{max} \leq 0.5\ ^\circ C$ and $\eta_{ATES} \geq 0.40$**

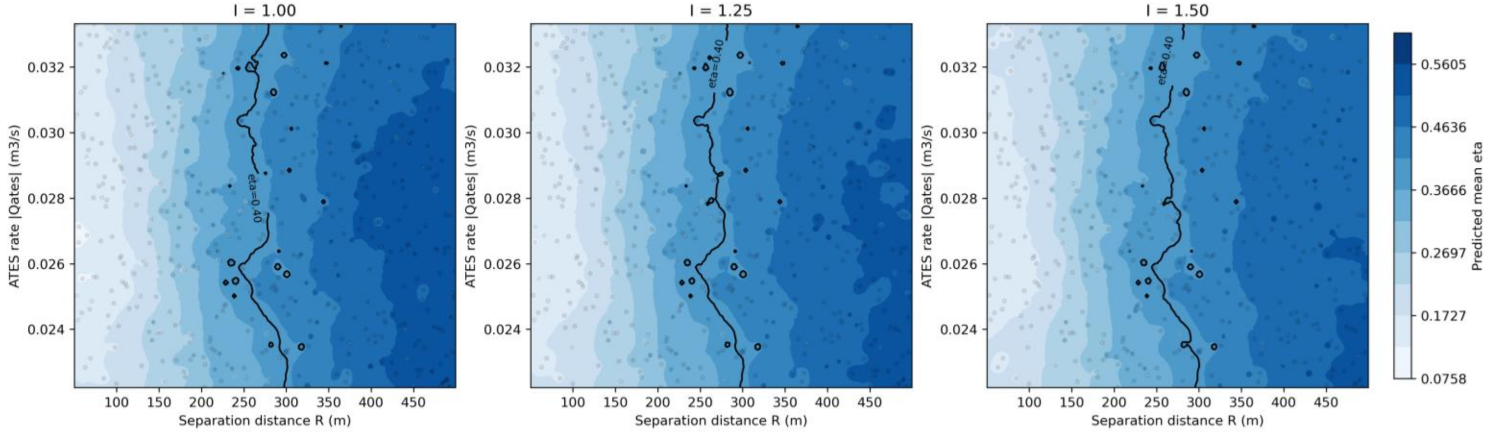
Thermal risk surface

- Risk decreases with distance
- Higher imbalance shifts the risk boundary outward



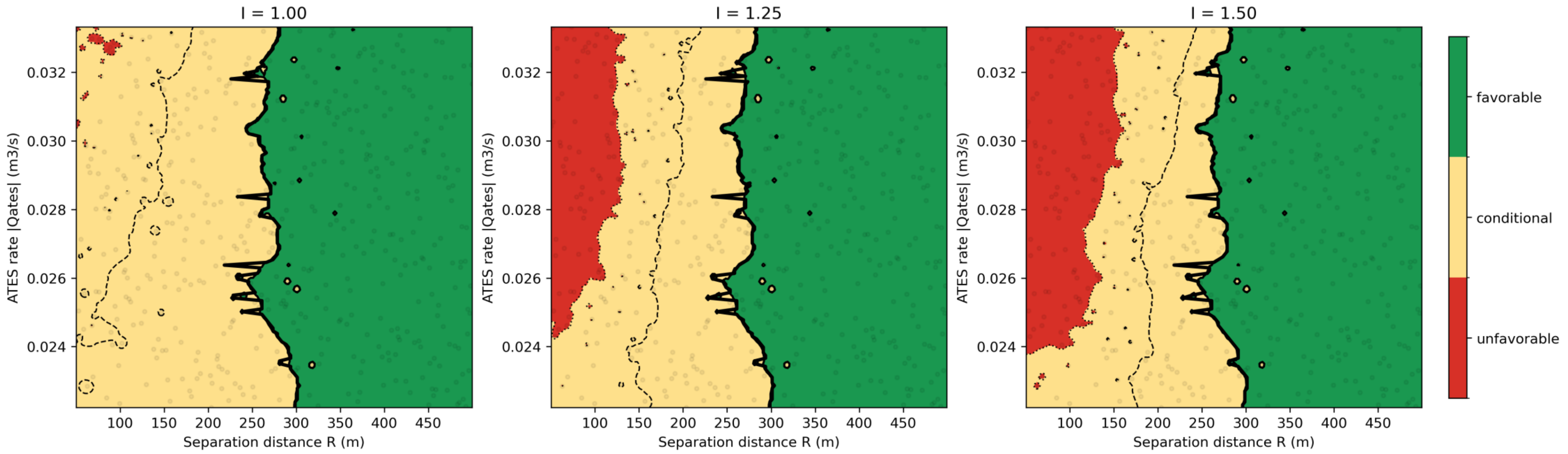
Performance surface

- Continuous η response
- Performance improves with distance



Next step: combine both surfaces into zoning map

Risk-performance zoning in (R, Q_{ATES}) space



Zoning logic

- **Favorable:** low thermal risk + $\eta \geq 0.40$
- **Conditional:** one objective is met, but the other is marginal or not met
- **Unfavorable:** high thermal risk + $\eta < 0.40$

How to read the map

- For a fixed Q_{ATES}: find the minimum required separation distance
- For a fixed R: find the maximum allowable ATES pumping rate

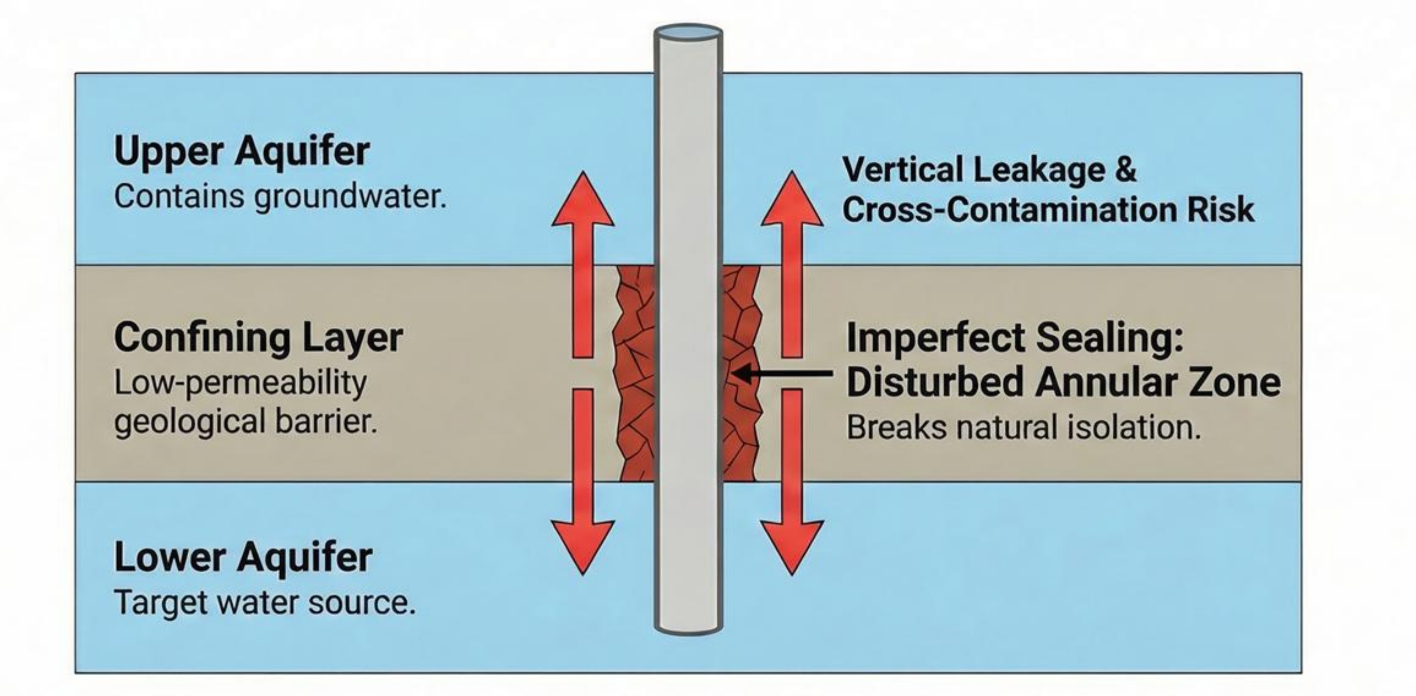
Conditional zone = operate with controls

- Reduce Q_{ATES}
- Reduce seasonal imbalance
- Apply monitoring or staged permitting

2. Preliminary assessment of drilling-induced leakage

Conceptual concern

- A pre-existing contaminant plume is assumed in the shallow aquifer, for example PFAS
- Imperfect sealing may create a vertical leakage pathway across the confining layer
- ATES operation may modify hydraulic gradients and transport along this pathway

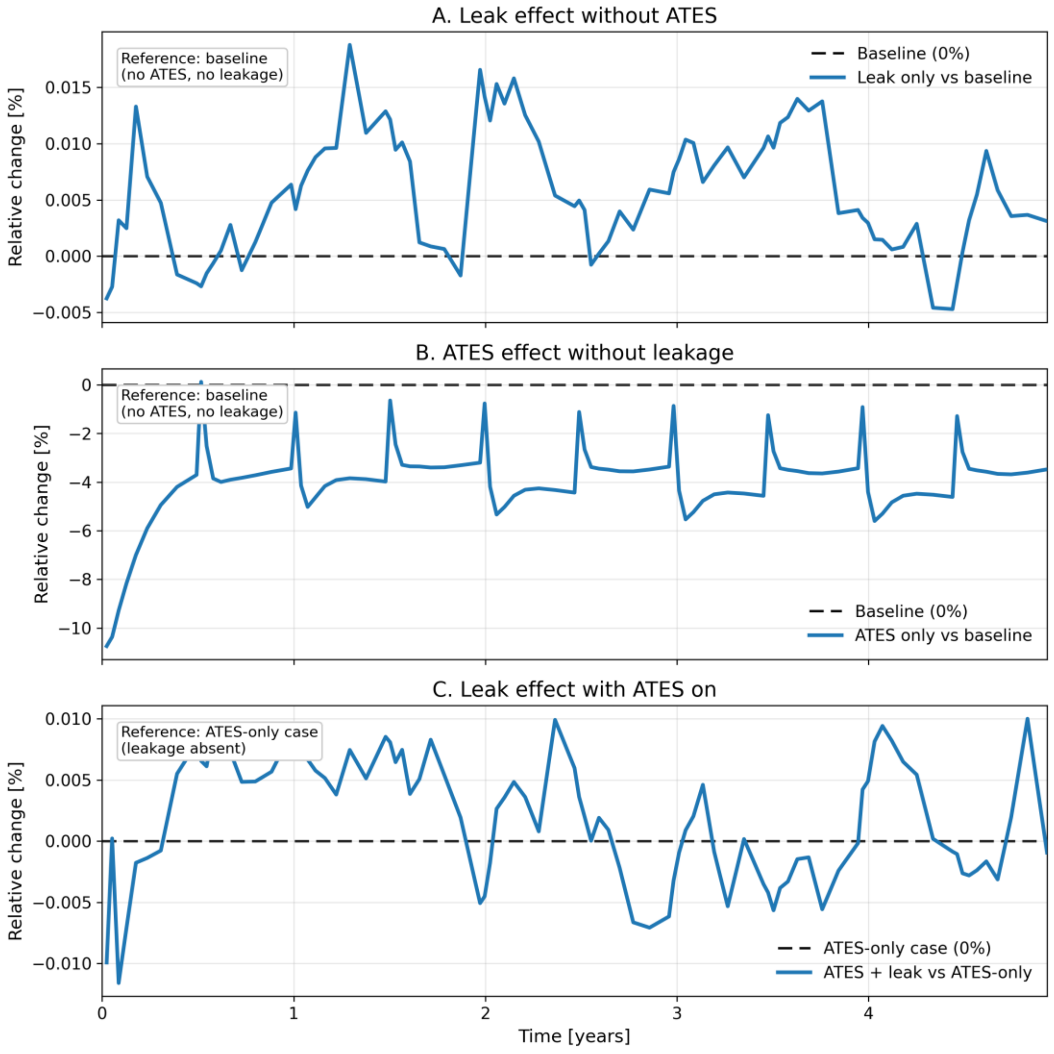


- Does drilling-induced leakage change contaminant concentration at the drinking-water pumping well under ATES operation?

Four-case comparison of drinking-water-well concentration under background migration, ATES, and added leakage

Cases compared

1. **Baseline (reference) :** no ATES, no added leakage, natural background concentration at DW well
2. **Leak only:** added leakage, no ATES
3. **ATES only:** ATES operation, no added leakage
4. **ATES + leak:** ATES operation with added leakage

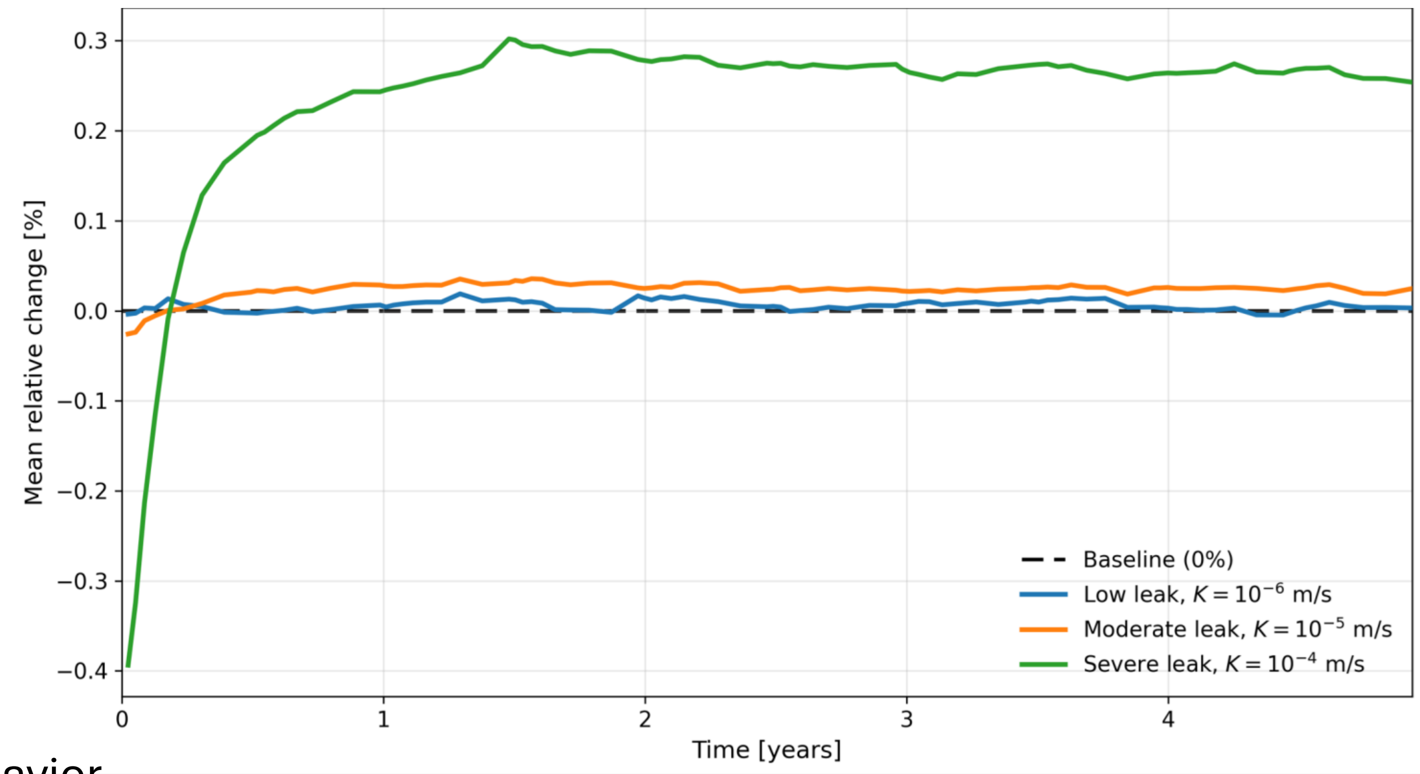


Key observations

- Leakage alone causes only a small relative deviation
- ATES operation produces the clearest and most periodic relative signal
- Adding leakage on top of ATES leads to only a limited extra change in this setup

Effect of leakage-path conductivity

- Low-conductivity pathway: negligible effect
- Moderately conductive pathway: limited effect
- Highly conductive pathway: clear deviation, but still modest in relative terms



Only highly conductive pathways produce a clearly visible signal in this simplified setup.

Next steps for leakage assessment:

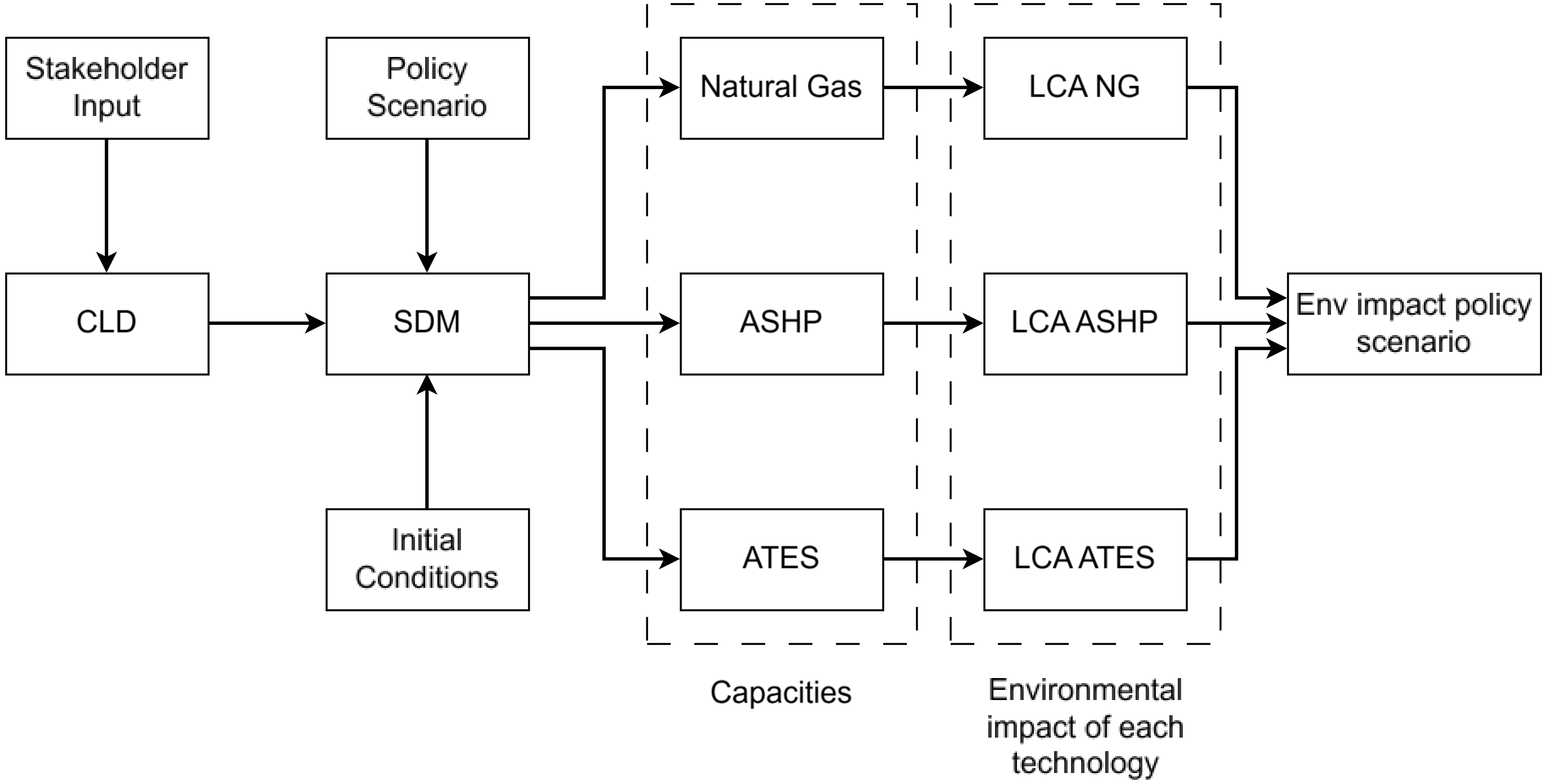
1. Move from relative signal to breakthrough behavior
2. Resolve transport mechanisms
3. Move toward realistic leakage pathway

Shallow Subsurface

WP 5b: Environmental impacts

Alexander Van Overmeiren

WP5b – Overview Work Package



WP5b – System Dynamic Model

- **Goal:** to understand and simulate complex, time-dependent, and feedback-intensive interactions between above and below ground subsystems

1. **Between economically competing** technologies: ATES, natural gas and air source heat pumps

2. Simulate ATES and groundwater extraction (GW) **interactions** quantitatively ➔ **Regulatory effects,** for example limits to the number of ATES wells

3. Perform policy scenario analysis and its influence on ATES adoption and the general renewability of the heating/cooling technology stock

WP5b – SDM – Economic Competitiveness and Decisions

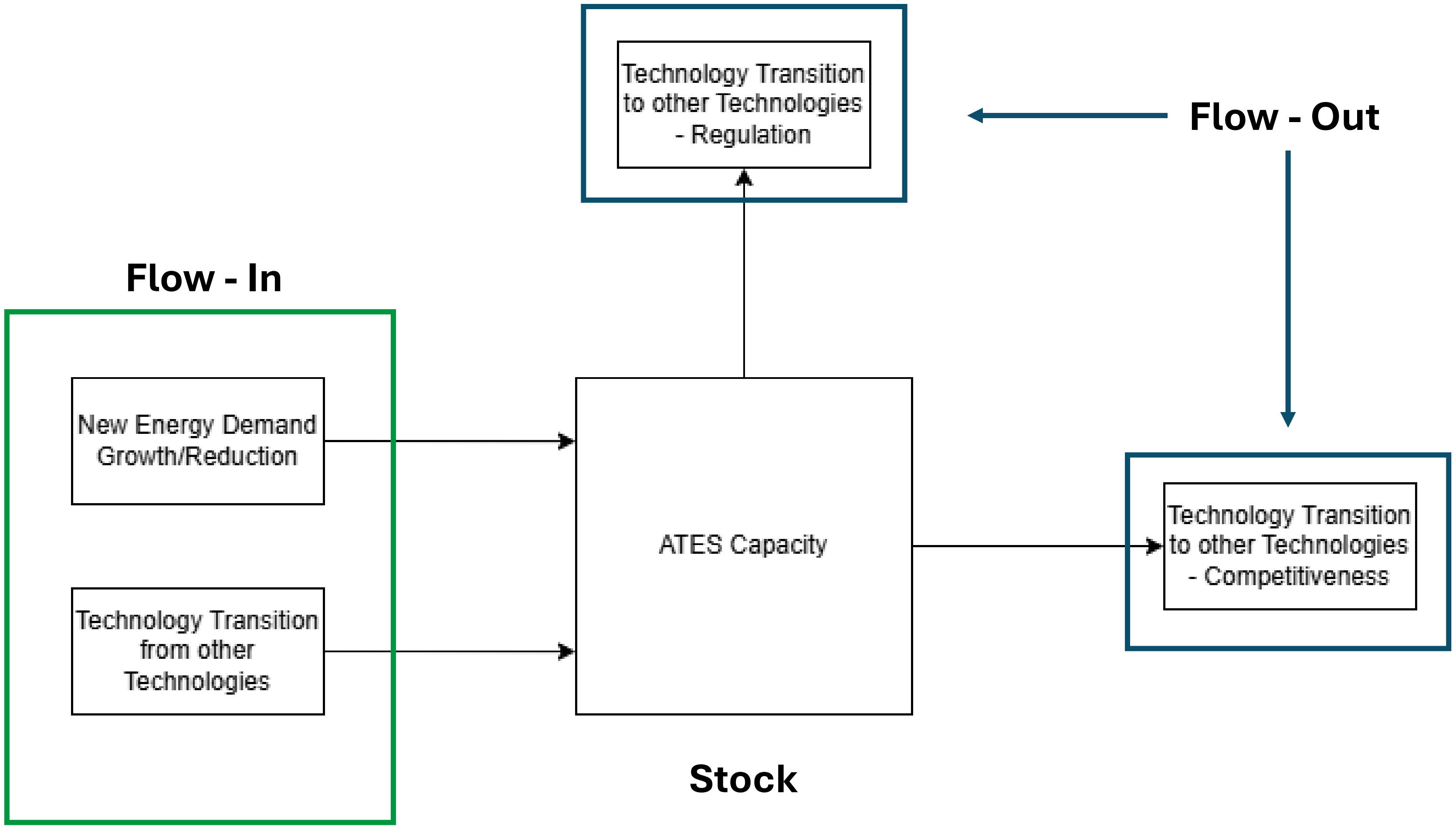
- In this model, **two decisions** are made in each time step by users.

    1. Do people **keep** their current technology ➔ NG still competes

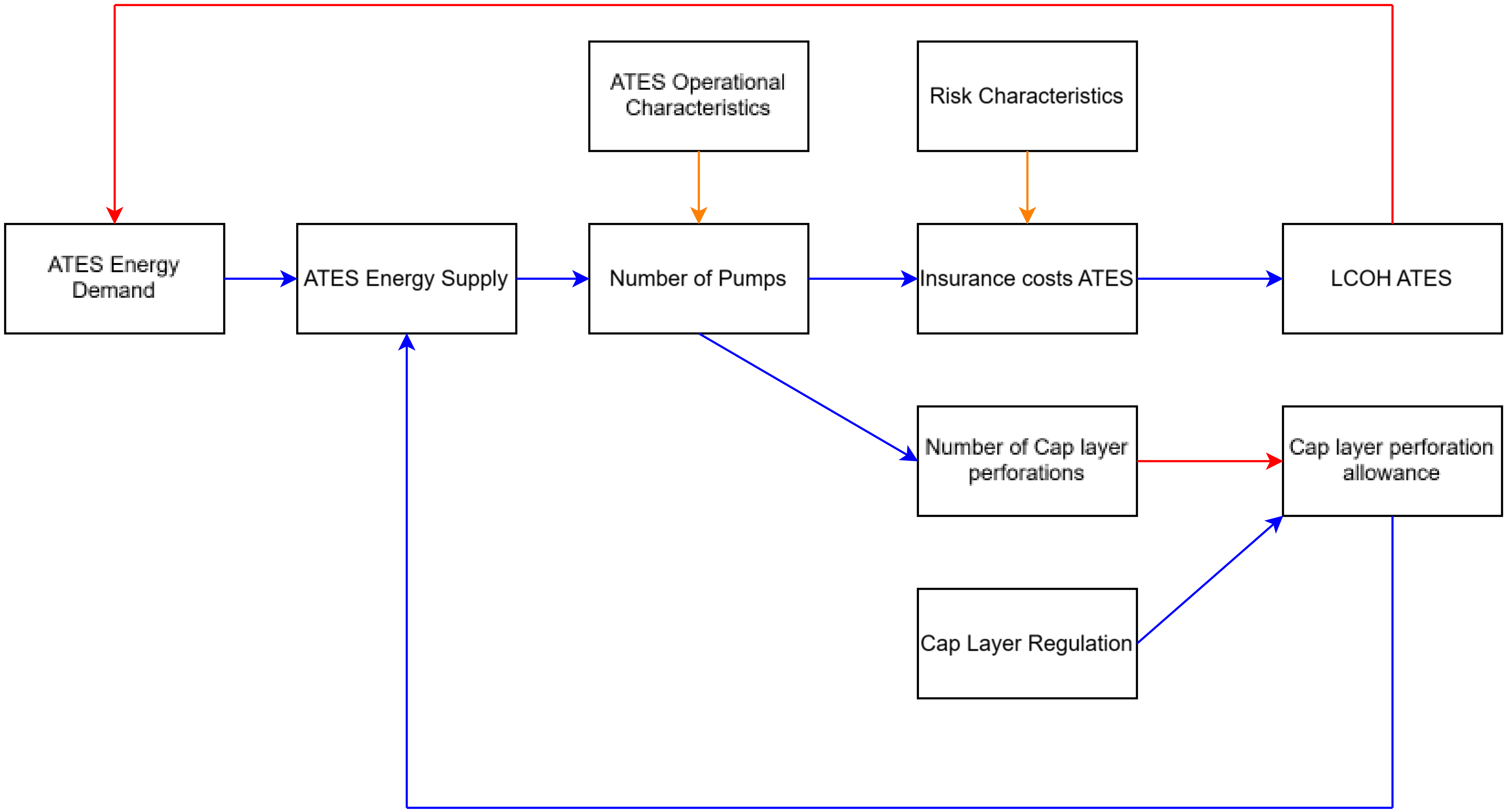
    2. New **energy supply** has to be a renewable option, in accordance to regulation ➔ NG does not compete anymore

- Recent iteration: heating and cooling demand are integrated.

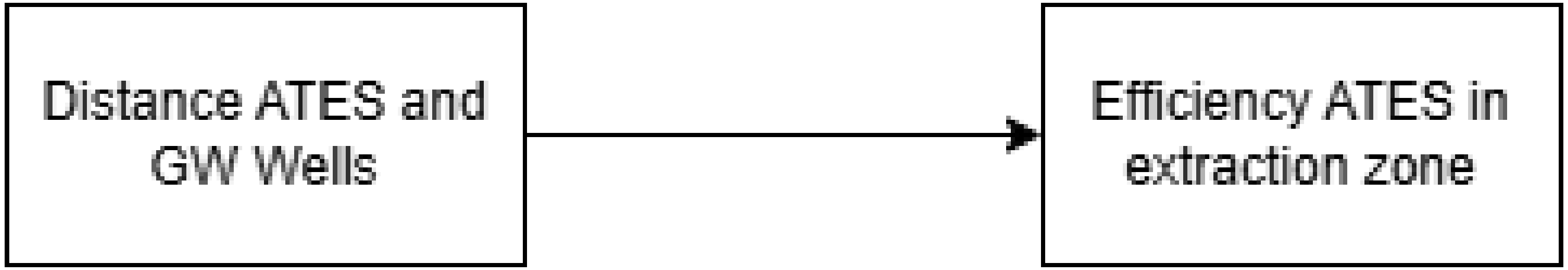
WP5b – SDM – Technology Transition



WP5b – SDM – GW Quality



WP5b – SDM – GW Quantity

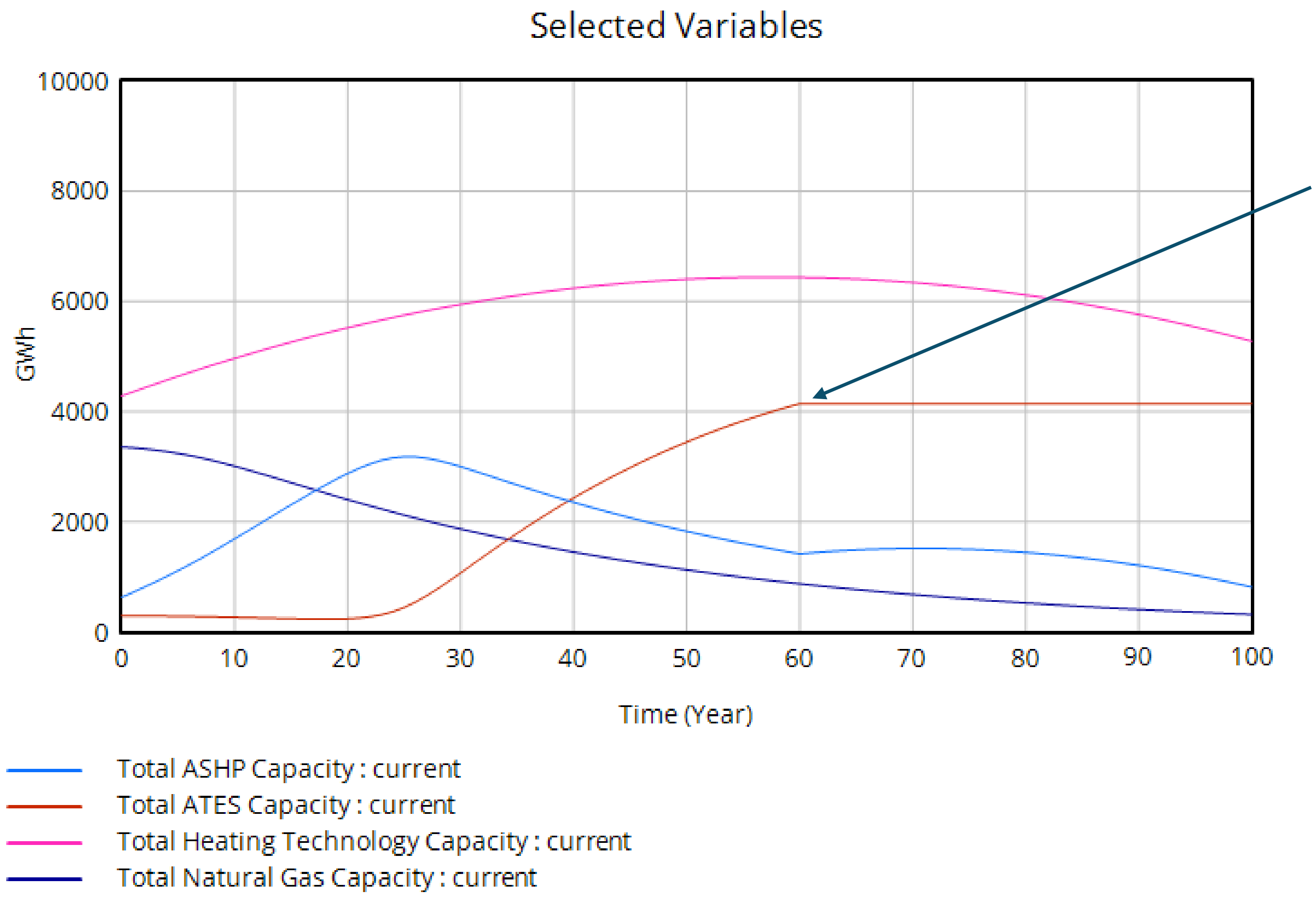


WP5b – SDM – Challenges

- Finding a quantitative interaction between ATES and GW

- Suggestions:
  - ATES → GW: Well failures and increased contamination risks.
    - Regulatory limit on # of wells/km^2
    - Insurance system in the style of fuel oil schemes such as Promaz
    - Changes in ion-concentrations ➔ Internalize added treatment costs
  - GW → ATES
    - Reduced efficiency due to the movement of heat/cold plumes

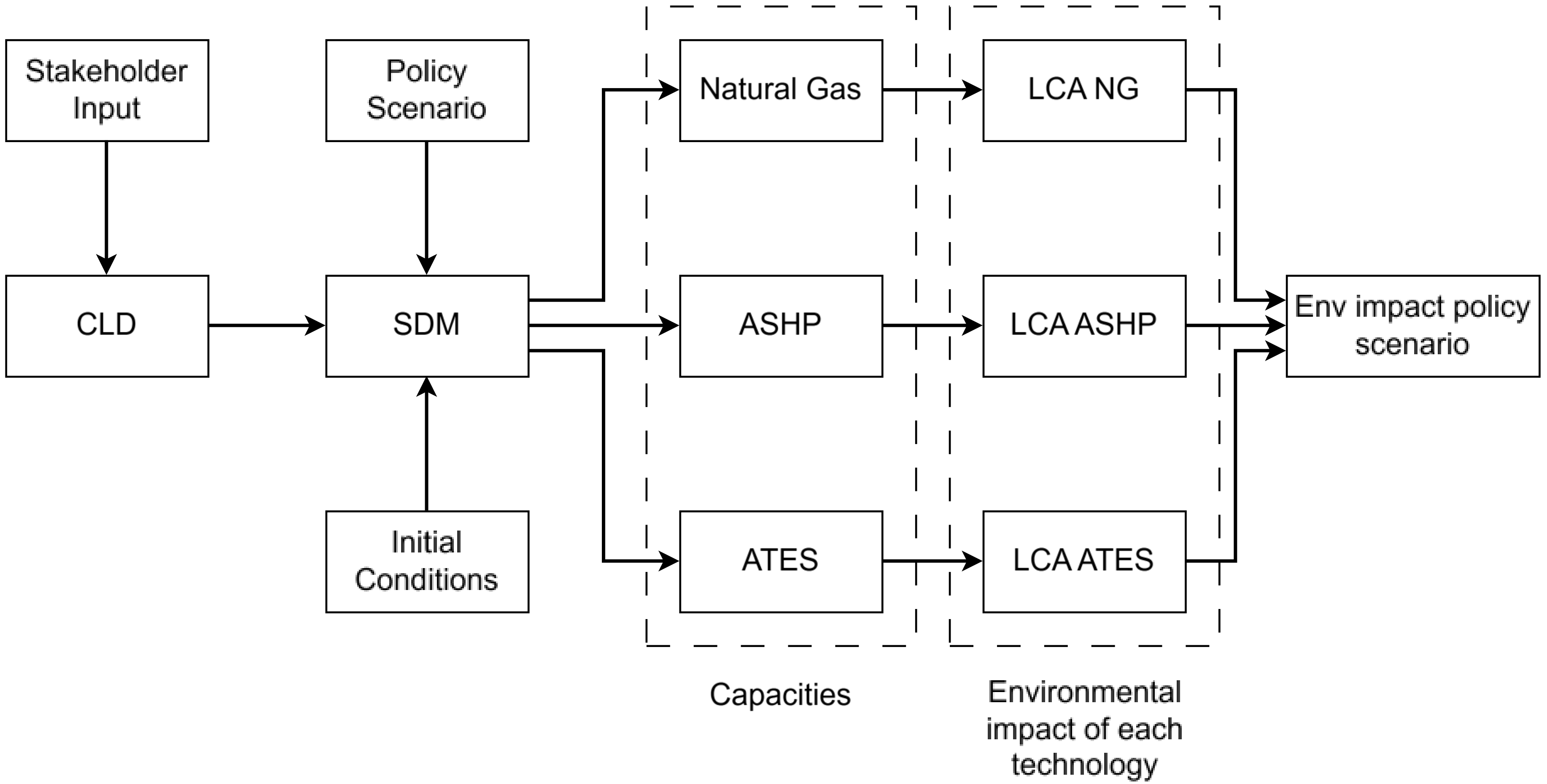
WP5b – SDM – Proof of Concept



Max # of perforations reached

WP5b – LCA of Policy Scenarios

- LCA of policy scenarios can be calculated using LCAs of each technology in combination with their adoption rate.



Shallow Subsurface

WP 5a: Economic impacts

Hanne Lamberts-Van Assche

Economic evaluation

Assess the **economic impacts** of the multifunctional use of the shallow subsurface

Integrate **uncertainties**

(e.g., electricity price, temperature)

Account for **flexibility**

(e.g., delaying investment)

Consider **strategic interactions** between subsurface actors

Groundwater extraction

- Extracts **groundwater** for the production of drinking water
- Monitors **groundwater quality** & **temperature difference** drinking water well

ATES

- Store and retrieve **thermal energy** in the aquifers
- Concerned with the **efficiency** of the ATES system & **temperature difference** ATES wells

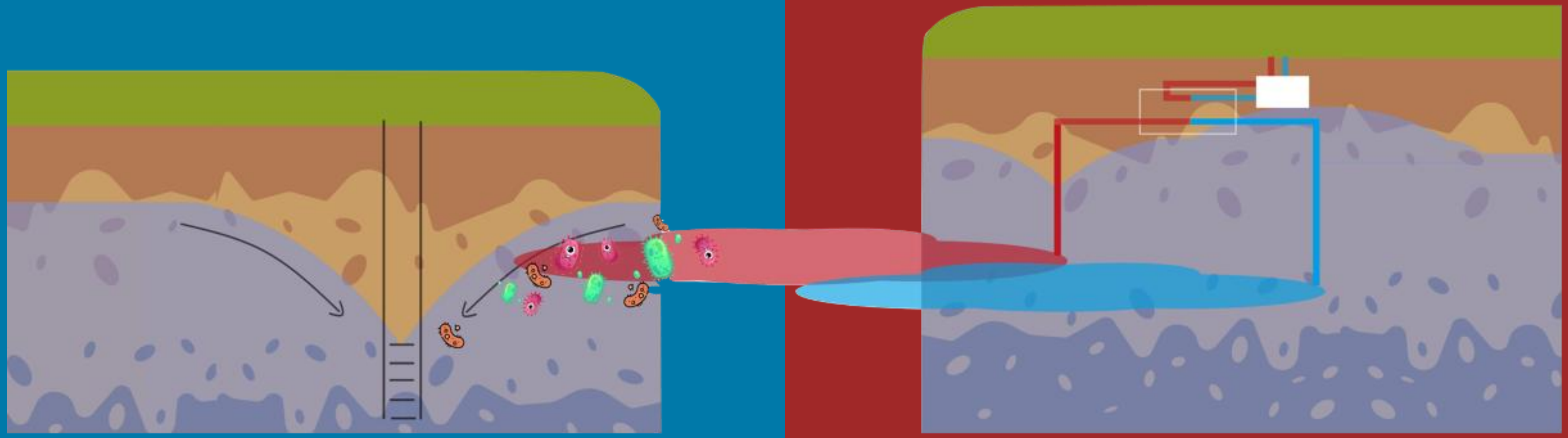
Multifunctional use

Water company

- **Operates existing** groundwater extraction wells

ATES

- Wants to **drill new ATES wells** due to a local heat demand



Risk of contaminants is increased due to drilling and temperature changes

Storage of thermal energy can be disturbed due to groundwater flow

Multifunctional use – Stage 1

Water company

- **Operates existing** groundwater extraction wells

ATES

- Wants to **drill new ATES wells** due to a local heat demand
- Decides on the **number** of ATES wells to be drilled

Multifunctional use – Stage 2

Water company

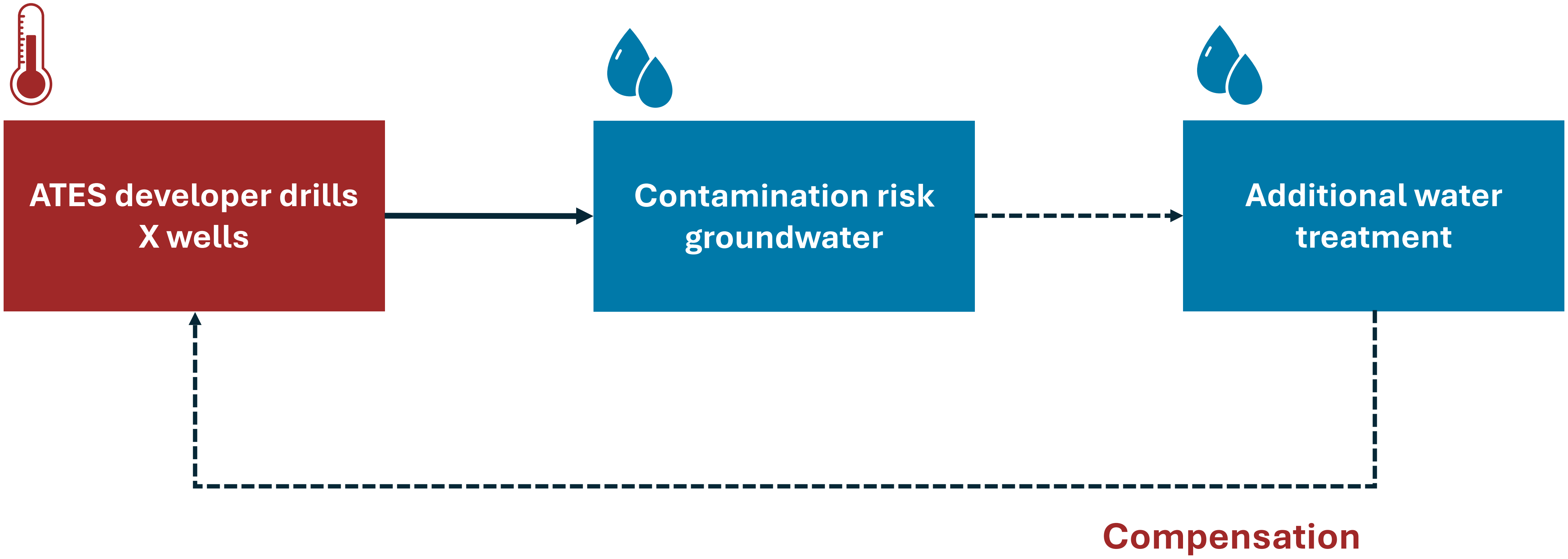
- **Operates existing** groundwater extraction wells

ATES

- **Operates ATES system** for the seasonal storage of thermal energy

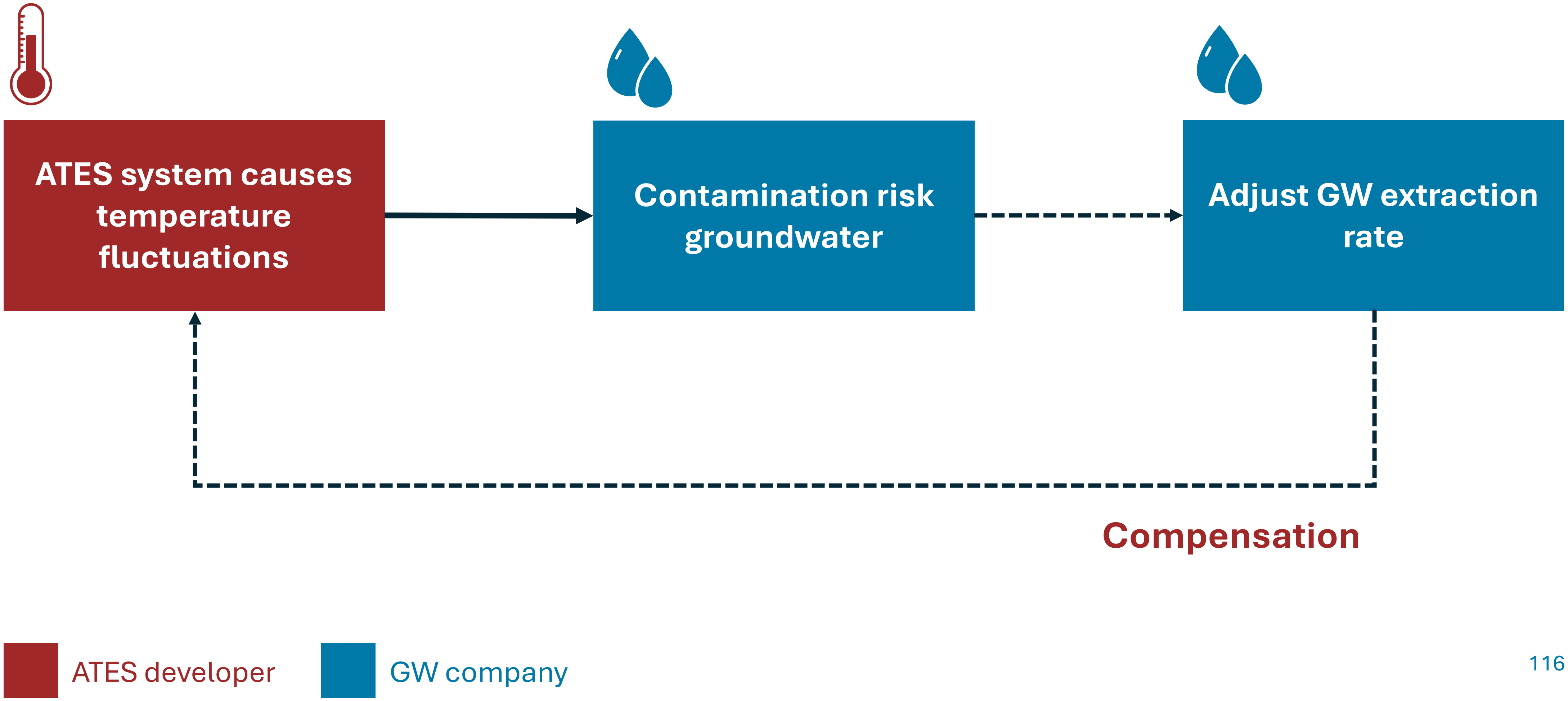
Compensation mechanism

Interactions (Stage 1)

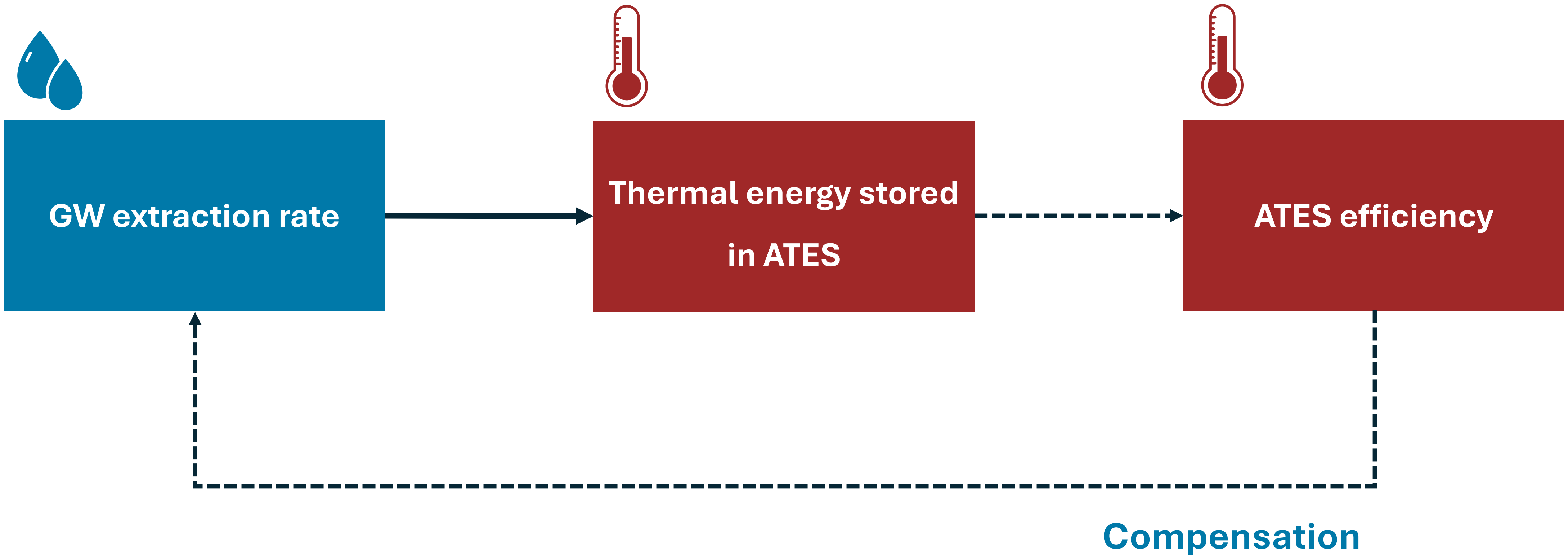


ATES developer GW company

Interactions (Stage 2)



Interactions (Stage 2)



ATES developer GW company

Multifunctional use

Water company

- Impact on **groundwater quality?**
- Impact on **groundwater extraction rate?**

ATES

- Impact on **timing of ATES development?**
- **Number of wells?**
- **ATES efficiency?**

Compensation mechanism

What’s next?

- **Development of the Real Options Game**
  - Research stay NTNU Trondheim Spring 2026
- **Play card game to explore compensation mechanisms**
  - Next on the agenda!

Shallow Subsurface

An interactive session

Let’s play a card game!

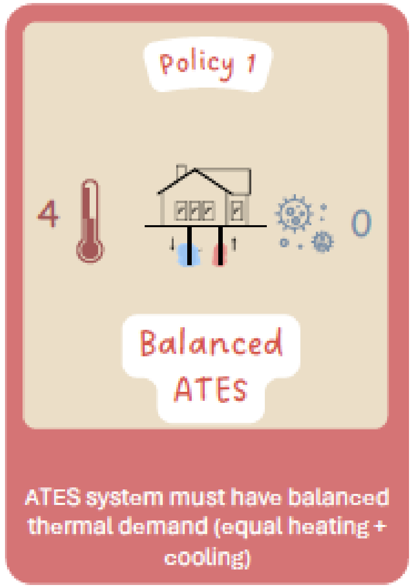
You’ll be divided in smaller groups of 4-5

1 drinking water team (2 people)

1 ATES team (2 people)

GOAL

Together reach the objective of
1 of the 3 policy pathways



Let’s play a card game!

There will be four rounds

1 drinking water team (2 people)

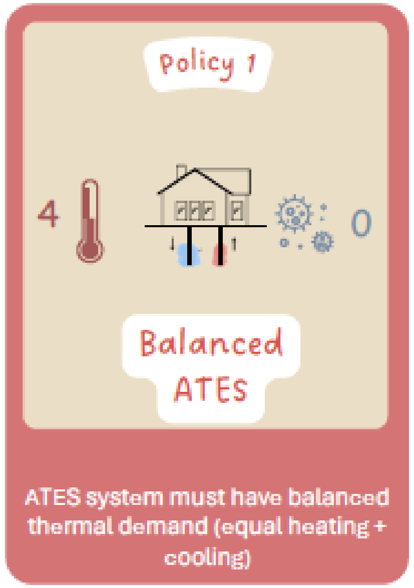
Round 1: set the scene

Round 2: play policy cards

Round 3: play investment decision cards (operational/indicator)

Round 4: compensation

1 ATES team (2 people)

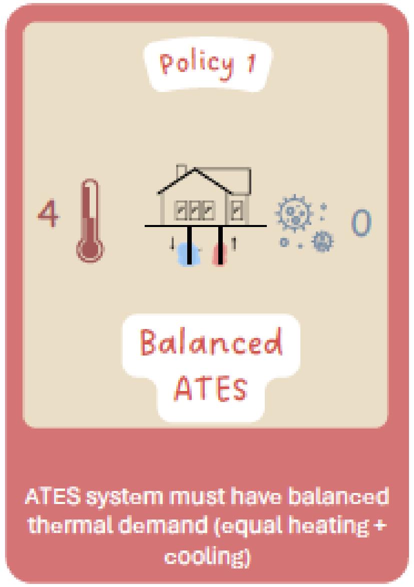


Let’s play a card game!

Name of the round during which this card can be played

Amount of energy/pollution/insurance fund gained or lost by playing the card

Explanation of what happens when this card is played

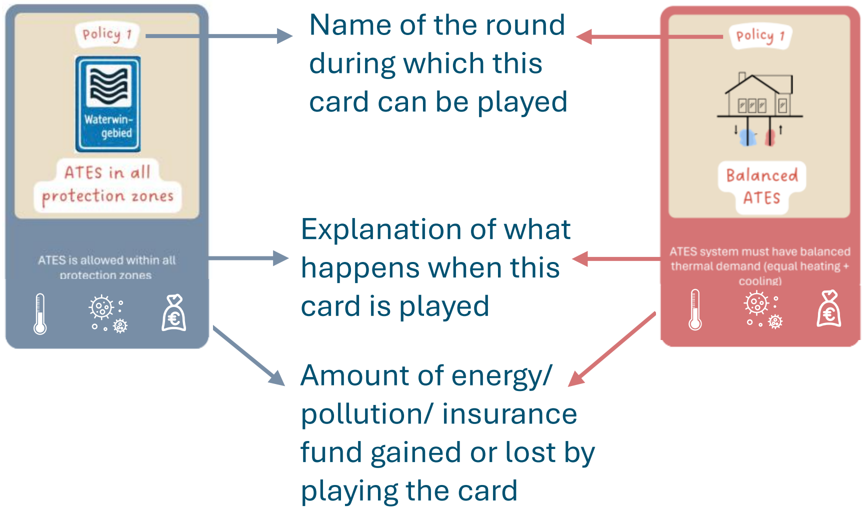


Cheat sheet for shallow subsurface development game

GOAL

Work together to achieve the objectives of the policy pathway, while ensuring that your interests as an ATES developer or drinking water production company are fully respected.

CARD LAYOUT



GAMEPLAY

Round 1: set the scene	Roll the pathway dice to set the policy pathway scene
Round 2: play policy cards	Draw one card from the other team & play one card of your choice
Round 3: play investment decision cards (operational/indicator)	**1.** Roll the dice to determine the current thermal and water demand **2.** ATES plays one card; DW plays one card in response. Do this twice
Round 4: compensation (optional)	**1.** Roll the dice to determine the risk for contamination/lower system efficiency **2.** Play one compensation card each

Teams

ATES Team 1	Groundwater Team 1
Ann Elen (HITA)	Helga Ferket (Dept. Omgeving)
Maxime Latinis (Fluxys)	Christel Dezayes (BGRM)
Mathias Possemiers (AGT)	

ATES Team 2	Groundwater Team 2
Stijn Bos (HITA)	Johanna Van Daele (Dept. Omgeving)
Stefanie Van Offenwert (Fluxys)	Dirk Willems (STORA)

ATES Team 3	Groundwater Team 3
Hans Veldkamp (TNO)	Stijn Valgaeren (MONA / Stad Geel)
Annabel Vaesens (AGT)	Koen Beerten (SCK CEN)
Alexandre Bellucci (Fluxys)	

Reflection

- **What do you think about a financial compensation mechanism between the groundwater company and the ATES developer?**
  - Acceptable?
  - Feasible?
  - Compensation in both ways? Or only from ATES to groundwater company?

Thank you!

DIAMONDS

Dynamic Integrated Assessment Methods

for Sustainable Development of the Subsurface