DIAMONDS

Advisory Committee – 25 February 2025

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

Agenda

- **08h30-09h00** Arrival at Tabloo, Gravenstraat 3, 2480 Dessel (www.tabloo.com)
- **09h00-10h45** Presentations DIAMONDS
- **10h45-11h00** Break
- **11h00-12h00** Presentations DIAMONDS
- **12h00-13h00** Lunch @Bistroo
- **13h15-16h00** Guided tour @Tabloo
- **16h00** End of the visit

Agenda

09.00: Welcome

09.10: WP1 PC&I

09.20: WP2/3 Sustainable production, with and without interference

10.15: WP4 Social impact assessment

10.45: Break

11.00: WP5a Economic impact assessment

11.30: WP5b Environmental impact assessment

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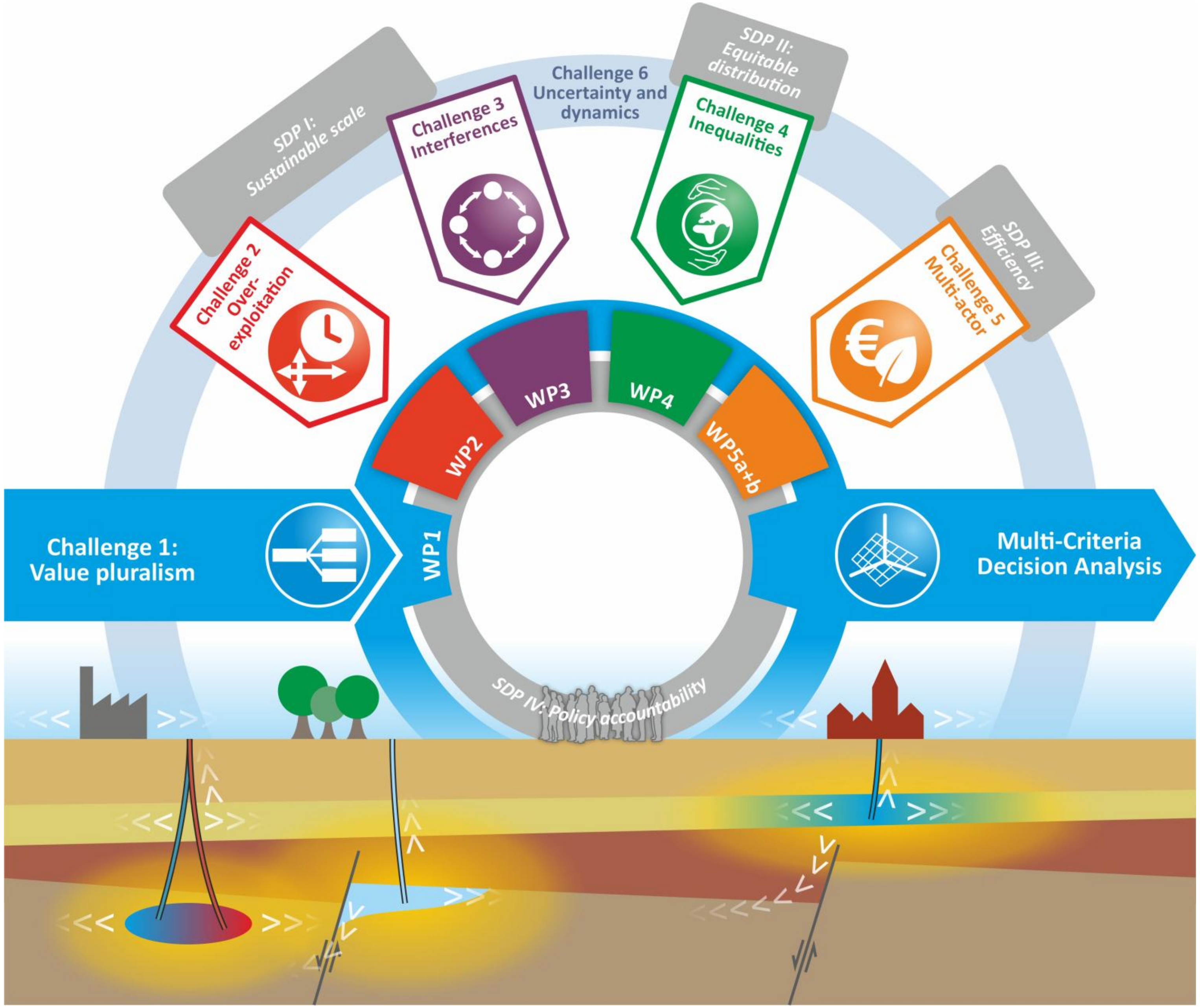

SDP I: Sustainable scale
Challenge 2 Over-exploitation
Challenge 3 Interferences
Challenge 6 Uncertainty and dynamics
SDP II: Equitable distribution
Challenge 4 Inequalities
SDP III: Efficiency
Challenge 5 Multi-actor
WP2
WP3
WP4
WP5a+b
WP1
Challenge 1: Value pluralism
Multi-Criteria Decision Analysis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

Subsurface development scenarios

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

WP 1

Integrative sustainability framework

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for Sustainable Development of the Subsurface

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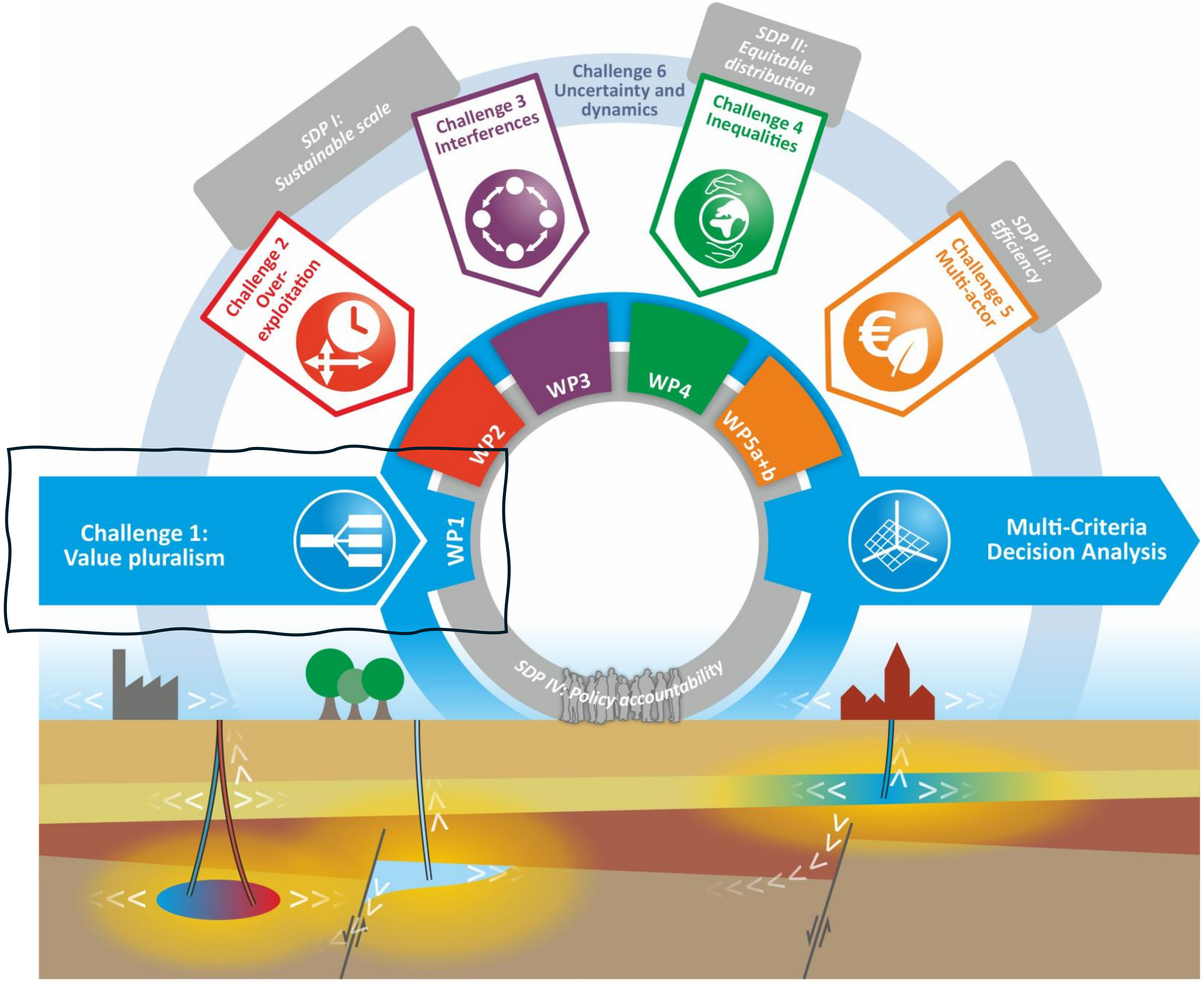
WP1. Integrative sustainability framework



Aim

1. Define the principles that represent the value pluralism, which serve as a basic outline for the other projects.
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).

Tasks

- Determine the principles at hand in the subsurface
- Determine representative sustainable development scenarios (SDS)
- Formulate criteria starting from the SDS activities individually
- Include possible impact of interference between the activities
- Formulate indicators for each criterion and activity
- Validate the PC&I framework

Tasks

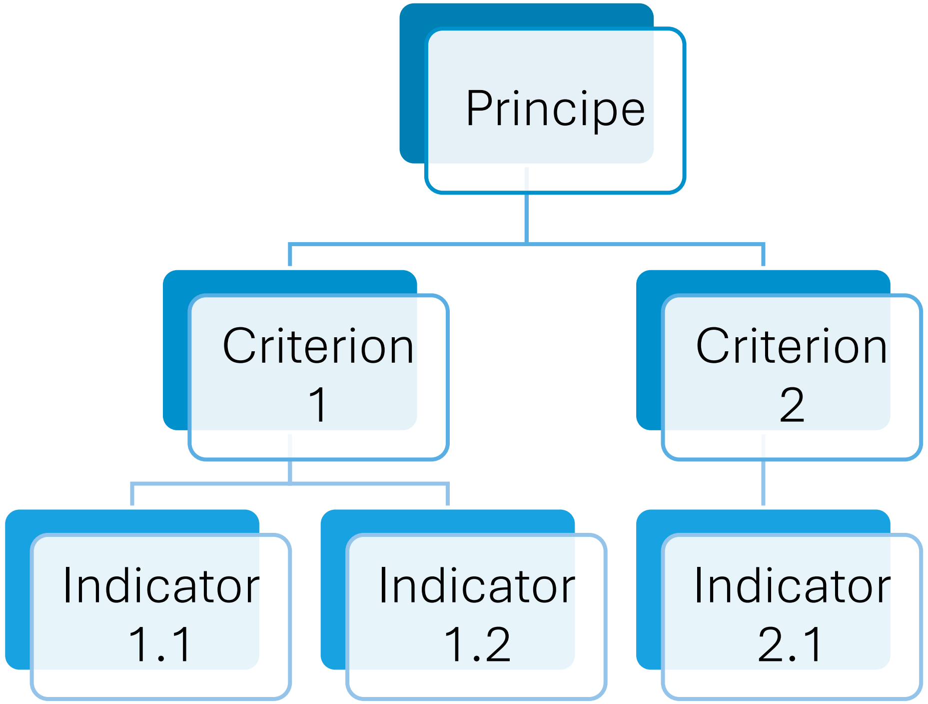
- ☑ Determine the principles at hand in the subsurface
- ☑ Determine representative subsurface development scenarios (SDS)
- Formulate criteria starting from the SDS activities individually
- Include possible impact of interference between the activities
- Formulate indicators for each criterion and activity
- Validate the PC&I framework

Schematical representation

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**



Principles

Determined based on a literature review, a two-round Delphi survey of national and international experts and a workshop with Flemish stakeholders - Government assignment (VPO)

- P1 - Principle of conserving resources and assimilative capacity
- P2 – Principle of efficient allocation
- P3 – Principle of fair (or just) distribution
- P4 – Principle of transparency
- P5 – Principle of inclusive governance
- P6 – Principle of responsible risk management

Subsurface development scenarios

Groundwater vs Aquifer Thermal Energy Storage (ATES)

Gas storage vs Deep Geothermal Energy

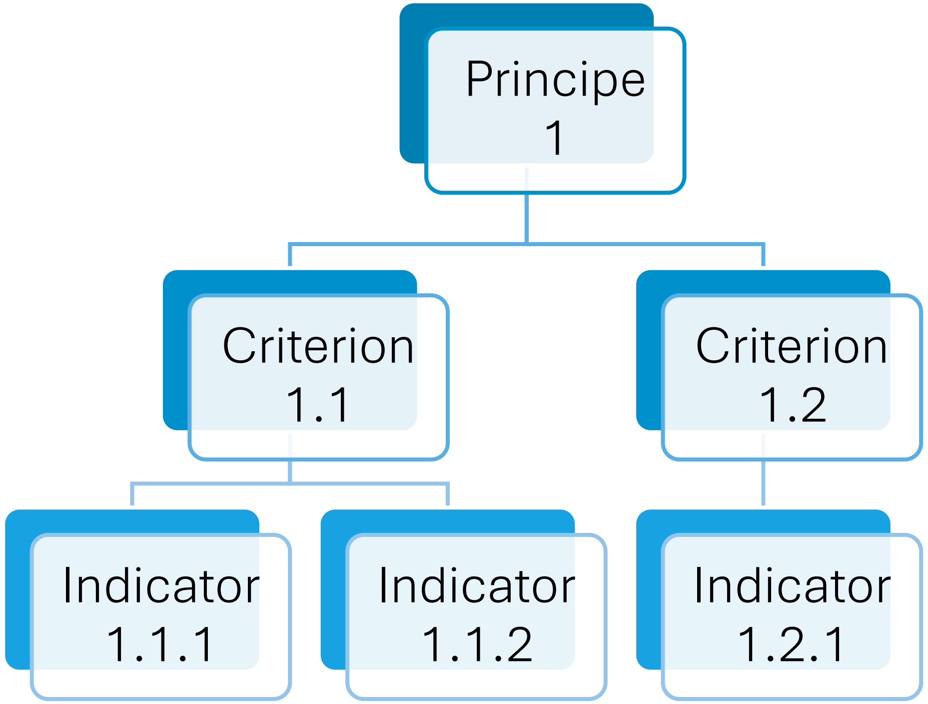
Deep Geothermal Energy with multiple doublet systems

Example:

Principle 1 – Conserving resources and assimilative capacity
Step a - Preservation of resources

Criterion 1.1 - Extractive activity: existing resource stocks are conserved implying that extraction does not exceed natural regeneration, within a human scale

Indicator 1.1.1 – Steady-state extraction rate

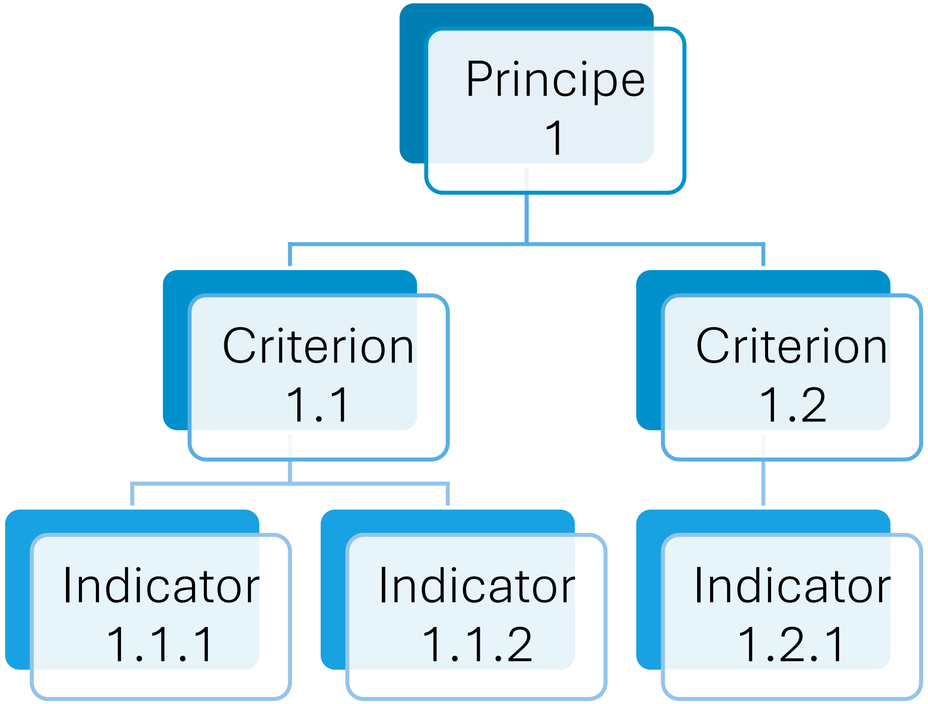


Example:

Principle 1 – Conserving resources and assimilative capacity
Step a - Preservation of resources

Criterion 1.2 - Additive activity: after ending the activity the subsurface will return to its initial state

Indicator 1.2.1 – Degree of expected return to initial state



Questions?

WP 2 & 3

Sustainable production, with and without interference

Shallow subsurface

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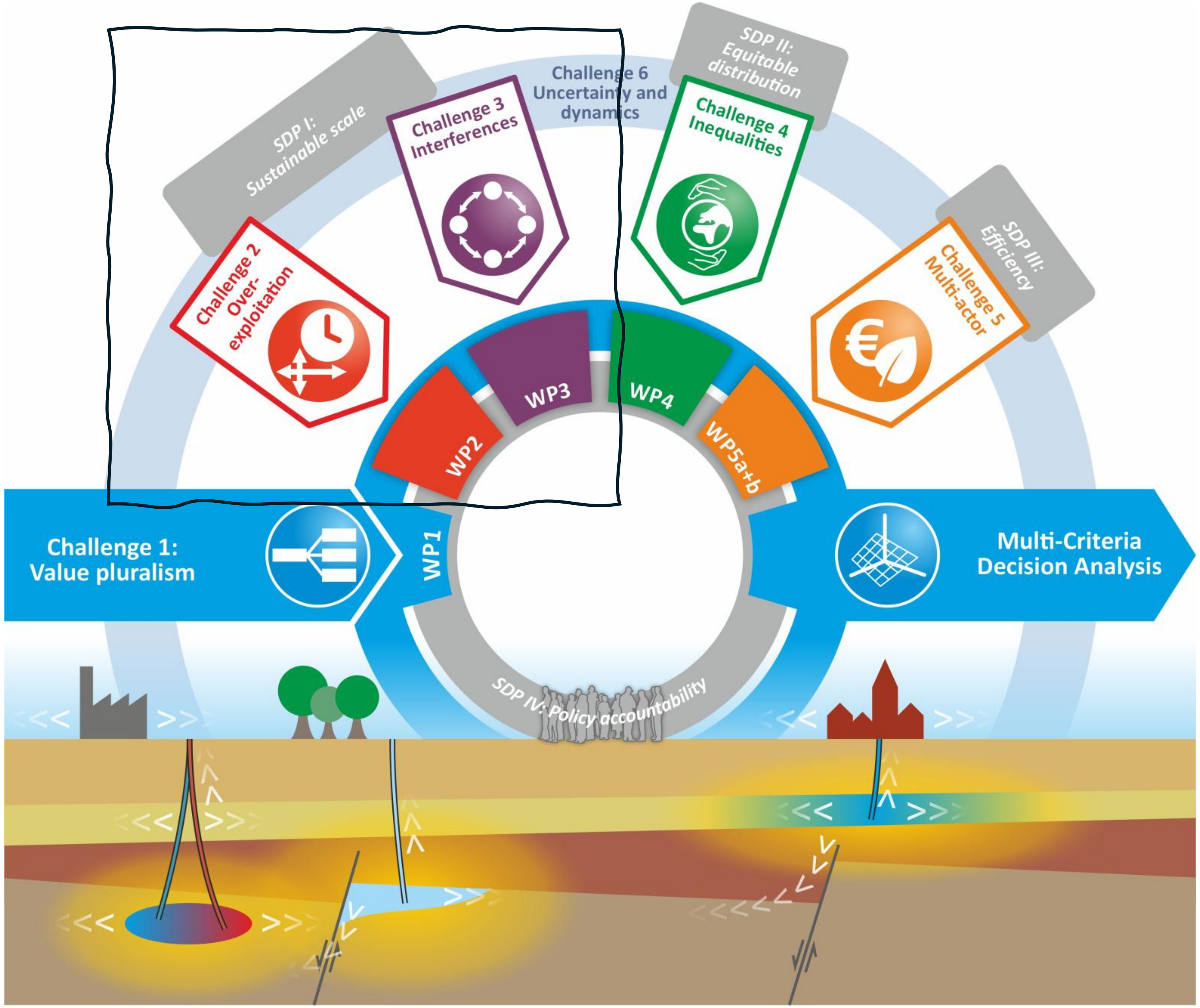

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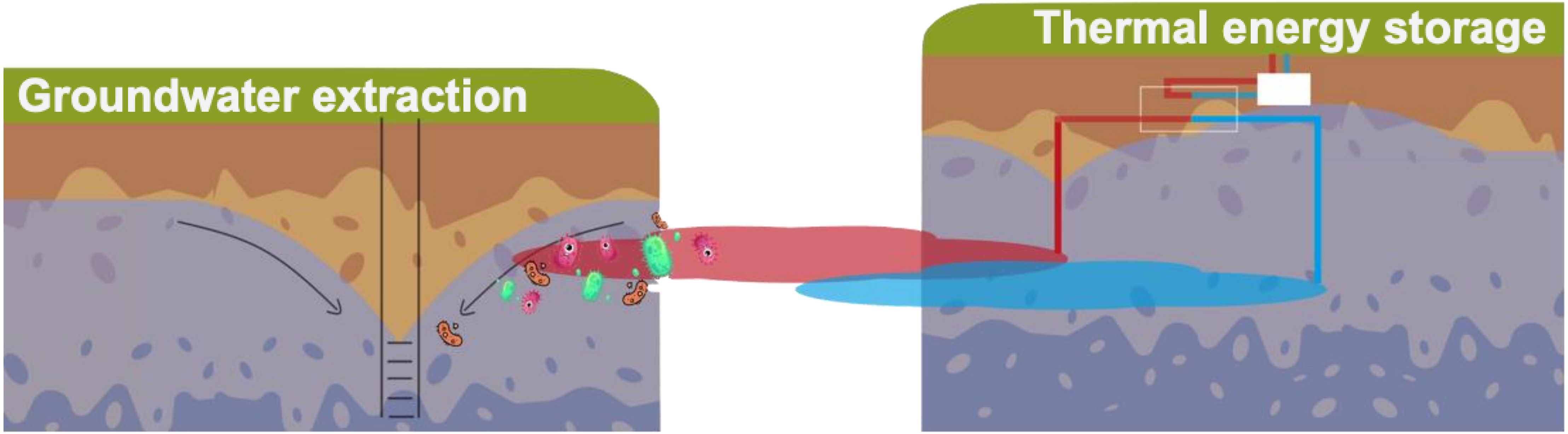
WP2. Sustainable production, no interference
&
WP3. Sustainable production, with interference effects

Competing shallow subsurface activities



Aim

Understand the interactions between groundwater extraction and shallow geothermal energy storage

What temperature changes are acceptable in terms of advection distance?

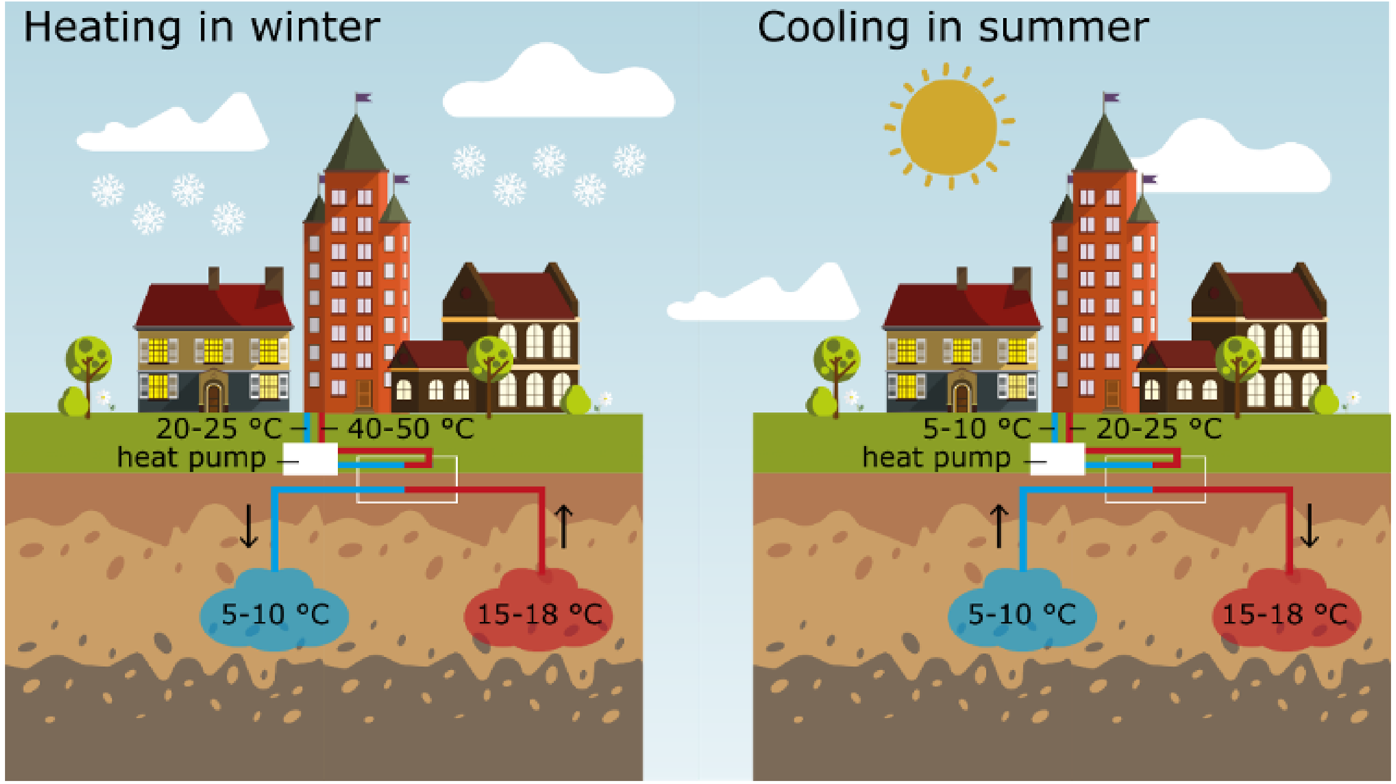
What thermal recovery is considered sustainable?

Tasks

- Develop **flexible modelling framework** to study the interaction.
- Examine **aquifer parameters** on the interaction.
- Examine **design parameters** on the interaction.
- Model **multiple ATES** under both balanced/unbalanced conditions.

ATES – Aquifer Thermal Energy Storage

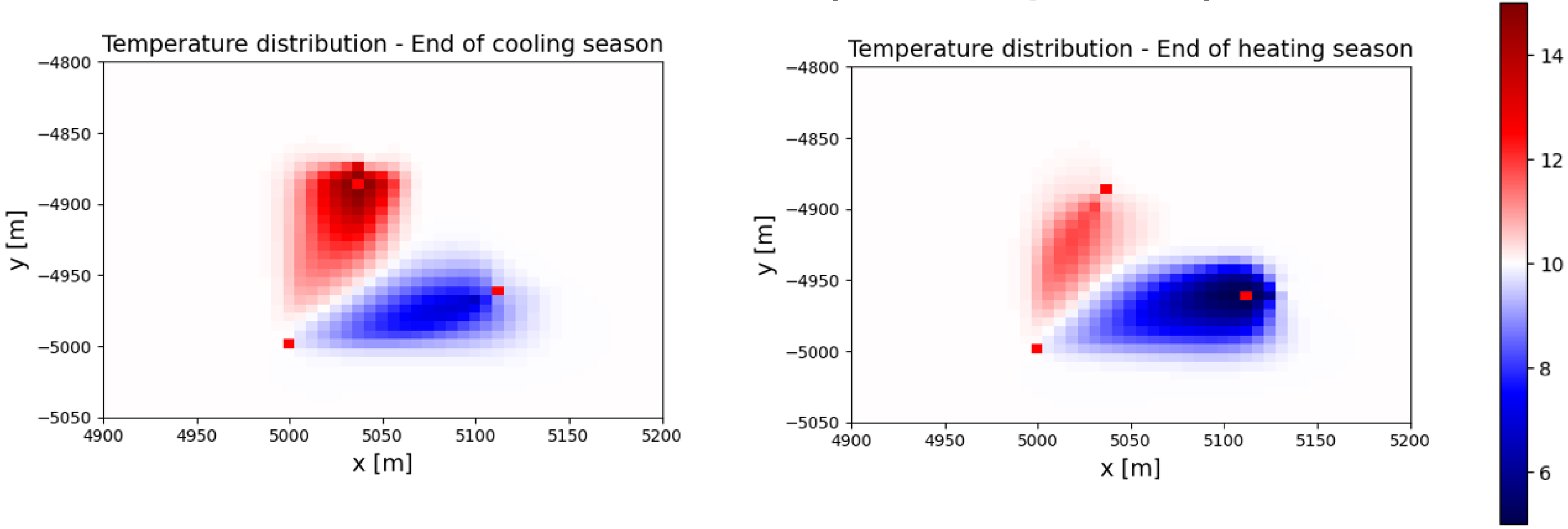
- Store thermal energy in an aquifer
- Heat/cool large buildings in winter/summer
- **May affect temperature in groundwater extraction**



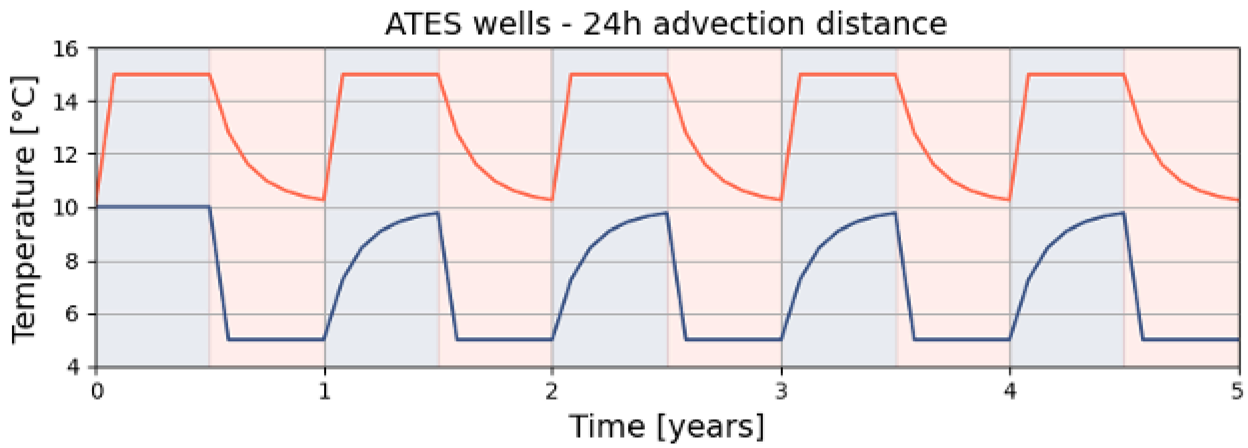
A case

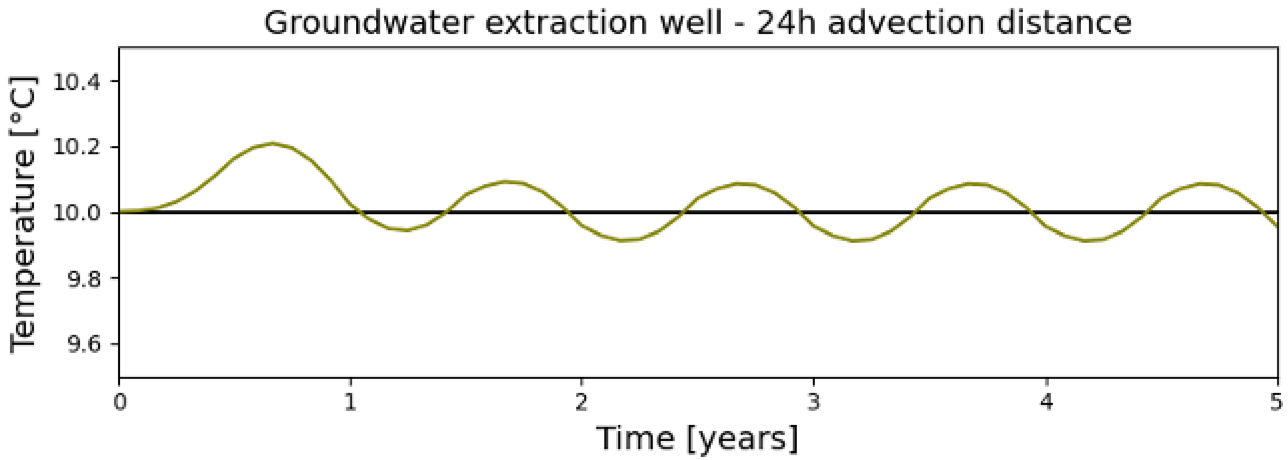
- **Based on** Grobbendonk extraction zone
  (22 000 m³/day from a sandy aquifer) and 2 500 m³/day ATES extraction/injection.
- We use Modflow 6 and MT3D to simulate groundwater flow and heat transport.

Extreme case: 24h advection distance (120 m separation)



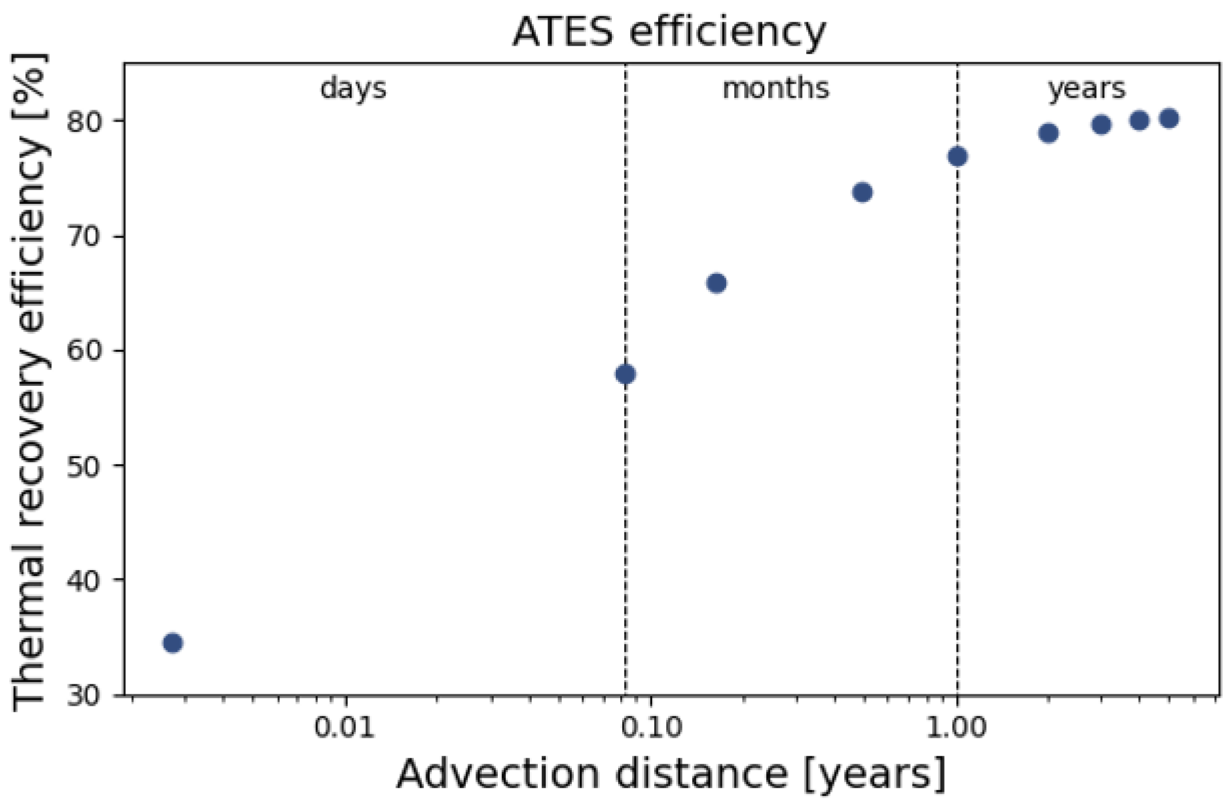
Temperatures in each well





For this example, with realistic aquifer parameters, but extreme design parameters (120 m/24h separation),
we find a limited effect of the temperatures in the extraction well.

What about the thermal recovery efficiency?



Preliminary conclusions

- Presumed interactions are confirmed.
- Temperature changes in extraction zone are small.
- **Use ATES within groundwater protection zones?**

WP 2 & 3

Sustainable production, with and without interference

Deep subsurface

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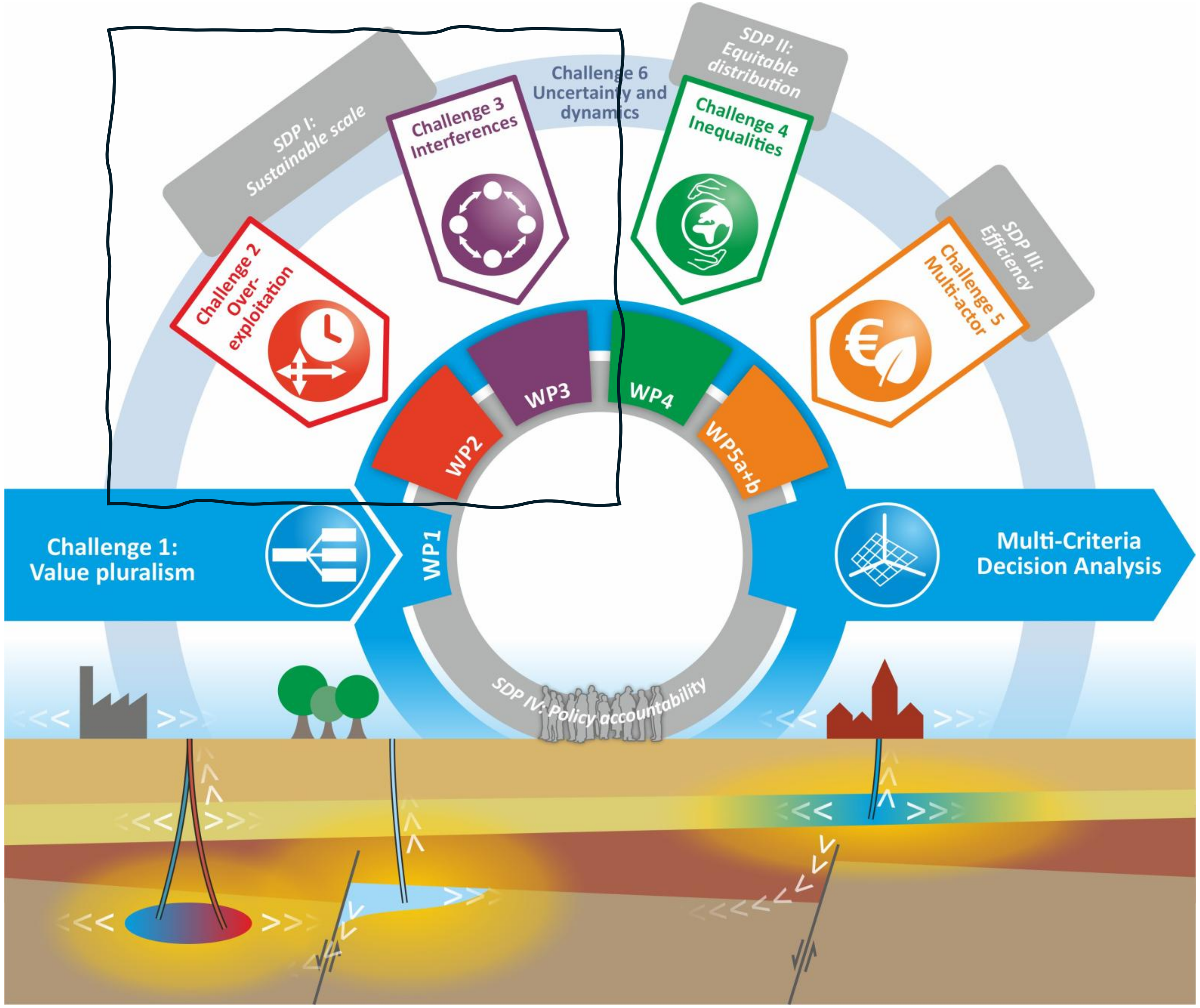


WP2. Sustainable production, no interference

&

WP3. Sustainable production, with interference effects

Aim

High-performance, physics-based modelling framework

Long and very long-term behavior (decades to centuries), with small scale dynamics (yearly to seasonal)

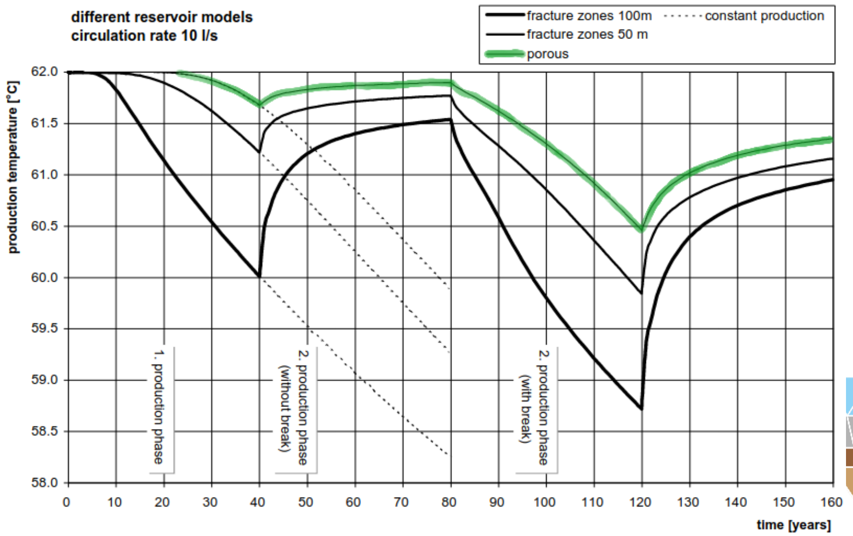
Support the technical aspect of TEA with **efficient models**

Tasks

- Develop **flexible modelling framework** to study the interaction.
- **Influence area and sustainability:** P,T and concept of sustainability
- **Planning and placement of wells**: efficiency and sustainability
- Model **multiple geothermal setups** to access interference

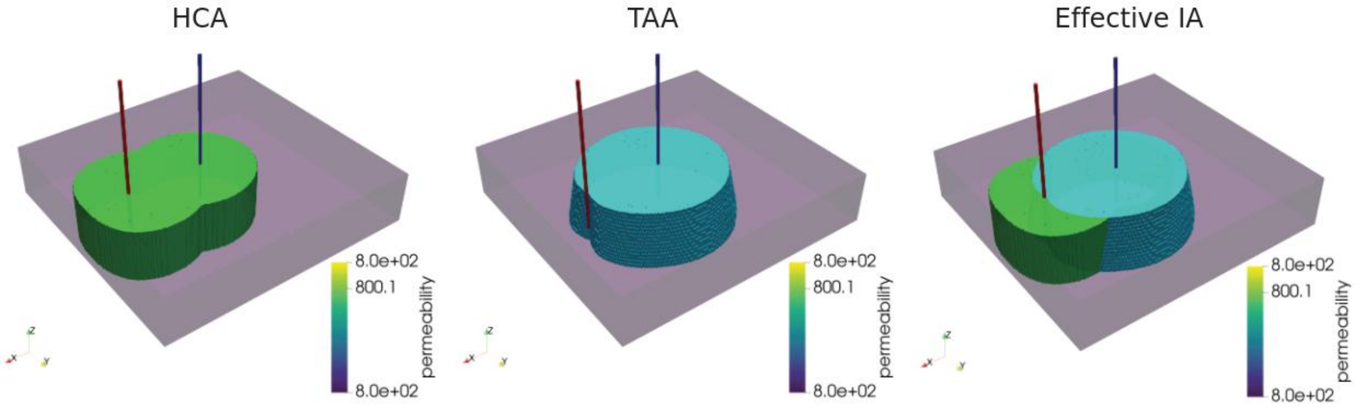
WP 2/3 - Deep Geothermal

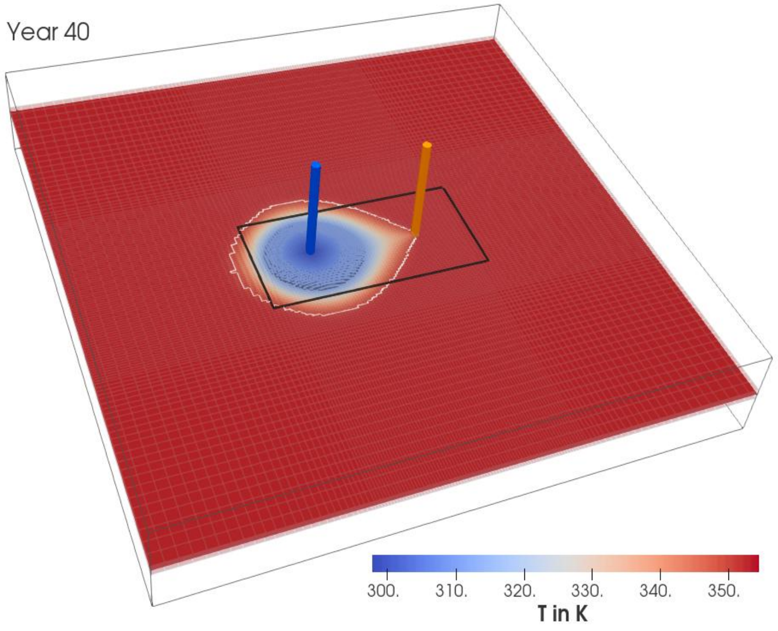
- Part 1: Influence Area and Sustainability
- Say we use a geothermal doublet for 20-50 years
- What happens afterwards?
  - How long does the subsurface stay cold?
- We know that the production well recovers quickly
- But what about the injector?



WP 2/3 - Deep Geothermal

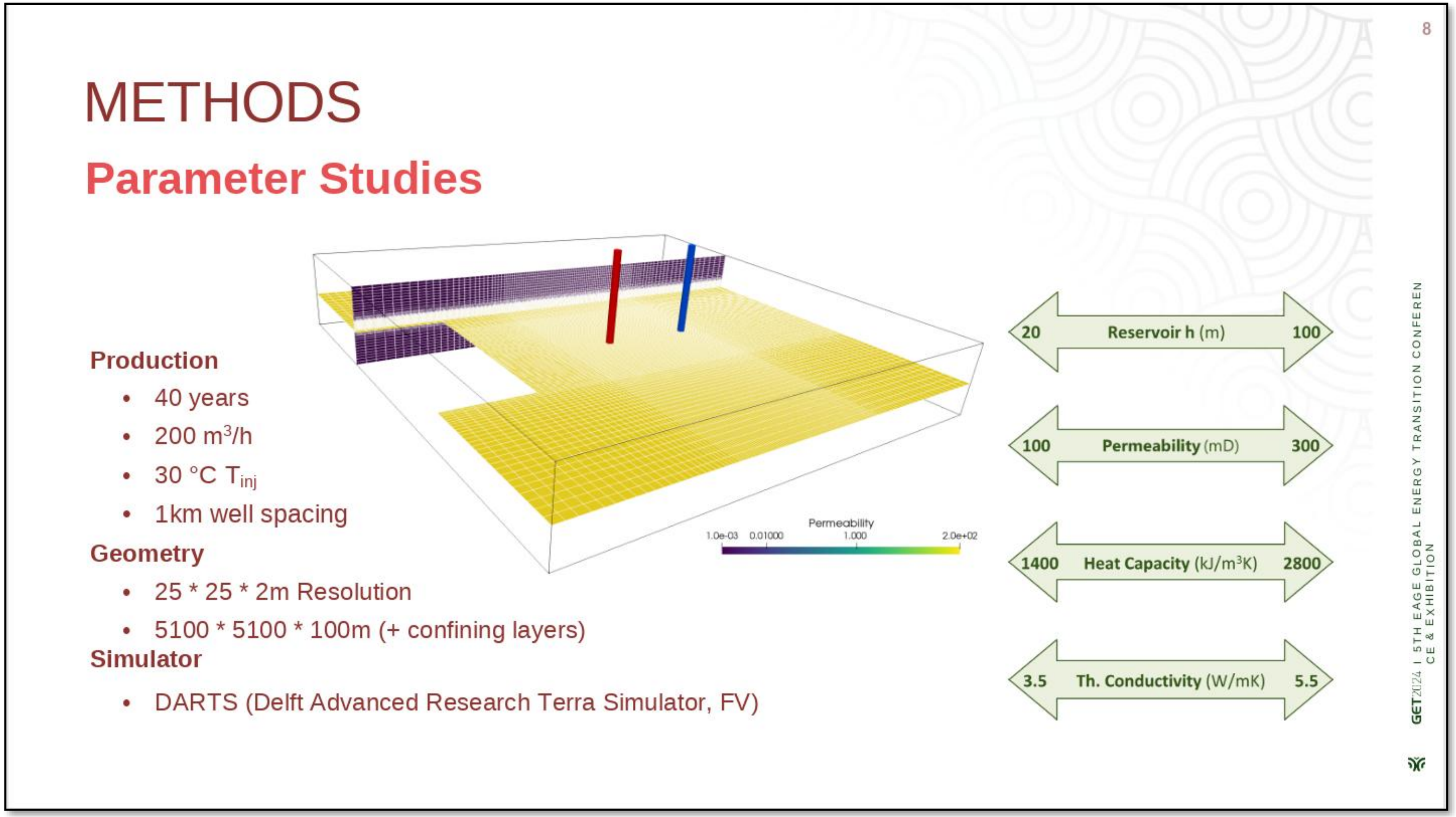
- We simulated running doublets for 40 years
- Then we stopped "production" but let the physical simulation continue
- We measured the average temperature in
  - The TAA (using its extent after production stop)
  - The license area





Chen et al. Geoenergy science and engineering, 2025

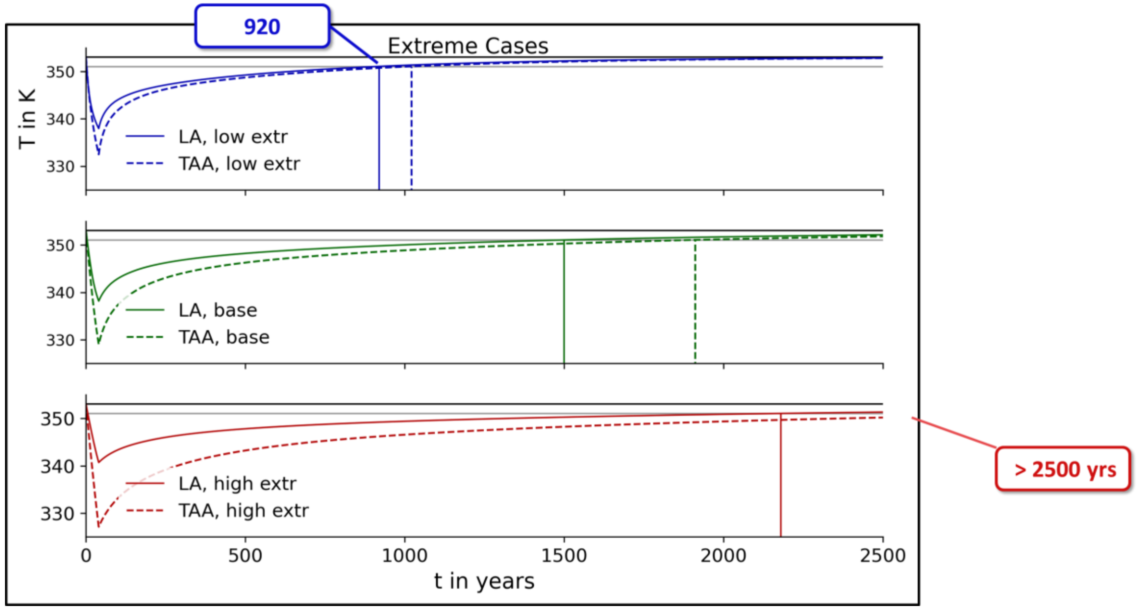
WP 2/3 - Deep Geothermal



Wallmeier et al. EAGE, Global Energy Transition, 2024

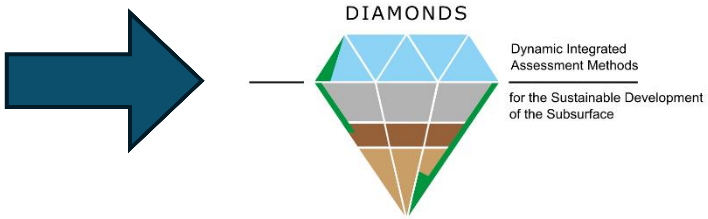
WP 2/3 - Deep Geothermal

- We defined "recharged" when the average T was back to 2K of its original temperature
- That takes really long



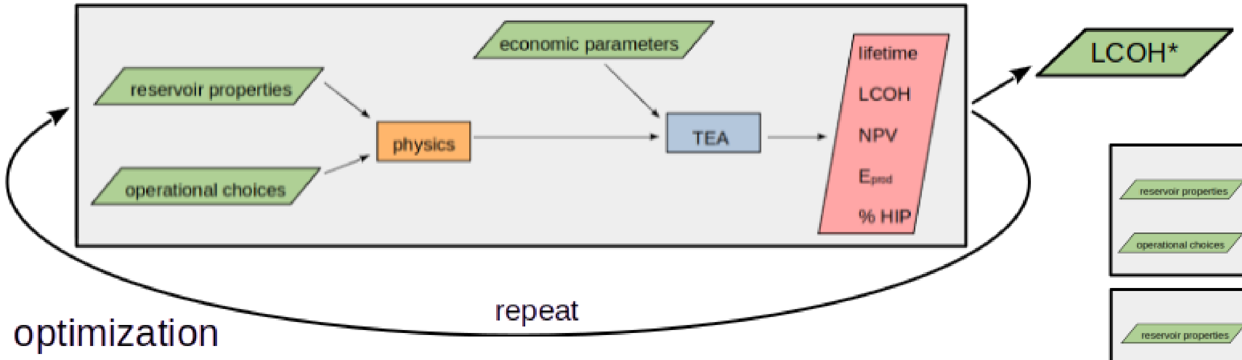
Wallmeier et al. EAGE, Global Energy Transition, 2024

- Next
  - More definitions of recharge
    - By Temperature recharge
    - By Energy recharge
    - By cold plume shrinkage
  - Measuring → predicting
  - to make large-scale models manageable

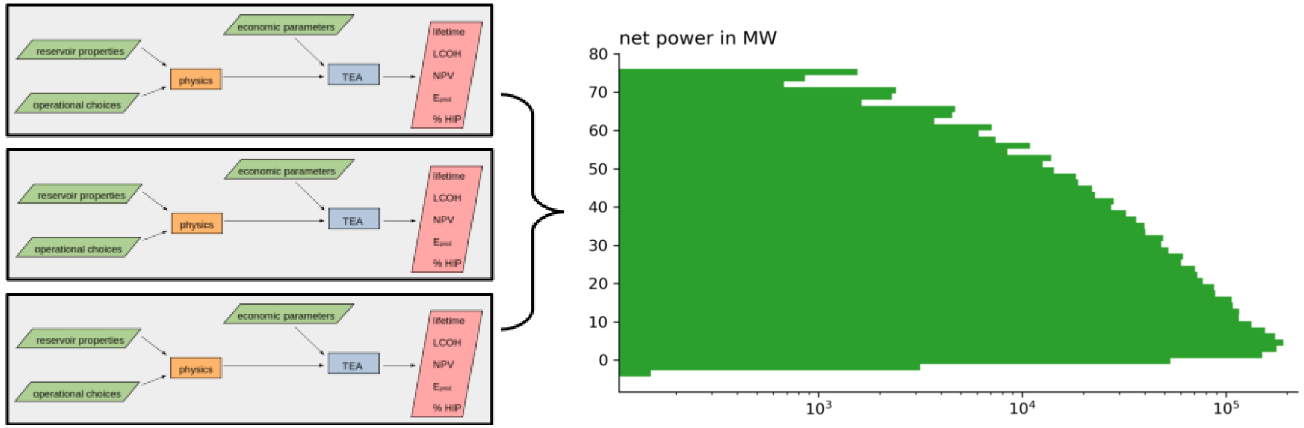


WP 2/3 - Deep Geothermal

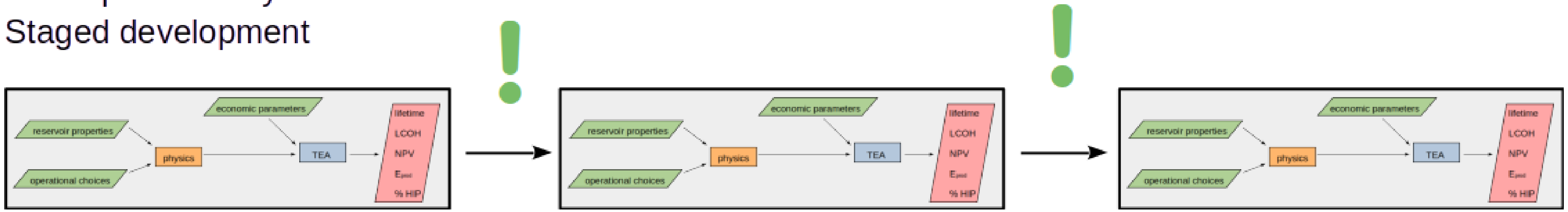
- Part 2: Analytical doublet model for Techno-economic Assessment



SA & UQ

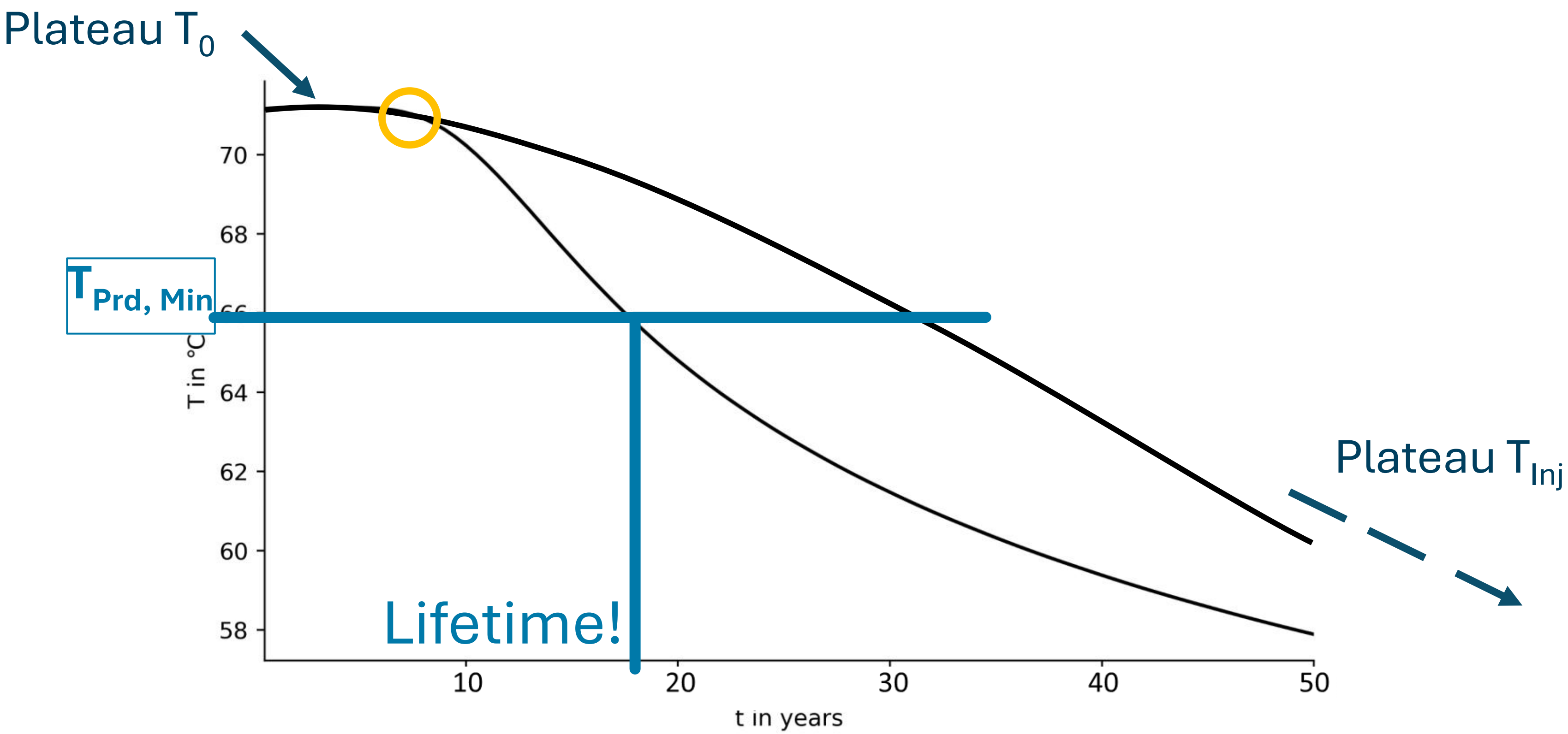


Real options analysis &
Staged development



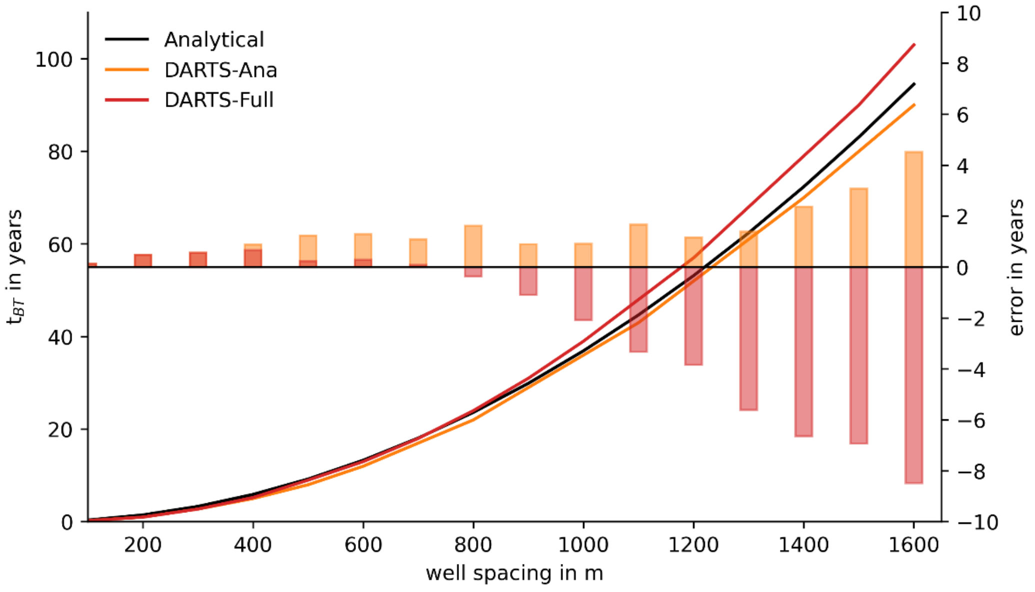
WP 2/3 - Deep Geothermal

- Main goal: production temperature over time
  - Helps us predict lifetime and produced power

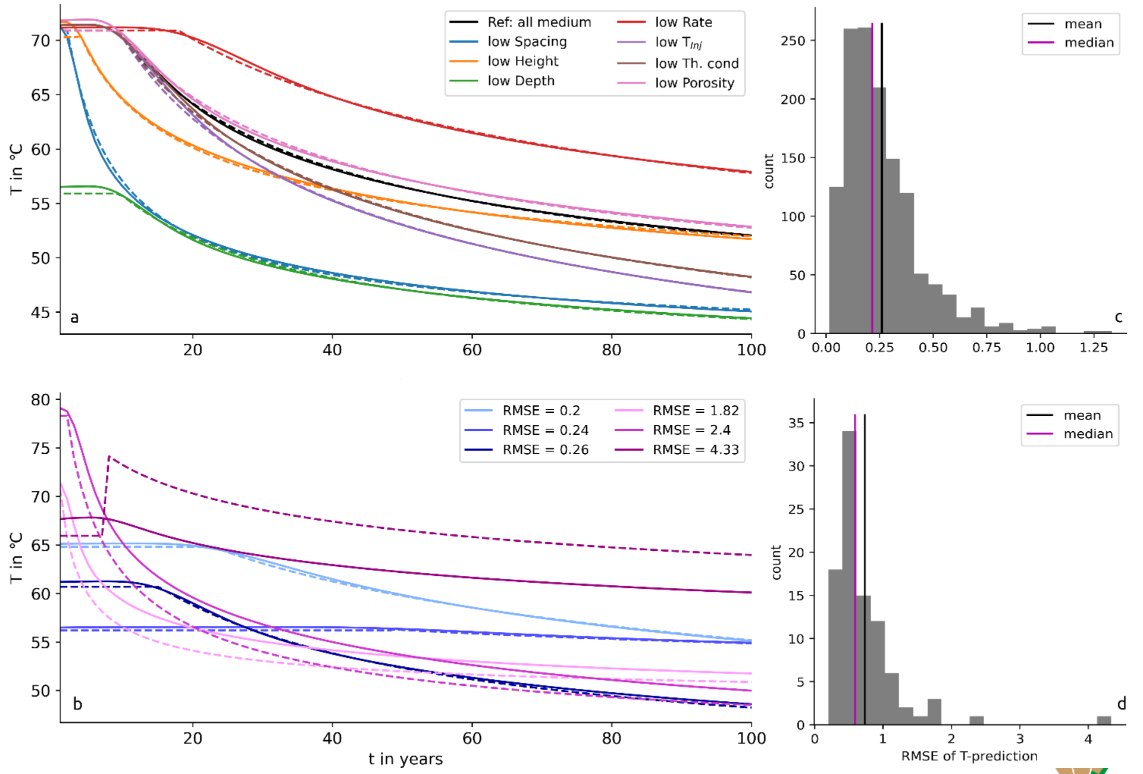


WP 2/3 - Deep Geothermal

- We can predict time of thermal breakthrough
- We're working on T(t) after that



Wallmeier et al. Stanford Geothermal Workshop, 2025



WP 2/3 - Deep Geothermal

- Lifetime prediction mostly works
  - RMSE ca. 3 years, bigger for “far future” beyond 40 years
  - But we still have ideas to make it better!

- Next
  - TEA-side
  - Optimization

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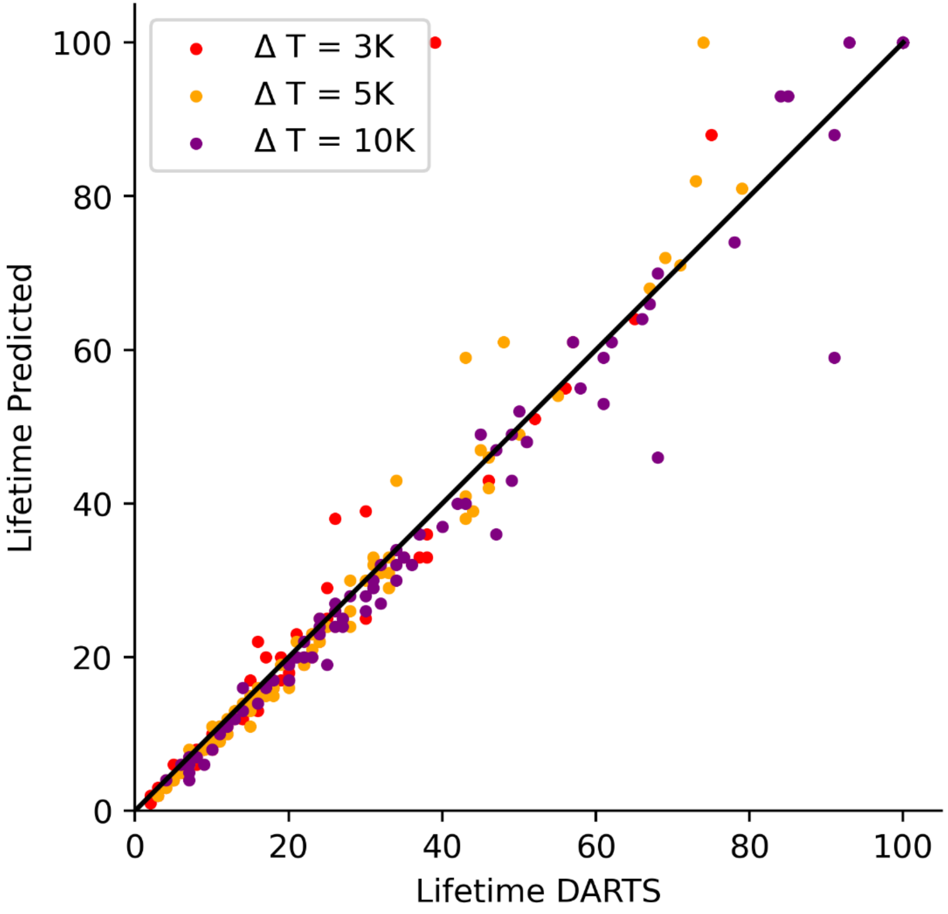

Wallmeier et al. Stanford Geothermal Workshop, 2025

WP 4

Social impact assessment

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for Sustainable Development of the Subsurface

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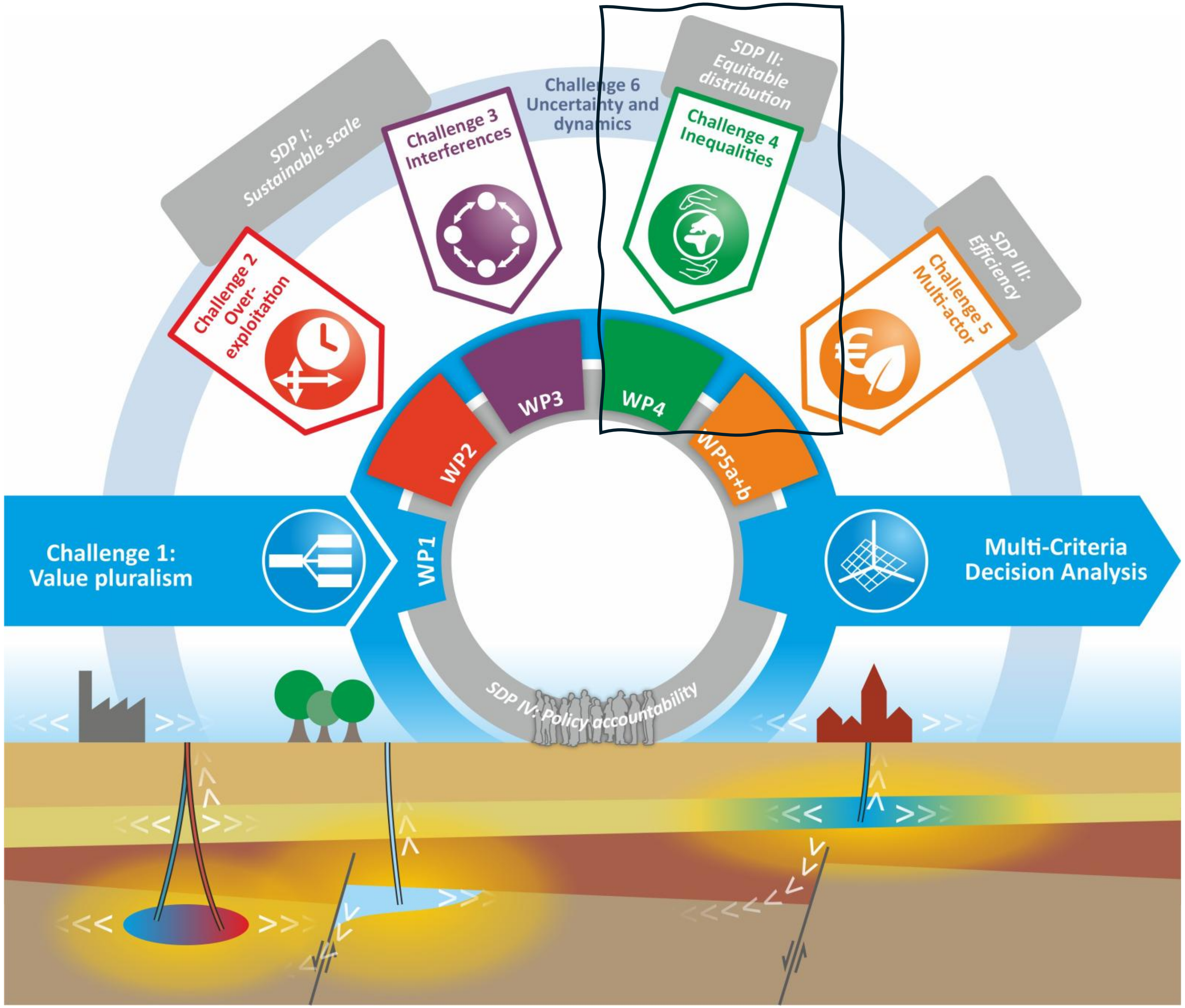

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WP4. Social impact assessment

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

Tasks

Determine if subsurface resources might be perceived as **public / common goods** & which **dimensions of justice** are seen as relevant for the development of these (currently researching)

Make an **engagement plan** that leads to a just involvement of relevant groups (year 2)

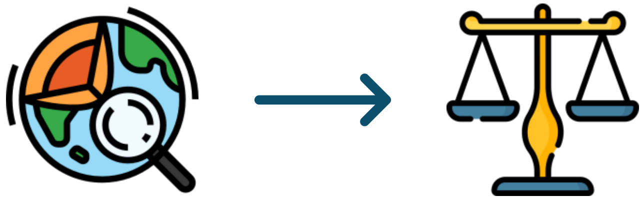
Determine potential **social impacts** of subsurface activities & how these (+ economic & environmental) impacts can be **distributed in a just way** (year 3)

Study the **social carrying capacity** for subsurface activities and how indicators like trust, (difference of) values, and recognition influence this capacity (year 4)

Research part 1

Study subsurface resources as **commons** (public/common goods) + establish **environmental justice** as a suitable guiding concept to develop these commons

- Methodology
  - Literature
  - 4 stakeholder workshops
- Status
  - Analysis → prelimenary results



The commons in the Campine area

- The Campine area had commons for many centuries
  - Inclusive communal practices

- Forced by law to privatise and exploit in the 18th century
  → resisted for another century

“The objective of maintaining an equilibrium and peaceful coexistence between the different interest communities, each acquiring sufficient benefits from the commons, was more important than pursuing the most commercial strategy.” (De Keyzer, 2013)

Prelimenary results – commons

Commons	
Subsurface resources belong to:	the **community**
	'nature' or 'the earth', especially deeper resources
	the **government** ('the state')
	everybody ('the nation')
	nobody
	the **owner** of the above-surface area
Subsurface resources are **global** commons	
More shallow resources belong to the ground-owner and deeper resources belong to the state	
Common management can lead to more social cohesion than exploitation by external company	

Excludability
Financial barriers
Infrastructural bariers
Knowledge bariers
Some subsurface resources **should be inaccessible** for general public
Inaccessibility can be overcome by **acting collectively**

Rivalry
When there is a **rivalry** or **conflict** between different subsurface activities, societal benefit is important to consider

Prelimenary results – justice

Justice	
Distributional justice	Energy resources <-> waste disposal resources Costs + benefits for some <-> costs for some + benefits for all If benefits are for everyone, then everyone should also bear the costs together
Procedural justice	Participation Importance of societal carrying capacity Consultation council for every type of activity (with citizens) Low-threshold societal debate Veto-power for local communities
Recognition justice	'Brussels' versus local communities -> lack of recognition of local context, opinions, … ?
Ecological justice / distributional justice for nature	Fair distribution of costs (waste) between humans & nature ? “rights of mother earth”
Intergenerational justice	
‘Deep time’ justice	
Global justice	
Possible conflict between more local governance (more procedural justice) and higher-level governance (more distributional justice)	

Prelimenary results – values / interests

Values	
Public health	Security / stability
Safety	Scientific basis
Fairness	Societal benefit / utility
Recovery (in context of groundwater)	**Transparancy**
Sustainability	Acceptance from local community
Good documentation for next generations	Caution (under uncertainty)
Accountability (for project developers)	Social cohesion
BATNEEC (Best Available Technology Not Entailing Excessive Costs)	**Participation**
Economic viability	Efficiency
Economical use of resource	Resource conservation
Biodiversity	**Environmental protection**

Prelimenary results – decision-making

Decision-making right	Fair management
Government	**Multi-level governance (subsurface resources don't stop at borders)**
Universities	Specific licensing systems for the subsurface
(Independent) government organisation	Specific policy for subsurface management
Community	Infrastructure owned by the government
Not politicians	Federal management
Experts / technici	**Company** to access and divide resource (so everyone has access) <-> **Independent organisation** to access and divide resource

WP 5a

Economic impact assessment

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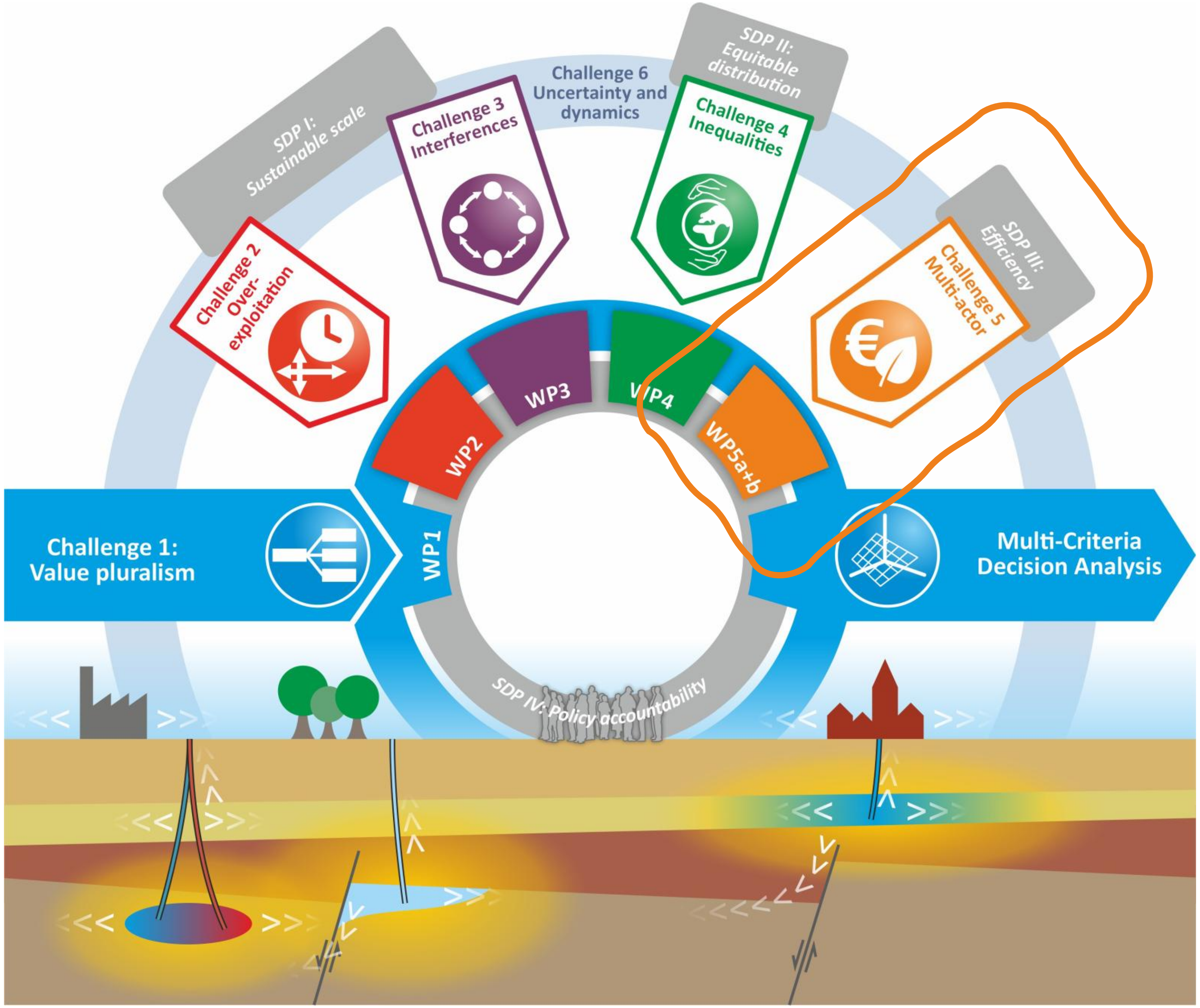

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WP5a. Economic impact assessment

Dr. Hanne Lamberts-Van Assche
Prof. Dr. Tine Compernolle
University of Antwerp
Faculty of Business and Economics

Aim

Evaluate the economic impacts of the various subsurface development scenarios

Consider various sources of uncertainty and flexibility options

Include strategic interactions between different actors in the subsurface

Tasks

Preparation of a **geo-technical backbone & market analysis** (year 1)

Perform an **economic evaluation** of the subsurface development scenarios (year 1)

Set up a **Real Options Analysis (ROA)** to find the optimal timing to invest in a subsurface activity (year 2)

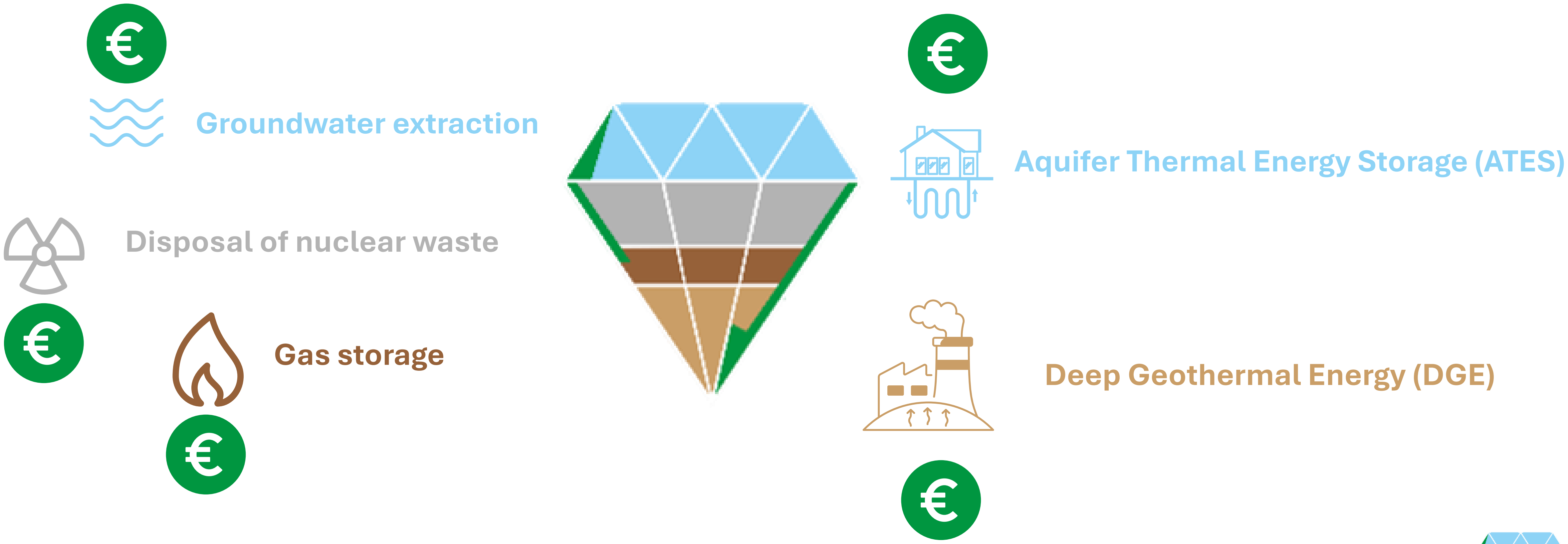
Develop **Real Options Games** to include strategic interactions between multiple actors (year 3)

Integrate economic evaluation with the **environmental impact assessment** (WP5b) (year 4)

Disclaimer

- No results (yet)...
- ... but insights in the methods that will be applied in WP5a
- ... and the type of info we may need

Subsurface activities

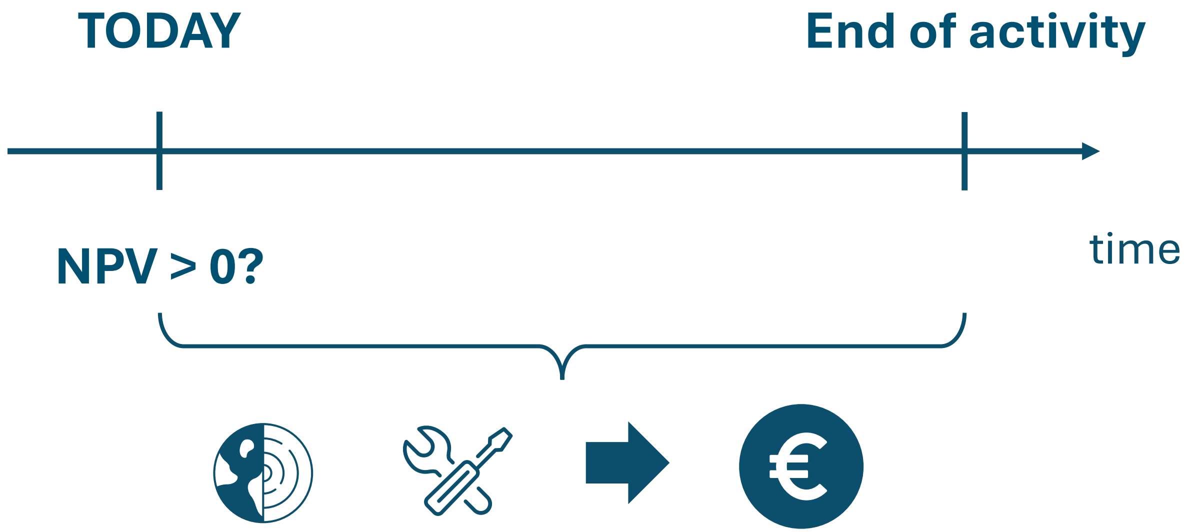


From Techno-Economic Assessment...

- The economic feasibility of **one subsurface activity** can be evaluated with a **Techno-Economic Assessment (TEA)**
- Calculate the **Net Present Value (NPV)** of an investment in a subsurface activity, at a particular location, given certain values for the electricity price/ temperature/permeability/...

From Techno-Economic Assessment...

⇒What is it worth today to invest in ATES/DGE/groundwater/...?

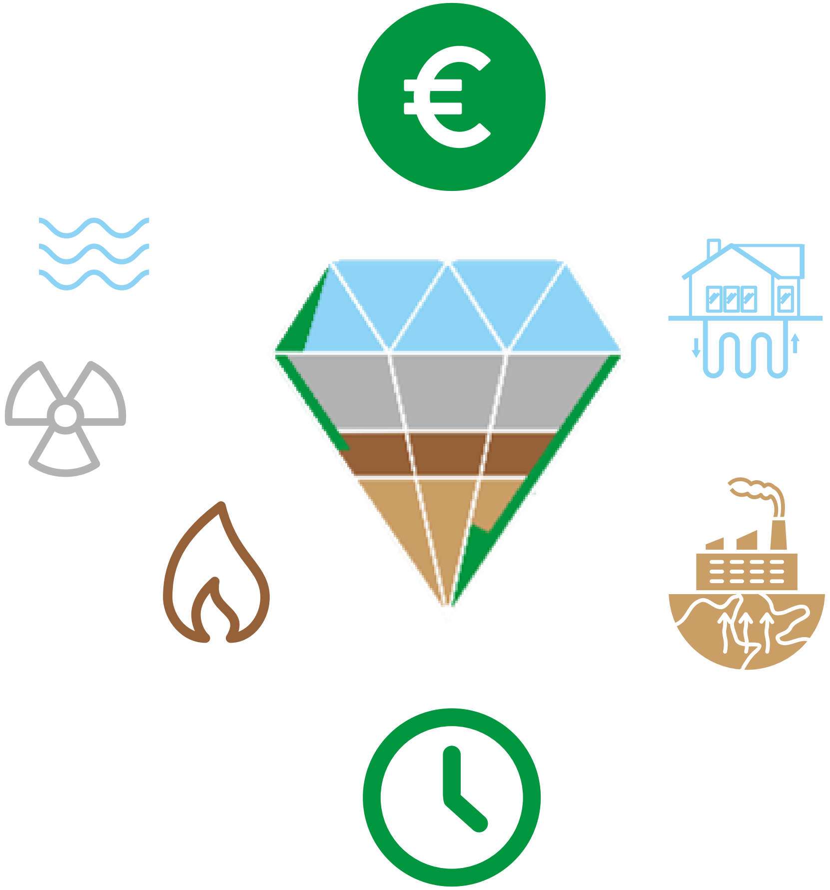


From Techno-Economic Assessment…

- **With a TEA of 1 subsurface activity, we ignore…**
  - Uncertainties in parameters
  - Flexibility in the decision-making
  - Interferences between activities
  - Strategic interactions between subsurface actors

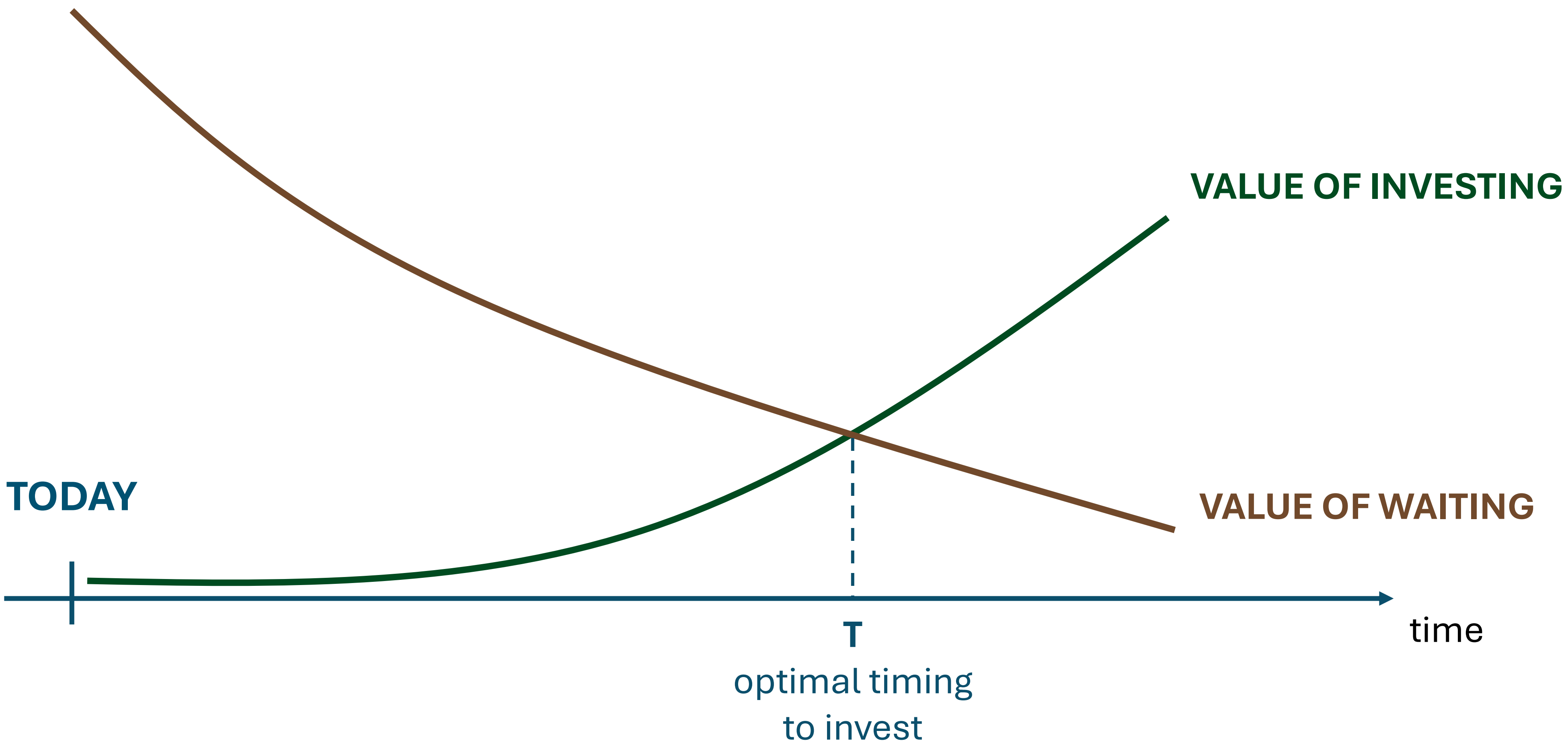
… to Real Options Analysis…

- The optimal investment decision of **one subsurface activity** can be evaluated with a **Real Options Analysis (ROA)**
- Find the **optimal timing to invest** in one subsurface activity, considering multiple uncertainties and the flexibility to delay decisions



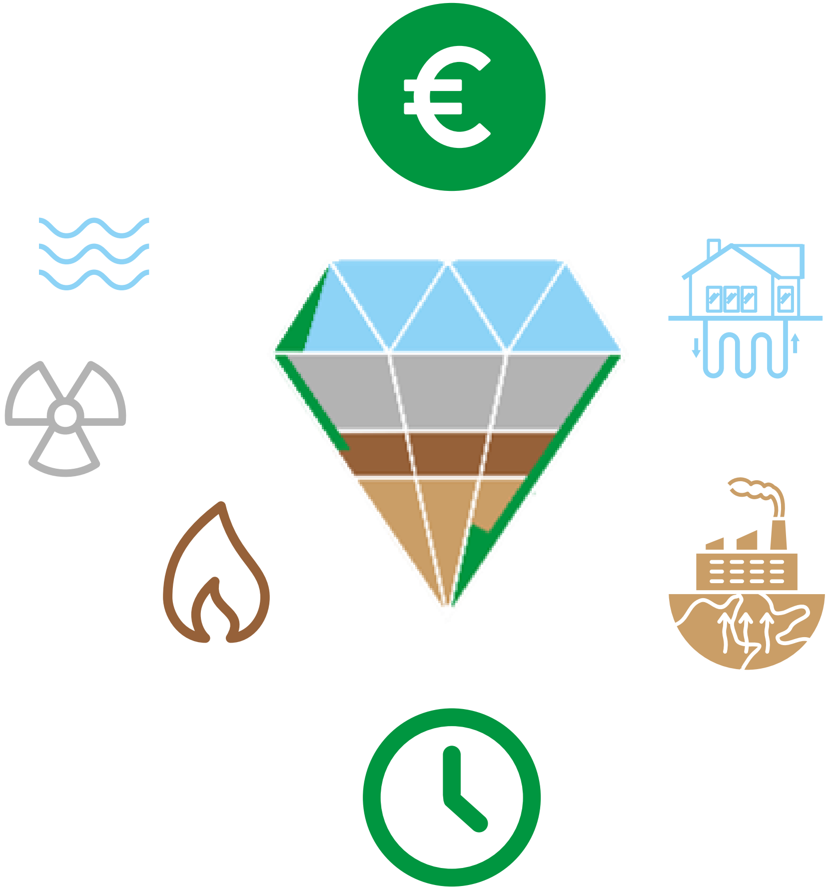
... to Real Options Analysis...

ATES



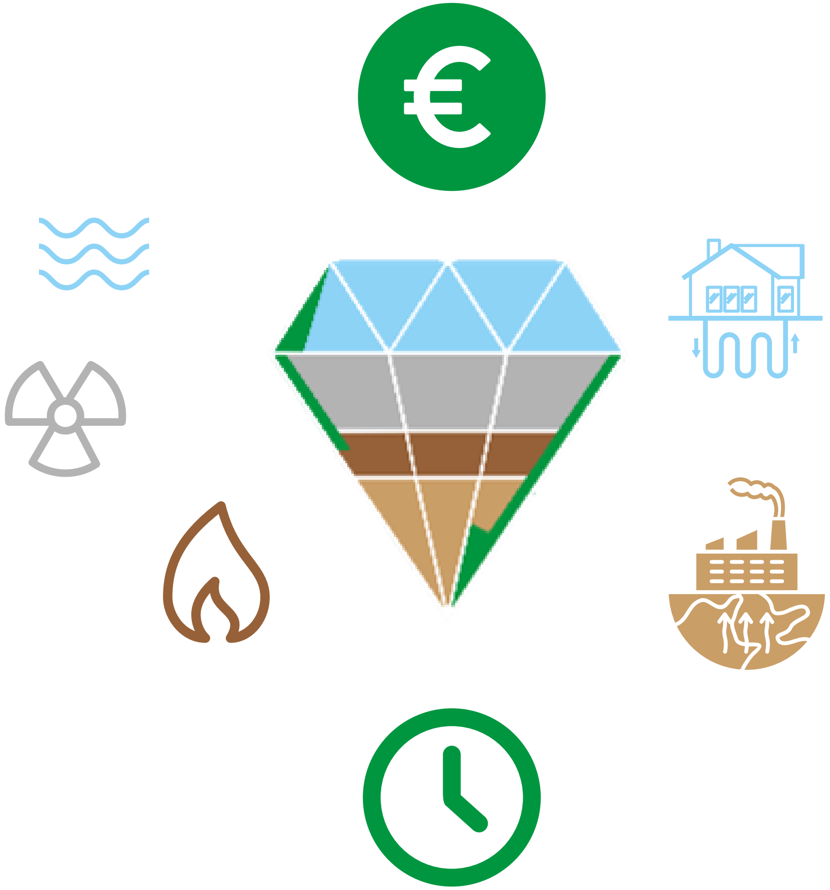
... to Real Options Analysis...

⇒What is the optimal timing to develop location X for ATES/DGE/groundwater/...?



... to Real Options Analysis...

- **With a ROA of 1 subsurface activity, we ignore...**
  - ~~Uncertainties in parameters~~
  - ~~Flexibility in the decision-making~~
  - Interferences between activities
  - Strategic interactions between subsurface actors

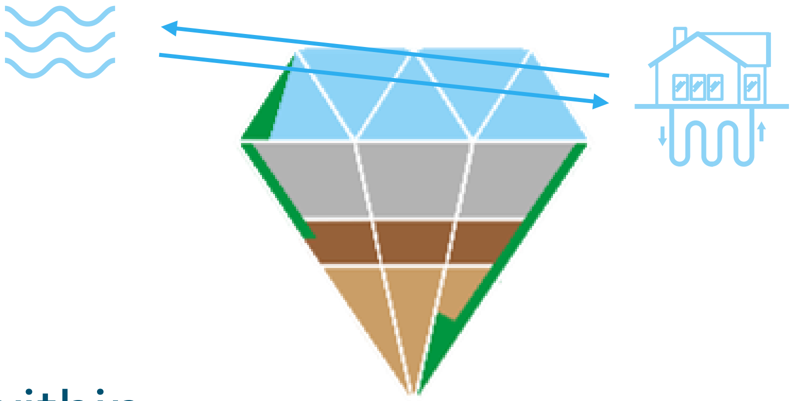


… to Real Options Games

- The optimal investment decisions for multiple **subsurface activities** can be evaluated with a **Real Options Game (ROG)**
- Evaluate how the **optimal timing to invest** in subsurface activities is affected by the possible interferences & interactions

Real Options Game – ATES & Groundwater

- **Player 1: groundwater company**
  - Public actor!
- **Uncertainties:**
  - Groundwater level
  - Electricity price
- **Effect on ATES?**
  - ATES not allowed within protection zones



- **Player 2: ATES developer**
  - Private actor!
- **Uncertainties:**
  - Hydraulic conductivity
  - Heating price
- **Effect on groundwater?**
  - Temperature difference compared to natural groundwater
  - Protection zones of water extraction

Real Options Games

Started

Groundwater vs. Aquifer Thermal Energy Storage (ATES)

Gas storage vs. Deep Geothermal Energy

Deep Geothermal Energy with multiple doublet systems

Future steps

Economic evaluation for ATES & groundwater (individually)

Identifying uncertainties for ATES & groundwater (individually)

Real Options Analysis for ATES & groundwater (individually)

Identifying possible interactions for ATES – groundwater

Develop Real Options Game for ATES – groundwater

Develop Real Options Analysis for DGE

The multi-actor challenge

- We value your feedback!
- If you want to have more insights in the method…
- If you want to give input on possible uncertainties, interactions or interferences,…
- If you want to share data…
- Contact us!

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Questions?

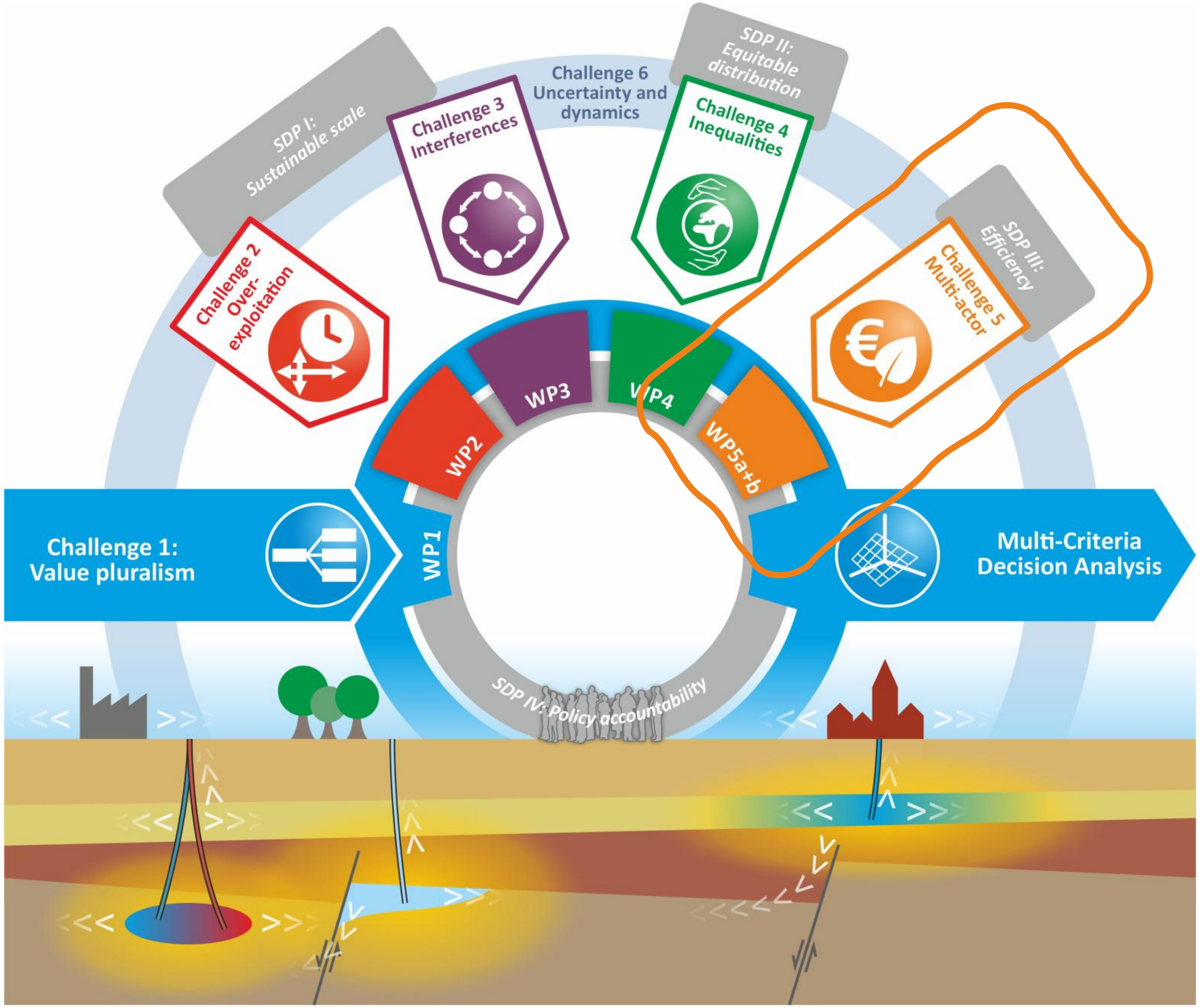
WP 5b

Environmental impact assessment

University of Antwerp

DIAMONDS

Dynamic Integrated Assessment Methods for Sustainable Development of the Subsurface



DIAMONDS

WP5b. Environmental impact assessment

Aim

Evaluate environmental impact of subsurface activities

Describe the subsurface system qualitatively and quantitatively

Enrich system with agents that use bounded rationality

Tasks

- Finish **causal loop diagram**
- Develop a **minimal system dynamic model** and gather data to quantify this system
- **Expand system dynamic model** progressively towards the causal loop diagram
- **Enrich** system dynamic model with methods from **behavioural economics (ABM)**
- Calculate environmental impacts using **prospective LCA** on scenario outcomes

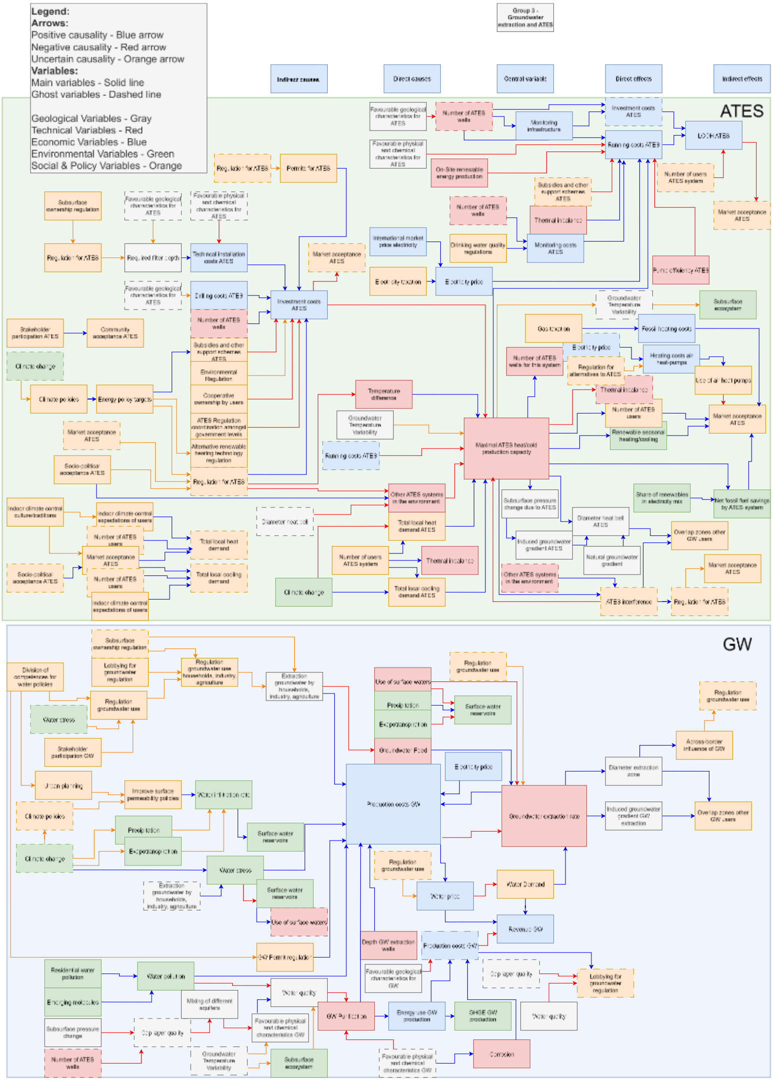
WP5b – CLD Paper – Stakeholers

- Currently all but one stakeholder role has been fulfilled!

Stakeholder roles	Representation	Case 1	Case 2
Bearer	3	3	3
Researcher	3	2	2
Policy designer	3	1	2
Policy maker	1	1	1
Permit advisor	2	1	1
Permit evaluator	1	1	1
Permit licenser	1	1	1
Developer	4	3	1
User	2	2	0

WP5b – CLD Paper – Detail

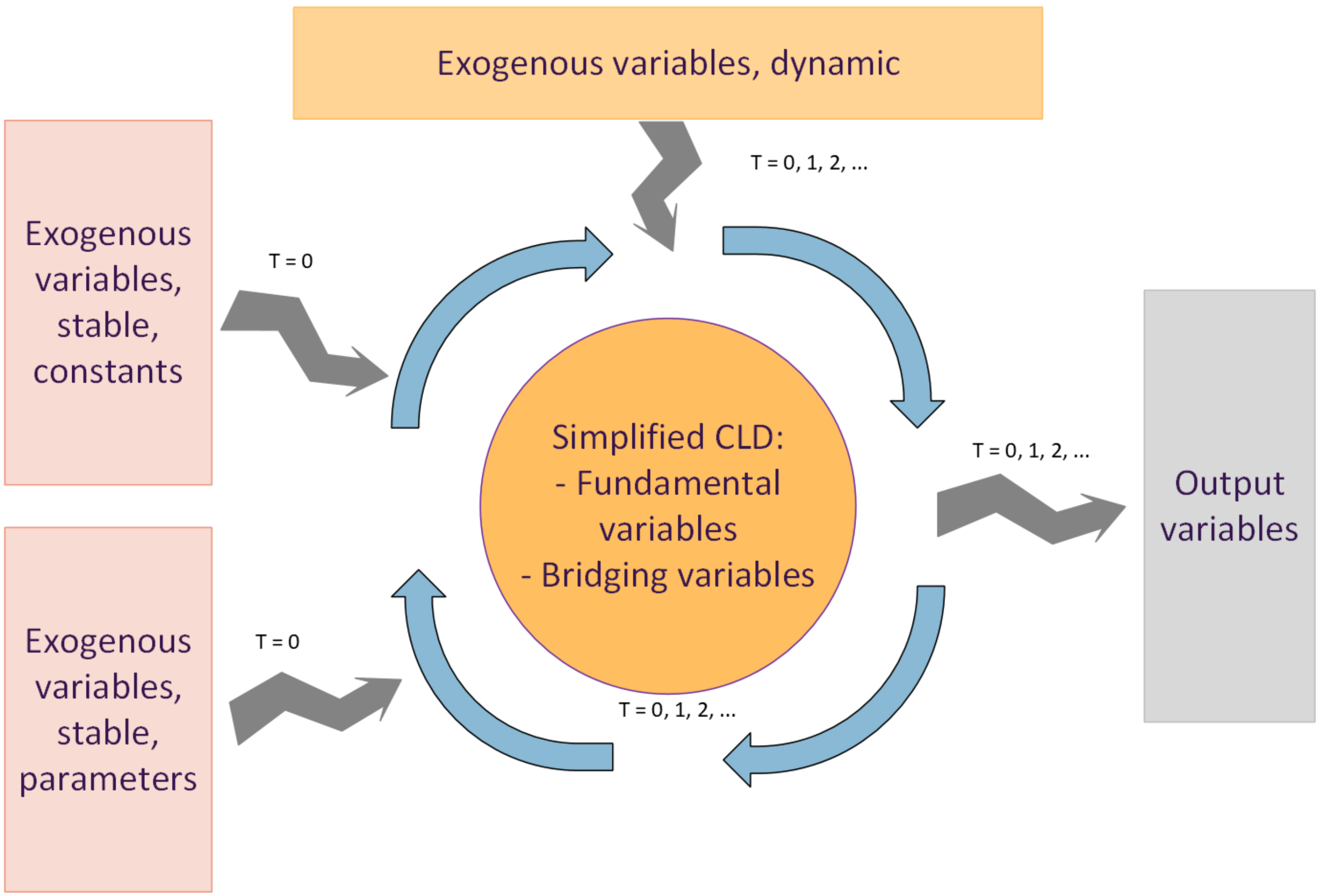
- Causal loop diagram of Case 1(v16) has 103 variables
  - High level of **complexity**
  - Difficult to interpret
  - Need to **categorize** the CLD
  - Need to **simplify** the CLD



WP5b – CLD Paper – Categorization

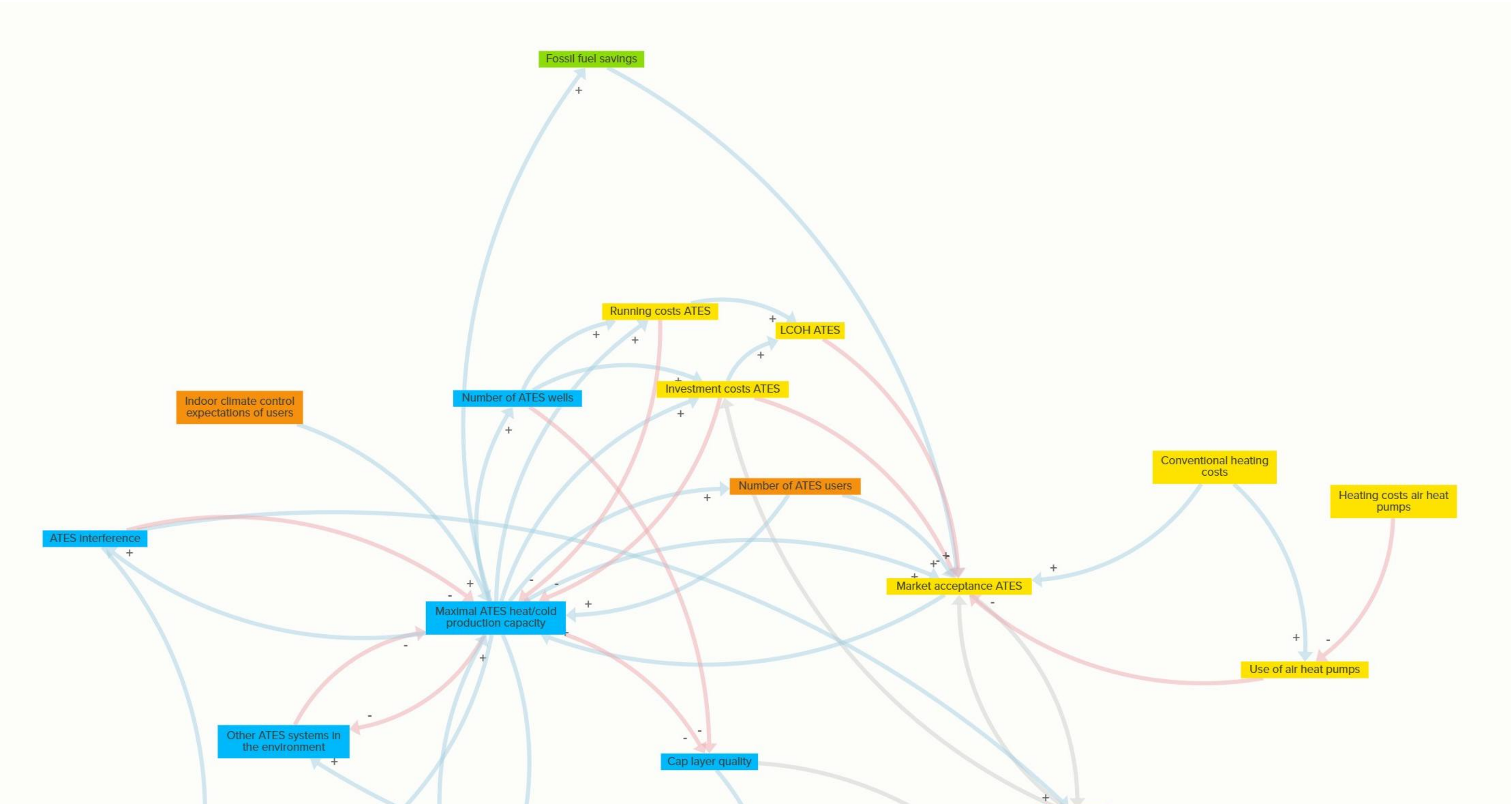
Thematic categorization	Model-systemic categorization	
Governance	Exogenous, stable, constant	Initial Conditions
Social	Exogenous, stable, parameter	
Economic	Exogenous, dynamic	
Environmental	Output	
Geotechnical	Endogenous, bridging	Part of the CLD
	Endogenous, fundamental	

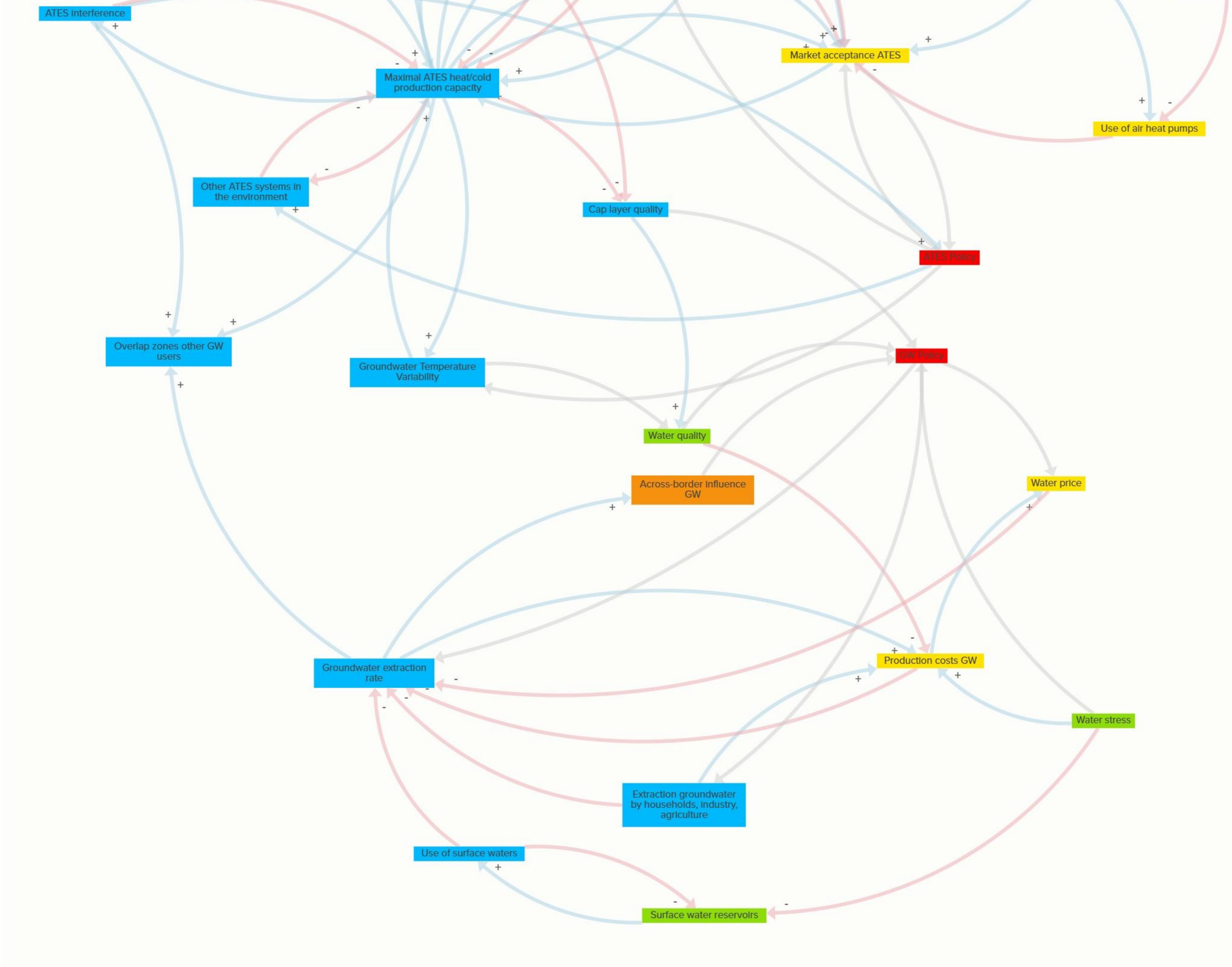
WP5b – CLD Paper – Simplification



WP5b – CLD Paper – Simplification

- 103 Variables ➔ 28 Variables




ATES interference
Maximal ATES heat/cold production capacity
Market acceptance ATES
Use of air heat pumps
Other ATES systems in the environment
Cap layer quality
ATES Policy
Overlap zones other GW users
Groundwater Temperature Variability
GW Policy
Water quality
Across-border influence GW
Water price
Groundwater extraction rate
Production costs GW
Water stress
Extraction groundwater by households, industry, agriculture
Use of surface waters
Surface water reservoirs

WP5b – CLD Paper – Analysis

1) Determine critical nodes
- Network Analysis

2) Discussion of topics
- Competition
- Social Acceptance
- Regulation
- Safety/risk
- Complementary activities/processes
- (Societal) Cost

3) Discuss critical loops

4) What unexpected parts are lacking?

WP5b – CLD Paper – Network Analysis

- Quantitative analysis of network
  - Degree Centrality
    - ➔ Most connections
  - Betweenness Centrality
    - ➔ Element of shortest path between two variables
    - ➔ Key bridges
  - Closeness Centrality
    - ➔ Distance to other variables
    - ➔ Spread information to rest of network

WP5b – CLD Paper – Network Analysis

Variable	Degree	Betweenness	Closeness
Maximal ATES heat/cold production capacity	1	1	1
Market acceptance ATES	2	2	/
Groundwater extraction rate	3	5	/
GW Policy	4	4	/
Production costs GW	5	/	/
Groundwater Temperature Variability	/	/	2
Investment costs ATES	/	/	3
ATES interference	/	/	4
ATES Policy	/	/	5
Cap layer quality	/	3	/

WP5b – CLD Paper – Feedback on CLD

- CLD is almost finished.
- Current version (both the simplified and detailed one) will be sent to stakeholders for feedback
- FB is welcome!

WP5b – SD Paper – Start up

- Create Excel sheet which includes an overview of all relations present in the CLD
- Read literature/books on quantification of CLD
- Study code of other researchers who developed comparable models

➔ Important for AC members: we will need data to develop and calibrate this model.

Questions?

Communication

DIAMONDS

Dynamic Integrated Assessment Methods

for Sustainable Development of the Subsurface

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Dynamic Integrated Assessment Methods fOr the sustaiNable Development of the Subsurface

Onderzoeksdiensten · 24 volgers · 11-50 medewerkers

Agenda

- **08h30-09h00** Arrival at Tabloo, Gravenstraat 3, 2480 Dessel (www.tabloo.com)
- **09h00-10h45** Presentations DIAMONDS
- **10h45-11h00** Break
- **11h00-12h00** Presentations DIAMONDS
- **12h00-13h00** Lunch @Bistroo
- **13h15-16h00** Guided tour @ Tabloo
- **16h00** End of the visit