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Research article

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Interdisciplinary solutions for sustainable management of geological resources: a case study in Flanders

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Abstract: The subsurface is increasingly being recognized as a multifunctional resource supporting key activities in the transition towards a sustainable society (e.g. geothermal energy, CO_2 storage and groundwater extraction). In existing literature, there remains a lack of integrative, cross-disciplinary research addressing the interactions and trade-offs between these activities. Addressing this gap is essential for sustainably managing the subsurface. This paper introduces the DIAMONDS Elevator, a conceptual framework designed to support such collaboration by organizing subsurface decision making across interconnected levels and facilitating knowledge exchange between disciplines. The framework is developed within the DIAMONDS research initiative and is applied to a case study on the multifunctional use of the subsurface in Flanders, focusing on interactions between aquifer thermal energy storage and groundwater extraction. Through this case study, we demonstrate how the DIAMONDS Elevator can be used to structure interdisciplinary analyses and decision-making processes, illustrated in detail from the perspective of an economics researcher. In addition, we position integrative methods and tools, including principles, criteria and indicators, within the Elevator framework. This paper shows how structured interdisciplinary approaches can enhance transparency, support scenario development and inform more sustainable subsurface governance. The DIAMONDS Elevator, as a visual guideline, intends to support interdisciplinary collaboration for sustainable subsurface management.

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Interdisciplinary research that considers multiple uses of the subsurface is required to address the challenges of sustainable subsurface management holistically. As we increasingly rely on the subsurface for resource extraction, energy storage, carbon sequestration and waste disposal, interactions between these uses become unavoidable. To explore these interactions and deal with potential trade-offs, interdisciplinary collaborations will be essential.

The subsurface is an invaluable part of the environment, providing essential resources and services that underpin modern society, including the extraction of fuels, minerals and groundwater, and geothermal heat, as well as the storage of energy and CO_2, and the disposal of nuclear waste. The growing demand for resources over time has led to increasingly intensive use of the subsurface, often without consideration of the environmental and social impacts of this use, and without recognition of the finite nature of the subsurface resources and available space (Compernolle *et al.* 2023).

These challenges are further exacerbated by the transboundary nature of many geological structures, which are subject to multiple regulatory frameworks. Combined with the critical role of the subsurface in the energy transition and decarbonization efforts, these challenges make sustainable subsurface management an urgent priority. Coordinated and sustainable strategies for subsurface management are therefore needed (Van Ree and Van Beukering 2016; Volchko *et al.* 2020; Compernolle *et al.* 2023).

While the need for subsurface management is widely recognized, the adequate level of sustainability, how it can be assessed and how it

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can be operationalized remain topics of ongoing scientific research and debate among stakeholders. Compernolle *et al.* (2023) identified six key challenges that must be addressed when striving for a sustainable management of the subsurface: (1) integrating value pluralism (balancing conflicting values from different disciplines); (2) defining the sustainable scale of resource development; (3) evaluating interferences; (4) guaranteeing environmental justice; (5) optimizing environmental and economic efficiency; and (6) handling uncertainties.

The first challenge expresses a clear need for an interdisciplinary and transdisciplinary approach, which was also recognized in related fields, such as urban underground space and development (Besner 2016; Norrman *et al.* 2024). Nevertheless, most existing research on subsurface management either focuses on a single activity from multiple disciplinary angles or examines multiple activities through the lens of a single discipline. This is illustrated with a brief overview of relevant literature.

Studies that adopt an interdisciplinary or transdisciplinary lens but focus on a single subsurface activity include Elshall *et al.* (2020), who advocated for a transdisciplinary approach to sustainable groundwater management – one that integrates ecosystem services, human activities, stakeholder engagement and uncertainty management within a unified framework. Another example is the work from Guglielmetti *et al.* (2025), who utilized spatial multi-criteria play-based analysis to assess the favourability of high-temperature aquifer thermal energy storage (HT-ATES) across the Swiss Molasse Plateau.

In techno-economics literature, numerous studies evaluate the feasibility or cost-efficiency of individual subsurface activities. For example, Daniilidis *et al.* (2022) conducted a techno-economic assessment of HT-ATES and calculated the levelized cost of heating (LCOH). Chen *et al.* (2018) developed a real options model to determine the optimal investment strategy for gas storage facilities, while López-Morales and Mesa-Jurado (2017) estimated the replacement costs of aquifers that provide groundwater in central Mexico. In addition, there is a recent trend bridging geology, environmental sciences and economics that advocates for the use of 'geosystem services' analogously to ecosystem services. The supporting, regulating, provisioning and cultural services provided by the subsurface can be included in economic analyses, and a growing body of academic literature advocates including them in the abiotic extension of the Common International Classification of Ecosystem Services (CICES) (Lundin-Frisk *et al.* 2024).

Within the social sciences, attention for general subsurface management has traditionally been relatively low. Research mostly focuses on individual projects, often in retrospect, exposing how poorer and racialized communities have borne a disproportionate share of environmental harm from extractive industries (Agyeman *et al.* 2016). In interdisciplinary settings, social sciences often tend to be invited from an instrumental perspective, in view of organizing stakeholder engagement and studying conditions for social support or acceptance of a particular project (or types of projects), typically aiming to facilitate successful implementation (Kluskens *et al.* 2024). However, there appears to be a growing interest in exploring structural inequalities and the broader social impacts of subsurface interventions, adopting a justice-orientated perspective: for example, Caballero *et al.* (2024) for groundwater; Towers and Cotton (2024) for nuclear waste management; Swennenhuis *et al.* (2022) for carbon capture and storage (CCS); and Parson *et al.* (2025) for geothermal energy.

In the fields of geology and engineering, studies commonly aim to optimize the performance of specific technologies or systems. Bloemendal *et al.* (2018) analysed the optimal design and spatial planning of multiple ATES systems to enhance their collective efficiency. More recently, Deleersnyder *et al.* (2024) examined geological interactions between groundwater extraction and ATES systems, investigating how spatial configurations influence performance and the risk of resource conflict.

A clear research gap emerges from these studies. There remains a scarcity of integrative, cross-disciplinary research that considers interactions and trade-offs between multiple subsurface activities. Addressing this gap is essential for developing coherent, sustainable strategies for managing the increasingly crowded subsurface.

A study commissioned by the Flemish government represents a first attempt to model interferences between different types of subsurface activities and to evaluate their impacts from geological, economic and social perspectives (Compernolle *et al.* 2025). To our knowledge, it is the only study to date that investigates multiple uses of the subsurface through a multidisciplinary lens. This early effort laid important groundwork and highlighted the need for a more comprehensive, research-orientated approach, which has since been taken up and expanded within the DIAMONDS (Dynamic Integrated Assessment Methods for the Sustainable Development of the Subsurface: https://www.uantwerpen.be/en/projects/dynamic-integrated-assessment-methods-for-the-sustainable-development-of-the-subsurface/) project.

In summary, sustainable subsurface management brings together multiple, often conflicting, societal needs, from energy and water provision to ecological protection. Addressing this complexity requires more than technical solutions; it calls for truly interdisciplinary collaboration. In this paper, we propose a novel framework for such an interdisciplinary approach to sustainable subsurface management, and we examine how collaboration between disciplines can be fostered and structured. This framework is developed within the ongoing research initiative DIAMONDS.

We begin by discussing strategies for building interdisciplinary research teams capable of navigating the tensions inherent in sustainable subsurface use. To support integration and dialogue across disciplines, we introduce the DIAMONDS Elevator, a conceptual framework designed to structure decision making and knowledge exchange. Next, the DIAMONDS Elevator is applied in practice. To this end, a case study on the multifunctional use of the subsurface in Flanders, with particular attention to the interactions between ATES and groundwater extraction, is introduced. Building on this case study, we illustrate how an economics researcher within the DIAMONDS project can use the DIAMONDS Elevator to structure an economic evaluation. Finally, we present additional methods and tools that contribute to the analysis of multifunctional subsurface use and show how these approaches are positioned within the DIAMONDS Elevator. Taken together, this paper aims to demonstrate how structured collaboration can make the complex interactions of the subsurface more transparent and how such an approach can inform more sustainable governance of the subsurface.

Building an interdisciplinary team

Building an effective interdisciplinary team is the first step towards overcoming the challenges on the path to a sustainable management of the subsurface, as identified by Compernolle *et al.* (2023), and unlocking the full potential of collaborative research. This section identifies the key disciplines for this endeavour, namely geology and subsurface or reservoir engineering, economics, environmental sciences, and sociology. For each discipline, we briefly indicate which of these challenge(s) it could help overcome, and how.

Geology and subsurface or reservoir engineering

The sustainable exploitation of subsurface resources depends fundamentally on a sound understanding of subsurface systems. Geology and geological engineering are necessary in locating resources, assessing their potential and guiding their extraction or use.

One of the critical contributions of geology lies in its treatment of time and space scales (Hermans *et al.* 2023). While most social, economic and political processes operate on human timescales,

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geological processes unfold over much longer periods, often spanning hundreds to millions of years. This perspective is essential for understanding phenomena such as resource formation and renewal, groundwater flow and recharge or the containment of slowly degrading radioactive waste. Spatially, geology extends across administrative or political boundaries. Geological units can span multiple jurisdictions, land-use practices and socio-cultural contexts. In *defining the sustainable scale* (Challenge 2 in Compernolle *et al.* 2023), the spatio-temporal perspective is indispensable for effective interdisciplinary collaboration and should underpin any resource-based assessment.

Coupled with the vast scales are high variability and uncertainty. Subsurface properties are often hidden from direct observation, and must be inferred through a combination of direct (e.g. drilling) and indirect methods (e.g. geophysical surveys). Geoscientists can help to characterize the subsurface, assess risks, monitor changes and help to understand the geological *uncertainty* (Challenge 6). This is emphasized by Scheidt *et al.* (2018) in their work on quantifying uncertainty in subsurface systems, and by Tas *et al.* (2026) focusing on decision making about project feasibility under uncertainty. These skills are particularly relevant when *evaluating interferences* between subsurface activities (Challenge 3).

Economics

Subsurface activities require substantial upfront investment, whether undertaken by individuals, firms or governments. To evaluate whether positive returns can be expected in the future, economists assess expected costs, revenues and the overall economic feasibility of subsurface projects. This economic perspective becomes even more critical when multiple subsurface activities are considered, as careful planning is then required to balance the economic viability of individual activities with the sustainable use of the subsurface. In doing so, economics contributes directly to optimizing *economic efficiency* (Challenge 5). However, remaining within ecological and social boundaries requires more than conventional economic analysis alone. Ecological economics, as a subdiscipline, explicitly incorporates these boundaries into economic decision making. In addition, economics as a discipline contributes to *handling uncertainties* related to long-term financial returns and investment risks associated with subsurface activities (Challenge 6).

First, economic analysis helps to determine the feasibility of each subsurface activity by estimating costs and potential revenues.

Second, it can quantify the financial impact of interactions between multiple activities, revealing how the multifunctional use of the subsurface affects the economic sustainability of each operation. For example, Daniilidis *et al.* (2021) provide a techno-economic evaluation of interferences between geothermal doublets. Nonetheless, standardization and comprehensive analysis is needed to consistently evaluate and reliably predict these interactions (Daniilidis 2024). *Evaluating interferences* (Challenge 3) from an economic perspective can help to support strategies to minimize interferences and conflicts.

Third, economics plays a key role in identifying the distribution of costs and benefits – whether they accrue to the investor, neighbouring subsurface users or the local community. In this regard, economic analyses intersect with *environmental justice* concerns (Challenge 4). To understand the distribution and ensure a fairer allocation of gains and burdens, collaboration with social scientists is needed (see the 'Sociology' subsection later in this section).

Lastly, economic theory offers insights into the strategic behaviour of potential investors, especially in contexts where multiple stakeholders may be competing for access to the same subsurface resource. Anticipating rival actions, investors may accelerate their operations to gain a first-mover advantage, potentially resulting in suboptimal or uncoordinated development. These dynamics underscore the need to *define sustainable use* thresholds (Challenge 2) and to design governance structures that account for *value pluralism* (Challenge 1) in resource decision making. To internalize these externalities (e.g. the 'damage' inflicted upon another actor) in decision making, economics can be (or should be) linked with environmental and social sciences, ensuring that the full ecological and social costs of subsurface use are incorporated into decision making.

Environmental sciences

Environmental assessments must move beyond a narrow focus on climate change mitigation to consider the broader ecological implications of subsurface activities. Assessment tools, such as life cycle assessment (LCA), are central to evaluating the environmental sustainability of subsurface activities. LCA is a standardized methodology that quantifies environmental impacts across the entire life cycle of a technology, process or service, from resource extraction, production and construction to operation and decommissioning. The impact assessment assigns data to a set of midpoint indicators (e.g. global warming potential or fossil fuel depletion) and optionally aggregates them into end-point indicators (ecosystem quality, human health and resource availability), which are then used to evaluate trade-offs between subsurface activities across assessed environmental domains (Hauschild *et al.* 2018). In this way, LCA can contribute to optimizing *environmental and economic efficiency* (Challenge 5) and integrating *value pluralism* into the evaluation process (Challenge 1).

While LCA is a valuable methodology to assess parts of the environmental impact of these technologies, it does not capture the full range of environmental effects (Stemmle *et al.* 2021). Technologies such as geothermal energy, underground gas storage or ATES inherently interact with their surrounding geo- and ecosystems. While these technologies can play a key role in decarbonizing the energy system, they also draw on supporting, provisioning and regulating ecosystem services, potentially disrupting local environmental dynamics (Bayer *et al.* 2013; Soltani *et al.* 2021; Rahman *et al.* 2022). For example, if ATES causes excessive changes in groundwater temperatures (greater than 10 K), this can adversely impact subsurface ecosystems (Blum *et al.* 2021). These negative environmental externalities can reduce public support and raise *environmental justice* concerns (Challenge 4), particularly in communities that bear disproportionate risks. Conversely, positive environmental impacts – such as improved air quality through the replacement of fossil-based heating – can bolster social acceptance by delivering clear co-benefits (Godinaud *et al.* 2024). Past experiences have shown that social support can be a major influence on the success or failure of geothermal energy projects (see the 'Sociology' subsection below). Therefore, *optimizing environmental efficiency* (Challenge 5), *evaluating interferences* (Challenge 3) and *defining a sustainable scale* (Challenge 2) require a holistic understanding of environmental effects, both at the surface and in the subsurface.

Sociology

From a sociological perspective, sustainable subsurface development entails addressing complex questions of distributional justice, intergenerational responsibility and participation in technology development and decision making under uncertainty.

First, sociologists are concerned with how impacts (economic, environmental or social) are distributed across individuals, communities and institutions. Every benefit or burden carries a justice dimension, raising the question of who gains and who pays (du Pisani and Sandham 2006; Schlosberg 2013). The urgency of

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climate mitigation can be used to justify uneven or harmful outcomes, disproportionately affecting vulnerable or marginalized groups (Nawaz and Satterfield 2024). Sociological inquiry into distributive and procedural justice is thus essential to support *environmental justice* (Challenge 4).

Second, the sociological lens draws attention to intergenerational justice. Although many subsurface technologies are deemed renewable from a geological perspective, their renewability can span beyond human timescales (Wallmeier 2024). Questions arise about how current decisions will affect future generations and whether today's benefits come at the cost of tomorrow's sustainability (Compernolle *et al.* 2023). These concerns intersect with the need to *define sustainable scale* (Challenge 2) and *handle long-term uncertainties* (Challenge 6), underscoring the importance of integrating long-term social perspectives into project planning and policy design.

Third, sociologists emphasize the need to engage social institutions, stakeholders and the general public during technology and project development, all of whom bring distinct values, risk perceptions and forms of knowledge to the table (du Pisani and Sandham 2006; Luyet *et al.* 2012). Even the concept of sustainable development itself is a normative framework shaped by ideological and cultural assumptions (Westing 1996). Decisions about which activity to implement, where and why inevitably reflect contested priorities and trade-offs. As widely acknowledged in the literature, social support is a critical condition for project success (Barich *et al.* 2021; Soltani *et al.* 2021). Projects that are geologically sound and economically feasible from a macro-perspective may still fail without the cooperation and trust of local communities due to the actual or perceived imbalance of impacts on the local v. the regional, national or global scale. Sociologists study how stakeholder involvement, participatory decision making and transparent communication can help to identify and address potential inequalities and diverging risk perceptions. These processes ultimately build trust and foster support, thereby contributing to the integration of *value pluralism* (Challenge 1) and guaranteeing *environmental justice* (Challenge 4).

Other disciplines

In addition to these core disciplines, other disciplines also contribute to sustainable subsurface management. Insights from law and policy studies are particularly relevant, given that many regulatory frameworks are still in development and often complex to unravel. Legal scholars can help to clarify rights, responsibilities and conflicts in subsurface use, while policy scientists can investigate the institutional dynamics that influence decision making and implementation. Within the case study presented in the next section, policy is treated as an exogenous factor, as we examine how rules and frameworks affect subsurface development. Nevertheless, understanding how such policies are formed and regulated remains an important topic for future interdisciplinary research. Additional contributions from disciplines such as political science, ethics and spatial planning could further enrich the integrated understanding needed to navigate the complexity of a crowded and contested subsurface.

Framework for integration of and collaboration between disciplines: the DIAMONDS Elevator

To facilitate interdisciplinary communication and collaboration, we developed the DIAMONDS Elevator as a conceptual tool to structure discussions between researchers, exchange perspectives and to develop a shared language across disciplinary boundaries. The Elevator is used to organize knowledge generation in a logical progression, while acknowledging that sustainable subsurface management is inherently iterative. Hence, researchers and other subsurface actors will frequently revisit earlier levels as new insights emerge.

The Elevator is used as a metaphor to illustrate the layered nature of subsurface management, the connections between different levels and the ability of researchers to move between these levels to gain insights. In this way, the Elevator also symbolizes the role of interdisciplinarity – as a facilitator of collaboration across levels, which is essential for building the knowledge and frameworks needed to achieve sustainable subsurface management. The DIAMONDS Elevator is visualized in Figure 1.

Conceptually, the Elevator operates within a 'building' constructed on foundations that represent long-term socio-economic pathways. From these foundations, the Elevator moves through four different but interdependent levels: Policy (Level 0), Planning (Level 1), Operational (Level 2) and Evaluation (Level 3). This sequence reflects a logical progression in which higher levels cumulatively account for assumptions, constraints and insights established at lower levels. Researchers from different disciplines can enter the Elevator, engage with one or more levels and contribute inputs that propagate throughout it.

Each level relies on inputs from multiple disciplines to develop coherent scenarios and enable integrated analyses. In this way, the DIAMONDS Elevator supports multi-level scenario development and assessment across disciplines. In addition to researchers, other subsurface actors – policymakers, users or citizens – can engage with the Elevator to access information across levels. While the framework follows a structured order, progress through the levels is rarely linear. Instead, insights related to societal concerns or policy shifts may inform technical planning, while technical challenges or opportunities can, in turn, influence policy development. This bidirectional flow underpins the iterative nature of the DIAMONDS Elevator and supports integrated, interdisciplinary assessment.

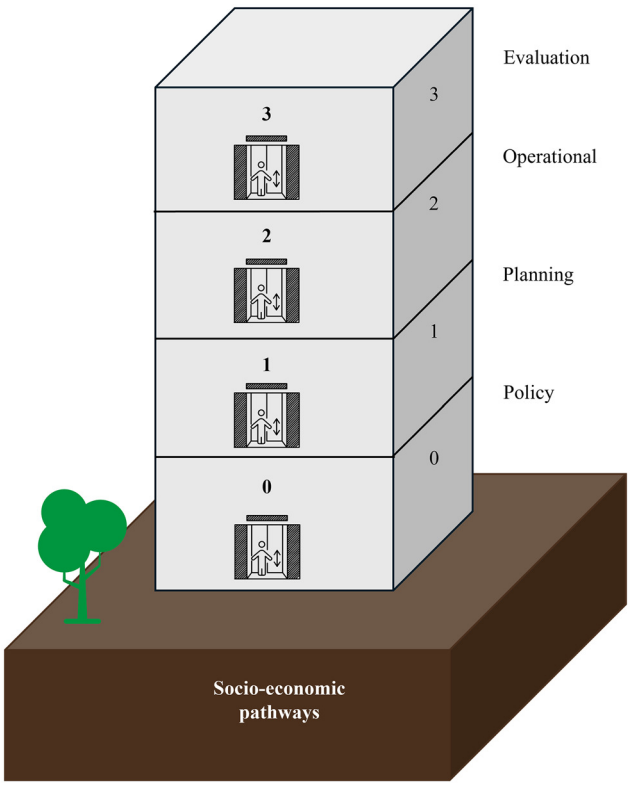

Fig. 1. The DIAMONDS Elevator illustrates the vertical interconnectivity between four distinct levels: Policy (Level 0), Planning (Level 1), Operational (Level 2) and Evaluation (Level 3). The subsurface actor can take the Elevator between levels, going up and down.

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Levels of the Elevator

The foundations: socio-economic pathways

The foundations of the building represent socio-economic pathways on which all other levels are constructed. As in a real building, foundations are difficult to change, yet critically influence what can be built above. These pathways reflect the prevailing norms, values, ideologies and societal dynamics: for example, levels of trust in government and science, and exposure to climate change. They shape public behaviour, election outcomes and, ultimately, policy at Level 0.

Level 0: Policy

Policy regulates nearly all aspects of subsurface development. It determines where and which activities may take place, licensing requirements, permissible depths, acceptable environmental impacts and operational constraints. Compared to socio-economic foundations, the policy level is more concrete, more localized and more amenable to change. As such, it directly shapes the options available to investors and operators.

This policy level feeds information both upwards and downwards: it increases societal awareness of resource constraints while also guiding the planning phase (Level 1) by providing researchers with a broader and more informed set of scenarios and priorities. The decisions made at Level 0 affect which activities can be selected in the planning phase.

Level 1: Planning

In the planning stage, the key task is to determine which activities will be pursued and at what scale. These planning choices are made within the boundaries set by policy (Level 0), but should also be informed by expected geological, economic, environmental and social impacts (see Level 3).

The selected activities provide input to Level 2, where detailed technical designs are developed for the activities. Based on the holistic evaluation at Level 3, the choices made at the planning level may need to be reconsidered; for example, by selecting a different activity or adjusting the planned scale.

Level 2: Operational

On the second floor, the focus shifts from which activities to pursue to how they should be designed and implemented. Here, operational decisions are made about the technical configuration of the selected activities and their expected performance.

This level is heavily reliant on contributions from geology and geotechnical engineering disciplines. Beyond designing for technical feasibility, operational parameters must also be optimized to enhance recovery efficiency and energy density while preventing irreversible damage to geosystem services. Geological modelling and simulation, and a technical assessment are needed to ensure that the finite capacity of the subsurface is respected, not exceeded.

The outcome of Level 2 is a detailed technical design; optimized primarily from a hydrogeological and technical perspective. A more holistic evaluation at Level 3 can inform the design at Level 2, resulting in a new design that can be re-evaluated at Level 3. This illustrates one of the feedback loops operating between different levels of the Elevator.

Level 3: Evaluation

On the third floor, the impacts of these operational choices are evaluated across (hydro)geological, economic, environmental and social dimensions.

The (hydro)geological impacts that are modelled at Level 2 are evaluated at Level 3 in terms of their significance for society.

The economic evaluation analyses the economic costs and benefits of investing in the selected activities, considering their performance and possible interactions with other activities (modelled at Level 2). The effect of uncertainties (geological, technical or economic) on the investment decision can be addressed.

Environmental evaluation examines how subsurface activities affect natural systems. Environmental impacts are assessed based on the technical designs developed at Level 2 and compared with alternative technologies. This evaluation considers whether the selected location can support the proposed activities without degrading geosystem and ecosystem services.

Social evaluation considers impacts such as the distribution of environmental benefits and burdens, stakeholder engagement, recognition of diverse values, and intergenerational justice. It evaluates whether the presence of various subsurface activities is perceived as fair, given the allocation of societal costs and benefits, and existing procedures for stakeholder involvement.

If the evaluation identifies negative outcomes, feedback loops direct attention back to the planning (Level 1) and operational (Level 2) levels for adjustment. Further iterations may require revisiting the policy level (Level 0) to consider broader regulatory changes. This iterative movement – up and down the Elevator – enables a dynamic process of scenario refinement and integrated decision making.

The subsurface actor

Researchers step into the Elevator and engage with different levels, moving up and down to access and provide information, and evaluate a particular subsurface development scenario (a combination of policy, planning and operational parameters). Other subsurface actors – such as policymakers, users or citizens – could also step into the Elevator and synthesize information across levels to make informed decisions.

Although the current use of the Elevator is mainly as an internal communication and research tool, it has potential value beyond the academic setting. By imagining how policymakers, developers or other subsurface actors might use the 'Elevator' and apply the information available at different levels, researchers are encouraged to refine their research questions and outputs. This exercise not only strengthens interdisciplinary collaboration but also demonstrates how the Elevator could evolve into a broader decision-support tool in the future.

It is important to emphasize that the Elevator is a tool that facilitates collaboration across disciplines within the DIAMONDS project, rather than a rigorous categorization system. Consequently, potential overlap between the different levels has been a recurring topic of discussion during project meetings. Nevertheless, visualizing and structuring research tasks within this Elevator clarifies communication about underlying assumptions, structures the types of analyses being conducted, identifies the inputs required from other disciplines or work packages, and helps to organize outputs. In the following section, the Elevator is applied to a case study, illustrating its use within a research project.

The DIAMONDS Elevator in practice: a case study

In this section, the DIAMONDS Elevator is applied to a case study with two coexisting activities: ATES and groundwater extraction. This section also provides an overview of the methods and tools that are currently used, or will be used, at each level of the Elevator.

Aquifer thermal energy storage and groundwater extraction

Groundwater is an important source of drinking water in Flanders and globally. Groundwater extraction occurs through wells that are

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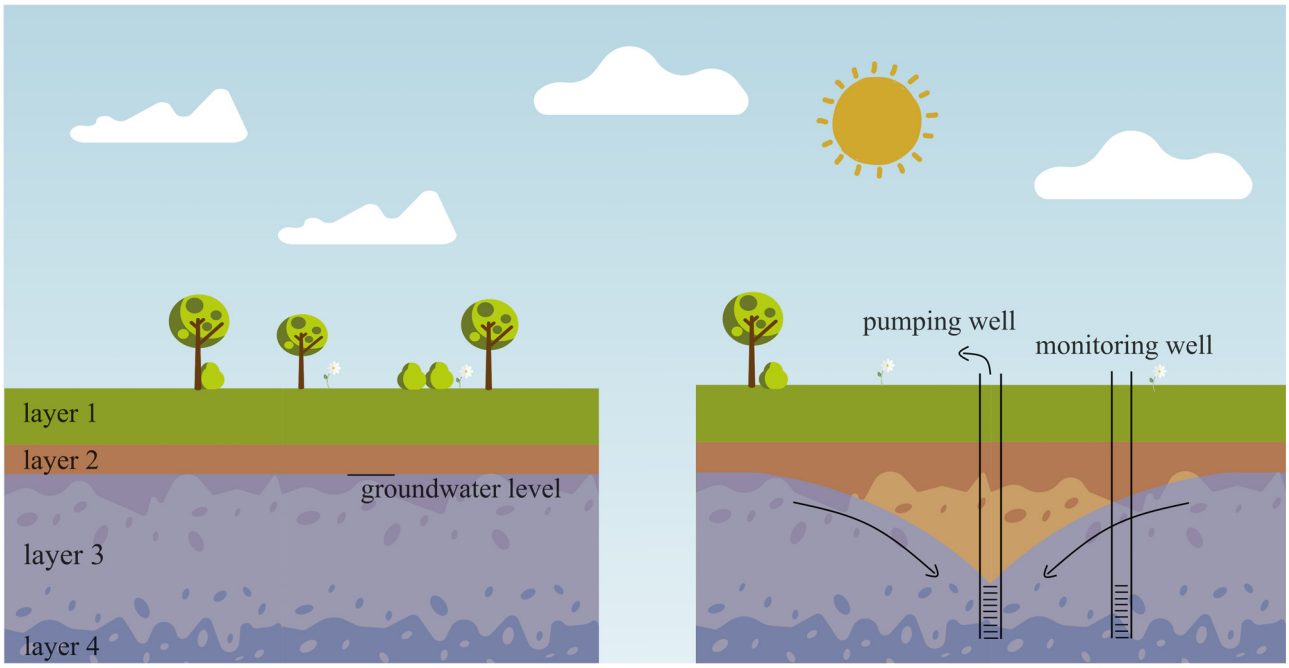

Fig. 2. Groundwater extraction takes place in permeable geological layers or aquifers. The extraction creates a groundwater flow towards the well, via a so-called 'cone of depression'.

drilled into aquifers. When water is extracted, the pressure in the aquifer drops and creates a pressure gradient that draws water towards the well (Fig. 2). To guarantee a sustainable use of groundwater, the rate of extraction should be limited depending on the natural recharge rate and the characteristics of the aquifers (Alley *et al.* 1999; Vandelois *et al.* 2025).

ATES systems can sustainably provide heating and cooling to large buildings or small district networks, particularly in regions with pronounced seasonal temperature variations. The systems seasonally store excess thermal energy from buildings in the subsurface and recover it when needed (Fig. 3). An ATES system minimally consists of one well doublet (a paired warm and cold well) in an aquifer. During winter, water is extracted from the warm well (where it was stored typically at a maximum of +5°C compared to the natural groundwater temperature of *c.* 12°C in Flanders) and directed to a heat pump, which further increases the temperature for space heating. After use, the cooled water (typically at −5°C compared to the natural groundwater temperature) is then injected into the cold well. In summer, the process is reversed: the cold water is recovered for cooling purposes after which the warmed return flow is injected into the warm well, preparing the system for the next winter season. The storage and subsequent recovery of thermal energy make ATES a very efficient, cost-effective and locally available solution to mitigate the effects of global warming and

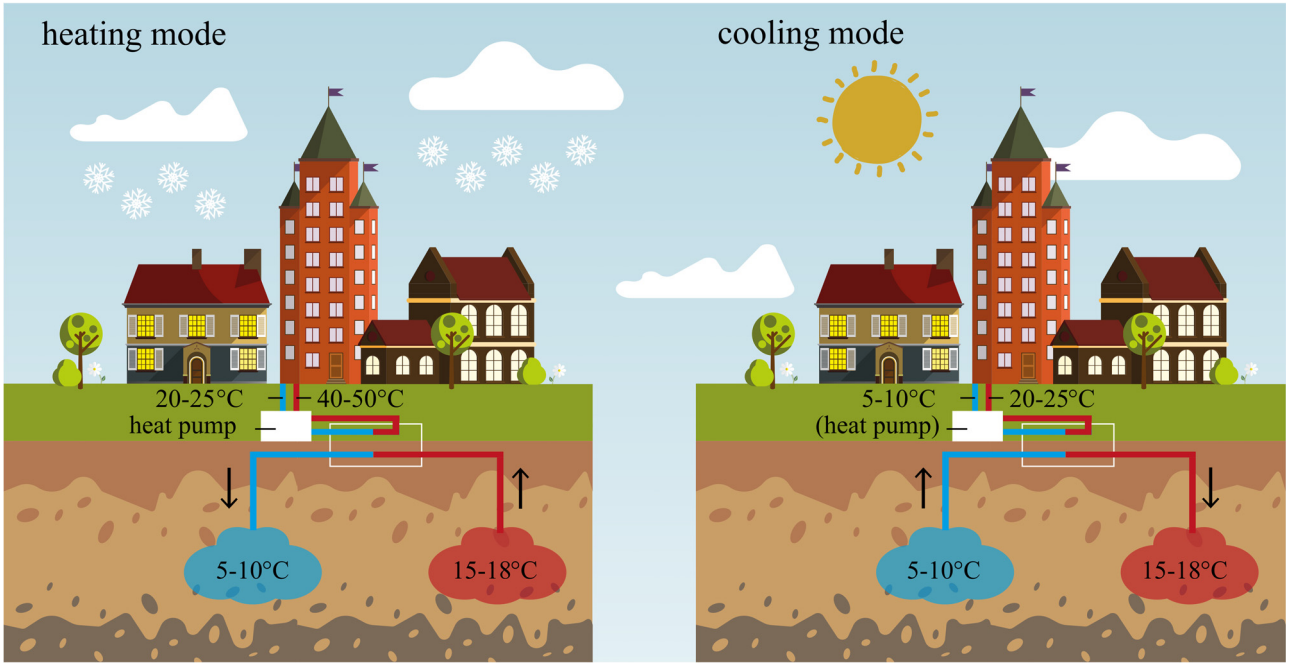

Fig. 3. An aquifer thermal energy storage (ATES) system uses groundwater from an aquifer to store hot and cold water. Source: figure retrieved from Tas *et al.* (2023), with permission from the authors, under the Creative Commons license (https://creativecommons.org/licenses/by/4.0/).

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prevent the emission of hundreds to thousands of tons of CO_2 per year per system (Jackson *et al.* 2024; Herrmann *et al.* 2026).

In a small and densely populated region such as Flanders, suitable geological formations for both groundwater extraction and ATES often overlap, as both systems target thick, productive aquifers. However, these activities can interfere with each other. The pressure gradient induced by groundwater extraction may cause the thermal plumes of the ATES system to drift away from the wells, potentially reducing thermal recovery efficiency from the ATES system (e.g. Tas *et al.* 2025). This may, in turn, affect the temperature of extracted groundwater intended for the drinking water supply. When these temperature changes remain below 10°C, the risk of affecting the groundwater quality chemically and biologically will probably remain limited, as evaluated in Bonte *et al.* (2011) and Possemiers *et al.* (2014). Stakeholder interviews and participatory sessions conducted within the DIAMONDS project provided additional insights (Van Overmeiren *et al.* 2025). Discussion revealed that drinking water companies continue to perceive this potential temperature change as having an important negative effect on groundwater quality, primarily out of precaution. The long-term effects of such temperature changes on groundwater extraction for drinking water production due to multiple ATES systems in the vicinity remain uncertain and should be evaluated on a case-by-case basis (Possemiers *et al.* 2014). Also, the effect of perforating confining clay layers by ATES drilling poses a concern for safeguarding groundwater quality, as they are the natural protection layers prohibiting lower-quality (and sometimes polluted) shallow water from entering deeper high-quality aquifers (KWR 2013; TNO 2021, 2022). While groundwater extraction has long been established across various locations in Flanders, ATES represents a relatively recent and emerging use of the subsurface (Fleuchaus *et al.* 2018).

Groundwater extraction is clearly regulated in Flanders. In 1985, the Flemish government adopted a decree on the demarcation of water extraction areas and protection zones (Vlaamse Regering 1985*a*), as well as a decree on the regulation of actions within these areas (Vlaamse Regering 1985*b*). In addition, the Flemish Regulation on Environmental Permits (VLAREM) prescribes several measures that must be taken when extracting groundwater (Vlaamse Regering 1995).

ATES is a more recent technology in Belgium. The conditions governing groundwater extraction and injection for thermal energy storage systems, such as ATES, are outlined in VLAREM (Vlaamse Regering 1995). The Water Code specifies the conditions under which a tax is due for groundwater extracted for thermal energy storage (Vlaamse Regering 2018). However, to date, there is no single policy framework that consolidates all conditions that an ATES system should meet to be granted a licence. Licensing occurs relatively slowly and on an individual basis, with little focus on sustainable subsurface space use. The permitted drilling depth, peak and annual pumped water volumes, and maximum injection temperature (25°C) are strictly regulated, as is the requirement for monitoring. However, there are no requirements on energy balance or target system efficiency in place. Also, no clear regulation exists in the case of (potential) interference or interactions with other ATES systems or subsurface activities in the vicinity. Industry-wide installation and operation standards should be put in place, as well as a more holistic and coordinated planning approach (Stemmle *et al.* 2025). Stakeholder participation within the DIAMONDS project also provided further insight into the permitting process for ATES systems (Van Overmeiren *et al.* 2025). Licences have often been requested and granted under a fragmented set of existing environmental regulations and, in the vicinity of drinking water wells, input from the precautionary drinking water companies has been highly valued.

Therefore, the current subsurface policy in Flanders is not yet sufficiently adapted to accommodate such emerging technologies and their coexistence with other subsurface activities. A key principle guiding shallow subsurface policy in Flanders is the 'first come, first served' approach, which grants priority rights to the activity that was established first. For the deep subsurface, a formal decree exists at the Flemish level that establishes the regulatory framework governing permit applications and conditions for activities in the deep subsurface. The *Decree on the Deep Subsurface* (Vlaamse Regering 2009) describes the permitting procedures for the extraction of hydrocarbons, the geological storage of CO_2, and the exploration and extraction of geothermal energy. Under this decree, permit applications are published, allowing other potential developers to come forward. In practice, however, this is only feasible if these actors were already preparing a permit application themselves.

In the shallow subsurface, the 'first come, first served' principle is embedded in the *Decree of the Flemish Government of 27 March 1985 Regulating Activities within Water Catchment Areas and Protection Zones* (Vlaamse Regering 1985*a*). Under this decree, other subsurface activities, such as ATES, are excluded from operating in the vicinity of groundwater extraction installations. However, both activities are considered valuable and serve different societal functions. The decree is formulated as a precautionary measure, aiming to minimize the risk of contamination or disruption to valuable aquifers. While safeguarding groundwater quality is important, such a conservative approach conflicts with the long-term objective of integrated subsurface management. Therefore, it is essential to consider both activities in tandem and evaluate the extent and significance of potential interferences.

The economist in the DIAMONDS Elevator

Within the DIAMONDS project, this case study examines whether two subsurface activities – ATES and groundwater extraction – can co-exist while complying with sustainability objectives. One of the key sustainability dimensions considered is the economic feasibility of both activities.

In this example, one DIAMONDS researcher – here, an economist – acts as the subsurface actor who uses the Elevator to gather all information and assumptions required for their economic analysis. The aim of this research is to evaluate the economic impacts of the proposed subsurface development scenario and account for uncertainty, flexibility and strategic interactions between actors – here, the ATES developer and the groundwater company.

The economist's trajectory through the Elevator is described below. Rather than beginning at Level 0, this researcher initially moves to Level 1: the case study focuses explicitly on interactions between ATES and groundwater extraction, and the selection of activities under investigation takes place at this level. From here, the economist moves up and down between levels to gather additional inputs and to generate economic outputs. The economist's trajectory is illustrated in Figure 4, showcasing (a set of) the possible choices and evaluations at each level, and highlighting those selected.

The foundations

Before moving to Level 1, it is important to consider the socio-economic foundations of the 'building' in which the DIAMONDS Elevator is situated. These foundations reflect the prevailing norms, values, ideologies and societal dynamics that shape public behaviour and, ultimately, policy at Level 0. To capture these foundations, the Shared Socio-economic Pathways (SSPs) are used as a standardized set of narratives. The SSPs describe alternative futures for human society, based on different trajectories of fossil fuel use and the social and economic factors driving that use (Climate Data Canada 2026).

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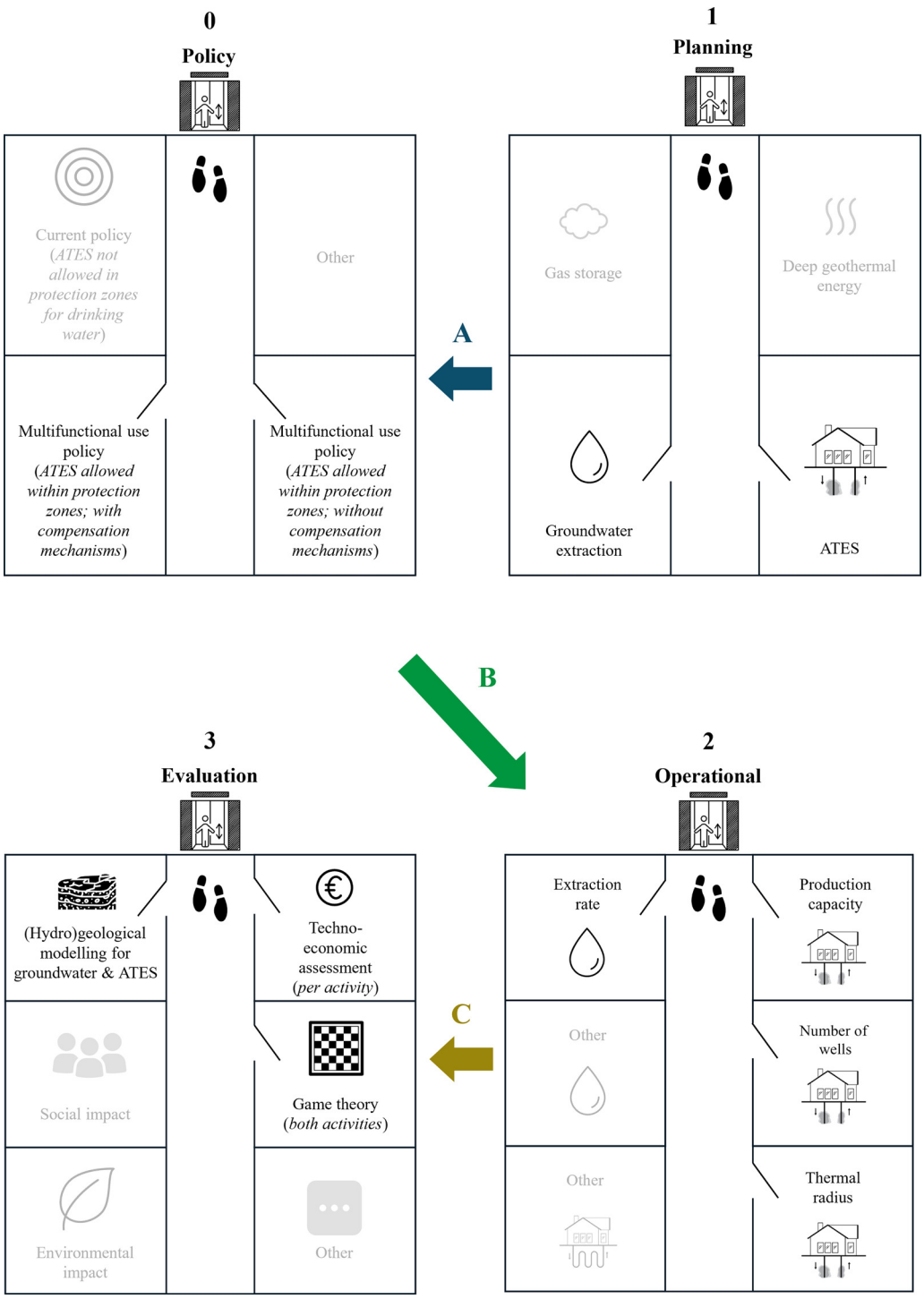

Fig. 4. The economist's trajectory – moving from Planning (Level 1) to Policy (Level 0) (arrow A), to Operational (Level 2) (arrow B) and finally to Evaluation (Level 3) (arrow C) – is presented to illustrate the build-up of an analysis or scenario with the DIAMONDS Elevator. The choices or selections made are indicated with an open door, whereas the unselected choices are shown in light grey.

The foundations also reflect the socio-economic context in which the economist has been educated and now operates. In this case study, the economist considers two contrasting economic paradigms: a free-market economy, and a market economy that explicitly accounts for planetary and social boundaries. The latter perspective aligns with the philosophy of ecological economics.

Level 1: Planning

At Level 1, the researcher determines which activities to pursue and at what scale. Within DIAMONDS, four subsurface activities are considered (Fig. 4): deep geothermal energy, ATES, gas storage and groundwater extraction. For this case study, the economist looks into ATES and groundwater extraction.

Level 0: Policy

The economist then travels downward to Level 0, to examine the relevant policy context and associated scenarios. At this level, existing policies governing ATES, groundwater extraction and their potential interferences are considered. In Flanders, subsurface policy currently follows a 'first-come, first-served' principle: the first

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established installation receives priority protection against future interference. Groundwater extraction, in particular, is highly regulated due to its long-standing role in subsurface use. Protection zones are delineated around groundwater extraction sites, within which other activities are highly restricted (Vlaamse Regering 1985*b*).

Under existing regulations and practices, ATES and groundwater extraction are therefore not permitted to operate in proximity. Since the aim of this case study is to explore how interferences between ATES and groundwater extraction might arise and influence investment decisions, hypothetical policy scenarios are developed that allow ATES systems to operate within the protection zones. In the first scenario, a compensation mechanism obliges ATES developers to compensate the water company for any potential negative impacts. In the second scenario, no such mechanism exists.

Level 2: Operational

With the activities and policy scenarios defined, the researcher moves upwards to Level 2. At this level, decisions concern the technical design and configuration of the selected activities.

For groundwater extraction, the key operational parameter is the extraction rate. For the ATES system, multiple parameters must be specified, including the maximum heating and cooling production capacity, the number of wells, depth, well spacing, flow rate, and the maximum design temperature difference. These parameters determine the thermal and hydraulic radii of influence of the ATES system. To ensure that the system is efficient and compatible with surrounding uses – i.e. protect groundwater quality – modelling groundwater flow and heat transport will be essential.

Crucially, the economics researcher does not determine these parameters alone. Instead, they are established in collaboration with hydrogeologists and engineers, who provide the technical knowledge necessary to define feasible operational configurations.

Level 3: Evaluation

Finally, the researcher reaches the Level 3, where several types of evaluation are performed. The economics researcher will now use all the information gathered at previous levels to perform the economic analyses themselves.

The (hydro)geological models for groundwater extraction and ATES are run to assess their behaviour under the selected technical parameters (Level 2) and to identify potential interferences. Note that the researcher (the economist) does not run these models themselves. Instead, researchers from geological and engineering disciplines will conduct these analyses and provide input to the researcher, exemplifying interdisciplinary exchange and collaboration within the DIAMONDS project.

The outputs from these models then provide input for the techno-economic assessment (TEA), to evaluate the technical and economic feasibility of each activity. Because the hydrogeological models are integrated with the TEA's technical backbone, this analysis forms a direct bridge between geological insights and economic decision making.

However, the TEA addresses only the performance of individual activities. The economics researcher is particularly interested in how interference between the ATES and groundwater extraction influences the decision making of each actor. To assess this, game theory is applied to model strategic interactions, recognizing that outcomes also depend on the actions of others (Matsumoto and Szidarovszky 2015). This is especially relevant in the subsurface, where hydraulically connected geological formations can create interdependencies amongst heterogeneous actors (Masroor *et al.* 2026).

Ultimately, the combined insights from hydrogeological modelling, TEA and game-theoretic analysis reveal how interferences between ATES and groundwater extraction shape the development pathways of the subsurface. Note that this trajectory will only reflect the economically optimal development pathways. To evaluate whether these pathways also represent sustainable development of the subsurface, other dimensions (e.g. environmental and social) must also be evaluated (Masroor *et al.* 2026).

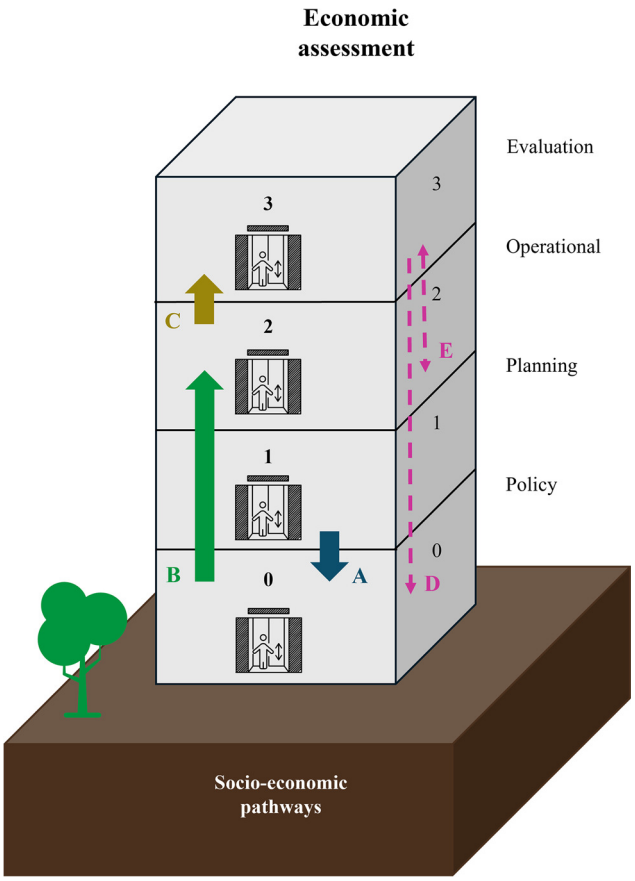

Fig. 5. The economist's trajectory with the DIAMONDS Elevator, starting at Level 1, going down to Level 0 (arrow A), going back up to Level 2 (arrow B), continuing up to Level 3 (arrow C), to complete the economic assessment. The results from the economic evaluation could feed back into the policy decisions (arrow D) or operational choices (arrow E). This illustrates the bidirectional and interdisciplinary character of the DIAMONDS Elevator.

This example illustrates how researchers can take the Elevator to perform research within the DIAMONDS project. They take the Elevator and collect the bits and pieces of information, assumptions, and choices they need for their analysis. The economist's trajectory – moving from Planning (Level 1), to Policy (Level 0), to Operational (Level 2) and to Evaluation (Level 3) – is summarized in Figure 5.

The results from the economic analysis may now feed back into earlier levels. The economic evaluation may inform policy revisions in the future (Level 0) – for example, whether to allow ATES within protection zones and accommodate compensation mechanisms, or not (dashed arrow D in Fig. 5) – or guide optimal design choices (Level 2) based on the (economically) optimal configuration of both activities (dashed arrow E in Fig. 5).

Methods and tools in the Elevator

The previous subsection illustrated the use of the DIAMONDS Elevator by an economics researcher. In this section, additional methods and tools that are currently in use, or will be used, at each

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Table 1. List of possible methods to deploy at each level of the DIAMONDS Elevator, and a brief description of each method

Level	Objective	Method	Brief description
0 – Policy	What are existing policy frameworks and future potential policy scenarios?	Document analysis	A document analysis can be conducted to map and understand existing policy frameworks on the management of the subsurface
1 – Planning	Which subsurface activities will be pursued and at what scale?	Geological modelling and simulation	Geological models and simulations underpin planning decisions by clarifying subsurface conditions and predicting how they will respond to human activities. A geological model is a representation of the subsurface that helps researchers to understand the conditions and developments underground. These models, developed in 1D, 2D or 3D, can represent geological structures, physical and chemical properties, and pressure or temperature conditions. Because subsurface data are often sparse and uncertain, multiple alternative models should be explored, each consistent with available observations (Ferré 2017; Athens and Caers 2019). At Level 1 of the Elevator, these models help to assess subsurface opportunities and constraints
2 – Operational	How should these subsurface activities be designed and implemented?	Integrated (hydro)geological and techno-economic assessment (TEA)	Integrated (hydro)geological and TEA is a methodological approach that evaluates the economic feasibility of a technology, process or value chain by linking (hydro) geological and technical parameters to economic outcomes. This approach forms a crucial bridge between geological models and economic decision making (Level 3). At Level 2, this method tests the feasibility and efficiency of detailed technical designs of wells, flow rates or configurations
3 – Evaluation	What are the geological, economic, environmental, and social impacts of this development of the subsurface?	Techno-economic assessment (TEA)	A TEA evaluates the technical and economic feasibility of each activity, linking changes in technical performance directly to economic outcomes. A typical TEA follows four key steps: (1) a market study, and defining the goal and scope of the TEA; (2) technical backbone, establishing the mass and energy balances (MEBs); (3) economic evaluation; and (4) interpretation of the results. The (hydro)geological models (Level 2) are connected to the technical backbone of the TEA. At this level, the TEA facilitates the evaluation of the economic feasibility of the selected subsurface activities
		Real options analysis (ROA)	ROA evaluates investment opportunities under conditions of uncertainty and managerial flexibility (Dixit and Pindyck 1994). ROA acknowledges the value of waiting, adapting or abandoning a project based on how future conditions unfold. This approach is particularly relevant for subsurface activities, which often involve large upfront investments, long time horizons and considerable uncertainty. For example, ROA has been applied to geothermal energy (e.g. Gkousis *et al.* 2024), CO_2 storage (e.g. Lamberts-Van Assche *et al.* 2023) and gas storage (e.g. Chen *et al.* 2018), allowing investors to assess under which future scenarios an activity becomes viable
		Game theory	Game theory is a mathematical model used to study strategic interactions between decision-makers, where the outcome for each actor depends not only on their own choices but also on the actions of others (Matsumoto and Szidarovszky 2015). This makes it a valuable tool for analysing and evaluating the shared use of the subsurface, where multiple actors, such as geothermal operators, groundwater users or policymakers, may have competing or overlapping interests
		Life cycle assessment (LCA)	LCA is a method to evaluate the environmental impacts of a technology or activity across its entire life cycle, from resource extraction and construction to operation and end-of-life. In the context of subsurface activities, LCA allows comparison of alternatives such as ATES v. fossil-based heating systems by quantifying emissions, resource use and ecological effects
		Social impact assessment (SIA)	SIA evaluates the future social impacts of an action or activity (Becker 2001). It is therefore suitable to evaluate and compare the social outcomes of different scenarios and activities for the subsurface. Mapping the societal context and integrating participation are seen as essential parts of an SIA (du Pisani and Sandham 2006)

Note that this list is non-exhaustive.

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level of the elevator are presented. Some of these methods were already introduced in the example of the economist applying the DIAMONDS Elevator. Table 1 provides an overview of the methods that can be implemented at each level, along with a brief description of each.

The included methods span document analysis, geological modelling and simulation, integrated (hydro)geological and techno-economic assessment, real options analysis (ROA), game theory, life cycle assessment (LCA), and social impact assessment (SIA). This list is non-exhaustive, as many other methods could be incorporated into the Elevator. Depending on the type and objectives of a research project, other methods may be more relevant. Table 1 therefore serves primarily to illustrate how the Elevator can be operationalized within a research context.

In addition to these level-specific methods, several tools span multiple levels of the Elevator. These transversal methods support subsurface actors in navigating between levels and in synthesizing the information to evaluate or plan the sustainable development of the subsurface in Flanders. Three transversal methods applied within DIAMONDS are discussed in more detail below: principles, criteria and indicators (PC&I), causal loop diagrams (CLDs), and multi-criteria decision analysis (MCDA).

Principles, criteria and indicators

The principles, criteria and indicators (PC&I) framework is a hierarchical framework used to assess the sustainability of economic activities. It comprises three levels: sustainability principles, which are translated into measurable criteria and subsequently operationalized through indicators. PC&I frameworks have been developed before: for example, for assessing the sustainability of agricultural systems (Van Cauwenbergh *et al.* 2007) and biodiesel production (Bautista *et al.* 2016).

Within the DIAMONDS project, the PC&I framework is being developed as a structured way of capturing the key challenges of sustainable subsurface management. The six challenges identified by Compernolle *et al.* (2023) are translated into six overarching principles, which provide both a conceptual foundation for the research and practical guidance for other subsurface actors using the Elevator. These principles were validated through a two-round Delphi survey conducted with subject-matter experts. Once the principles were established, criteria and indicators were developed by researchers from different disciplines within the DIAMONDS consortium. These criteria and indicators will be validated in the near future through a second expert survey. Compliance with this PC&I framework helps to ensure that subsurface activities remain within ecological and social boundaries.

The PC&I framework clarifies which principles must be respected, specifies the criteria relevant at each level of the Elevator, and links these criteria to measurable, discipline-specific or interdisciplinary indicators. These indicators can be tested across different subsurface development scenarios, using appropriate methods and models (Level 3). By spanning all Elevator levels, the PC&I framework ensures that decisions made at the Policy (Level 0), Planning (Level 1), Operational (Level 2) and Evaluation (Level 3) stages remain aligned with the overarching sustainability objectives.

To illustrate how the PC&I framework is applied within the DIAMONDS Elevator, Figure 6 shows the pathway followed by a researcher applying the PC&I framework. The researcher first examines the current policy landscape at Level 0 to understand the existing regulatory constraints. Next, the researcher ascends to Level 1, where the set of activities to which the PC&I framework will be applied are selected. The technical configurations chosen at Level 2 then provide essential input for the evaluations performed at Level 3. At Level 3, analyses from multiple disciplines – economic, environmental, social and geological – feed into the indicators within the PC&I framework. These indicators are used to assess the desirability and sustainability of the selected activities, either individually or in combination.

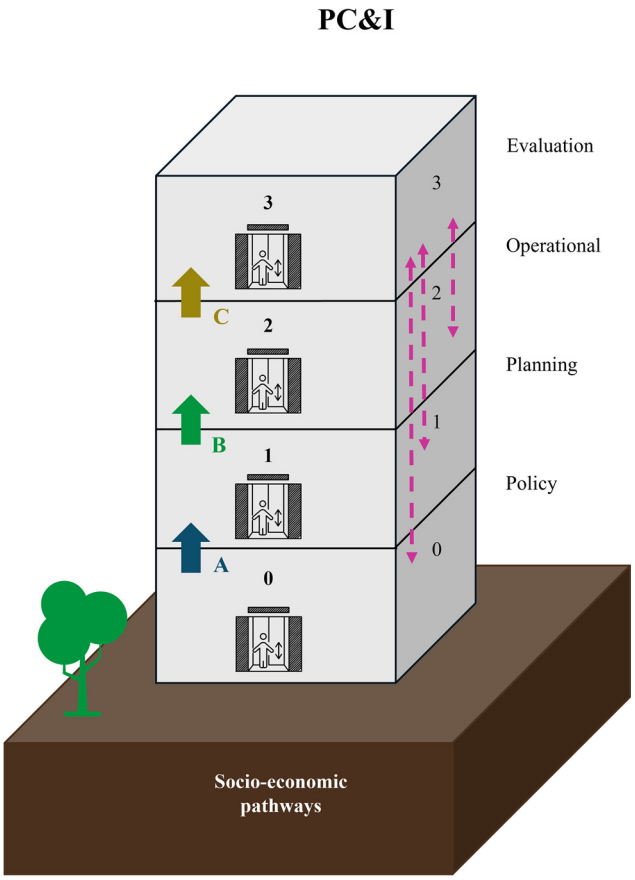

Fig. 6. The PC&I trajectory with the DIAMONDS Elevator. After gathering input at all levels, the results of the PC&I framework may result in changes at those levels, resulting in an iterative process.

In contrast to the economist in the DIAMONDS Elevator, who gathers information at Levels 0 to 2 and conducts an economic evaluation at Level 3, the PC&I researcher gathers information across all levels, including Level 3. The role of the PC&I researcher is to synthesize these diverse inputs into a holistic assessment of the sustainability of the subsurface development scenario.

The results of this assessment can subsequently inform all lower levels. They may indicate how policy at Level 0 could be adapted to promote more sustainable outcomes, which activities are viable or preferable in the planning at Level 1, and how operational design choices at Level 2 should be adjusted to meet PC&I criteria. In turn, these changes may lead to a reassessment at Level 3. Moreover, insights gained through repeated application of the PC&I framework can prompt critical reflection on the adequacy and robustness of the framework itself, allowing for its iterative refinement where necessary.

In this way, applying the PC&I framework requires continuous interaction with other researchers in the DIAMONDS Elevator, including geologists, engineers, economists and social scientists, highlighting its fundamentally interdisciplinary character.

Causal loop diagram

Causal loop diagrams (CLDs) are qualitative system models that support subsurface actors in visualizing and understanding the dynamic interactions within complex socio-ecological–technical

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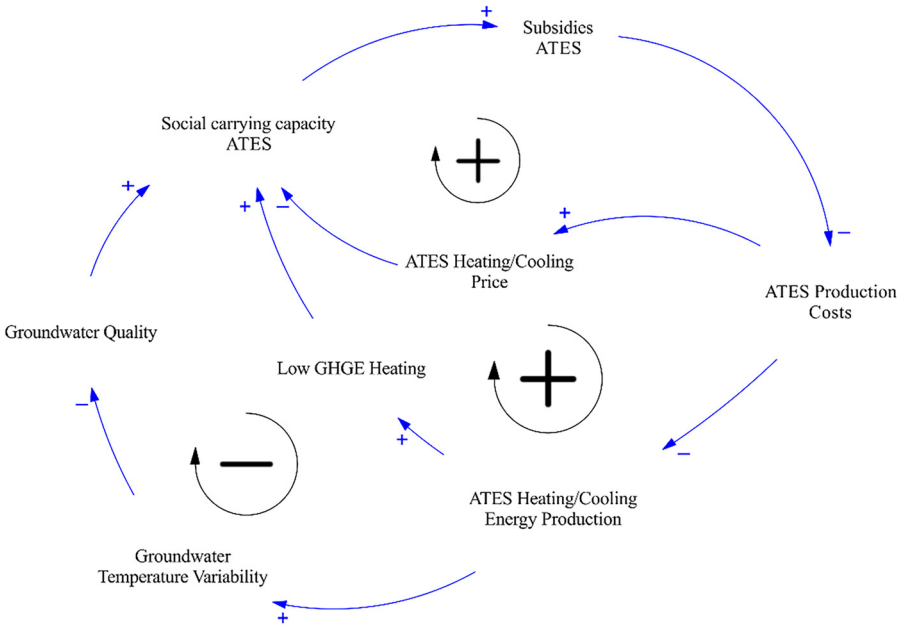

Fig. 7. An illustrative representation of a subsurface system using CLDs, included here to show how the method visualizes the system's interdisciplinary nature. Arrows indicate causal links between variables, with a '+' sign signalling the cause and effect move in the same direction, and a '−' sign indicating movement in the opposite direction. If variables form a loop, a '+' sign marks a self-reinforcing loop, while a '−' sign marks a balancing loop. ATES, aquifer thermal energy storage; GHGE, greenhouse gas emissions.

systems. By mapping causal relations between technical, social, economic and environmental variables, CLDs provide a system-level overview that highlights key feedback loops and unintended consequences.

Figure 7 presents a conceptual and simplified CLD of an ATES system, illustrating how CLDs integrate diverse scientific perspectives. The diagram includes variables from multiple disciplines, such as groundwater temperature (geological/technical), energy efficiency (economic), emissions (environmental) and social carrying capacity (social). The loops shown in Figure 7 – two reinforcing and one balancing – span disciplinary boundaries and reveal cross-cutting insights that could be overlooked in a single-disciplinary analysis. For example, the CLD illustrates how policies aimed at enhancing social carrying capacity may have unintended negative effects if technical factors, such as impacts on groundwater quality, are neglected. In this way, CLDs enable the subsurface actor to identify system-wide risks and synergies before committing to specific courses of action.

CLDs are frequently used to analyse human–nature interface problems, as their building blocks are discipline-independent (Perrone *et al.* 2020). This characteristic allows experts from different fields to develop a shared language when modelling subsurface systems. Pluchinotta *et al.* (2022) demonstrated how CLDs help stakeholders to move beyond discipline-specific perspectives and develop a more holistic and shared understanding of the system under study. CLDs describe systems using variables and causal relationships between these variables (Haraldsson 2004). These relationships can be positive, negative or scenario-dependent. Several relations together can form self-reinforcing (+) or balancing (−) loops.

Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) is a decision-support tool that assists subsurface actors in navigating trade-offs between economic, environmental and social criteria. In environmental decision making, particularly within ecological economics, MCDA provides a robust framework for capturing and quantifying value pluralism (Compernolle *et al.* 2023). It supports the coherent and flexible integration of all dimensions of sustainability and accommodates both qualitative and quantitative criteria. Moreover, MCDA can be tailored to specific temporal and spatial contexts (Garfì *et al.* 2011).

As a formal mechanism for structuring stakeholder engagement, MCDA enhances participatory decision making, especially in contexts involving multiple actors (Van Schoubroeck *et al.* 2024). Within DIAMONDS, MCDA is used to address value pluralism in subsurface management while explicitly accounting for uncertainty. By integrating outputs from all levels of the Elevator, MCDA connects subsurface models, policy priorities, technical designs and social evaluations into a coherent decision-making framework. In practice, it supports the synthesis and ranking of alternatives as subsurface actors move up and down the Elevator. As an ultimate deliverable, the project aims to advance the state of the art by integrating MCDA with ROA, resulting in a decision tree that supports go/no-go decisions based on the assessed criteria.

Together, these three tools – PC&I, CLD and MCDA – guide subsurface actors in navigating the different levels of the Elevator and synthesizing the information generated throughout the process. The PC&I framework establishes structure and boundaries, CLDs reveal system-wide dynamics and feedback, and MCDA integrates and ranks alternatives, thereby supporting the final decision-making step.

Conclusions

Sustainable management of the subsurface requires the balancing of diverse societal needs, technical constraints and ecological limits. In this paper, we illustrated how such complexity can be addressed through interdisciplinary collaboration, as previously advocated for by various research groups. To this end, we established a team of researchers from geology, hydrology, physics, geo-engineering, economics, social sciences and environmental engineering.

The DIAMONDS Elevator structures subsurface research and management into four interconnected levels: (Level 0) Policy, (Level 1) Planning, (Level 2) Operational and (Level 3) Evaluation. By allowing information and feedback to move up and down these levels, the Elevator provides a framework for geologists, engineers, economists, social scientists and policymakers to align their contributions and assumptions. This enables researchers and other subsurface actors to better understand how geological characteristics, technical designs, policy choices and societal values interact.

Next, we demonstrated the use of the DIAMONDS Elevator in practice. To this end, an exemplary case of multifunctional use in Flanders, with the coexistence ATES and groundwater extraction in

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the shallow subsurface, was presented. For this case, we illustrated how a researcher in the DIAMONDS project – an economics researcher, in this example – would enter and use the Elevator tool to structure their analyses. Finally, other relevant methods and tools for the sustainable subsurface management were outlined and positioned within the Elevator. Three methods were identified that spanned across all levels: PC&I, MCDA and CLDs. PC&I and MCDA can guide the researcher or subsurface actor throughout the process by embedding sustainability principles and supporting transparent trade-offs. CLDs help in understanding the interactions and feedbacks between subsurface activities and across sustainability dimensions.

Together, these practices and tools highlight that true interdisciplinarity can go beyond assembling expertise: it demands structured frameworks that foster communication, reveal feedback loops and enable scenario development across scales. The DIAMONDS Elevator makes complex interactions more transparent, while the integrative methods strengthen the robustness of decision making. Looking ahead, the Elevator has the potential to evolve from an internal research tool into a broader decision-support framework for policymakers and practitioners in subsurface governance. By embedding interdisciplinary methods within this structure, we take a step towards more sustainable management of the subsurface.

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