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Abstract

The subsurface provides multiple resources of which the exploitation has a lasting impact on future potential provision. Establishing sustainability in terms of fundamental principles, and fitting these principles into a practical framework, is an ongoing endeavour focused mainly on surface activities. The principles of ecological economics lead to six challenges that summarize the current limitations of implementing science-based sustainable management of geological resources in the medium to deep subsurface: integrating value pluralism, defining sustainable scale, evaluating interferences in the subsurface, guaranteeing environmental justice, optimising environmental and economic efficiency, and handling uncertainties. Assessing and managing geological reservoirs is particularly intriguing because of slow resource regeneration, complex spatial and temporal interactions, concealment, and naturally dictated opportunities. In answer to the challenges, visions are proposed that outline how an indicator framework is needed for guidance, how indicators require reservoir models with extended spatial and temporal scope, how environmental inequity of social values are to be considered, and how real option games combined with life cycle assessment can be used for optimising efficiency. These individual solutions are different facets of the same problem, and can be integrated into one overarching solution that takes the form of dynamic multi-criteria decision analysis.

Introduction

Like ecosystems, the subsurface can be considered as a geosystem, a complex, interlinked system, providing life supporting, regulating, cultural, and provisioning services and a variety of activities are being explored and developed at varying depths (Van Ree & Van Beukering, 2016). However, the subsurface space suitable for these activities is limited and therefore overexploitation as well as competition between its usages is already taking place. With the ambition to reach climate neutrality, the demand for subsurface usage will further increase through for example, increased geothermal energy production, bioenergy production combined with CO_2 utilization and storage, and the temporal storage of green hydrogen. Notably, each subsurface activity can leave temporary (typically change of pressure, change of temperature, or induced seismicity) but also lasting (more often change of chemistry, change of rock properties, subsidence, or brine displacement) impacts which may affect other potential (future) (sub)surface activities as well as related economic, environmental, and social processes on the surface (Michael et al., 2016). Figure 1 gives an image of how different activities could be stacked in the subsurface and visualises the conceptual basis of the upcoming discussion on challenges and visions for sustainable subsurface management.

Sustainable subsurface management includes reducing the risk of resource depletion, resource sterilization, overstressing the larger ecosystem, minimizing safety risks, as well as avoiding litigation between industry operators. Today's social context expects that this is done with transparency and clarity of the roles of regulators and various concerned actors and public (Mouter et al., 2018). Planners should be able to take into account uncertainties and manage interference effects. Such planning should ideally be done at a basin-wide scale before resource development occurs and subsequently be reviewed periodically as knowledge improves (Field, 2018).

Placing sustainability at the heart of regulatory frameworks could allow national and local governments to create a shared vision across different groups of stakeholders on how to plan and regulate subsurface developments for the long term and within a carbon-neutral energy system, while taking into account multiple sources of uncertainty and process dynamics (Gray, 2013). However, establishing an effective policy framework to adaptively manage and regulate the use of the subsurface is currently not feasible because the interactions between the underlying geological, environmental and socioeconomic processes are not fully understood. Additionally, even generally accepted concepts like sustainability seem to lose their meaning in the subsurface, where time scales are geological and impacts to the surface ecosystems are less direct.

Based on a non-comprehensive literature review, we first explore the concept of sustainable development in relation to the subsurface and identify five challenges that need to be addressed for geological resources to be managed in a sustainable way. Additionally a sixth transversal challenge is identified, related to the dynamic and uncertain nature of geological reservoir characteristics, the expected impacts resulting from its development and the attributed values. Secondly, for each of these challenges, we explore the current state-of-the-art and specify current key issues. Thirdly, for each of the five challenges, we describe a vision for future research such that existing knowledge gaps can be closed, and discuss how uncertainty and process dynamics (the sixth challenge) can be included. This process of identification and exploration is applied to the medium to deep subsurface as a natural or artificial storage system, which allows to explore all aspects without making the topic too broad and complex. The deep subsurface starts from various depths, typically between 200 and 500 meters in countries that have this legally defined. In practice, degrading water quality due to increasing natural salinity is a good indicator of the start of the deep subsurface.

Sustainable subsurface development

Given the societal importance of the subsurface (Van Gessel et al., 2017; Vidovic et al., 2020), the need to plan subsurface utilization carefully and the need to use the subsurface in a sustainable way is increasingly being acknowledged by competent authorities, as well as by scientists in the field of Earth Sciences and Natural Resource Economics. Understanding of earth materials, processes & management as well as applying geological skills and practices, are considered important in reaching the Sustainable Development Goals (SDG). See for instance Gill (2017) and the International Geoscience Programme (s.d.) for a detailed overview.

Countries and regions working on achieving SDGs are observing an increased demand for subsurface use and express the need for a science-based decision support framework. Policy goals are to avoid conflict of use, to balance 'use and preservation' and to align subsurface use with above-ground sustainability objectives in a context where the general public is critical for the usefulness of geological resource exploitation and concerned about safety risks (Griffioen et al., 2014).

The concepts of sustainability and sustainable development emerged in the 1980s and the most well-known definition of sustainable development was provided in the famous Brundtland Report. It defined sustainable development, as development which ''meets the needs of current generations without compromising the ability of future generation to meet their own needs'' (Commission, 1987).

The literature is full of attempts to further define the term and several debates on how to approach the concepts of sustainable development and sustainability have emerged (Robinson, 2004). Whether presented as an 'efficient, just and sustainable economics' (Daly, 1992), 'triple bottom line' (Elkington & Rowlands, 1999),'or 'doughnut economics' (Raworth, 2017), striving for sustainability boils down to (i) ensuring that collectively the Earth's resources are not overexploited (sustainable scale), (ii) making sure no one falls short on life's essentials (equitable distribution of costs and benefits), and (iii) doing this at the least environmental and economic cost (efficiency). To these general principles of sustainability, a fourth can be added, namely (iv) developing supporting policies through stakeholder involvement and participatory evaluation. This last principle relates to the accountability of policies (and projects), to a growing emphasis on 'just transition' towards sustainability (e.g. Krawchenko and Gordon (2021) , and to the ethical consideration of value pluralism (Martinez-Alier et al., 1998).

Following up on the concept of sustainable development, sustainability assessment procedures are also being developed. Sustainability assessments are tools to help policy makers decide about the actions to take (or not to take) to make society more sustainable. To avoid reducing sustainability to a consideration of separate environmental, social and economic factors and to avoid omitting factors, one should take a principles-based approach to sustainability assessments. Furthermore sustainability assessments should not focus on minimising negative impacts but define the conditions of sustainability that a project is required to meet (Pope et al., 2004). Hence, the four sustainability principles outlined above could be seen as the fundamental rules to which subsurface use and related policies should comply in order to be considered sustainable. In order to practically evaluate or assess this sustainability, these principles must be further translated into operational criteria. These criteria represent the conditions that a plan, programme or project needs to meet in order to comply to the principle(s) to which they link. Subsequently the criteria ought to be translated into sustainability indicators. These are measurable quantitative, qualitative, continuous, or categorical variables, translating sustainability into a practical set of measures that can be used to inform policy- and decision-making (Singh et al., 2009; Tanzil & Beloff, 2006). Criteria and indicators thus should be developed as user-friendly techniques to evaluate and integrate a.o. (hydro)geological, environmental, economic and social impacts. The current trend in sustainability evaluation (ex post) and assessment (ex ante) is to move from multi-disciplinarity to trans-disciplinarity and holism, where adequate sustainability evaluations account for the interactions and interdependencies across different sustainability themes (Sala et al., 2015), including paying attention to the variety in human appreciation of various aspects of the plans, programmes or projects under consideration (Gunton et al., 2022).

To develop a sustainability indicator framework for geological resources (Figure 2) in line with the fourth principle described above, we need to first specify the principles of sustainable subsurface management more concretely according to the views of various concerned actors, and to develop an appropriate method for defining and assessing criteria and related indicators for sustainable subsurface development. Particular attention needs to be paid to "connect stakeholder values with scientific accounts of what is 'out there' to be valued" (Gunton et al., 2022), that is to say, what is possible to measure and monitor regarding a plurality of sustainability impacts), and the management of trade-offs between the plurality of values being identified (challenge 1). With regard to the first of our sustainability principles, we need to create further understanding on how to define a sustainable scale of geological resource utilization and avoid overexploitation (challenge 2). Furthermore, scientists should create knowledge on how subsurface activities can operate in the vicinity of each other, avoiding conflict of use and seizing opportunities to create synergies (challenge 3). A fourth challenge relates to the second principle, i.e. how to distribute the societal impacts of subsurface development equitably within and across generations (challenge 4). Geological resources should also be exploited efficiently, relating to the third principle of sustainable development, within the limits of what has been defined as a sustainable scale. The challenge relates to the exploitation of geological resources at the lowest environmental and economic costs (challenge 5). Data uncertainty, heterogeneity and process dynamics are identified as a sixth, transversal challenge (challenge 6). Figure 2 shows how these challenges are linked to the principles of sustainable subsurface management.

Subsurface development and management will take place in a context where impacts cannot be determined exactly, where there are unknowns that we know of as well as unknown unknowns, and where geological, environmental and socio-economic processes evolve over time. Hence, in each of the first five challenges, careful consideration is given to the presence of uncertainties and the dynamic context in which subsurface developments take place. In the next sections, we further detail these challenges and present our vision on how to address them.

CHALLENGE 1. Sustainability assessments for subsurface developments: identifying and integrating a plurality of values

As explained above, ruling principles for sustainable development have so far not been applied specifically to the subsurface. Therefore, currently, there is no common understanding of what these sustainability principles involve for 'sustainable subsurface management', and what criteria could and should be put forward to guide holistic sustainability assessment and evaluation, and how to measure them. As a result, existing indicator frameworks related to subsurface utilization primarily focus on a single subsurface use and on the technology deployed.

As regards subsurface resources, sustainability indicators to measure and monitor the status of groundwater quality and quantity are the most developed and applied. UNESCO, with the support of the International Atomic Energy Agency and the International Association of Hydrogeologists, proposed a set of indicators that are based on measurable and observable data, providing information about groundwater quantity and quality (contemporary state and trend) and that are focused on social (groundwater accessibility, exploitability and use), economic (groundwater abstraction, protection and treatment requirements) and environmental (groundwater vulnerability, depletion and pollution) aspects of groundwater resources policy and management (Vrba et al., 2007). The indicators proposed by this group, although simple, are both science-based and policy-relevant, and have been applied to various cases in Europe (Lamban et al., 2011), Asia (Sangam, 2014), and South America (Hirata, 2007). A comprehensive study of water sustainability indicators has been carried out by Pires et al. (2017) who evaluated an extensive list of 170 indicators related to water use and management. These authors considered four sustainability criteria related to social, economic, environmental, and institutional aspects, and identified which indicators of water use and management fulfil these criteria. Their evaluation process yielded a list of 24 key indicators that meet the four criteria. An example is the water poverty index, providing a better understanding of the relationship among the physical extent of water availability, its ease of abstraction, and the level of community welfare. This indicator evaluates 5 strategic elements: resource, access, management capacity, uses, and environment. Other indicators address one or two components of sustainability, allowing to see an aspect of sustainable water use and management from a specific angle. An example of a one-dimensional environmental indicator is drinking water quality, to be measured as the share of samples failing drinking water quality standards in the total number of drinking water samples. An example of a one-dimensional economic indicator is the price of water charged to farmers for irrigation (Pires et al., 2017)

Other indicator frameworks, developed to assess the sustainability of other types of geological resource use, rather focus on the technology that is adopted and not on the resource itself. Regarding geothermal energy extraction, Shortall et al. (2015) for example defined 10 sustainability goals and determined 20 core and 18 optional sustainability indicators as a means to measure and monitor sustainability. Whereas hydrogeological indicators make up the majority of environmental indicators in measuring the sustainability of groundwater use and management (Pires et al., 2017), the sustainability assessment framework proposed by Shortall et al. (2015) to evaluate geothermal energy projects does not include any (hydro)geological indicators. 9 of the 10 sustainability goals cover economic, above-ground environmental and social aspects. Only the goal ‘renewability’ addresses the geological resource itself, which seems too restrictive for the protection of this resource. Furthermore, the indicators selected to measure the sustainability goal ‘renewability’ are: ‘estimated productive lifetime’, ‘fluid reinjected’, and ‘resource reserve capacity ratio’ and give no insight about underlying (hydro)geological conditions.

Sustainability assessments of CO_2 capture and storage (Vögele et al., 2018) and bioenergy with CO_2 capture and storage (Fajardy et al., 2018) tend to neglect hydrogeological indicators in their evaluation. A recent sustainability assessment on the selection of an underground hydrogen storage site does include ‘technical’ (hydro)geological criteria (Nemati et al., 2020). However, these criteria are only used to assess the technical ‘feasibility’ of the site to store hydrogen. The (hydro)geological criteria are not defined to assess ‘sustainability’ impacts.

For the management of groundwater resources sustainability indicators have been well developed, tested, and evaluated, however, indicators to sustainably manage the subsurface as a whole, accounting for its multifunctional use and stretching beyond the lifetime of a single activity are missing. A principle-based indicator framework for the sustainable management of the subsurface can help to provide information about the state of the geological resource and associated environmental and socio-economic processes, to evaluate policy plans and actions, to reveal trends on the functioning of the system or to assess subsurface management scenarios to better understand how well each alternative moves towards a desired state. Relying on the lessons from the development of indicator frameworks for groundwater management (Vrba et al., 2007), the main challenges will involve (i) standardization of the sustainability principles, (ii) identifying denominators common to as many cases as possible to allow for comparisons, (iii) accounting for differences in local, regional, and global scale, and (iv) determining which indicator value would be considered as a 'good' or 'sustainable' value to target.

To operationalise the concept of sustainable subsurface development and to create a principle-based sustainability indicator framework, the four sustainability principles identified above should be further specified for sustainable surface development, and this in a way that is meaningful and accountable to various concerned actors, while yet sufficiently practical. Therefore this first research challenge comprises of developing tools to capture the relevant views and value judgements of concerned actors, including a broad range of academic disciplines. Such tools would be useful for decision-making processes, but also to support inter- and transdisciplinary research activity focussed on defining assessment criteria and indicators.

CHALLENGE 2. Defining a sustainable scale of resource development, avoiding overexploitation

While sustainability is a very common concept, it is less straightforward what could be meant by sustainable use of the subsurface. In absence of literature that deals with this essential element we analyse this challenge in larger detail. This provides for the first time a fundamentally improved understanding of the different aspects of sustainable scale, which allows to define a path forward specifically for geological resources. This also seems to hold lessons for surface resource development, especially regarding the practical implementation of the theoretical concept of sustainable scale.

In search of the scientific or logical answer to the question 'how much of subsurface resources can be sustainably extracted', we return here to the definition of sustainable scale, as proposed by Daly (1992). One interesting element in his departing point is that 'how much' is also linked to 'how'.

Sustainable scale of non-geological resources

Sustainable development as defined by Daly (1992) is a macro-economic principle. An optimal scale is one at which the long-run marginal costs of production and consumption are equal to the long-run marginal benefits. According to ecological economics theory, exceeding this optimum leads to anti-economic growth, and ultimately to overall deprivation. In spite of being crucial, 30 years from its definition, the idea of an optimum scale largely remains a theoretical formalism without a commonly agreed method to determine the cost and benefit of scale expansion. In order to make this theory more practical, the following principles are introduced that translate the macro-level constraint to the micro-level. At micro-level, it is important to distinguish between renewable and non-renewable resources (Daly, 1990).

The main sustainable objective of renewability is preserving natural capital. This implies preserving both the regenerative and assimilative capacities. Regeneration focusses on the resource, and on harvesting not more than can be regrown. Assimilation zooms out to the whole ecosystem and its primary function as a sink for whatever is produced by the elements of the ecosystem, including waste streams from resource use (i.e. pollution; see example of fisheries by Folke and Jansson (1992). Renewability here means that the absorbing limits are not exceeded. A more concrete way of looking at this, is that renewable resources are produced at a steady-state scale that can be maintained indefinitely, and do not affect the ecosystem to such degree that it could not recover without permanent damage.

Defining sustainable exploitation of non-renewable resources is less straightforward. The regenerative principle is still valid, but any exploitation inevitably is one step towards depletion, so the regenerative principle would always be violated. However, starting from the basic objective to preserve natural capital, Daly (1990) argues that exploitation of non-renewable resources (divestment) is justified when at the same time renewable resources are increased (investment). In this way, at macro-level a steady-state is realised (El Serafy, 1989).

This reinvestment principle allows the conditional use of non-renewable resources, rather than preserving them for eternity as passive capital. But it does pose some practical questions, such as which non-renewable and renewable resources should be paired.

It is easy here to think of non-renewable geological commodities like naturally occurring hydrocarbons (oil, gas, or coal). Non-geological examples can be found for specific pollutants that not or hardly break down, but in terms of actual resources, non-renewable often means fossil (as in fossilised). The reason is that fossil resources usually require geological times or rare geological events to accumulate.

Equally challenging is estimating the cost of economic growth, which is determined by the additional stress that we put on the ecosystems and the diminishing of its services, which can be irregular and unpredictable (Daly, 2015). This is further discussed under challenges 5 and 6. However, the point of optimal scale lies at the limit of overexploiting a resource, and may be close to one of the ecosystem tipping points, points of instability that are difficult to estimate. This emphasizes that understanding scale goes beyond renewability and pairing, but also about ecosystem stability and consequences of non-reversable events. Avoiding resource overexploitation also requires a better understanding of the impact and reach of the individual activities. While this objective is clear, the practical translation poses problems as is visible from the typical scope of case studies that does not allow to comprehensively describe the extend of ecosystem-wide effects.

Sustainable scale and geological reservoirs

The gaps between disciplinary boundaries are clear when looking for sufficiently detailed ecological economic studies of geological resources. These are strongly underrepresented with the notable exception of groundwater studies, a discipline that is more closely linked to ecological studies and scaling production to reach a steady-state is a very well-established principle. This does not mean that this principle is firmly implemented, overexploitation is still very common. Regardless, groundwater is an insufficient basis to discuss the whole range of geological reservoirs. Therefore we start by analysing how the scale principles apply to each type (Figure 1), and what this adds to the traditional view on sustainability.

Geological reservoirs can loosely be defined as porosity of a geological unit that at some point has become filled with a commodity. In those instances, the commodity can be extracted as a resource. But also after the commodity has been extracted, or if the porosity was never filled with anything of interest, the pore space itself may be an interesting resource. In many storage projects, for natural gas, hydrogen or CO_2, this is the case. In case of geothermal energy, the resource is heat that may be tied both in the reservoir space as a fluid and its rock matrix. Although extracting geothermal energy typically requires fluid extraction, the fluid itself is not the resource, it is usually reinjected after the useful heat is removed. What is referred to as a reservoir, can either already hold a physical commodity, be used for temporal or permanent storage, or refer to heat stored in the physical compartments of the reservoir complex.

Such distinctions come into play when considering renewability, because we need to consider both the resource and porosity. Compared to typical surface examples, the difference between renewable and non-renewable is more blurred because of the longer time scales. The strength of the sustainable development principles of Daly (1990) is that it gives meaning to this grey zone. Except in areas with very high heat flow (Axelsson et al., 2003) geothermal exploitation for direct use will typically not happen in a steady-state production (e.g. Daniilidis et al. (2020)). Instead, a project will be depleted after several decades, and will take as long or longer to recover (cf. regenerate, regrow). Yet, we can still operate it as a renewable resource, because a cluster of projects can be operated sustainably. Steady-state production would then be met if the operational projects is limited, such that the oldest projects are regenerated at the moment that the last possible projects have reached temporary depletion.

The natural regeneration rate of most fossil fuel resources such as oil or natural gas, is extremely low, too low to allow for a similar scheme. These are therefore non-renewable resources in any practical meaning of the word. Permanent storage of CO_2 also falls in the same category: once a reservoir such as a deep aquifer is practically filled with CO_2, different processes such as dissolution and precipitation will continue to reduce the amount of free CO_2, but typically at rates that exceed that of subsurface management time horizons.

This is different for seasonal storage projects such as for natural gas or hydrogen (Bünger et al., 2016). These projects claim the pore space for decades, but upon abandonment they will largely recover the cushion gas, and be restored to their original state. This is a renewable resource concept not explicitly covered for non-geological applications, but does not conflict with its principles. Note that the renewability of the stored commodity (e.g. green, red or black hydrogen) would not affect that of the pore space. Returning to its original state is of course an important precondition. If reservoir operation would result in a collapse of porosity, or the once impermeable seal would be perched by fault reactivation or improperly abandoned wells, then the value of that storage site has been damaged and its intrinsic value diminished for future generations.

It is useful to draw the line of what does and does not fall under the sustainable scale challenge. Induced seismicity that leads to permanent damage of a reservoir does, but the more frequent earth movements that cause damage to surface infrastructure typically do not mean that an unsustainable amount of resource has been extracted. If in such scenarios resource extraction rates are limited or an activity is completely banded, then this is because of economic, environmental, and safety considerations under challenges 4 and 5.

The pairing principle and geological storage

The pairing principle, in which divesting non-renewable is compensated by increasing renewable capital, is a more difficult principle, and increasingly so for geological resources. This principle appears logical and can easily be imagined for straightforward examples, where use of fossil fuels can be compensated by increasing forested land to the degree that it would increase biomass and offset CO_2 emissions. But pairing the use of fossil fuels with a-biotic renewable resources such as wind or solar, seems more difficult. The natural stock of resources present on earth at a given point of time is referred to as natural capital (Costanza et al., 1997). Furthermore investing in installed capacity in such a way that it improves access throughout following generations, also comes with sustainability challenges, including the availability of critical minerals.

More importantly in the scope of this paper, is that renewable geological resources such as geothermal energy face similar issues when used to counterbalance non-renewable resources. Heat can be stored underground, but only in active storage-production schemes. Because it dissipates too quickly, it cannot be stored to be used decades from now, and more importantly, would not be a renewable capital. So pairing non-renewable and renewable energy may only be possible to a limited degree.

Preserving the portfolio of the total capital when pairing may incorrectly be perceived as restricting it to apples for apples. This is not strictly the case, but does lead us down the path of exploring what can be reasonably compared or substituted to come to fair pairing. This seems like a complication, but potentially can make sense in examples where pairing otherwise seems impossible. If a CO_2 storage project claims reservoir space in a non-renewable way, then one pairing solution is to invest to offset future CO_2 emissions, so that for each unit of CO_2 that is stored in a non-renewable way, the potential to avoid one additional unit of CO_2 in a renewable way is created. In that way, CO_2 avoidance is properly compensated, even if an intrinsically different resource (porosity) has been consumed.

Assimilative geosystem services

The concept of services comes from ecological economics wherein it is said to be derived from the ecological functions of nature that benefits human (De Groot et al., 2002). As these ecosystem functions directly and indirectly contribute to human welfare (for instance, climate and water regulation, food production) they are grouped under the term of ecosystem services to represent all the goods that are valued by humans (Costanza et al., 1997). Similar to the concept of ecosystem services, geosystem services is a term that is used to broadly refer to the functions and goods obtained from the subsurface benefiting the humans (Van Ree & Van Beukering, 2016). Geologists by training think of the subsurface in terms of resources, not in geosystem or ecosystem services. The latter is a wider context, and important for part of renewability assessment. Resources, including reservoirs, are the most obvious service that a geosystem offers. Other types of services may be very diverse, and go as far as include cultural heritage. However, in terms of geological reservoirs, it are assimilative geosystem services that are most important.

Assimilation of an ecosystem refers to the ability to accommodate waste streams of specific processes or activities. Typically, the resource is specific and localised, while the assimilating sink is a service linked to the broader ecosystem in which the waste product is absorbed in a non-localised way. This is also underlined by the thermodynamic basis that is sometimes promoted as a scientific foundation, postulating that the entropy of the waste product will be higher, as it is diluted in the atmosphere or another medium. Through a few examples, we will learn how the line between resources and assimilative services easily gets blurred in the underground.

When taking the example of fossil fuels, then one could argue that their sustainable scale is limited firstly by the assimilative potential of the worldwide ecosystem for CO_2 emissions, rather than by their depletion rate. This is why CCS technology is an option, even when it involves concentrating CO_2 at the expense of additional fuel (energy) use. CCS therefore deals with the most urgent sustainability problem of rising CO_2 emissions, even though it may accelerate the depletion of fossil fuels. This seems to align with the general principles proposed by Daly (1990), so let's explore this in more detail.

Assume a simplified case where oil is produced using CO_2-Enhanced Oil Recovery so that the storage rate of CO_2 balances exactly the CO_2 released from oil. At least with regards to CO_2, there is no net impact on climate, and the assimilative potential of the ecosystem is not used. On the resource side, non-renewable oil is being depleted, and this depletion has to be offset by investing in a renewable energy resource. By depleting the oil field, storage space is created. This new resource is immediately used for the storage of CO_2, and therefore does not need to be compensated. So for CO_2-EOR to be fully sustainable from the scale perspective, these three criteria have to be met, of which pairing depleting oil reserves with investing in renewable energy capital may well be more difficult than the storage of CO_2.

This example reveals an underlying question: why would dispersing CO_2 in the ecosystem (release to the atmosphere) be regarded as assimilative, while storing it locally in the same ecosystem (storing it concentrated in a geological reservoir) be approached as using a resource (pore space)? An important question, since Daly (1990) makes a clear distinction between both, and remains less specific on the assimilative resources.

The answer seems to be that the principles are incomplete, in that also waste assimilation should be split into renewable and non-renewable assimilation, or rather carrying capacity. This difference seems more obvious in the geological realm, but is equally valid in surface examples. Waste products that are released and can be fully broken down by natural processes make use of the renewable carrying capacity: a steady-state can be established in which natural processes can keep up with a constant waste stream, without permanently damaging the ecosystem services. On the other hand, other waste such as heavy metals will accumulate in the ecosystem. Certain levels are tolerable, but when through cumulative releases these are exceeded, the ecosystem is being negatively affected. Another example is brine displacement or expulsion into fresh groundwater, a potentiality when for example geologically storing CO_2. Both are instances of non-renewable use of carrying capacity.

It therefore makes sense to distinguish both types of carrying capacity, and apply the same pairing principle to non-renewable usage. Once done, the question of whether storage space is a resource or an assimilation service becomes more of a semantic discussion. This is also where linking sustainability to subsurface uses reveals that an extension or reformulation of the sustainability principles of Daly (1990) is needed, which warrants an elaborate discussion in its own right. This publication will remain resource oriented, but from a sustainability perspective, a resource cannot be separated from the other services that the geosystem or wider ecosystem provides.

The challenge

The general challenge of the sustainability principles as they have been recognised since Daly (1990), is their practical determination of especially the scale of resource exploitation. It certainly makes more clear what criteria different reservoir and storage activities in the mid to deep subsurface should meet to be considered to operate partially or fully at a sustainable scale. The typically extended time frame that comes into play when applying them to geological reservoirs is not only a challenge, but leads to a more fundamental exploration of what sustainability, renewability and pairing means. This forced revisit of basic principles is what will lead to a new vision of creating the micro-economic approach to make this well-established theory more applicable, ultimately allowing to provide a science-based answer to determine sustainable scales of exploitation.

CHALLENGE 3. Potential interference effects between subsurface activities, now and in the future

Interference effects between subsurface activities influence the scale of their operations, as well as their effect on ecosystem services. Evaluating these influences includes how far their impacts reach

3-dimensionally as well as through time. This is a major challenge, especially for the deeper subsurface, where this can rarely be modelled exactly because the geological and reservoir context is only indirectly and partially known (Hermans et al., 2022). Also, sustainability requires that present and future generations have equal opportunities to meet their needs. This long-term perspective was equally central to challenge 2, although it is emphasized here because interference is also discussed here between contemporary activities, but also consecutive one, such as reuse of a depleted oil or gas reservoir. Interference can have a much larger footprint than the scale of a resource, both in vertical and horizontal direction.

Existing hydrogeological and reservoir models are tailored to a singular subsurface activity and the literature on individual subsurface reservoir management is abundant (Alam et al., 2021; Lund & Toth, 2021; Saeid et al., 2019). However, these reservoir models do not provide knowledge about the dynamic interaction effects between multiple subsurface activities (Willems et al., 2017), especially when the type of activities differs. Although the need for understanding interaction effects and planning subsurface use is increasingly being acknowledged in past research projects (e.g. Angus+ or GeoERA-GeoConnect³d), such projects do not seem to have been able to make this step in practice. Therefore, current state-of-the-art remains limited to high-level generalized workflow frameworks as proposed by Michael et al. (2016) for CO_2 geological storage or qualitative descriptions of expectable mutual effects of different subsurface applications on each other (Bauer et al., 2013). As a result, competent authorities are managing the subsurface without a solid scientific reference frame and often on a project-by-project basis. Hence, more detailed characterization and quantification of site-specific processes and interference effects is required to progress into more specific evaluations.

Different subsurface applications have their own characteristics that must be modelled, but their integration in the management at the basin scale requires to describe and evaluate the asymmetric relations between different activities. The storage of high-level radioactive waste is a typical example, that has a very limited influence radius beyond the actual storage complex, but which is potentially very sensitive to the presence of other activities nearby. For most mixed activities, it is important to at least consider if such asymmetries come into play.

The main related challenge is the scale of the model. Typically, model size is limited to a scale deemed sufficient to avoid too much influence from the boundary conditions (Daniilidis et al., 2016), but this approach neglects the potential interference from other users outside the simulated zone (Daniilidis et al., 2021): a more general framework is thus needed that considers the basin or other relevant geological unit as a whole. Moreover, deterministic models are commonly considered for deep subsurface reservoirs (Saeid et al., 2015), even though uncertainty is often large. This prevents assessing the uncertainty of the prediction. This aspect becomes even more important for interferences, as stakeholders are primarily interested in geological scenarios that would yield strong interferences and potentially affect their own production (Ferré, 2017).

Challenge 3 can be seen as an extension of challenge 2, in that the different aspects of foreseeing the interaction of reservoir activities that can be separated in space and time, adds significantly to the complexity of the problem and uncertainty of the outcome. Nevertheless, evaluating the sustainability of one activity is possible only in respect of other activities that are or can be developed.

CHALLENGE 4. Social Impact assessment and Environmental Justice

Although subsurface activities contribute to economic progress, it is said to potentially create structural inequities that disproportionately impact the residents around the site of development

(Malin et al., 2019). Subsurface activities often suffer from social opposition, often attributed to the neglection of relevant values (Mouter et al., 2018). Apart from accounting for inter-generational equity, sustainable subsurface development should also consider inequities in the exposure and risk of vulnerable groups in the present (Agyeman et al., 2002). Therefore, the concept of sustainable development raises important challenges for subsurface developments in terms of justice, equity and fairness (McLaren, 2012). The concepts of (environmental) equity and justice refer to fairness in both process and outcome. As already referred to in challenge 1, the process aspect (in line with the fourth sustainability principle) requires an inclusive and non-discriminatory approach wherein decision-makers adopt a transparent process that recognises the representative voices of people that may be affected, and that acknowledges that not all relevant criteria can be objectified and interpreted by sciences alone.

The focus of challenge 4 is set on the outcome aspect, wherein the spatial distribution of costs and benefits are balanced across groups, avoiding the disproportionate distribution of undesirable characteristics on a potentially burdened population (Greenberg & Cidon, 1997). However, it needs to be stressed that process and outcome are inevitably strongly linked. Talking about outcome, also means addressing process to some extent, as is clearly shown in the passages below. In practice, environmental inequity continues to exist, often because of social disparity based on race, ethnicity, gender, and socioeconomic status (Ringquist, 2005). Past subsurface uses involving drilling and mining have impacted local communities by exposing them to toxic hazards and creating social inequities (Malin et al., 2019). To address environmental inequity arising from the disproportionate distribution of costs of subsurface activities, we deploy the concept of environmental justice. This does not only consider equity, identification and engagement of vulnerable populations, but also includes discourse for fulfilling the basic needs for the functioning of local communities (Schlosberg, 2013). The concept of environmental justice needs to be addressed for subsurface developments as social acceptance of subsurface developments remains a barrier. It is important to understand the kind of injustices, where they exist and who is impacted by them. Environmental justice can be further understood based on four tenets: recognition justice (who is affected and who is recognized or ignored as a stakeholder?), distributional justice (how are various groups affected?), procedural justice (what mechanisms of inclusion or exclusion are at play in the decision-making?) and restorative justice (how to compensate affected groups?) (Jenkins et al., 2016; Jenkins et al., 2018).

Although there is a significant amount of research on environmental justice, limitations exist when it comes to implementation for subsurface activities. According to Jenkins et al. (2018), the discourse on low carbon energy systems that include geothermal energy and Carbon Capture and Storage (CCS) fails to put justice into practice-based approaches. The concept of justice is explicitly put forward as an analytical tool, as a “lens through which we can begin to tackle related environmental and climate justice issues” (Jenkins et al., 2018). Low carbon energy systems like CCS face social acceptance issues wherein local communities mistrust the project developers to treat them in a fair and equitable manner (Bradbury et al., 2009). Braun (2017) mentions that residents living in proximity of a potential CCS site are less likely to accept CCS development. This “not-in-my-backyard" attitude can be attributed to the perceived risks of CCS developments as subsurface developments are hidden and easy to mistrust for the residents. Tiwari et al. (2021) claim that injustices need not only occur from the implementation of the service, but could also emerge from the way the decision process is designed. For instance, for a CO_2 capture and storage project in Barendrecht (the Netherlands), Terwel et al. (2012) examined the reasons for the cancellation of the execution of the project. In addition to safety concerns related to the project, the residents gave testimony of a negative attitude stemming from a lack of trust in the decision-makers to maintain a transparent and fair process. Cuppen et al. (2015) argue suspicion towards decision-makers arises due to the “goal rational – meta frame” where the planners seek to minimize the risk imposed by the technology instead of accounting for and resolving the concerns that the residents might have. Although the United Kingdom (UK) Research Council has tried to include the elements of “procedural fairness mechanisms” for geoengineering decisions by creating a “social impacts panel” and “stage-gate appraisal”, McLaren (2012) claims that it lacks in providing a platform for the negatively affected groups to voice their concerns. Cuppen et al. (2015) present that engaging stakeholders that may impact or be impacted by the process or outcome needs to be understood as a dynamic process. Therefore there is a need to gain more insight into the dynamics regarding institutions-organizations-governments-residents relationships involved in subsurface developments.

Within the context of subsurface development, there is a need for examining structural inequities and the power dynamics of the stakeholders involved in the process. The challenge lies in identifying the potentially affected population (recognition justice) and understanding the impact of inequities (distributional justice). This resonates with experience regarding large scale surface infrastructure projects (e.g. wind farms, airports, …) and ongoing scholarly debate on the role and content of social impact assessment (SIA) (Becker, 2001; Konieczyńska et al., 2020). More recently, the term social life cycle assessment or analysis (SLCA) has become ‘in vogue’, within the framework of life cycle thinking (Alomoto et al., 2021; De Luca et al., 2015). The literature on social indicators, SIA and SLCA is vast and growing, but despite continuous and expanding scholarly research efforts, there is not yet a standardized methodology for SIA or SLCA to the same amount as it exist for e.g. environmental LCA. In relation to subsurface activities a huge challenge still lies ahead to identify valid key social criteria and indicators. A first attempt in that regard was made by Rafiaani et al. (2020) for CCUS technologies, bases on expert elicitation at the European level.

CHALLENGE 5. Developing geological resources at the lowest environmental and economic cost

Respecting challenges 1 to 4, subsurface development should take place at the least environmental and economic costs. Current economic and environmental impact evaluations of subsurface storage activities are project based and evaluate the development of subsurface activities from a technology perspective. Techno-economic assessments are widely adopted to calculate the levelized cost of energy (see e.g. Formhals et al. (2021) on geothermal energy storage), the full life cycle costs (see e.g. Seo et al. (2017) on CO_2 capture and storage), or a project’s profitability (see e.g. Matuszewska et al. (2020) on geothermal energy storage). By integrating geo-technical and economic processes, a techno-economic assessment allows to understand how geotechnical aspects impact the economic feasibility of different system configurations or value chain scenarios, but still need to be paired with an environmental impact evaluation because typically there is a trade-off between environmental and economic costs.

The environmental performance is often assessed using emission factors (see e.g. Hosseini et al. (2021) and Schüppler et al. (2019) on geothermal energy storage), exergy analysis (see e.g. Yapparova et al. (2014) on aquifer thermal energy storage, or Zhou et al. (2018) on CCS), or environmental life cycle analysis (see e.g. Petrescu et al. (2017) on CCS). Especially for the evaluation of CO_2 capture and storage these assessment methods are regularly used, as witnessed by review papers that screen existing literature about techno-economic assessments of CCS (Li et al., 2019), and environmental life cycle assessments of CCS (Wang et al., 2022). These assessment methods can also be integrated to analyse trade-offs in environmental and economic impacts across different value chain scenarios (see e.g. Roefs et al. (2019)). Also, to evaluate the integration of geothermal energy storage in renewable energy systems, exergy analyses have been combined with techno-economic analysis, by applying multi-objective optimization to optimally design the system such that it is most efficient, cost effective, and least carbon intensive (Abbasi Kamazani & Aghanajafi, 2022; Mousavi et al., 2021; Welsch et al., 2018). For geological hydrogen storage, environmental and economic assessments are more limited. Simon et al. (2015) for instance study the geological potential for hydrogen storage in Spain, considering the full value chain and all the associated economic aspects. Al Rafea et al. (2017) also consider environmental and health costs.

Nonetheless, current economic and environmental impact assessment to evaluate subsurface activities show limitations related to the system boundaries of the analysis and the considered time frame. Most studies have narrow system boundaries and do not consider interactions with other subsurface activities. Narrow system boundaries typically exclude indirect effects or unexpected trade-offs. In addition, the timeframe of the analysis is limited to the expected lifetime of a single subsurface activity. Currently, there are no studies that evaluate the economic and environmental impacts of sequential investment decisions or alternative production scenarios after well closure. Furthermore, although it is being recognized that the evaluation of subsurface activities is subject to geological, economic, and policy uncertainties, and that parameter values fluctuate in time, most economic and environmental impact assessment models are static. In techno-economic assessments, uncertainty is mostly addressed by a sensitivity analysis to understand how sensitive the results are for changing parameter values, or by an uncertainty analysis to understand the outcome distribution.

However, it has been demonstrated that the traditional discounted cash flow methods and sensitivity analyses are inadequate to deal with issues such as uncertainty and the irreversibility of investment decisions (Dixit, 1994; Trigeorgis, 1996). Adding a time component in environmental and economic impact assessments is important to account for geo-technical learning, managerial flexibility and development adaptation. Formhals et al. (2021) for instance, present a more dynamic system design, considering in their study a stepwise integration of solar thermal collector, medium deep borehole thermal energy storage and waste heat sources. Strategies for integrating new components and decommissioning existing infrastructure are compared by energetic, economic and environmental means. The time frame of the study is divided into three periods, enabling changes in the system design at the start of each period. This analysis is close to decision tree analysis and real options analysis, which are considered more suited for analysing irreversible investment decisions under uncertainty (Dixit, 1994; Trigeorgis, 1996). Real options models are regularly developed to evaluate the value of flexibility and the likelihood that investment in a CCS value chain will take place (see Li et al. (2019) for a review). However, applications of the real options theory to other subsurface developments are rather limited. Furthermore, environmental life cycle assessments (LCA) are mostly static as well, or only seasonal variation in environmental impact is sometimes considered (Tian & You, 2019).

Although current impact assessments of subsurface utilization create knowledge on the economic conditions and geo-technical requirements to implement subsurface activities such that they are both economically feasible as well as environmentally desirable, little is known about how to develop *the geological resource* at the least environmental and economic costs, considering the multifunctional and potential future use of the geological resource at hand. Interactions with other and future subsurface activities are neglected. Such narrow system boundaries will then typically exclude indirect effects or unexpected trade-offs. The research challenge lies mainly in the presences of uncertainty, the lack of precedents, the complex relation between the large range of impacts and significant differences in temporal and spatial scales of geological, economic and environmental impacts, further complicates the evaluations. Due to an evolving context, no single option is self-evidently the best, since commitment to an option could mean foregoing other options.

A 6TH, TRANSVERSAL CHALLENGE: uncertainty and process dynamics

For each of the above challenges, it is important to acknowledge the presence of uncertainties. The nature of uncertainty is not only caused by incomplete knowledge but also by the variability of situations and evolutions over time. It is therefore important to make a distinction between several types of uncertainty (Dixit, 1994). In the context of subsurface development, market uncertainties relate to the price uncertainties that affect the profitability of subsurface activities and the decision to invest. The firm-level decision to invest in oil or gas extraction, or the underground storage of natural gas or CO_2 will be affected by the prevailing and expected energy and CO_2 prices. Under market uncertainty, the opportunity cost of investing immediately, rather than waiting and keeping open the possibility to invest at a later point in time, is a significant component of the firm's investment decision and should be taken into account in any economic assessment.

Uncertainty about the value of the environmental services provided by the subsurface will affect the decision on a policy level to develop a geological resource or not. Technical uncertainty relates to the physical difficulty of completing a project. It is unknown how much time, effort and materials will ultimately be required. Technical uncertainty can only be resolved by undertaking the project as actual costs unfold as the project proceeds. In the context of subsurface development, this uncertainty is particularly strong as the feasibility is unknown. Geological uncertainty is caused by imperfect knowledge about subsurface characteristics, there is uncertainty about how much energy, gas, or water can be produced, how it will be migrate through the reservoir because of unresolved heterogeneities, and there is also uncertainty about material properties. This type of uncertainty can partly be resolved by obtaining geological information through, for example, exploratory drillings. Geological information creates value by improving decision-making processes, an aspect that is more and more being recognised because of its public good characteristics, leading to the view that geological information is not correctly priced in the existing economic markets (Häggquist & Söderholm, 2015).

Uncertainties also prevail with respect to institutional change. The way the subsurface can be developed within society also depends on the institutional environment as shaped by governments and social movements (Busch & Hoffmann, 2009). Not only regulatory frameworks change in time, also stakeholders' expectations and claims will develop in the future, impacting decisions related to subsurface development.

Visions for future research

Five main challenges are identified, which need to be addressed in order to sustainable manage geological resources: Sustainability assessment (identifying and integrating a plurality of values); defining a sustainable scale of resource development (avoiding overexploitation); potential interference effects between subsurface activities, now and in the future; environmental justice; developing geological resources at the lowest environmental and economic cost. A transversal challenge of the uncertainty and process dynamics was also identified. The five corresponding visions (Figure 2) outline how to approach those challenges, indicating each time how they are influenced by uncertainty, the sixth challenge. Although strongly interdisciplinary, these visions are united by their common goal, and the fifth vision ends with integrating the individual visions. Figure 3 shows how the principles, challenges, and visions are connected.

VISION 1. Identifying and integrating all relevant views by engaging all stakeholders

To understand what 'sustainable subsurface development' actually involves, a hierarchical sustainability assessment framework consisting of three levels (sustainability principles, criteria, and indicators) needs to be developed, properly acknowledging the views of all parties involved. Although this can be expanded to all geological resources, developing a framework for geological storage options is a sensible priority. Through the development of appropriate geological, environmental, economic, and social impact assessment models, these indicators can be scored and their relations and trade-offs analysed.

However, sustainability and hence also the sustainable development of the subsurface, is ultimately an issue of human behaviour, which includes negotiation under conditions of deep contingency and uncertainty. The sustainable use of the subsurface is a normative concept, rooted in real world problems and very different sets of values and moral judgements (Robinson, 2004). Therefore, besides geological reservoirs models, integrated with environmental and economic assessment models, also methods of deliberation should be developed.

Through a plural value lens and a with a clear link to debated principles and criteria, indicators for the sustainable development of a geological resource can be identified (considering time horizons of a few centuries and without focussing on a single activity). To create such an indicator framework, researchers could use a combination of expert elicitation and participatory research methods – stakeholder mapping, stakeholder interviews, specific survey techniques (such as Q methodology or Delphi method), focus group discussions, and multicriteria decision analysis. These can assist, all in their own way to specify the relations between different stakeholders involved, to explore their rationales, discourses and relevant value judgements, and to compare and weigh up different views and types of information on subsurface development, as well as provide enriched insight on the quality and availability of particular information.

Similar hierarchical frameworks have been developed before for assessing the sustainability of farm systems (Van Cauwenbergh et al., 2007) and biodiesel (Bautista, Enjolras, et al., 2016; Bautista, Narvaez, et al., 2016). While redesigning these to be applicable for geological storage, and other subsurface uses, comes with specific challenges, doing so opens-up the appraisal of subsurface development from a wide range of evaluative perspectives, participants and appraisal criteria. It is thereby important to emphasize multiple rationalities, reflexivity, learning, uncertainties, and the perception of subsurface activities as open systems coevolving with their context. Capturing relevant views and value judgements of concerned actors, while respecting the ecological economic principles of sustainable scale (visions 2 and 3), distributional justice (vision 4) and efficiency (vision 5), the pluralistic evaluation framework Gunton et al. (2022) offers a promising starting point.

VISION 2. Long-term and basin-scale modelling to define a sustainable scale of resource development, avoiding overexploitation

Sustainable scale needs to be evaluated starting from the discrimination of renewability and non-renewability of the resource in place. That resource may be an actual commodity, reservoir porosity, or both. Sustainably exploiting non-renewable resources requires they can be properly paired with reinvesting in increasing renewable capital.

These objectives require input that goes beyond the narrow focus of current reservoir simulations. These typically produce results such as reservoir performance or direct environmental impacts. In particular the time horizon needs to be extended to also determine the level of recovery and the potential for re-use of depleted reservoirs. Equally the modelled volume typically needs to become larger to determine the renewability of the whole resource, rather than the resource found in one licenced area.

The extension of the current reservoir simulations to look beyond evaluating the performance, recovery rate and the lifetime of individual subsurface projects (e.g. (Willems & Nick, 2019), means including long-term changes in resource production schemes to replace constant production. A next step is to move away from predetermined to dynamic scenarios (such as (Saeid et al., 2015) where projects follow realistic staged development based on reservoir performance or other simulation output parameters or uncertain stakeholder opinions that influence investment decisions. Where relevant, reversibility of the exploitation is to be included (e.g. seasonal storage). More generally, more attention needs to go to field recovery time and permanent impacts from partial recovery. Where necessary, mitigation options need to be evaluated.

At the other end of the time scale, increased resolution allows studying the effect of seasonal demand changes on production, and evaluate potential effects of geological uncertainty. The difference between an average and realistic scenario is often underestimated. Seasonal gas storage for example frequently deviates from seasonal production and storage cycles, because the storage site is the end-of-line of all buffering solutions and may some years not or only partly be used. This results in more irregular and unpredictable production cycles than is commonly assumed.

Each simulation needs to be linked to a basin-scale evaluation, or any other scale that is the correct representation of the total resource. This clear step away from licenced areas or other project-based subdivisions is needed to come to a proper resource management, which includes establishing the sustainable scale of exploitation, for renewable resources in terms of their overall exploitation and regeneration rates, and for non-renewable in terms of their cumulative impact on ecosystem services.

Realising these elements is an important but feasible step from the current state-of-the-art methodologies. Including them systematically in modelling objectives allows determining the overall use of resources and loss of services, and whether this is done in a renewable or non-renewable way, and for which elements pairing should be invoked. Such results create the first layer of context needed for assessing the sustainable scale of the activity.

Further beyond the current state-of-the-art frontier, is dealing with challenge 6 (uncertainty). Moving outside of the better explored licenced area will increase uncertainty, and forecasting deeper in time will cumulate the effects of those uncertainties. This would require a probabilistic and high-performance modelling framework that can evaluate additional processes such as site development changes, site abandonment, site conversion, natural recharge and re-equilibrium processes, recovery times, degree of recovery.

VISION 3. Coupled activity models to identify potential interference effects between subsurface activities, now and in the future

All the only partly known subsurface heterogeneities in combination with the variety of resource development scenarios makes it extremely challenging to evaluate the production and recovery of subsurface resources, because factoring in all elements will increase the complexity of a model in a non-linear way. Add to that the necessity of modelling different kind of activities, each with their specific points of attention, and in a larger subsurface setting, and we are clearly beyond what a large-scale refined model can feasibly achieve. This would be a complex, highly case specific model, with high computational costs and so intricate that it could impede future use, either for uncertainty

analysis, or for practical evaluation of somewhat different settings. One way forward would be combining different models, with different degrees of detail and objectives, in a framework that allows them to interact (possibly using an open modelling interface, Moore and Tindall (2005)).
Such a more generic framework of loosely coupled models for interference analysis looks like a more sensible approach that can serve as an adaptable basis for different basins, making use of existing and potentially interchangeable models to keep the workload efficient (cf. (Aydin & Caers, 2013; Celia & Nordbotten, 2009). This framework also allows to assess the importance of asymmetric interferences between different activities within the same basin while assessing the influence of geological uncertainty through global sensitivity analysis. The required scale to study interference optimally may need to be investigated a-priori and the geological parameters dominating the interference identified. Potentially, a semi-analytical or physically-based approach is needed to derive the interference, and therefore the framework needs to be able of creating hybrid mated models.
Part of the vision is that interference between subsurface activities should not just be seen as a negative, complicating factor that should steer us away from using geological resources. On the contrary, when correctly managed, interference may lead to more optimised synergetic exploitation which will increase the reserves of both renewable and non-renewable resources. This will overall increase the sustainable scale at which these can be produced.

VISION 4. Social Impact Assessment and Environmental Justice

To consider the social impacts of subsurface developments, specific methodologies can be operationalised to account for each tenet of environmental justice. The vulnerable population that could be disproportionately impacted by the project can be identified using spatial risk analysis and stakeholder mapping (recognition justice). As indicated in vision 1, stakeholder mapping or tools such as Q-methodology can be used to identify and understand the power dynamics, socio-political fabric, and perceptions and concerns of residents vis-à-vis particular subsurface developments (procedural justice). In the same vein, Discrete Choice Experiments, a survey-based method used to measure the stated preferences to value a non-market entity, can be applied to test social acceptance of subsurface developments.

But also identifying relevant social indicators that can determine how various groups in society might be affected (distributional justice) remains a challenge, particularly at a generic level. Further refining methodologies for Social Life Cycle Assessment through meta-analysis of documented case studies is one way forward, as well as performing scoping analyses of available data that can offer an indication of the social fabric and amenity value in areas suitable for particular subsurface developments and how they might be impacted (e.g. through national comparison of a set of regions, or through international comparison).

Including the tenets of justice in itself does not guarantee equity and fairness in the process. There needs to be a shift from traditional economics to a more multi-disciplinary approach that includes the disciplines of politics, social sciences and law. Finally, environmental justice of subsurface developments should not be considered as an ideological and righteous component of decision making. Rather it should involve co-creation of a fair outcome in iterative processes by engaging institutions-governments-communities-regional bodies with equal opportunities to voice their concerns.

VISION 5. Developing geological resources cooperatively at the lowest environmental and economic cost

Multifunctional and long term use of a geological resource could be assessed by integrating real options and game theory to understand how private and public actors would strategically decide on the subsurface capacity to use, while taking into account different types of uncertainty.

Real option games combine the best of two worlds: by integrating real options analysis with game theoretic concepts, both uncertainty and strategic decision making are incorporated in the analysis. Azevedo and Paxson (2014) indicate that most real option games only consider two firms in a single factor single option game context where the value of the investment depends on one single stochastic variable. By taking a numerical approach to real options games, different sources of uncertainty and flexibility options can be integrated while considering multiple actors. The perspective of private investors can then be compared with the perspective of a social planner who is responsible for the development and management of the subsurface as a whole, given the development options available for the reservoir considered.

Such method will give insights into the likelihood that for the subsurface activities under consideration a specific development pathway will be selected, given the multiple sources of uncertainty and the flexibility options that are available. Furthermore, such analysis will increase understanding about the geological and economic boundary conditions that determine the selection of a specific pathway, the interdependency between different subsurface activities, and the risk-benefit balance. Such economic assessment could be integrated with dynamic environmental LCA studies to analyse the environmental implications of the different subsurface development pathways and to identify trade-offs between environmental and economic impacts across different development scenarios. Also the environmental LCA community starts gradually to understand the benefits of adding a time component in the analysis by adopting a consequential approach (Zamagni et al., 2012). Consequential LCA targets the question: “How will flows change in response to decisions”? (Curran et al., 2005). Consequential LCA is a market-based approach focusing on tracing the consequences, inducted by a decision, forward in time, and takes the data on (affected) marginal suppliers into account. Dynamic LCA accounts for changes in energy and resource use over time and gives insight into how the environmental impact of a technology evolves over time (Lueddeckens et al., 2020).

Even more, to achieve full integration of all sustainability dimensions, it might be more appropriate to adopt the ecological economics’ quantitative way of dealing with value pluralism in environmental decision-making, i.e. multi-criteria decision analysis (MCDA) (Gowdy & Erickson, 2005). MCDA methods are amongst the most flexible ones to address environmental decision-making as they can be made site and time specific, and qualitative and quantitative attributes can be considered simultaneously (Garfi et al., 2011). Furthermore, when multiple stakeholders are involved, a formal process to structure stakeholder interactions such as MCDA can improve the quality of the outcome. Although MCDA can account for uncertainty (Van Schoubroeck et al., 2021), it does not allow to take into account that project developments are made in consecutive steps through time and that there exists managerial flexibility to abandon the project or adapt its development in response to learning and fluctuating price processes. By integrating MCDA with real options analysis, static MCDA could be transformed into dynamic MCDA. Decision trees developed in economic real options models only consider economic criteria to evaluate decisions in time. By integrating social, environmental, and geological thresholds to base go/no-go decisions on, a real options approach accounts for a multitude of values. In this way, foundations for dynamic MCDA are laid.

Conclusion

In order to understand how to manage the subsurface in a sustainable way, it is important to first understand what sustainability entails, and how that concept translates to the subsurface. Our approach proposes to start from the three sustainability principles of ecologic economics: sustainable scale, equitable distribution of costs and benefits, and environmental and economic efficiency. Based on the current state-of-the-art in multiple disciplines, especially focussed on geological resources in the medium to deep subsurface, six challenges are identified that obstruct bridging sustainability theory and practice. Five corresponding visons demonstrate that addressing these challenges requires significant scientific advancement, but not beyond the realm of what is possible today. It is however not a pure scientific undertaking. Where possible, an objective framework of indicators needs to be constructed, but some questions do also require broad stakeholder input.

The first challenge 'value pluralism', is overarching and practically translates into defining a principle-based indicator framework that is able to catch all relevant aspects in a standardised way to guide decision-making processes. We propose a hierarchical sustainability assessment framework consisting of three levels, with sustainability principles at its base, then criteria, and indicators as a top layer. This framework should work in tandem with different models to bring insight into the importance of indicators, and their relations and trade-offs. The concept of such framework also serves as a guide to identify knowledge gaps, in particular where the scientific insight to value indicators is currently lacking. As such, this framework is the binding level for the other visions.

The violation of the sustainable scale principle is strongly associated with resources in the deeper subsurface, and is split over challenges and visions 2 and 3. Sustainability of scale is fundamentally defined in function of the renewability of a resource, or its potential to re-invest its non-renewable capital (pairing). We extend this approach to all ecosystem services, including all geosystem services, so that it applies to resources as well as assimilative properties of the ecosystem. Doing so makes more sense for geological resources because of the specific time and volume dimensions. As such, studying geosystem services may also deepen the understanding of near-surface sustainability evaluations. In challenge 3 the dimensional particularities are linked to interference effects between different subsurface activities, and the potential to optimise subsurface use. Due to the long-lasting imprints of several activities, influences may extend well beyond the active lifetime of resource exploitation, making the succession of different activities require specific evaluation. The visions that address the challenges focus on how to realise a better understanding of actual situations. Current modelling shortcomings can be addressed by extending the simulation timeline to include closure and recovery and by modelling the influence of an activity such as geothermal at the scale at which it can be considered to be renewable (i.e. simulating the full production and recovery cycles of several direct use geothermal projects). Increasing the time and spatial scale while maintaining the flexibility to adapt the model to swap out activities and model under uncertainty seems to plead for a framework of loosely coupled models instead of ad-hoc super models.

Exploitation of resources needs to respect fair distribution of its impacts and benefits, which becomes particularly visible for residents around a development site. The process requires an inclusive and non-discriminatory approach and transparency of process, as well as fair representation of opinions, and can be divided into identifying potentially affected population (recognition justice) and understanding the impact of inequities (distributional justice). Apart from a fairness principle, such practices are also considered to be fundamental in creating social acceptance. Where it concerns indicators that cannot be fully objectified, the process may move beyond this to partly replace purely science-based criteria and indicators. Several methodologies exist (e.g. survey-based methods, social life cycle assessment) to establish partial input, but optimising these, linking their results, and bringing them to a generic level remains an open line of research. Such development should be seen as a shift to a more comprehensive multi-disciplinary approach.

While the previous challenges and visions provide guidance and borders, the third ecological economic principle calls for realising this in the most efficient economic and environmental way. The established techniques underlying techno-economic assessments and life cycle assessments offer a sound basis, but their application is typically too limited, with timelines too short, scopes too narrowly focussed on a single activity, and assessments incomplete in terms of indicators that are considered and optimised. We propose combining real options and game theory to better understand and foresee economic strategic decision taking under uncertainty, and embed it into a dynamic (i.e. with time component) environmental LCA to also include environmental trade-offs. The importance of this evolution is gradually being recognised by the scientific community.

Building on that identified trend, a next step would be the integration of all sustainability dimensions into a multi-criteria decision analysis, which would become dynamic by integrating real option analysis and its decision trees. This opens the outlook on a single integrated approach that would include social, environmental and geological thresholds, embedded in a framework that allows for economic and environmental optimisation. This would not only be a framework for evaluating the sustainable use of the subsurface, but also enable guiding subsurface management with a resource perspective, i.e. considering the geosystem as a whole, instead of evaluating individual projects.

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Figure Captions

Figure 1. Conceptual view of stacked activities in the subsurface. (1) groundwater extraction; (2) storage site for high-active nuclear waste; (3) coal mine; (4) seasonal storage site for natural gas or hydrogen; (5) enhanced oil recovery; (6) CO_2 geological storage; (7) geothermal doublet.

Figure 2. Schematic view of the relations between the four sustainable development principles, current challenges of science-based subsurface management, and related visions on how to move forward (with SDP = sustainable development principle).

Figure 3. The relation between the four sustainable development principles, and the five challenges and respective visions, as identified for geological resources.

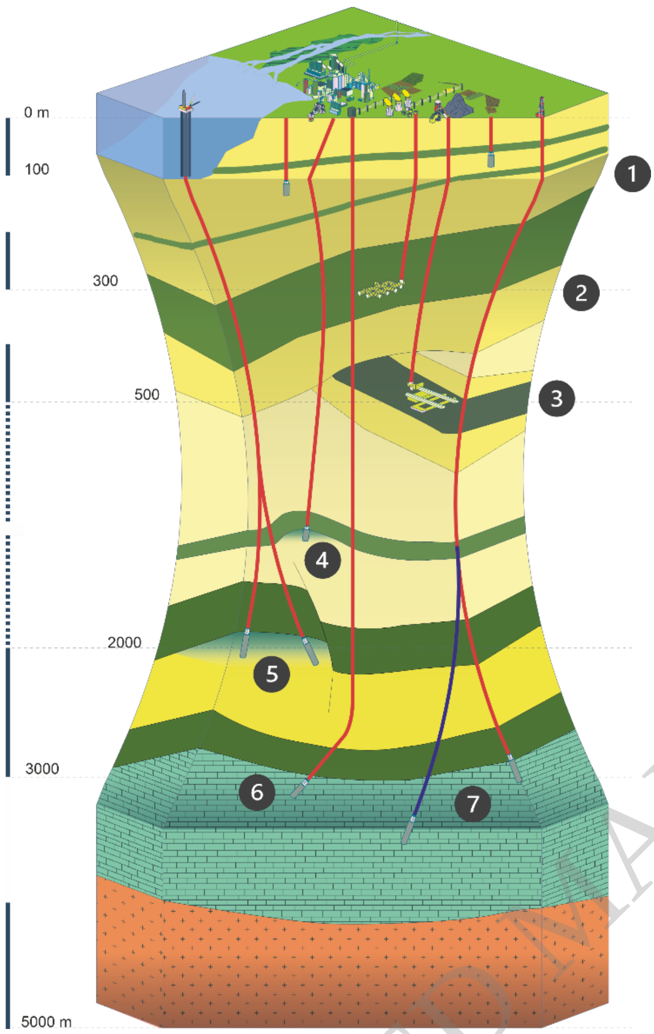

Figure 1

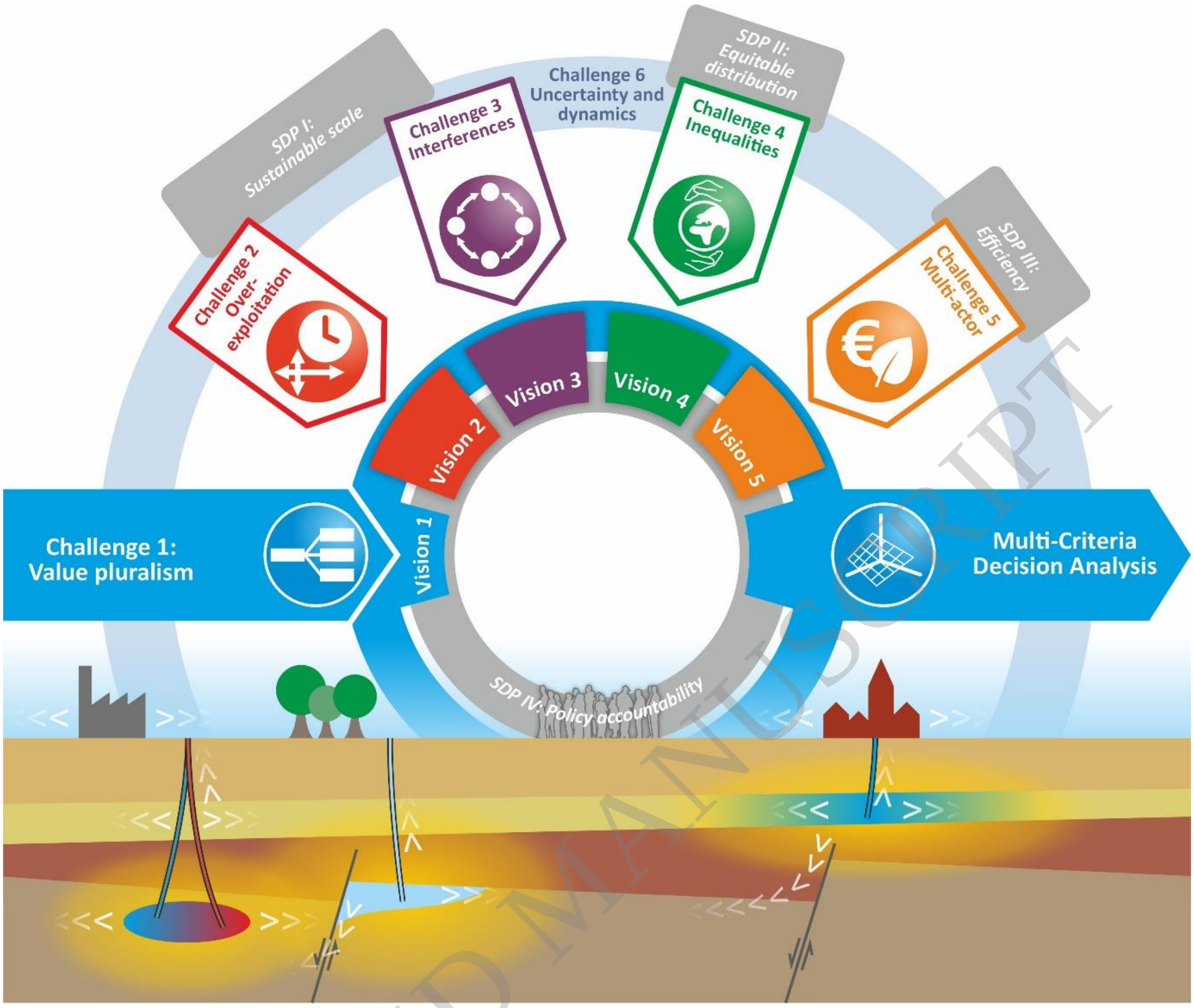
SDP I: Sustainable scale
Challenge 3 Interferences
Challenge 6 Uncertainty and dynamics
SDP II: Equitable distribution
Challenge 4 Inequalities
SDP III: Efficiency
Challenge 5 Multi-actor
Challenge 2 Over-exploitation
Vision 2
Vision 3
Vision 4
Vision 5
Vision 1
Challenge 1: Value pluralism
Multi-Criteria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

Figure 2

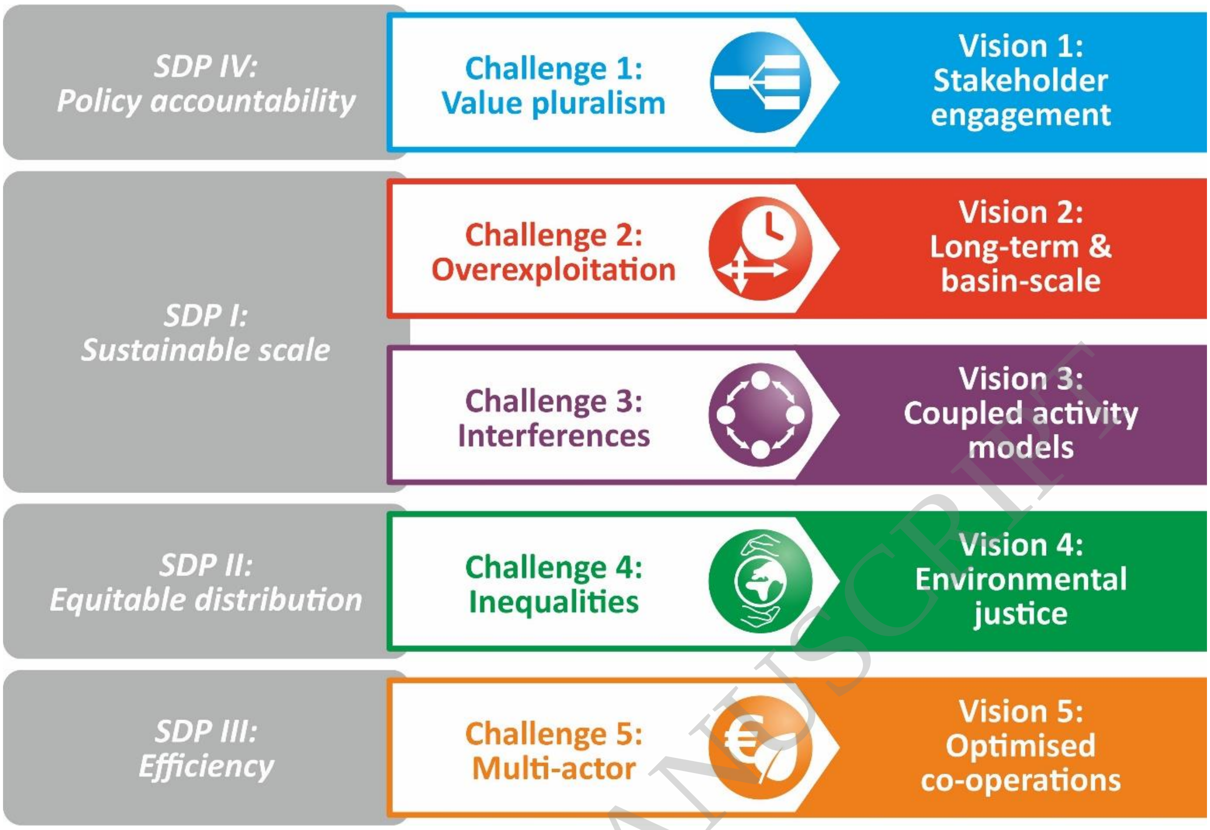
SDP IV:
Policy accountability
Challenge 1:
Value pluralism
Vision 1:
Stakeholder engagement
Challenge 2:
Overexploitation
Vision 2:
Long-term & basin-scale
SDP I:
Sustainable scale
Challenge 3:
Interferences
Vision 3:
Coupled activity models
SDP II:
Equitable distribution
Challenge 4:
Inequalities
Vision 4:
Environmental justice
SDP III:
Efficiency
Challenge 5:
Multi-actor
Vision 5:
Optimised co-operations

Figure 3