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# Underground space, the legal governance of a critical resource in circular economy

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ABSTRACT

During the last two decades the enhanced multiple use of underground resources and space led to a growing number of issues which the current European Union (EU) and/or its Member States (MS) national legal and regulatory frameworks and knowledge bases are not able to manage efficiently, from a sustainable development perspective. With a focus on Europe, this study is a horizon scanning review to raise awareness on this situation and highlight new need for governance solutions which may fit diverse legal and authority settings in the different jurisdictions, and support the transition towards a more circular economy, decoupling subsurface resources and space use from the negative impacts this use frequently causes. It involves the legal acknowledgement of underground resources and space as mostly finite resources. The identification of resources owners, the conflicting interests of the multiple stakeholders, the clear designation of the physical conditions and dynamics related to each resource category, the interactions between subsurface and surface resources are making the regulation, planning and use of subsurface natural resources a complex, but necessary task for public authorities. Establishing a harmonized public authority scheme of permitting and sustainable resource management, supported by the development of a 3D (and 4D) information and resource classification system should be a priority for the EU and its MS. The preliminary results and legal analogues indicate that underground space utilization can also be assessed in the criticality context.

## 1. Introduction

Natural caves for shelter, excavation pits for stones and storage are dated back to prehistoric times and the use of underground space evolved over the history (Hooke, 2015; Von der Tann et al., 2020). The deepest known natural cave is 2.2 km,[1] the deepest manmade structure is a 12.3 km long drillhole, and mankind mapped the Earth to the very core (6371 km) analysing reflections and refractions of seismic waves. Human-made materials now outweigh the Earth's entire biomass, technology mass production rate has increased to 65 Gt per year, most of which is extracted from the ground (International Resource Panel (IRP), 2020; Elhacham et al., 2020).

The decreasing availability of surface space and its rising cost, the new utilization needs and novel engineering resulted in the growing use of underground space during the last decades. Visioners consider geoengineering a potential response to global challenges[2] (Gardiner and McKinnon, 2020), and six of the fourteen global megatrends are directly related to the utilization of underground space (European Commission (EC), 2020c).

The scientific research has followed this trend. Four research clusters are identified in this field, on urbanization, on engineering of underground infrastructures, on subsurface natural resources extraction, and on spatial information management originating either from the land use planning or the georesources domain (3D data acquisition, data modelling, representation and dissemination).

Studies on underground urbanization cover the allocation of surface functions into the subsurface (Broere, 2016; Zhou and Zhao, 2016; Kishii, 2016; Mielby et al., 2017), the harmonization of the new functions with the traditional infrastructure (Lee, 2018), the economic aspects (Kaliampakos et al., 2016; Qiao et al., 2017), and sustainability

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[1] https://en.wikipedia.org/wiki/List_of_deepest_caves.
[2] https://futureofwork.itcilo.org/digital-transformation-are-you-ready-for-exponential-change-futurist-gerdleonhard/.

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context (Huanqing et al., 2016; Volchko et al., 2020). The works on inter-urban infrastructure deal with engineering, tunneling aspects. A few national technical and legal reviews are available (Broch, 2016; Takasaki et al., 2000; Zaini et al., 2017), and the social aspects also received attention (Lee et al., 2016). The legislation on traditional subsurface resources such as minerals, fossil fuels, groundwater, and geothermal energy is studied in details (EC, 2017; Goodman et al., 2010; Hámor, 2002, 2004b; Mitchell et al., 2016; Soltani et al., 2021)).

Few researchers studied the conflicts among the different uses (Field et al., 2018; Li et al., 2013; Takasaki et al., 2000) and the sustainability context. A limited number of works address the legal complexity of underground space use in different countries (International Tunnelling Association, 2000; Hámor et al., 2020; Volchko et al., 2020), and articles on the legal framework are usually restricted to the national scale (Kishii, 2016; Takasaki et al., 2000; Zhou and Zhao, 2016). There is no international comprehensive system describing subsurface space and its resources and no study available on the circular economy or the criticality context.

On the basis of current knowledge, this study provides a review of the present and potential future uses of underground space with a simplified typology and a summary of their interlinked issues; assesses the legislation in force in the EU and its MS, and the competent authority scheme; presents the information management practices and concepts; and outlines a proxy assessment of underground resources in the context of criticality. The discussion has an emphasis on the legal acknowledgement of underground space as a strategic national resource and asset; the options for regulating its complex planning and use both on EU and national level; as well as highlights options for economic incentives and annuities.

## 2. Methodology, terminology

This study uses the term "*underground space*" for the solid part of the Earth crust which is below the soil cover and which can be physically reached, used and utilized at the current technical level and ensuring economical, environmental and social sustainability. The marine domain is out of the scope. There are other terminologies in the literature, such as subsoil, subsurface space, underground resources, etc. which are reviewed in details (Hámor, 2004a; Volchko et al., 2020). The terminology on *criticality*, *circularity*, *governance*, and *resilience* is presented in the *Results* and *Discussion* chapters. Ontologies exist for the conventional resources, for example on minerals on international[3] and EU scale.[4]

The major emphasis of this work is on the governance and the regulatory framework of underground space in the EU. For the purpose of this study, the EUR-Lex database, as well as the national legislation major reports (e.g. EC, 2017; Hámor, 2002; Hámor et al., 2019) and datasets (e.g. European Commission, 2021) were used.

Community law ("*acquis communautaire*", or "*acquis*") is often referred to as "*supranational*" law. Primary legislation includes treaties and international conventions. Treaties define the thematic scope of the Community law, the responsibilities of decision-making bodies and the legislative, executive and juridical procedures. Secondary law takes the form of: (a) regulations, directly applicable and binding in all MS; (b) directives, binding as to the objectives to be achieved, while leaving to national authorities the choice of form and means to be used; and (c) decisions, binding for those to whom they are addressed. The acquis is directly applicable as a ground for justification of an appeal in the courts of all MS.

Union competences are governed by the principles of subsidiarity and proportionality. Under the principle of subsidiarity, in areas which do not fall within its exclusive competence, the Union acts only if and in so far as the objectives of the proposed action cannot be sufficiently achieved by MS, either at central or regional and local level, but can rather, by reason of the scale or effects of the proposed action, be better achieved at Union level (TFEU) Art. 5). Under the principle of conferral, the Union acts only within the limits of the competences conferred upon it in the TFEU.

## 3. Results: one earth crust with various resources and uses

### 3.1. Utilization of underground space, typology, and conflicts

Underground, the Earth's subsurface, is home to multiple resources, many of them of the highest importance to human well-being. Minerals extraction is one of the oldest human subsurface activities. Minerals (metalliferous ores, industrial and construction minerals, coal) are finite, stock-type underground resources (Table 1). Approximately 300 000–800 000 $km^2$ of land is directly impacted by extractions (Cherlet et al., 2018). The Mponeng gold mine in South Africa, the deepest operating mine in the world[5] has surpassed 4 km.[6] The largest open pit is Bingham Canyon mine[7] in Utah with 1.2 km depth and 4 km diameter.

Oil and gas are also finite resources, although state-of-art production techniques can maximize the output and at some fields in situ hydrocarbon generation and replenishment by continuous migration sustains elongated, quasi renewable production (EC, 2014). Millions of boreholes penetrate underground at different depths, such as geotechnics and environmental monitoring (0–100m), waste injection (100–1000 m), nuclear tests (150–800 m), water (10–2000 m), geothermal energy (2–6000m), minerals and fossil fuels (10–12000 m), underground coal gasification (UCG, Bhutto et al., 2013) (100–600 m), and carbon capture and storage (CCS) (1000–3000 m) (Table 1, modified after Field et al., 2018). The deepest drillhole in the world is the Sakhalin-2 hydrocarbon well in Russia[8] reaching 12 376 m. In Europe, the 9101 m deep geological research well at Windischeschenbach in Germany is the

**Table 1**
A potential clustering and typology of underground resources.

| Underground resources use | | Typical depth interval | Resource type |
|---|---|---|---|
| extraction of natural resource | minerals | 0–4000 m | stock type, finite, non-renewable |
| | oil & gas | 0–6000 m (max. 10.6 km) | stock (and flow) type finite, non-renewable |
| | geothermal energy | 0–6000 m | flow type conditionally renewable |
| | groundwater | 0–2000 m | flow type conditionally renewable |
| | geophysical forces | not relevant | flow type infinite, renewable |
| use of underground space | gas & water storage | 100–3500 m | natural/manmade, finite |
| | CCS | 1000–3500 m | natural/manmade, finite |
| | waste disposal | 0-1500(?) m | natural/manmade, finite |
| | defence | 0-1000(?) m | manmade, finite |
| | research & archives | 0-2400[27] m | natural/manmade, finite |
| | urban infrastructure | 0–100 m | manmade, finite |
| | interurban infrastructure | 0-2300[28] m | manmade, finite |

[3] https://www.ogc.org/docs/is.
[4] https://inspire.ec.europa.eu/.

[5] https://www.nsenergybusiness.com/projects/mponeng-gold-mine/.
[6] https://undergroundexpert.info/en/scientific-research-and-technology/analytics/the-deepest-mines-in-theworlds/.
[7] https://www.911metallurgist.com/blog/15-largest-mines-on-earth.
[8] https://en.wikipedia.org/wiki/Kola_Superdeep_Borehole.

deepest.

The temporary storage of natural gas,[9] liquefied natural gas, compressed air[10], hydrogen and synthetic gas (Gupta et al., 2015; Kruck et al., 2013), pumped water (European Energy Research Alliance, 2018),[11] electrolysis-methanation-oxyfuel (Bader et al., 2019), and thermal energy (Nordell, 2012) are increasingly important segment of underground space use. They counterbalance the seasonal and daily variations of energy production induced by the renewables input or political conflicts. These are realized in depleted hydrocarbon fields, closed mines, salt formations and porous saline aquifers, as mapped by the ESTMAP project for the EU (ESTMAP, 2016).

For carbon dioxide storage underground, the long term performance of both engineered and geological barriers is a must (Rubin and De Coninck, 2005; Global CCS Institute, 2020). The candidate host formations are similar to natural gas storage sites. There are 26 commercial CCS facilities in operation or construction worldwide, including two in the EU (Netherlands, Ireland).

Geothermal energy is renewable, although poorly designed production may cool down the wells' host rocks and aquifers (Lund and Tóth, 2020). Shallow heat pump systems are operating between 2 and 200 m. The geothermal doublets and triplets are deep drillholes, some 1000–2000 m deep, for instance in the Paris Basin where the Upper Jurassic aquifer is extensively used for urban heating (Boissavy et al., 2019). The enhanced geothermal systems' depth (EGS) is similar to the hydrocarbon fields, and the "Hot Dry Rock" technology applying hydraulic fracturing in inclined wells is also similar to the production of unconventional hydrocarbons.

Other geophysical resources are the gravity field (tidal energy), magnetic field, rocks' piezoelectricity, and radioactivity (decay heat). These are used in navigation, energy production, exploration but options have not been fully exploited yet.

Groundwater is the primary source of freshwater for two billion people and, despite its importance, knowledge on large groundwater systems is limited (Richey et al., 2015; Maliva, 2016). The groundwater use by the industry and agriculture is increasing. Many groundwater bodies are fossil reserves with limited recharge potential from the surface, therefore it is a conditionally renewable resource. Groundwater is a mobile medium, so subsurface activities may unintentionally connect fresh with saline aquifers, pristine with contaminated waters, changing not only the quality but the hydrodynamics. Hence it is the most exposed to environmental conflicts.

Underground urban infrastructure is another historical subsurface facility cluster. Beside the historical (cellars, catacombs, war shelters, graveyards, construction mineral pits, water supply, sewage) and conventional utilities (electricity, gas, district heating, telecommunication, subway), most surface functions now can be found beneath cities such as commerce, leisure, parking, apartments. Buildings may now extend to tens of meters downwards. The Deep Pit Hotel of Shanghai in a former quarry is the deepest building in the world, the 16 levels reach 80 m. The Gjøvik Olympic Cavern Hall in Norway is 55 m deep (Broch, 2016). A concept of the Earthscraper of Mexico City is an upturned 300 m pyramid with 65 levels. In Europe, the deepest underground parking is in Leiden, the Netherlands, with its 22 m. In Hangzhou, China a 12-level parking is 40 m deep. Novel applications appeared during the last decade, such as geothermal energy and unconventional hydrocarbons extracted from beneath cities through inclined and horizontal wells, or the Hyperloop,[12] travelling at 700 miles/hour in floating pod inside low-pressure tubes or tunnels (European Commission, 2020e; European Commission Staff Working Document, 2020e).[13]

Interurban infrastructure includes tunnels used for water supply, sewerage, hydroelectric power, railways, roads, and utility cables (electricity, telecommunication), and pipelines (oil, gas, water, carbon dioxide, chemicals, sewage, waste water). The longest tunnels exceed 100 km, the biggest diameter is 17.6 m,[14] and the Gotthard Base Tunnel (Switzerland) is the deepest (2300 m). The total length of road tunnels is estimated ca. 3040 thousand km in the world.[15] The length of oil and gas pipelines (incl. liquefied petroleum gas (LPG) and refined products) in the world is more than 2 million km.[16]

The world generates 2 billion tonnes of municipal solid waste annually and ca. 33% of it is landfilled.[17] The generated 50 billion tons/year ore processing tailings (Franks et al., 2021) are partly used as backfill material in mined out underground cavities, thus improving long-term ground stability of mined areas and reducing the environmental footprint that such material may cause if stored on the surface. Injection and reinjection into wells, landfilling, backfilling, deep underground waste disposal are legally available options in the EU for numerous waste streams both on EU and MS scale.

Safe radioactive waste disposal is a complex social and technical challenge, underground final storage of high level radioactive waste being a preferred option under development in several countries. In Europe, Belgium (Mol), Finland (Onkalo), France (Bure), Sweden (Forsmark and Äspö) and Switzerland (Grimsel) constructed underground laboratories to assess the feasibility of long-term radioactive waste storage. In Germany at the Asse, Gorleben and Morsleben sites the further developments are halted for the time being. The WIPP site[18] in Carlsbad, New Mexico in a Permian salt formation at 700 m depth is the world's first licensed facility for the final storage of high level transuranium radioactive waste.

The information on underground defence facilities is rather sporadic. During WWII Germany commissioned 143 underground factories[19] producing various weapons and military equipment. The plant Heinkel-162 (Salamander) was built in underground salt mine at the depth of 300 m. The Neckarzimmern site, a former gypsum mine is the biggest underground facility (170.000 $m^2$)[20] of the Bundeswehr. USA, Russia, Japan, and Sweden had similar facilities until the end of the cold war. 75% of the nuclear test sites were underground,[21] the depth of the explosion wells is 150–800 m.[22] The number, depth and extension of underground military and civil protection command centers, warfare storage facilities, shelters, bunkers is unknown but a few have public

[9] https://www.eia.gov/naturalgas/storage/basics/; http://naturalgas.org/naturalgas/storage/; https://www.energyinfrastructure.org/energy-101/natural-gas-storage.

[10] https://www.sciencedirect.com/topics/engineering/compressed-air-energy-storage.

[11] https://energystorage.org/why-energy-storage/technologies/sub-surface-pumped-hydroelectric-storage/https://www.osti.gov/

[12] https://www.zdnet.com/article/what-is-hyperloop-everything-you-need-to-know-about-the-future-oftransport/.

[13] https://ec.europa.eu/energy/topics/oil-gas-and-coal/shale-gas_enhttps://ec.europa.eu/jrc/en/openecho https://ec.europa.eu/info/research-and-innovation/research-area/energy-research-and-innovation/geothermalenergy_en.

[14] https://en.wikipedia.org/wiki/List_of_longest_tunnels.

[15] https://en.wikipedia.org/wiki/List_of_countries_by_total_road_tunnel_length.

[16] https://www.offshore-technology.com/comment/north-america-has-the-highest-oil-and-gas-pipeline-lengthglobally/https://en.wikipedia.org/wiki/List_of_countries_by_total_length_of_pipelines.

[17] https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html.

[18] https://www.wipp.energy.gov/.

[19] https://undergroundexpert.info/en/underground-space-use/implemented-projects/world-underground-plants/.

[20] https://de.wikipedia.org/wiki/Gipsstollen_(Neckarzimmern).

[21] https://en.wikipedia.org/wiki/List_of_nuclear_test_sites.

[22] https://en.wikipedia.org/wiki/Underground_nuclear_weapons_testing; https://www.bbc.com/news/world-asia-35244474.

websites, such as the Pantex Plant in Texas.[23]

Experimental research facilities and archives is a rapidly growing segment of underground space use. The China Jinping Underground Laboratory for neutrino capture and dark matter is the deepest in the world,[24] at 2.4 km depth. The Gran Sasso National Laboratory in Italy is located at 400 m and its area is 6000 $m^2$. CERN, the cyclotron particle accelerator at the border of France and Switzerland is 27 km long.

The Svalbard Global Seed Vault[25] in the Norwegian archipelago carved 100 m inside the mountain with 60 m overburden in the permafrost, accommodating 4.5 million seed accessions. Germany is saving its cultural heritage at 400 m underground at the Barbarastollen former mine supply tunnel[26] near Freiburg im Breisgau.

Our digital society is increasingly exposed to the electromagnetic damage by solar storms. The "Carrington event" in 1859 had significant impacts on the telegraphs. Nowadays, server centers and digital archives tend to go underground. The GitHub Arctic Code Vault, located 250 m deep in the permafrost in the Svalbard archipelago in a decommissioned coal mine, stores open source software codes in multiple forms.[25]

Although the major focus of this work is on underground space, the analysis of its uses and of related conflicts requires a holistic approach covering all underground resources. Table 1 identifies two major groups of underground use:

- natural resources extraction
- underground space use,

Twelve categories of related resources, with their respective depth range and type are identified in Table 1. Underground installations require both favorable natural (geological, hydrogeological, geochemical, seismic, etc.) conditions and careful engineering design. Good engineering can control and outweigh less favorable natural settings. The classification on criticality is discussed later.

The underground space can also be classified on the basis of its different geological settings, such as porosity and transmissivity, geotechnical and tectonic characteristics, the presence of karstic features in carbonate rocks, nature of the host rock and of the overlying rock formations.

Fig. 1 illustrates both the conflict field and the synergic interlinkages of underground resources. Groundwater is clearly the most impacted underground resource with documented cases in seven other underground use clusters. There are also issues inside the sector, such as illegal, poorly designed wells connecting and polluting pristine aquifers, unsustainable extraction, etc. There are ca. 300 transboundary groundwater aquifers in 145 countries, and since 1948 there have been 37 acute conflicts[29] (Dellapenna and Gupta, 2009).

The two other major hubs are the underground urban infrastructure and the mineral resources industry (Environmental Justice Atlas)[30]. Most of those pressures are related to environmental protection but there are examples for physical collisions, social tensions, and the rally for underground space use has manifested in legal disputes during land use planning and at permitting of new projects at given locations. The issues in urban environment are studied in details in the cited literature.

Conflicts correlate with the density of existing underground facilities, the limited availability of potentially suitable geological conditions and host rocks, and poor governance, such as the non-sustainable first-come-first-served principle as summarized by Field et al. (2018). The presentation of all issues is out of the size limits of this study but a few, which ended up in legal action, are selected below.

In Hungary, the question whether drillholes belong to the landowner or the former operator induced a Court procedure (EC, 2017). Wells with a water production permit often produce gas, on the contrary, drillholes with a hydrocarbon permit may produce water. Fracking induced earthquakes at unconventional hydrocarbon fields or used for the development of EGS are documented[31] (Goertz-Allmann et al., 2011; Soltani et al., 2021), and the UK Trespassing Act was amended because of the inclined or horizontal wells extending beneath private lands.[32]

Deeper geothermal wells usually require a gas separator for $CO_2$, $CH_4$, $H_2S$ but selling of these by-products can be complicated from the authorization point of view (royalty, etc.). Legal conflicts happen inside the heat pump sector too, for instance, in a residential area in Schleswig-Holstein heat pumps reached out to the underground of the neighbour thus cooling down the neighbours' subsoil environment. Therefore, the regional regulation set a minimum 6 m distance from the fence for heat pumps (Goodman et al., 2010).

In the aggregates sector, speculative operators extract gravel and sand with landscape work permits in order to avoid the more demanding mineral permitting procedure and royalty payment. A general dilemma in the extractive sector is how can the state legally force companies to do uneconomic extraction in sake of the complete extraction of all valuable but sub-economic minerals of a deposit, as well as promoting the sustainable after-use of mine voids (tunnels, shafts, galleries, pits, ponds) and extractive waste.

In cities, underground infrastructure changes groundwater flow patterns and poorly sealed, old cellars are frequently flooded. This also raises the question of how deep parts of the house can penetrate with a construction permit based on a geotechnical report usually lacking a more complex geological study or an impact assessment. This is particularly relevant in a saturated flat „2D" country, such as Hungary or the Netherlands.

Underground inter-urban linear infrastructure and their protective pillars are usually no-go zones for minerals extraction and other underground installations. These facilities, urbanization and other competing surface land uses in general lead to the "sterilisation" of mineral deposits. This sterilisation can also result from poor land-use planning practice, where decisions are not considering valuable underground assets. To overcome such a problem quarry master plans have been developed in some countries to safeguard access to minerals of strategic importance to economy.

### 3.2. An analysis of legal governance

#### 3.2.1. Legislation in force

The EU acquis and most of the national legislation are dominated by the Continental Law which is ruled by the hierarchical set of published acts approved by national parliaments, and subordinate regulations issued by the government or ministers. Regional and local governments are usually also legislators in their sphere of authority. The lower level legislation must be in harmony with the ones above. The harmony should be ensured among the sectoral laws, but legal collisions are frequent and resolved by public administration or court rulings; which cause delays and costs, and may deter investment in resource exploration and production.

In spite of the fact that "*Management and efficient use of space, the*

[23] https://pantex.energy.gov/about.

[24] https://undergroundexpert.info/en/scientific-research-and-technology/analytics/the-deepest-undergroundstructures/.

[25] https://www.seedvault.no/about/the-facility/.

[26] https://www.genusit.com/germany-protecting-cultural-heritage-war-natural-disasters/[25] https://archiveprogram.github.com/arctic-vault/.

[27] China Jinping Underground Laboratory, China, https://undergroundexpert.info/en/scientific-research-andtechnology/analytics/the-deepest-underground-structures/.

[28] Gotthard tunnel, https://www.bbc.com/news/world-europe-36423250.

[29] https://www.unwater.org/water-facts/transboundary-waters/.

[30] https://ejatlas.org/.

[31] https://www.insidescience.org/news/2019-year-fracking-earthquakes-turned-deadly.

[32] https://www.brachers.co.uk/insights/fracking-and-trespass-laws.

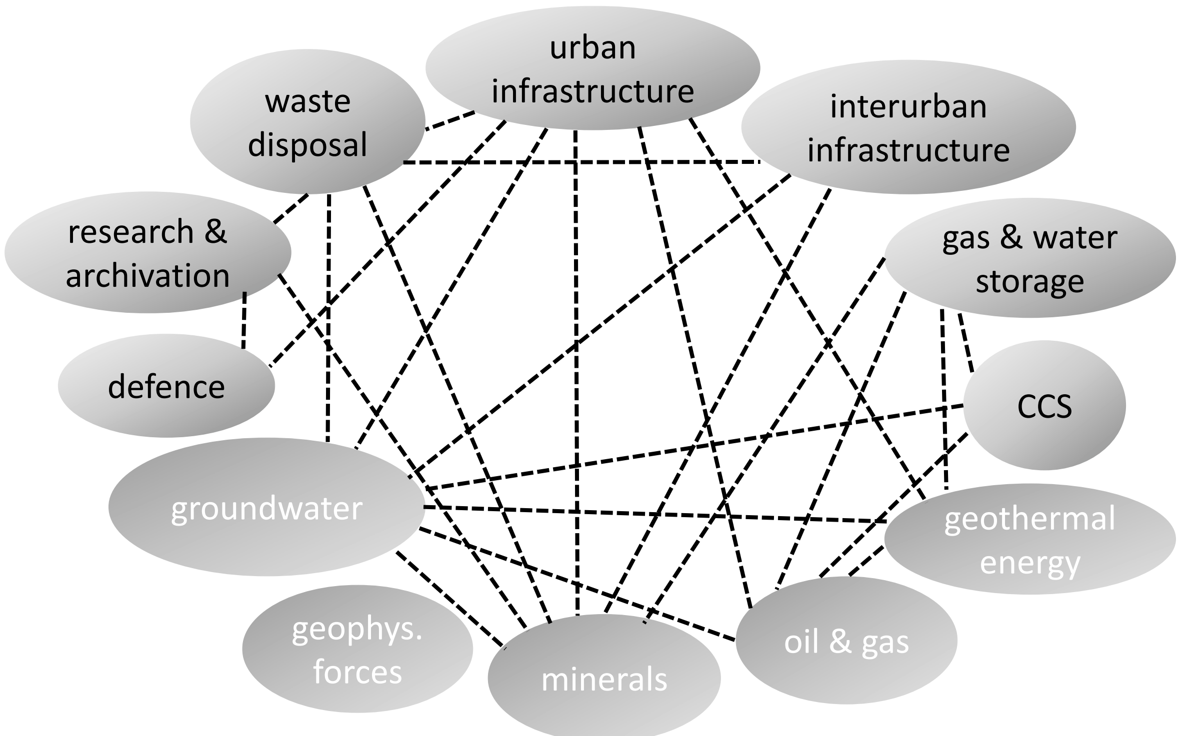


**Fig. 1.** Interlinkages and pressures between underground resources use.

*environment and natural resources*" is a distinct chapter in the Directory of EU legal acts, the provisions relevant to underground resources are limited. The TFEU on the top of the hierarchy presents the spheres of exclusive and shared competences covered by the acquis, the rest of the regulatory fields remaining with the MS jurisdiction. The relevant sectors are transport (Titles VI, XVI), industry (Title XVII), environment (Title XX), energy (Title XXI), and civil protection (Title XXIII).

According to Art. 191, Union policy on the environment shall contribute to the pursuit of prudent and rational utilization of natural resources. The Council must unanimously adopt measures affecting town and country planning; quantitative management of water resources or affecting, directly or indirectly, the availability of those resources; land use, with the exception of waste management; significantly affecting a country's choice between energy sources and the structure of its energy supply (Art. 192). Art. 196 on civil protection acknowledges both natural and manmade disasters. Raw materials are mentioned in the TFEU in the context of secure international supply and trade. The Euratom Treaty has provisions on uranium and thorium mining and supply (Art. 52, Annex II and IV).

The acquis does not cover the property right issues on national assets, such as natural resources (land, minerals, fuels, water, etc.), although certain elements are regulated, such as concession tenders to ensure undistorted open competition, environmental protection, construction products to achieve technical safety. The Charter of Fundamental Rights) has principles on property rights (Art. 17): "*Everyone has the right to own, use, dispose of and bequeath his or her lawfully acquired possessions. No one may be deprived of his or her possessions, except in the public interest and in the cases and under the conditions provided for by law, subject to fair compensation being paid in good time for their loss.*" The detailed rules on ownership are subject to sovereign MS rules (Art. 345 of TFEU).

Fuel minerals are traditional EU policy and regulatory fields since the European Coal and Steel Community (1951) and the Euratom Treaty (1957). The Raw Materials Initiative (EC, 2008) established the non-energy non-food raw materials policy of the EU (Christmann, 2021). Occupational health, technical safety, waste management, environmental impacts, and supply security are covered by the acquis (Hámor, 2002; Hámor, 2004b; EC, 2017; Hámor et al., 2019), but ownership and resource management details are left to MS (Table 2). The Extractive Waste Directive (2006/21/EC), inter alia, has specific provisions on management of excavation voids, for example backfilling.

In most countries, minerals in situ are national, or sometimes regional assets but in a number of countries construction minerals belong to the landowner, e.g. Austria, France, Netherlands, (EC, 2017; Hamor et al., 2019). Likely, this is one of the reasons why MS may not support new initiatives to regulate, for example, common mineral reserves classification or defining "mineral deposits of public importance" on EU scale (MINATURA2020, 2016). Many countries make a distinction on strategic (or critical, reserved) minerals, and the access to the exploration and extraction rights of these is more complex (e.g. by means of concession tendering).

Hydrocarbons (oil and gas) are treated in-depth in the acquis. As part of the competition policy, the Hydrocarbons Directive (94/22/EC) requires MS to publish their calls on oil and gas exploration and production in the EU Official Journal and sets principles for the evaluation of the applications. A few MS applied this provision voluntarily on geothermal energy (Italy, Hungary), metalliferous ores and coal (Hungary), coalbed methane (Belgium, Poland), gravimetric survey (Croatia). The Natural Gas Directive (2009/73/EC) is mainly on supply security, consumers protection, access to transmission systems, etc. Pipeline networks are subject to the Directive but with no details on the underground setting. The health and safety aspects of drillings are covered by a specific directive mainly applicable to hydrocarbons and geothermal energy but also relevant for exploration of non-fuels (Table 2). In MS with significant hydrocarbons industry (e.g. Denmark, Romania) there are distinct Petroleum Acts besides the non-fuel Mining Acts, and legislation implementing the Gas Directive (Mitchell et al., 2016).

Geothermal energy is defined in the Renewables Directive (2009/28/EC) as "*energy stored in the form of heat beneath the surface of solid earth*", but the Directive and other pieces are limited on indicative targets in the energy mix, efficiency of and accounting energy from heat pumps, etc., with no provisions on the geological aspects or resource

**Table 2**
Legislation on underground resources at European Union and Member States level.

| Underground resources utilization | | European Union secondary law | | EU Member States national legislation | |
|---|---|---|---|---|---|
| natural resource extraction | minerals extraction | [37] Environmental Impact Assessment Dir. (+Strategic EA Dir.), Seveso Dir. | Extractive Waste Dir., Workers Safety & Health at Mines Dir., Procurement Dir., Coal Mines Closure Dec.[38] | laws on permitting -procedural by EIA Act, Public Administration Act, | Mining Act, Subsurface Resources Act, National (State) Assets Act, Civil Code, Environment related laws |
| | oil & gas extraction | | CH Exploration Dir., Natural Gas Dir., Concession Dir., Procurement Dir., Workers Safety & Health at Drilling Dir.[39] | | Oil & Gas Act, Mining Act |
| | geothermal energy | | Renewable Energy Dir., Energy Efficiency Dir., Water Framework Dir., Groundwater Dir.[40] | | Renewable Energy Act, Mining Act, Water Act |
| | geophysical forces | | None | | Geological/Geodesy/Navigation Acts |
| | groundwater | | Water Framework Dir., Groundwater Dir.,[41] | | Water Act and by-laws |
| underground space use | gas & water storage | | Natural Gas Dir., Concession Dir., Energy Infrastructure Reg.[42] | | Energy Act, Oil & Gas Act |
| | CCS | | CCS Dir., Energy Infrastructure Reg.[43] | | Mining Act |
| | waste disposal | | Waste Framework Dir., Landfill Dir., Radwaste Dir., Extractive Waste Dir.[44], | | Waste Management Act, Landfill Act, Nuclear Energy Act |
| | defense | | Defence Products Dir.[45] | | Defence Act |
| | research & archives | | none[46] | | Cultural Heritage Act, R&I Act |
| | urban infrastructure | | Constructions Dir., Buildings Energy Performance Dir., Concession Dir., Public Procurement Dir.[47] | | Spatial Development and Land Use Planning Act(s), Construction Act, Civil Code |
| | inter-urban infrastructure | | Critical Infrastructure Dir., Constructions Dir., Natural Gas Dir., Gas Transmission Reg., Concession Dir., Procurement Dir., Energy Infrastructure Reg., Tunnels Safety Dir., Transport Network Reg.[48] | | Spatial Development and Land Use Planning Act(s), Energy Act, Oil & Gas Act, Telecommunication Act |
| information management (incl. geohazards) | | | INSPIRE Dir., Env. Info. Dir., Re-use Public Information Dir., statistics acquis[49] | | Environmental Information Act, Geoinformation Acts, sectoral by-laws of information management |

classification. It is an explicit entry in the EIA Directive (2011/92/EU), and re-injection of geothermal waters is dealt with in the Water Framework Directive (2000/60/EC). On national scale, the supervision of geothermal energy is more complex, typically, it is subject to shared competences among the Mining Act, Water Act, Renewables Act and their by-laws (Goodman et al., 2010). In most countries the permitting of shallow heat pump systems is by the local municipality in frame of construction permit, the deeper wells and EGS are supervised by the mining inspectorates in co-operation with the water and environmental authorities. The ownership of geothermal energy is not always explicit in national codes. In Hungary, the Mining Act requires the establishment of 3D geothermal protective pillar in depth in order that the planned volume of geothermal energy extracted with the given technology for at least 25 years is ensured.

Geophysical resources (other than geothermal heat flux and radioactive energy), such as the magnetic field, gravity, and the compressional/extensional energy of rocks, are not covered by the acquis. Lithosphere plates move several centimetres annually (e.g. Einarsson, 2008), whereby active continental rifting, with its associated volcanism bringing the hot Earth's mantle close to the surface is exposed in a few countries (Iceland, Ethiopia).In Iceland the high-enthalpy geothermal energy production by means of an EGS from shallow magmatic chambers is assessed by the Icelandic Deep-Drilling Project.[33] The relevant national legislation is usually restricted to the geological and geophysical research and the use of the gravity and magnetic fields in navigation and geodesy.

Groundwater management is regulated by the acquis. The Water Framework Directive (2000/60/EC) introduced the principles of river basin scale management (for surface water) and the designation, inventory and protection of groundwater bodies. They include provisions on conflicting underground space activities, for example (Art. 11), MS may authorize injection of water used for:

- geothermal purposes;
- resulting from hydrocarbons or minerals extractions;
- for technical reasons;
- pumped groundwater from mines or civil engineering works;
- natural gas, LPG and carbon dioxide for storage purposes; and small quantities of substances for scientific purposes.

[33] https://iddp.is/.

Because of the detailed water acquis, the national legislation has less degree of freedom for sovereign solutions. The storage of natural gas, LPG, and carbon dioxide in geological formations which are permanently unsuitable for other purposes, is regulated mainly in the Energy Infrastructure Regulation (347/2013/EU) and the CCS Directive (2009/31/EC). Annex II of the former lists, inter alia, underground gas storage, and the permanent storage of anthropogenic carbon dioxide in geological formations. The CCS Directive is the most detailed piece of acquis from the technical perspective of underground space use. Its Annex I on the geological site characterization sets parameters to be measured and assessed, and prescribes a 3D geological model accompanied by a dynamic simulation tool for predicting the long-term behaviour of the storage complex. The transposition of the CCS Directive is reflected in the national/regional energy, gas, and mining acts.

The waste acquis, dating back to 1975, was the first dealing with the use of underground space. The Waste Framework Directive (2008/98/EC)) acknowledges backfilling among recovery options (*non-hazardous waste used for reclamation in excavated areas or for engineering in landscaping*), and lists a number of underground disposal options: deposit into land (e.g. landfill), land treatment (e.g. sludgy discards in soil), deep injection (e.g. pumpable discards into wells, salt domes or naturally occurring repositories), surface impoundment (e.g. placement of liquid or sludgy discards into pits), engineered landfill, permanent waste storage (e.g. emplacement of containers in a mine). The Landfill Directive (1999/31/EC) was the first to provide technical details on geological and engineered barriers, such as permeability of strata, interactions with groundwater, geohazards, monitoring scheme, etc. Since the waste field is well covered by the acquis, there is less variability left for national approaches. The Radioactive Waste Directive (2011/70/Euratom) is limited to procedural issues, geological disposal is mentioned only in its Preamble. Therefore, EU countries design their national radioactive waste legislation in accordance with the International Atomic Energy Agency[34] and OECD Nuclear Energy Agency[35] standards.

The use of underground for defence purposes is not regulated in the acquis, military aspects in general are excluded from the scope of the Directives. Underground facilities for defence purposes are regulated by national procedural laws on permitting new projects, the competent authority (usually the Ministry of Defence) having an absolute right for veto. Similarly, the legislation on research, and on cultural heritage does not have any reference on underground space.

Despite of the rapid urbanization in Europe and the explicit mandate in the TFEU, urban and land-use planning are not regulated at the EU level. The attempts on establishing common rules for spatial development and land-use planning have not been fruitful. The acquis relevant to underground urban infrastructure are on constructions, buildings energy performance and tunnels safety. The Preamble of the Constructions Directive (305/2011/EU) acknowledges the importance of geological settings, the mechanical resistance and stability is a basic requirement (Annex I), but the details remain with the national law and European standards (e.g. Eurocodes 7 (EN 1997) and 8 (EN 1998), on Geotechnics and Seismic Design, respectively).

The inter-urban underground infrastructure is treated in the acquis, energy and transportation grids are explicitly in the scope. Annex II of the Energy Infrastructure Regulation (347/2013/EU) and its Implementing Regulation (1113/2014/EU) define high-voltage underground transmission cables, electricity storage facilities in underground infrastructure or geological sites, high-pressure gas pipelines and connected underground storage, crude oil pipelines and anthropogenic carbon dioxide pipelines. The focus of this Regulation is on administrative measures, not on technicalities. The Regulation on Transport Network (1315/2013/EU) covers railway and road tunnels. Mobility must be ensured in the event of natural or manmade disasters, and infrastructure requirements ensure quality, efficiency and sustainability of transport services. The Tunnels Directive (2004/54/EC) applies to all tunnels in the trans-European road network with lengths of over 500 m, and it establishes minimum safety measures. There is no reference on the dual or multiple use of such road tunnels, or on geological criteria. The national legislation have limited degree of flexibility to adopt own rules for energy and transport networks. Energy and transport lines are in scope of the Directive on Critical Infrastructures (2008/114/EC).

The Environmental Impact Assessment (EIA) Directive (2011/92/EU) is a "horizontal" law to be also applied for underground projects (mines, quarries and related facilities, drillholes, pipelines, road and rail tunnels, groundwater abstraction and recharge, storage, etc.). Soil and land are listed among the natural resources, and land use is a condition to be considered when locating a new project. The Strategic Impact Assessment (SEA) Directive (2001/42/EC) is to ensure that strategic plans and programmes on town and country planning or land use, and which set the framework for development of projects listed in the EIA Directive, are preceded by an environmental assessment. The Seveso Directive (2012/18/EU) on prevention of major accidents involving dangerous substances covers onshore underground gas storage in natural strata, aquifers, salt cavities and disused mines, tailings disposal facilities, and other underground technical installations. Art. 13 stipulates that MS must ensure that the objectives of preventing major accidents and limiting the consequences of such accidents for human health and the environment are taken into account in their land-use policies.

The rest of land-use planning and/or spatial development is entirely under the sovereign jurisdiction of MS, managed at national, regional and local levels. The European Spatial Development Perspective (ESDP) (Committee on Spatial Development, 1999) promotes sustainable development through a more balanced use of land but it remains on 2D surface scale. CEMAT[36] (Council of Europe Conference of Ministers Responsible for Spatial/Regional Planning) has guiding principles which do not cover minerals among underground natural resources (Council of Europe, 2020). Land use plans may have absolute ban or conditional dispositive clauses on underground projects. Less frequently, these have protective provisions on safeguarding mineral deposits (Hámor et al., 2021; MINLAND, 2021).

#### 3.2.2. Competent authorities, permitting

It is difficult to draw a general outline for the current regulatory composition of permitting underground activities in Europe, except for mineral resources related national policies and legislation which are well documented. The historically developed public administration

[34] https://www.iaea.org/.
[35] https://www.oecd-nea.org/.

[36] https://www.coe.int/en/web/conference-ministers-spatial-planning.
[37] Directive 2011/92/EU, Directive 2001/42/EC, Directive 2012/18/EU
[38] Directive 2006/21/EC and daughter decisions, Directive 2014/24/EU, Directive 92/104/EEC, Decision 2010/787/EU.
[39] Directive 94/22/EC, Directive 2009/73/EC, Directive 2014/23/EU, Directive 2014/24/EU, Directive 92/91/EEC.
[40] Directive 2009/28/EC, Directive 2012/27/EU, Directive 2000/60/EC, Directive 2006/118/EC.
[41] Directive 2000/60/EC, Directive 2006/118/EC.
[42] Directive 2009/73/EC, Directive 2014/23/EU, Regulation 347/2013/EU.
[43] Directive 2009/31/EC, Regulation 347/2013/EU.
[44] Directive 2008/98/EC, Directive 1999/31/EC, Directive 2011/70/Euratom, Directive 2006/21/EC.
[45] Directive 2009/43/EC.
[46] The acquis on R&I is voluminous but does not deal explicitly with underground space.
[47] Regulation 305/2011/EU, Directive 2010/31/EU, Directive 2014/23/EU, Directive 2014/24/EU.
[48] Directive 2008/114/EC, Regulation 305/2011/EU, Directive 2009/73/EC, Regulation 715/2009/EC, Directive 2014/23/EU, Directive 2014/24/EU, Regulation 347/2013/EU, Directive 2004/54/EC, Regulation 1315/2013/EU.
[49] Directive 2007/2/EC, Directive 2003/4/EC, Directive 2003/98/EC.

differs across MS and, in a number of MS across regions. For the sectors covered by the acquis (energy, transport, environment), regulatory models are rather uniform. The competent authorities and institutions involved in the supervision of underground resources are summarized on Table 3.

Minerals, fossil fuels, underground gas storage, CCS and closed geothermal systems are typically supervised by mining authorities which in some countries (Sweden, Portugal, Hungary) are parts of the geological survey. Major decisions, such as publication of concession calls usually rest with the minister. Regional mining inspectorates are sometimes integrated into government offices, as one-stop shops (Germany, Hungary) which implies that the project developer can submit all of its applications at the same "window" and in response, the resolution of the regional government office integrates all requirements of the competent professional co-authorities involved in the given permitting. In a number of countries (Netherlands, Belgium, Austria) aggregates (construction minerals) extraction is planned in the frame of spatial development plans by regional planning councils (EC, 2017). In France, this is done within regional quarrying master plans according to a scope and an outline defined at the national level. Geological surveys are government agencies providing the information services related to these resources.

Water management is usually a shared competence between water district (river basin) agencies and the environmental inspectorates, the former mainly being in charge of quantitative and qualitative monitoring and management. Several entities may constitute the knowledge base for groundwater, such as water research bodies, environmental agencies and geological surveys.

Waste landfills are permitted by environmental inspectorates. Geological disposal sites of radioactive waste are usually supervised by an independent nuclear energy agency.

The urban and inter-urban underground infrastructure is governed by the land-use planning authorities, such as the regional planning councils and local municipalities. The latter also are in charge of construction permitting, usually with the involvement of the mining authorities and geological surveys when underground structures, geohazards or mineral reserves are affected. This joint decision making is rather common for underground space use projects. Another standard co-authority is the environmental inspectorate, for the simple reason that quasi all underground activities and installations require an environmental impact assessment. The knowledge base for urban and inter-urban underground planning is rather heterogeneous. Major cities can afford to operate an own department with planning and running a spatial information system. The rest usually outsource these tasks to engineering and land use planning companies who approach the land register offices, geological surveys, geotechnical databases, mining inspectorates, environmental information services for data ad hoc, as the project requires. The availability of qualified staff able to handle and understand complex data may be an issue and lead to questionable plans and decisions.

The geophysical fields are used for minerals and fuels exploration, navigation, etc. Data acquisition, modelling, conservation and dissemination are generally part of the remit of geological surveys. The permitting of underground structures for research facilities or archives is usually treated as for mines. Defence facilities are specific installations permitted by the military authorities, with involvement of mining authorities under classified conditions.

In general, there is at least one level of appeal against first-instance resolutions, the second-instance central (national) authority, or directly the Court of Justice (or Court of Public Administration). Eventually, clients can submit the appeal to the Supreme Court or the Constitutional Court in case they question the legal provision itself.

### 3.3. Information management

The public access to environmental information, statistics, re-use of public information, and business secret are regulated on EU scale (Table 2). Nevertheless, the most relevant is the INSPIRE Directive (2007/2/EC) on public digital spatial information infrastructure, and interoperability between the various public geographic information systems, which indicates several spatial data themes relevant to underground space, such as soil and subsoil, geology, mineral resources, land use, buildings, utility services, regulation zones (incl. mining sites), natural hazards, energy resources, etc. The detailed ontologies and data interoperability standards are available for most spatial themes.[50]

The EU Geoconnect3D project[51] links geological settings and the exploitation of the subsurface. A structural framework is created with essential planar structures and reveal the connection among the existing models. The structural framework models annotated with geo-manifestations allow the integration of complex cross-thematic research. The EuroGeoSurveys' European Geological Data Infrastructure (EGDI)[52] serves information on underground resources and geohazards.[53] Geohazards are often neglected screening filters in spatial development plans.

In Germany, the Federal Institute for the Geosciences and Natural Resources has several projects on the 3D modelling of underground space use (BGR, 2016). UBA, the Environmental Agency of Germany (Kahnt et al., 2015) introduced the concept of "potential utilization zone" as a possible instrument for subsurface spatial planning. Subsequently, three federal states were used as case studies to determine which kinds of data are available for subsurface spatial planning and what restrictions exist.

Van der Meulen et al. (2013) and Griffioen et al. (2014) demonstrate 3D subsurface information management in the Netherlands. DINO is the main tool and dataset containing boreholes, seismic lines, groundwater data, chemical and physical data, and four subsurface models. BRO,[54] the Dutch National Key Registry of the Subsurfaceis a tool with blocks of key registers where registration objects are linked to a specific location. This information system is to serve the new policy for integrated planning on the use of the underground space. The monitoring of the subsurface activities means 4D, in other words, the continuous or periodical update of subsurface data would imply a quasi-authority mandate for TNO, a government agency.

Information management of the underground is intended to support not only spatial planning but:

- Provides the competent authorities with data and knowledge on its subsurface assets, including the provision of elements essential to proper land-use planning;
- Provides investors with data and information on potential subsurface resource targets, including underground space;
- The United Nations Economic Commission for Europe established the United Nations Framework Classification (UNFC)[55] for Resources. UNFC is an internationally applicable scheme for the sustainable management of energy and mineral resources, bioenergy, water, anthropogenic resources, and renewables. Resource quantities are classified on basis of three criteria that reflect technical (incl. geology), socio-economic and planning (feasibility) dimensions. It serves mainly the interest of governments by supporting the comparison of different resource types and categories. The industry and financial markets, including the European Securities and Markets

50 https://inspire.ec.europa.eu/data-specifications/2892.
51 https://geoera.eu/projects/geoconnect3d6/.
52 http://www.europe-geology.eu/about-egdi/.
53 http://www.europe-geology.eu/geohazards/
54 https://basisregistratieondergrond.nl/english/.
55 https://unece.org/sustainable-energy/unfc-and-sustainable-resource-management.

**Table 3**
Simplified scheme of legislative bodies, permitting authorities, support agencies, levels of appeal with competence over underground resources.

| Political & legislative bodies | Competent (first instance permitting) authorities & government agencies | Executive, management entities | Jurisdiction & second instance appeal |
|---|---|---|---|
| Parliament | environmental inspectorates, mining inspectorates, (or directorates), municipalities, geol. surveys, soil surveys, civil protection | water district directorates, waste management companies, land use planning & engineering companies, utility companies, other agencies | Constitutional Court Supreme Court |
| Government (ministries) | | | Court(s) of Justice |
| Regional & Local Government(s) | | | second instance authorities (if any) |

Authority (ESMA),[56] prefer the use of other international or national standards.

### 3.4. Circularity and sustainable development

Sustainable Development is an internationally agreed objective enshrined in the 17 UN Sustainable Development Goals in 2015. The development of a circular economy is a key component of any strategy to meet the UN SDGs.[57] In the EU, the concept of circularity evolved gradually during the last 15 years from policy fields such as the waste acquis, natural resources strategy, raw materials policy and resource efficiency, both in connection with carbon neutral industry and energy policies (European Commission Staff Working Document, 2020d). These were integrated into the 2020 Circular Economy Action Plan (European Commission, 2020e), one of the building blocks of the European Green Deal (EC, 2019). Circular economy is core to sustainability, by reducing the primary natural resource demand and use by economy in absolute sense, and decoupling it from economic growth and environmental impacts by improving resource efficiency, productivity, re-use, recycling, industrial ecology, and environmental performance along the different value chains (IRP, 2011).

Concerning legislation, the EU EIA Directive requires "*a description of the likely significant effects of the project on the environment resulting from … the use of natural resources, in particular land, soil, water …, considering as far as possible the sustainable availability of these resources; … recovery of waste*". According to the Ecolabel Regulation (66/2010/EC), criteria must consider the whole life cycle of products, such as substitution of hazardous substances by safer substances, use of alternative materials or designs, durability and reusability of products, and net environmental balance between the environmental benefits and burdens. The Ecodesign Directive (2009/125/EC) on energy products has similar parameters of circularity: e.g. possibilities for reuse, recycling and recovery of materials and energy; use of recycled materials; ease of reuse and recycling through materials and components, ease of disassembly, component and material coding standards for reuse and recycling, extension of lifetime through modularity, upgradeability, reparability. The Regulation on construction products (305/2011/EU) requires the sustainable use of natural resources, "*(a) reuse or recyclability of the construction works, their materials and parts after demolition; (b) durability of the construction works; (c) use of environmentally compatible raw and secondary materials in the construction works.*"

Minerals extraction can be considered sustainable if mining contributes proactively to the UN SDGs without generating harmful impacts (Mancini et al., 2019). This has not been accomplished yet, despite all the good intents from the industry and governments. While the production of minerals provides a major contribution to the UN SDGs, there are still open issues with transparent reporting of the sustainability performance of companies and individual production sites.

The EU being particularly dependent on raw materials imports regularly identifies materials considered as critical to its economy, the first assessment having been published in 2010 (EC, 2010). The 4th edition, in 2020 list includes 28 minerals, coking coal and natural rubber (EC, 2020a).

Resource efficiency, recovery and recycling, the important elements of circularity have been interpreted in the context of critical minerals (Mathieux et al., 2017) and this is becoming an aspect in the environmental impact assessment of extractive projects (Hamor et al., 2021). Decision 2009/607 on the ecolabel criteria for hard floor-coverings and Decision 2017/1217 for hard surface cleaning products were the first precursors in this respect by setting relative indicators on acceptable waste generation, water and energy consumption, and land use impacts relative to the mineral output.

In order to protect landscape and obtain public acceptance, "*invisible mining*"[58] is an emerging initiative to locate mining facilities into the subsurface, and position and design surface installations into a landscape "*camouflage*". The Decision 2002/272/EU set a quantitative scheme on the acceptable visual impact for quarries. However, invisible does not mean without environmental impacts.

The extractive industry frequently generates a range of by-products

[56] https://www.esma.europa.eu/sites/default/files/library/2015/11/2012-607.pdf.
[57] https://sdgs.un.org/.
[58] https://www.csiro.au/en/Research/MRF/Areas/Resourceful-magazine/Issue-07/Invisible-mining.

in addition to the targeted resource. For example, the hydrocarbon sector produces thermal water, brines, natural $CO_2$, sulphur. Ore mines produce metals collateral to the major carrier metal, aggregates from the overburden and host rock, sulphur from sulphidic mineralizations, and many mines supply pumped drinking water to nearby settlements (Dill, 2009).

Similar circularity and sustainability provisions are found in the Water Framework Directive (2000/60/EC), e.g. the balance between abstraction and recharge of groundwater must be ensured in order to protect groundwater bodies (Art. 4), and it acknowledges that there are many competing groundwater uses (Art. 11).

There are numerous good examples of pro-circularity practices in the underground domain, for example, the parallel or flexibly changing, dual or multiple use of the same underground space and facility. At the WIPP site radioactive waste disposal and neutrino capture experiments fit well. In Moscow, during WWII the metro turned into shelter at nights. The Kelvedon Hatch bunker in UK was a RAF base during the war, then a civil protection facility and now it is an adventure park.[59]

In Kuala Lumpur a 9.7 km long, 30 m deep, 13 m wide “Smart tunnel”[60] accommodates a deviated river, infrastructure cables, and a road, the latter is also capable for water management during flooding at ca. 30 m depth. However, the concentration of too many functions at critical infrastructures may increase their vulnerability. Mines and quarries while in operation, due to progressive rehabilitation, increasingly use their space for alternative activities such as waste landfill, recreation, and other industry projects (Pearman, 2009; Hámor et al., 2021).

The change of underground space use in time is a better approach than abandoning an underground site. At Canfranc, Spain the railway tunnel was transformed into a national laboratory. Mining companies seek sustainable use of their closed sites (Xiea et al., 2020; Hámor et al., 2021), such as cultural heritage, research, storage and food production. Many derelict aggregate production sites turn into biodiversity paradises (Eden project)[61], some becoming legally protected areas, recreation lakes, PV plants, or brown fields for industrial development (Pearman, 2009).[62] The utilization of underground mines, especially in case of metalliferous ores and coal, requires careful planning because of the groundwater and its aggressive geochemical character (Mborah et al., 2016; Kivinen, 2017; Kretschmann, 2020). Success stories exist, such as geothermal energy production at the Heerlen coal mine,[63] museums in ore mines,[55] archives and research labs in extracted salt domes in Germany, energy storage, etc. Depleted hydrocarbon fields are preferred sites for gas storage, CCS, geothermal energy production and could become major targets for the future storage of hydrogen.

The underground urban infrastructure could also change functions but the creation of flexible underground structures for multiple uses should be in the mindset of designers, investors and competent authorities.

### 3.5. *Criticality*

The assessment and evaluation of the absolute and relative importance of natural resources to an economy, has been in focus of researchers and legislators. The different approaches and methodologies include the valuation of ecosystem services[64]; protected species and habitats on the ground of legislative approval procedure (EU Natura 2000 Framework)[65]; the valorization of mineral and fuel reserves (Otto, 1997; Radwanek-Bak et al., 2020)[66]; the definition of criticality on basis of multiple non-quantitative criteria, e.g. EU critical infrastructure on condition that its disruption or destruction would have a significant impact on social and economic functions (Directive 2008/114/EC); energy infrastructure of common interest (Regulation 347/2013/EU) as function of supply security, market integration, open competition and sustainability. Monetary valuation of urban underground space and cost analysis is studied too (Kaliampakos et al., 2016; Qiao et al., 2017). Criticality can be also defined on the ground of absolute scarcity (e.g. land in islands, water in arid settings) (Committee of Regions, 2020).

The most traditional approach is to define criticality as the positioning of a given resource in a orthogonal two-axial system, one axis being an evaluation of supply risks, the second one being the economic importance of the activities that could be impacted by a supply disruption. This methodology is used for the assessment of non-energy non-food raw materials critical to the EU economy. It implies the calculation of quantitative composite indicators that define the value for each axis (EC, 2020a), including geographic concentration of the production, country governance, import reliance on the supply risk side, and substitution potential and sectoral added value on the economic importance side. On basis of historical traditions (e.g. state/royal monopoly over salt, gold, coal) and other considerations (royalty potential, independent supply, ownership issues) MS have other legal classes of minerals (e.g. “reserved” minerals in Slovakia, “scheduled” minerals in Ireland, “concession” minerals in Sweden).

Fig. 2 is a first empirical attempt based on expert judgement rather than on measurable parameters to assess the criticality of the subsurface resources and uses listed in Table 1 from a European perspective, a proxy approach to indicate the non-quantitative estimate of relative criticality of underground space use types and other major underground resources groups as a function of demand (economic importance) and supply (availability + vulnerability (conflicts, environmental issues, service disruption)). The arrows reflect the estimated future trend of the resource clusters. Although the demand and supply of many of these resources may differ a lot across countries, regions and localities, groundwater and underground urban infrastructure are the two resources which are under increasing competition between different end-uses and stress in many regions of Europe. Hydrocarbons’ importance is still significant and domestic reserves are limited, but due to the decarbonization efforts, its criticality is diminishing in the EU. On the contrary, the number of critical non-fuel raw materials doubled in nine years (from 14 to 30) and this trend is expected to continue.

For CCS, not storage space but capture technology, transmission logistics, long term sealing and economics are the limiting factors. The assessment of underground gas storage and water-based energy storage show similarities to CCS. As well as geothermal energy, however, its non-sustainable exploitation led to temporary depletion and environmental conflicts at several sites. The interurban underground infrastructure has an outstanding economic importance, part of it is *ex lege* classified as critical in the context of the impacts that a service disruption would cause, but the space available for its further extension does not seem restricted. Another part of the interurban infrastructure (“*energy infrastructure of common interest*”) is also classified in the acquis. Locating infrastructure underground decreases its vulnerability to natural hazards and terrorist actions but all underground uses have a surface outlet, representing a concentrated risk, “bottleneck”.

As a good indicator of the progressing circular economy in the EU, waste landfilling and deep disposal are not a critical use of underground space, their volume and importance being rapidly decreasing. By 2017

[59] https://secretnuclearbunker.com/.
[60] https://www.roadtraffic-technology.com/projects/smart/.
[61] https://www.edenproject.com/.
[62] https://www.mining-technology.com/features/new-uses-for-old-mine-shafts.
[63] https://www.buildup.eu/en/news/district-heating-network-heerlen-flooded-coal-mines-circular-district-heating [54] https://whc.unesco.org/en/list/1344/.
[64] https://ec.europa.eu/jrc/en/science-update/eu-ecosystem-services-valued-almost-125-billion-year.
[65] https://ec.europa.eu/environment/nature/natura2000/index_en.htm.
[66] https://corporatefinanceinstitute.com/resources/knowledge/valuation/mining-asset-valuation-techniques/.

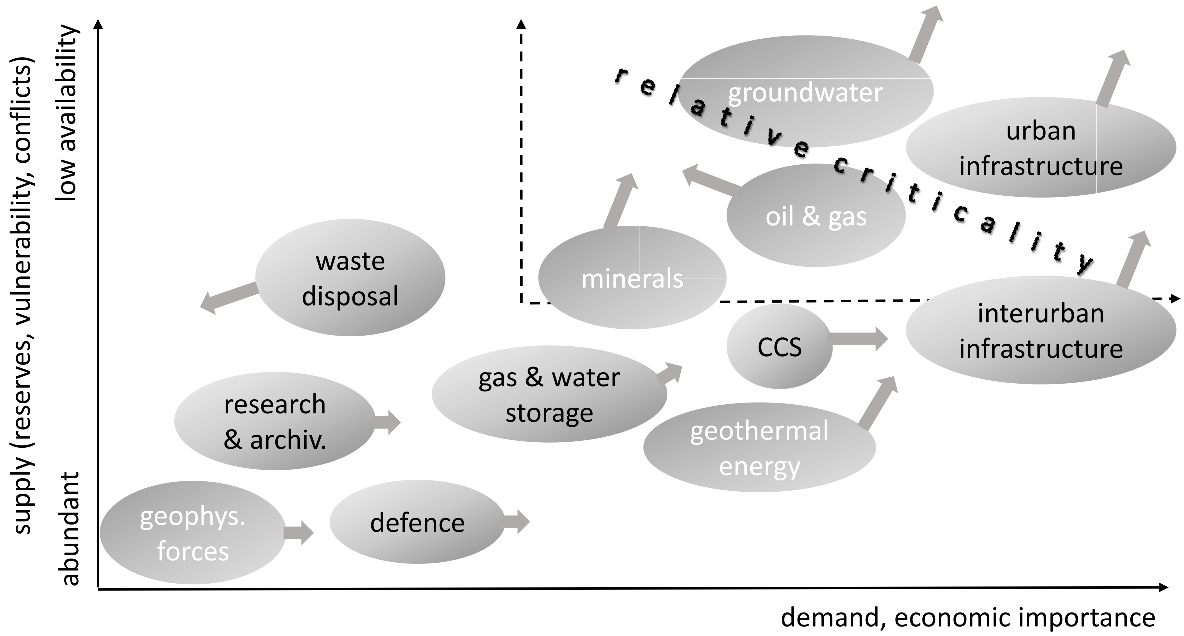


**Fig. 2.** The relative criticality and their trend of underground resources and space, as defined in Table 1.

only 10% of the EU-scale direct material input had been eventually landfilled (European Commission Staff Working Document, 2020d). Defence applications, research and archival underground space use activities are likely not critical.

As stressed, this assessment is to show that the evaluation of the relative criticality of subsurface assets and their use and utilization should, in an ideal case, precede legislative and subsequent permitting actions and be integrated in land-use planning procedures. Parameters such as social and economic impacts of disruption of service of underground infrastructures, substitution options (e.g. relocation, replacing function), vulnerability to geohazards and unsuitable geo-environment must also be taken into account. Local and regional-scale assessments may change the results significantly when integrating local geology, economy, and social data. However, it is not the objective of this study to further elaborate on this. As a concluding remark, most clusters of underground space use are subcritical at present but this scenario may rapidly change in the future.

## 4. Discussion - Good governance of underground space

The acquis is limited to general rules on public administration. According to Arts. 41–42 of the Charter of Fundamental Rights, every person has the right to have his or her affairs handled impartially, fairly and within a reasonable time by the institutions and bodies. This includes the right (*a*) to be heard, before any individual measure which would affect him/her adversely is taken; (*b*) to have access to his/her file, while respecting the legitimate interests of confidentiality and business secrecy; (*c*) for the obligation of the administration to give reasons for its decisions; (*d*) to have the Union make good any damage caused by its institutions in the performance of their duties. Natural or legal persons residing or having registered in the EU have right of access to documents of the institutions and bodies of the Union.

The concept of good governance emerged 20+ years ago (UN, 1998) to describe how public institutions conduct public affairs and resources in the preferred way. It was a model to compare ineffective political systems with viable "developed" ones, e.g. applied to minerals producing countries in comparison with consumer countries also with a mature extractive sector. In line with this bi-polar approach, the definition in the acquis is in the EU–ACP partnership context (EC, 1998): *"Good governance implies managing public affairs in a transparent, accountable, participative and equitable manner showing due regard for human rights and the rule of law. It encompasses every aspect of the State's dealings with civil society, its role in establishing a climate conducive to economic and social development and its responsibility for the equitable division of resources."* Interpretations on resource governance is usually restricted to minerals and fuels (Natural Resource Governance Institute, 2020; Commission on Sustainable Development of the United Nations,[67] UN International Resource Panel, 2020). In summary, good governance is the 4$^{th}$ dimension of sustainable development, the driving force that stimulates the necessary convergence of its economic, environmental and social dimensions at different scales, i.e. international, supranational, national, regional, local, and corporate level, most of which is applicable to the utilization of underground space too (UNDP, 2020; Hámor et al., 2019).

The concept of resilience emerged as a potential response to increasing global risks and vulnerability of economies (EC, 2020b). It is reacting to shocks or persistent structural changes by either resisting them (*absorptive capacity*) or by adopting a degree of flexibility and making minor changes to the system (*adaptive capacity*) (Navracsics et al., 2015). When disturbances are not manageable, a resilient system engineers bigger changes (*transformative capacity*). Its only legal definition in the acquis is "*the ability to face economic, social and environmental shocks or persistent structural changes in a fair, sustainable and inclusive way*" (Regulation 2021/241/EU). Well and consciously governed underground resources may significantly increase the resilience of economy and society.

As presented above, the acquis regulates several underground projects and provides horizontal rules on EIA, civil protection, open competition, and information management. However, the efforts on establishing common rules at EU level for soil and subsoil, non-fuel minerals, and land use planning were not successful for a major reason: these resources represent the fundamental (critical, strategic) material assets of nations, and the subsidiarity principle has been applied when such legislative initiatives had been proposed (Christmann et al., 2014; Montanarella, 2015). This is maybe the most contradictory in case of critical raw materials which are published in a Commission Communication (EC, 2020b), not a source of law, or in case of land use planning for which there is a mandate for legislation as set in the TFEU.

[67] https://sustainabledevelopment.un.org/intergovernmental/csd19.

In most cases, EU legislation was a response to emerging issues (e.g. Extractive Waste Directive 2006/21/EC) but sometimes it precedes new technologies and situations (e.g. CCS Directive 2009/31/EC).

As part of overall resilience, the surface and underground infrastructures must also be resilient (Makana et al., 2016), i.e. able to resist, absorb, and recover from incidents that may result in disruptions. They must function sustainably and be adequately protected against different risks and able to "*bounce back*" into operation in the event of disruptions (EC, 2020f). In response to challenges (weather extremes, COVID19, carbon-neutral economy, terrorism) (EC, 2020c) the regulatory and legislative environment is likely to evolve both at sectoral level and through overarching thematic policies. MS will likely update their national legislation and, in absence of an EU framework, this would occur in an uncoordinated and uneven manner, leading to greater fragmentation and a more uneven playing field, breaching EU competition principles. As a preliminary conclusion, it is unrealistic to expect any coherent legislative initiative on the EU level to cover the supervision and management of all subsurface resources, including space. Nevertheless, policy communications and guidance documents may promote coordinated legal solutions.

The issues related to subsurface resources and end-uses indicate that it is not appropriate to develop governance only at national level either. As already noted by researchers (Field et al., 2018; Volchko et al., 2020), the currently prevailing "*first-come-first-serve*" practice does not have too much in common with good governance and prudent management of assets. Legislation usually follows an evolutionary pathway of gradual amendment of existing pieces of legislation, fundamental changes usually occurring in association with political landslides or unforeseen major events with a significant social impact. In most countries, the legal governance of underground space requires the amendment of the Constitution and/or the Civil Code and/or of the Act on National Assets where the original ownership of underground natural resources are regulated. Such amendments should also set clear provisions on the absolute or relative depth to which the ownership of the land and surface installations extends (i.e. parking levels, cellars, heat pumps, geothermal wells). As an alternative, Mining Acts ruling the ownership of minerals and fossil fuels may also accommodate these enhanced provisions on underground space.

In an ideal case, the above high level legal acts or the Act on National Spatial Development provide a methodology to evaluate the respective importance of underground resources and of their uses. An extended strategic impact assessment (SEA) is also a good candidate to provide a frame for the inventory and assessment of underground space. A further developed criticality assessment methodology, based on the principles outlined in this paper can be a basis for the assessment.

Another essential governance component is to transform 2D land use planning into 3D spatial planning, accompanied by a standard on the harmonized classification of these resources. The Strategic Implementation Plan of the European Raw Materials Innovation Platform (EC, 2013) also calls for this transition. In order to avoid the further sterilisation of underground space by urbanization and other land uses, priorities must be defined and access to the priority resources be safely guarded. The identified potential and prioritized underground space should be further defined by dynamic geospatial modelling, then establishing a designated spatial protective pillar, similar to mining plots or groundwater water bodies, and indicating them in the land register. The surface access outlet to subsurface installations and activities must be also designated in the land register and integrated in the conventional 2D land-use planning.

An example of good practice are the guidelines published by the European Commission (EC, 2010) on how to conciliate mineral resources extraction and natural reserves, as established under the Natura 2000 directives. There are numerous existing legal analogues for it (Natura 2000, geothermal pillars, critical infrastructure, energy infrastructure of common interest, drinking groundwater bodies, etc.).

The national permitting procedural rules are complex and difficult to change. Nevertheless, central government agencies which are capable of managing a nation-wide spatial planning information system on underground resources and update it periodically (4D) (Geological Society of London, 2019),[68] such as geological surveys, environmental agencies, spatial planning entities, shall be mandated with authority rights that enables them to enforce and control information supply and host classified information too. The Dutch example based on a specific framework law and a clear assignment of responsabilities and of public resources, could be a source of inspiration for other MS. Flexibility in the development of such 3D land-use planning support information systems has to meet the need for accommodating higher resolution data in some specific areas, such as urban areas.

The theoretical evidence of feasibility exists. The Netherlands is the first country in the EU which made a revolutionary legislative step in the above direction although the implementation experiences yet to come. The Environment and Planning Act (Omgevingswet),[69] came into effect in 2021, it combines and simplifies the regulations for spatial projects. Dozens of environmental legislation and hundreds of regulations for land use, residential areas, infrastructure, the environment, nature and water will be integrated. The Act replaces 15 laws, including the Water Act, the Crisis & Recovery Act and the Spatial Planning Act, and eight other laws. Currently, municipalities have over 100 land-use plans, the single environmental plan for the entire area will replace all. Citizens or companies will be able to apply for a digital permit at a 'one-stop-shop' and the municipality or province will make the decision. However, the geospatial information system's, BRO's thematic layers yet cover only ca. 20–30% of the resources this paper considers.

Financial and fiscal instruments are important regulatory tools indicating a country's policy on underground resources. Companies involved in the use and exploitation of underground resources have to face specific taxes and annuities. Landfill taxes, water use fees, environmental levies are rather common in most jurisdictions. Some governments also choose to encourage, by subsidies, the use of specific resources, in support to their efforts to foster sustainable development. An example are geothermal energy projects. In some countries, they benefit from direct subsidies and incentives, and preferential electricity rates. Underground urban infrastructure is usually charged by the real estate property tax, as surface buildings. Gas storage interurban infrastructure operators pay concession fees and royalties.

In most jurisdictions, both the minerals and fuels extraction activities pay royalties, on the basis of different calculation methods (profit-, value-, volume-based resource rent) which can be different for specific commodities or extraction methods. The collected royalty can feed either central, regional or local budgets (Otto, 1997; Nita et al., 2018). Progressively increasing land use tax in Slovakia is encouraging intensive exploration to avoid the blocking of a promising area by speculators (EC, 2017). During economic crises, governments tend to allocate a so-called "*windfall tax*" or "*Robin Hood tax*" on profitable major mining and energy companies. In summary, there is a wide array of diverse financial and fiscal tools already in use that have an impact on underground resources and their uses. Depending on the policy objective to be achieved, governments may consider the introduction of a new annuity on underground space use, similar to concession fees or royalties. The smart re-allocation of such a tax may incentivize the sustainable use of underground space, similar to land tax or groundwater fee (Creutzig, 2017). IRP, 2020 and Christmann (2021) call for a small international resource tax of a few per mil on the ad valorem production. It could have an impact on the development of a global minerals governance framework supported by the establishment of an International Mineral Agency, inspired by the well-functioning International Energy Agency

[68] https://www.earthdoc.org/content/papers/10.3997/2214-4609.201902008?crawler=true.

[69] https://www.government.nl/topics/spatial-planning-and-infrastructure/revision-of-environment-planning-laws.

model (IEA, 2021). The appearance of new natural resources, such as water, on the commodity stock exchange[70] can be another evidence that prudent economic governance is core to good governance.

The COVID19 disaster may improve societal resilience and accelerate the integration of Europe, thus the regulation of sectors which are out of the scope of the TFEU. Paving the way for the sustainable development of a newcomer resource group may disturb the interest of conventional sectors. However, it is the core interest of EU countries "*to pursuit prudent and rational utilization of natural resources*" (TFEU), where underground space has a rapidly increasing weight.

## 5. Conclusions

A number of resources and current uses of underground space are critical or may become critical in the near future, such as urban and interurban underground infrastructure, geothermal resources, minerals and groundwater. The current policy, legislative, institutional framework as well as the information and knowledge management both on EU and national level appears inefficient to cope with this trend. The good practice cases presented in the context of circularity do not counterbalance the dominantly finite, non-renewable character of these resources.

Legislation usually acts *a posteriori* solving existing social, economic and environmental issues, and quite frequently is not sustained by adequate budgetary, human and technical resources. This horizon scanning study is for raising awareness of EU and national decision makers and legislators to act pro-actively in this field, otherwise the steering of subsurface resources will remain for the ad hoc, diverse rulings of the courts of justice. The aborted attempts on regulating land-use planning, soil (and subsoil) and minerals in the acquis indicate that an EU level legislative action on underground space is not a realistic scenario at present. The "first-come-first-serve" permitting practice of underground projects, the existing priorities set in the acquis (critical infrastructure, energy infrastructure of common interest) and in national legislation may block new projects that would use underground resources or space.

A clear governance framework, based on knowledge, transparency, stakeholder involvement and accountable reporting on the four dimensions of sustainable development (respectively, the economic, environmental, governance and social dimensions) is needed to assess subsurface resources, including space, and regulate their end-uses in a harmonized way. A set of coordinated legislative initiatives on national scale such as transforming the current 2D land use planning into 3D spatial planning with periodical updates (4D), also submitted to strategic environmental assessment, could much improve the current situation of not perfectly coordinated policies and actions. This harmonized approach requires stronger legal mandates, and adequate budgetary, human and technical resources, for national/regional/local competent authorities. Nevertheless, this co-ordination would not compromise the principle of subsidiarity and proportionality enshrined in the EU treaties.

The development of national/regional knowledge bases, based on 3D (4D) public digital spatial geoinformation system, with a common EU architecture, conceived as a common good, in essential to the development of this governance scheme. A foundation is provided by the INSPIRE Directive (2007/2/EC), and the capable institutional framework is functioning in most EU countries. A 3D inventory of underground resources potentially capable of meeting multiple future needs is an essential precautionary measure to foster a resilient society. The current period of COVID-19 crisis and the multiple natural resources related challenges that the EU, and its Member States are confronted with, should motivate EU, national and regional authorities, as well as concerned stakeholders, to engage in the development of a harmonized governance framework for the sustainable use of underground resources and space.

[70] https://prudentwater.com/en/water-investment/; https://smartwatermagazine.com/news/smart-watermagazine/future-water-traded-stock-exchange.

## Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as an official position of the EC.

## CRediT authorship contribution statement

**Mária Hámor-Vidó:** funding, project administration, supervision, data collection, conceptualization, validation.
**Tamás Hámor:** conceptualization, methodology, investigation, writing original draft, legal context, criticality, circularity.
**Lili Czirok:** information management, geophysical resources, data collection, technical editing.

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