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Preface to the special issue of the Division Energy, Resources, and the Environment at the EGU General Assembly 2025

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Abstract. The division on Energy, Resources, and the Environment (ERE) of the European Geosciences Union (EGU) follows an interdisciplinary approach to serve society with provision of solutions to challenges of our time and in the future. The global energy landscape is undergoing a profound transformation driven by the urgent need to mitigate climate change and achieve net-zero emissions. This transition necessitates a multidisciplinary approach that integrates geoscience with engineering, environmental science, and policymaking to address the complexities of resource utilisation, energy storage, and environmental stewardship. This volume of Advances in Geosciences presents papers covering key themes from recent developments, beside others, in geothermal systems, critical raw materials, carbon cycle dynamics and renewable energy integration, emphasizing the role of interdisciplinary research in overcoming technical, economic, and societal challenges.

1 Introduction

The imperative to transition toward sustainable energy systems – while ensuring resource efficiency, environmental protection, and socio-economic equity – requires unprecedented integration of geoscientific innovation. The 2025 General Assembly (GA) of the European Geosciences Union (EGU), through its Energy, Resources, and the Environment (ERE) division, addressed this challenge across their subprogramme groups, including integrated studies, renewable energy, geo-storage, raw materials and resources, and coupled processes in geo-energy systems as well as inter-and transdisciplinary sessions. This volume of Advances in Geosciences (ADGEO) reflects the diverse and interdisciplinary scope of the ERE programme and continues a tradition of twelve previous special issues (Bruckman et al., 2021, 2022; Kühn et al., 2013, 2015, 2016, 2024a, b; Juhlin et al., 2014; Martens et al., 2017, 2018, 2019, 2020). The publications collected here provide a snapshot of the latest research presented in ERE sessions during the 2025 EGU conference.

2 Integrated studies

The ERE division provides an overview of its multi- and interdisciplinarity, which is essential to tackle challenges of the future. Beside others, this is to provide adequate and reliable supplies of affordable energy and other (geo-)resources, obtained in environmentally sustainable ways, which is the basis for economic prosperity, environmental quality and political stability. In that way, geoscience underpins aspects of the energy mix that fuels our planet and offers a range of solutions for reducing global greenhouse gas emissions as the world progresses towards net zero.

The preservation, protection, and fruition of cultural heritage are closely related to the scientific knowledge of the component materials, their history and surrounding environment, and how these affect the characteristics and transformation of historical objects, structures, and sites. Geosciences represent a valuable partner for studies in conservation science and archaeometry, providing a solid background for addressing a number of questions revolving around natural and artificial geomaterials (stones, ceramics, mortars, pigments, glasses, metals, etc.), their features and settings.

Energy system modelling and integrated assessment approaches are essential tools for understanding and optimizing the complex interactions within modern energy systems. By simulating these interactions, stakeholders can make informed decisions that improve energy security, support economic viability, and minimize environmental impact. The urgent need for sustainable development strategies has amplified the importance of innovative tools that can evaluate the impact of industrial activities on ecosystems and human health. Integrated assessment models and industrial ecology tools such as material flow analysis, life cycle assessment, and input-output analysis are crucial for evaluating and mitigating environmental impacts.

3 Renewable energy

Renewable energy has become a new source of electrical power. By their very nature, wind, solar, hydro, tidal, wave and other renewable forms of generation are dependent on weather and climate. Modelling and measurement for resource assessment, site selection, long-term and short-term variability analysis and operational forecasting for horizons ranging from minutes to decades are of paramount importance. Spatial and temporal modelling of renewable energy systems, both in a prospective as well as in a retrospective manner, are key.

A worldwide transition towards “net zero” requires decarbonisation of diverse sectors, including the electricity generation, over the upcoming decades. On the supply side, renewable energy resources vary across a wide range of time scales, from minute-wise, seasonal, to interannual. In a changing climate, the patterns of renewable resources as well as their variability can also change.

Clean energy transition is a central concept to energy and climate policies, and in this context the need for geothermal resources utilisation is accelerating. Geothermal energy can be extracted from different, often complex, geological settings (e.g., fractured crystalline rock, magmatic systems, or sedimentary basins). Current advancements also target unconventional systems (e.g., enhanced geothermal systems, super-hot, pressurized and co-produced, super-critical systems) besides conventional hydrothermal systems. Shallow geothermal energy applications complement deep systems, including traditional closed- and open-loop borehole heat exchangers as well as so-called energy geo-structures.

4 Geo-storage

The intermittency of renewable energy sources necessitates robust storage solutions to ensure grid stability. Thermal energy storage, hydrogen storage and compressed air energy storage systems rely on subsurface reservoirs, aquifers and geological formations to balance seasonal and diurnal demand fluctuations.

The safe disposal of radioactive waste remains a contentious issue requiring multidisciplinary expertise. Deep geological repositories rely on multi-barrier systems, including bentonite buffers and crystalline host rocks, to isolate radionuclides over millennia. Natural analogues and underground research laboratories provide critical insights into long-term geochemical and mechanical stability, while public acceptance depends on transparent communication and stakeholder involvement.

As the global demand for carbon neutrality intensifies, CO_2 geological sequestration has emerged as a key method for mitigating carbon emissions. This process involves the long-term storage of CO_2 in deep geological formations such as depleted oil and gas reservoirs, saline aquifers, and unmineable coal seams. While the core of CO_2 sequestration lies in the safe and permanent storage of carbon, recent advancements suggest that its potential extends far beyond carbon management alone.

5 Raw materials and resources

The growing demand for raw materials, coupled with the need to reduce the environmental footprint of the resource sector, highlights the importance of accurately characterizing both primary (ore) and secondary (recycled) material streams. Critical raw materials are crucial for local and global economies in their pursuit of climate goals and societal and industrial needs. The high demand for these materials is set to boost mineral production. Meeting these targets necessitates accessing more diffuse and lower-grade deposits, and sourcing materials from a wide variety of sources. Sourcing critical raw materials from primary ores, by-products, and mining residues is an environmental subject but also an economic opportunity.

Understanding the pivotal relationship between carbon and life processes is essential to address global issues like climate change, the origin of life or to support planetary exploration. Carbon is the backbone of life on our planet and its cycle is perhaps the most influential in all of science linking natural and anthropic phenomena. Carbon cycle include the transformation of organic matter through geological processes, creating materials such as kerogen, coal, and graphite.

6 Process coupling and monitoring

Numerous cases of induced and/or triggered seismicity resulting either directly or indirectly from injection and/or extraction associated with anthropogenic activity related to geo-resources exploration have been reported in the last decades. Induced earthquakes felt by the general public can often negatively affect public perception of geo-energies and may lead to the cancellation of important projects. Furthermore, large earthquakes may jeopardize wellbore stability and damage surface infrastructure.

Faults and fractures are critical components of geological reservoirs, exerting significant control over the physical and mechanical properties of subsurface formations. Their influence on fluid behaviour and fluid-rock interactions plays a crucial role in the success and safety of geo-energy applications, including geothermal energy, carbon capture and storage (CCS), and subsurface energy and waste storage.

Chemical reactions between infiltrating fluid and the rock matrix alter the composition and structure of the rock, either creating or destroying flow paths. Strong, nonlinear couplings between the chemical reactions at mineral surfaces and fluid motion in the pores often lead to the formation of large-scale patterns: networks of caves and sinkholes in karst areas, wormholes induced by the acidization of petroleum wells, porous channels created as magma rises through peridotite rocks.

7 Inter-and transdisciplinary sessions

While the need for global cooperation in the face of global trends is obvious, funding mechanisms for environmental research and monitoring are still largely organised on a national and regional basis. Despite declared intentions to improve cooperation and thematic coordination in the formulation of related research and infrastructure programmes, concrete cooperation is hampered by a lack of resources and time for consultation, even in the case of thematically appropriate calls. This affects not only collaborative projects but also the improvement of interoperability and, ultimately, the concerted development and sustainable operation of services.

Environmental challenges of the 21st century demand a concerted scientific effort to understand the complex interactions within the Earth system. Open and accessible wordclass sustainable research infrastructures together with enhanced international cooperation are crucial to foster innovation in the field.

The implementation of ambitious system-wide strategies, such as the "Sustainable Development Goals" and global climate policies, requires a holistic approach that integrates the economy, energy, land, food and water systems. Integrated assessment models have advanced science and policymaking but often lack representation of subnational dynamics, such as gender, within-region income distribution, and other social and spatiotemporal heterogeneity.

8 Conclusions

ERE was running 33 sessions in the lead and co-organised 10 additional ones. From the more than 20 000 abstracts contributed to the General Assembly 2025, well beyond 1000 came from ERE members. One highlight of the conference was the great debate about the question "Will a paradigm shift from on-shore to off-shore mining serve the future of humanity?" to which the division contributed significantly.

The energy transition demands a paradigm shift in geoscience research, prioritising sustainability, resilience and equity. By bridging traditional disciplines – from mineralogy to climate science – and fostering global cooperation, the geoscience community can drive innovations that decarbonise energy, secure raw material supplies and protect ecosystems. Future research must emphasize the integration of emerging technologies and circular economy principles to ensure that resource exploitation aligns with planetary boundaries.

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