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The DGE-ROLLOUT project: Deep geothermal energy potential of Carboniferous carbonate rocks in North-West Europe – History, characterisation, modelling and exploration

Martin Arndt, Tobias Fritschle, Anna Thiel & Martin Salamon*

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Following the Paris Agreement and the European Green Deal, the research on geothermal energy presently experiences a renaissance. The expansion of renewable energies is a key asset to secure the well-being and health of citizens and future generations and to protect the natural habitat. Aiming to become the first climate neutral continent, the European Commission attributes responsibility to all parts of society and economic sectors.

Deep geothermal energy (DGE) may play a significant role in the future energy mix considering its base load capacity, and its almost infinite and ubiquitous occurrence. The EU Interreg North-West Europe funded project DGE-ROLLOUT ("Roll-out of Deep Geothermal Energy in North-West Europe", https://www.nweurope.eu/DGE-ROLLOUT) aims to contribute to the characterisation, modelling and exploration of the hydrothermal potential of North-West Europe (NWE). The main focus of the project lies on the Lower Carboniferous carbonate rocks of the Rhenohercynian Basin, which are expected to constitute a favourable DGE reservoir.

The usability of hydrothermal heat and power from carbonate reservoir rocks strongly depends on the local geological setting and lithological features that developed through time. The DGE-ROLLOUT project was initiated based on the experiences attained from the establishment of extensive hydrothermal energy extraction in both the Paris and the Molasse basins. However, all across NWE the utilisation of naturally occurring deep thermal water for energy production has attracted the commonality for several decades:

In the Paris Basin, especially the Ile-de-France region, the main DGE target is the Dogger aquifer which is used extensively for district heating purposes since the 1970s (Le Brun et al. 2011). To date, 46 operations target the generally 1,600 to 1,800 m deep aquifer (Boissavy et al. 2021).

Research on the hydrothermal use of the Molasse Basin in the south of Germany and Austria also started in the 1970s, however, a commercial use was not initiated before the 1990s (Goldbrunner 2010; Homuth 2014, and references therein). To date, 25 projects in Germany[1] and seven projects in Austria (Lassacher et al. 2018) target the mainly Upper Jurassic carbonate reservoir rocks in depths of generally 1,000 to 4,000 m.

Major activities of DGE exploration and exploitation in Belgium, the Netherlands, Great Britain and Ireland developed from the 1970s and 1980s onwards:

In the Belgian province Hainaut, three wells with depths of 1,447 m, 1,579 m, and 5,403 m were drilled to extract thermal water from Lower Carboniferous limestones. The energy extracted from these fissured and karstified carbonate aquifer in the Mons Basin is still used for feeding public buildings (hospital, swimming pool), a residential district and a fish farm with cascading heat supply (Licour 2014; Hoes et al. 2021; Petitclerc, pers. comm.).

In the Netherlands, several exploration wells were drilled into Lower Cenozoic sedimentary rocks, that time. However, geothermal heating and cooling of buildings did not occur until 2006, when thermal water from an abandoned mine was exploited (Kombrink et al. 2012). In 2007, the first geothermal doublet was installed in porous sandstones of Upper Jurassic to Lower Cretaceous age at a depth of c. 1,600 to 1,700 m for the purpose of heating greenhouses (Willems 2012; Mijnlieff 2020).

The first geothermal well in Great Britain was completed in late 1981. The investigation targeted Triassic sandstones at a depth of c. 1,700 m in the Wessex Basin, and production was incorporated in the district heating scheme of the city of Southampton (Thomas & Holliday 1982; Barker et al. 2000).

*Addresses of the authors:
Geological Survey of North Rhine-Westphalia, De-Greiff-Str. 195, 47803 Krefeld, Germany (martin.arndt@gd.nrw.de)

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E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart, Germany, www.schweizerbart.de

Although the supply is presently limited due to mechanical issues, the original well is still operating (Pharaoh, pers. comm.).

In Ireland, several c. 500 m deep boreholes were drilled for the purpose of geothermal investigation in the 1980s (Murphy & Brück 1989); however, no geothermal energy was produced. In 2008, two boreholes with depths of approximately 1,400 m were drilled in Newcastle in the Carboniferous Dublin Basin. Although the planning permission for combined geothermal heat and power production was granted, this project failed to materialise for non-technical reasons (Blake & McConnell 2021).

DGE-ROLLOUT endeavours to gather the existing knowledge in an international and multidisciplinary geoscientific team to refine and promote the energy transition in NWE. Besides the Geological Survey of North Rhine-Westphalia in Germany (Geologischer Dienst Nordrhein-Westfalen – GD NRW) as the lead partner, the national geological surveys of Belgium (Institut Royal des Sciences Naturelles de Belgique – Service Géologique de Belgique – RBINS-GSB), France (Bureau de Recherches Géologiques et Minières – BRGM) and the Netherlands (Nederlandse Organisatie voor Toegepast-natuurwetenschappelijk Onderzoek – TNO) represent the public organisations within this project. In addition, research institutions (Fraunhofer Einrichtung für Energieinfrastrukturen und Geothermie IEG – Fh-IEG; Technische Universität Darmstadt – TU Da; Vlaamse Instelling voor Technologisch Onderzoek – VITO) as well as industry partners (DMT GmbH & Co. KG – DMT; Energie Beheer Nederland B.V. – EBN; RWE Power AG – RWE) play active parts in the execution of the project. In addition to the ten project partners, DGE-ROLLOUT collaborates with a further ten sub- and associated partners, including the British Geological Survey (BGS), the Geological Survey of Ireland (GSI) and the European Geothermal Energy Council (EGEC) (Fig. 1).

The DGE-ROLLOUT project is structured in three administrative work packages (Management, Communication and Long-term Effects), one investment work package (Heat Pump Technology: Usability and Upscaling for NWE) and three implementation work packages. The latter include "Work Package T1 – Mapping and Networking", "Work Package T2 – Decision and Exploration Support", and "Work Package T3 – Testing for Production Optimization" (Salamon & Thiel 2019; Fritschle et al. 2021a). The publications within this special issue mainly deal with the work carried out within those three implementation work packages.

Work Package T1 seeks to provide a reconciled and common knowledge baseline for the DGE market development in the project area. This includes the preparation of a transnationally harmonised depth and thickness map of the Lower Carboniferous (Mississippian/Dinantian) carbonate reservoir rocks, a compilation and evaluation of various geothermally relevant market principles and parameters, as well as the development of facilitation tools for investors and end-users.

Work Package T2 is the financially most substantial work package within the project. The major aim is to fill existing information gaps by acquiring transnational 2D seismic surveys, conducting drilling operations, reprocessing vintage seismic data, and producing a variety of subsurface 2D and 3D models. In addition, specific projects and regions are assessed in collaboration with investors, end-users and the public with regard to their DGE potential.

Work Package T3 aims to increase the efficiency of existing geothermal systems, and to implement new or improved production techniques in the fields of reservoir behaviour, cascading systems, and thermal energy storage to enhance CO_2 reduction. Furthermore, a number of feasibility studies, experimental approaches and numerical simulations investigate the DGE potential as well as cascading opportunities in selected prospect localities.

This ZDGG special issue, which originates from presentations held at the 19th International Congress on the Carboniferous and Permian (XIX ICCP 2019) in Cologne (Germany), introduces the first results of the DGE-ROLLOUT project and is supplemented by studies covering similar topics outside the scope of the project.

All contributions, which are shortly introduced in the following paragraphs, tackle essential questions in the light of the DGE potential of Carboniferous carbonate rocks in NWE, such as: (i) How has deep geothermal energy developed in NWE over the past decades? (ii) What are the characteristics and potentials of the Lower Carboniferous carbonate rocks in the subsurface of NWE? (iii) How can the integration of various geothermal data and modelling approaches improve our understanding of DGE aquifers? (iv) What is the impact of fault zones and alterations on the DGE potential of an anticipated carbonate reservoir?

Broothaers et al. introduce insights into the development of DGE in the Campine Basin in Northern Belgium, which started in the 1950s when the Tournhout well was one of the first to confirm the existence and hydrothermal potential of the Lower Carboniferous Limestone Group. Since then, the results of further explorations and renewed interest in DGE led to more investigations – including the recent Balmatt project in Mol, which demonstrates the feasibility of a geothermal power plant and the technical challenges that emerge from such a project.

The roll-out of the deep geothermal potential of the Lower Carboniferous in Great Britain is thoroughly presented by **Pharaoh et al.** who evaluate the geothermal prospectivity of early Carboniferous limestones to the north and south of the Wales-Anglo-Brabant Massif. The authors point out various geological aspects for the assessment of these potential geothermal reservoirs from provincial down to outcrop scales.

The contribution of **Narayan et al.** further evaluates the geothermal potential and possible energy outtake for six specific regions in England and Wales based on a variety of geothermal parameters including burial depth, temperatures and transmissivities. The authors demonstrate that Mississippian lime- and dolostone horizons can have a high productivity although they have not been considered potential geothermal targets in Great Britain to date.

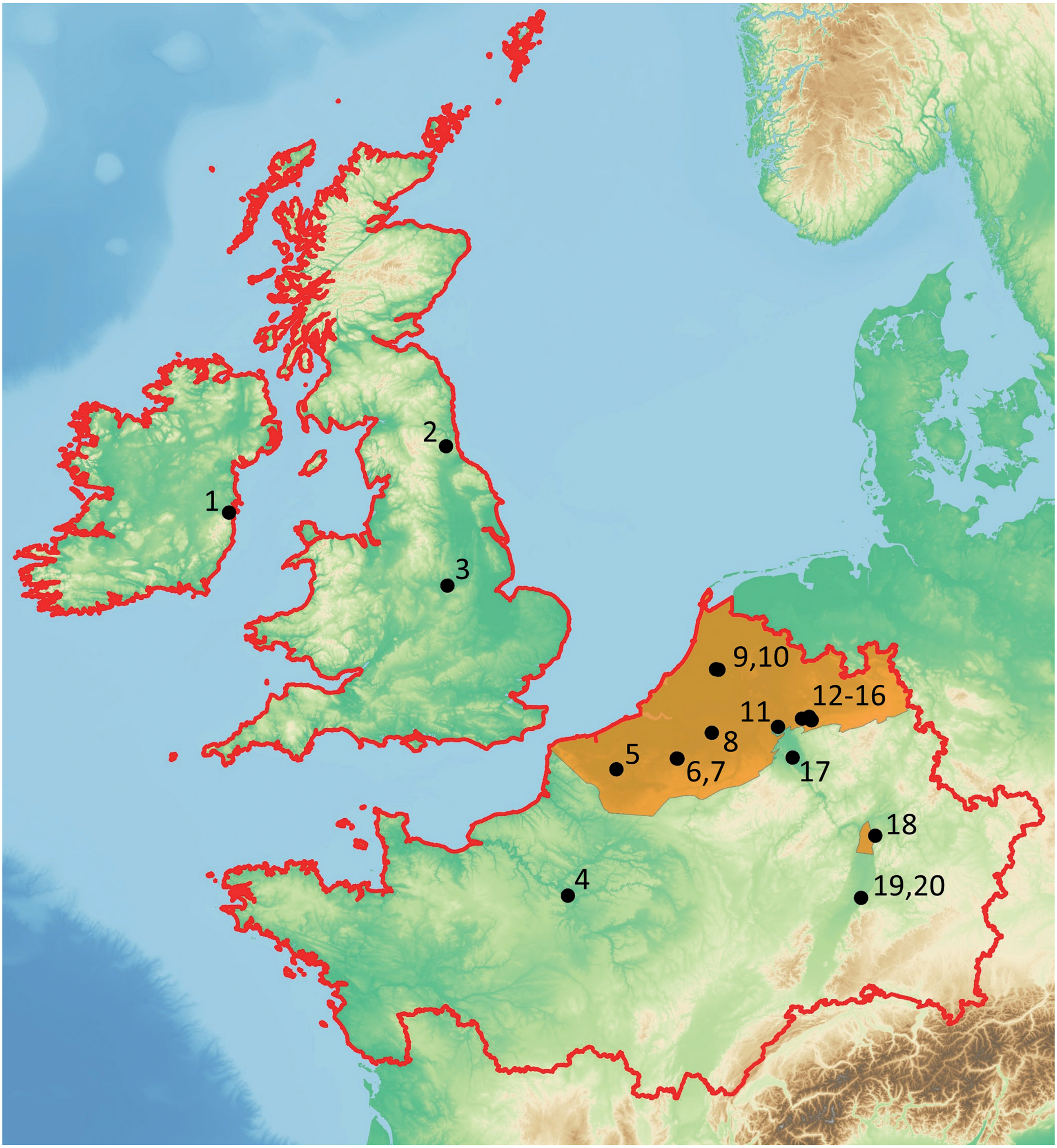

Fig. 1: Outline of the Interreg NWE area (red) and the principal DGE-ROLLOUT project area (orange). Project partners of the DGE-ROLLOUT project include: 1 – Geological Survey of Ireland; 2 – Durham University; 3 – British Geological Survey; 4 – Bureau de Recherches Géologiques et Minières; 5 – Université de Lille; 6 – Institut Royal des Sciences Naturelles de Belgique – Service Géologique de Belgique; 7 – European Geothermal Energy Council; 8 – Vlaamse Instelling voor Technologisch Onderzoek; 9 – Energie Beheer Nederland B.V.; 10 – Nederlandse Organisatie voor Toegepast-natuurwetenschappelijk Onderzoek; 11 – Geologischer Dienst Nordrhein-Westfalen; 12 – DMT GmbH & Co. KG; 13 – Deutsches Bergbau-Museum; 14 – unique Wärme GmbH & Co. KG; 15 – Ruhr-Universität Bochum; 16 – Fraunhofer Einrichtung für Energieinfrastrukturen und Geothermie IEG; 17 – RWE Power AG; 18 – Technische Universität Darmstadt; 19 – Deutsche Erdwärme GmbH & Co. KG; 20 – GeoThermal Engineering GmbH.

Pracht et al. provide a comprehensive and detailed overview of the lithology, stratigraphy and structure of the Mississippian throughout Ireland including an estimation of the geothermal potentials of the Dublin and Lough Allen basins.

The 3D subsurface geometry of Dinantian carbonate reservoir rocks in northern France and southwestern Belgium is presented by **Laurent et al.**, whose modelling approach is based on data of 1,128 boreholes and 532 km of newly reprocessed seismic reflection profiles. The detailed model indicates the extension of the potential reservoir to the major frontal and lateral ramps of the Allochthon Main Basal Thrust of the northern Variscan front.

A similar 3D modelling approach was performed for the subsurface of the German federal state North Rhine-Westphalia (NRW). **Arndt** gives an outline of the geothermal potential of Lower Carboniferous rocks including their expected depth, thickness and estimated temperatures. Major implications for the model derive from the lithostratigraphic features of the Dinantian platform carbonate rocks and the Kulm deposits both of which are also comprehensively described in this contribution.

Besides the aforementioned studies, the deep subsurface of NWE is also intensely explored by the Dutch project partners EBN and TNO within the scope of the SCAN programme[2] from which several reports have been published. These include the characterisation of the Dinantian with seismic interpretations and depth conversions (ten Veen et al. 2019), a petrophysical report (Carlson 2019), a facies analysis (Mozafari et al. 2019), a burial and structural analysis (Bouroullec et al. 2019), a fracture characterisation (van Leverink & Geel 2019), and a temperature model (Veldkamp & Hegen 2020).

Further local and regional studies within this special issue deal with various aspects of deep subsurface carbonate rocks from the Middle Devonian to the Lower Carboniferous:

In westernmost Germany, green-field operations are currently being undertaken to include hydrothermally acquired energy from Middle to Upper Devonian and Lower Carboniferous limestone horizons into the district heating network currently fed by the lignite-fired power plant Weisweiler. **Fritschle et al.** provide insights into the local geology, present their preliminary geotectonic 3D model and outline the first exploration steps undertaken towards the geothermal prospect.

Pederson et al. present the results of a multi-proxy field and laboratory study of Devonian reefal carbonate rocks in the Steltenberg quarry of the Northern Rhenish Massif in NRW. The authors describe the impact of a regional fault zone on the geothermal properties of the carbonate unit and reveal various forms of alteration during the distinct stages of the development of the potential reservoir.

The final contribution of the special issue presents a custom-made stochastic workflow for the quantification of uncertainties in 3D models in the northern Upper Rhine Graben by **Van der Vaart et al**. An assessment of the explorational risks and guidance measures to reduce uncertainties in this prominent central European geothermal region is provided.

All of the here published studies focus on important constituents for promoting the use of deep geothermal energy and investigating the deep subsurface of North-West Europe. DGE-ROLLOUT is convinced that the extensive development of hydrothermal energy extraction can considerably contribute to decarbonisation and to the expansion of renewable resources to sustain the environment and to nurture the citizen's well-being. We hope that our research will enhance the awareness of the potential of deep geothermal exploration and will emphasise its importance for further efforts in advancing this future-oriented technology in the light of the current energy transition.

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